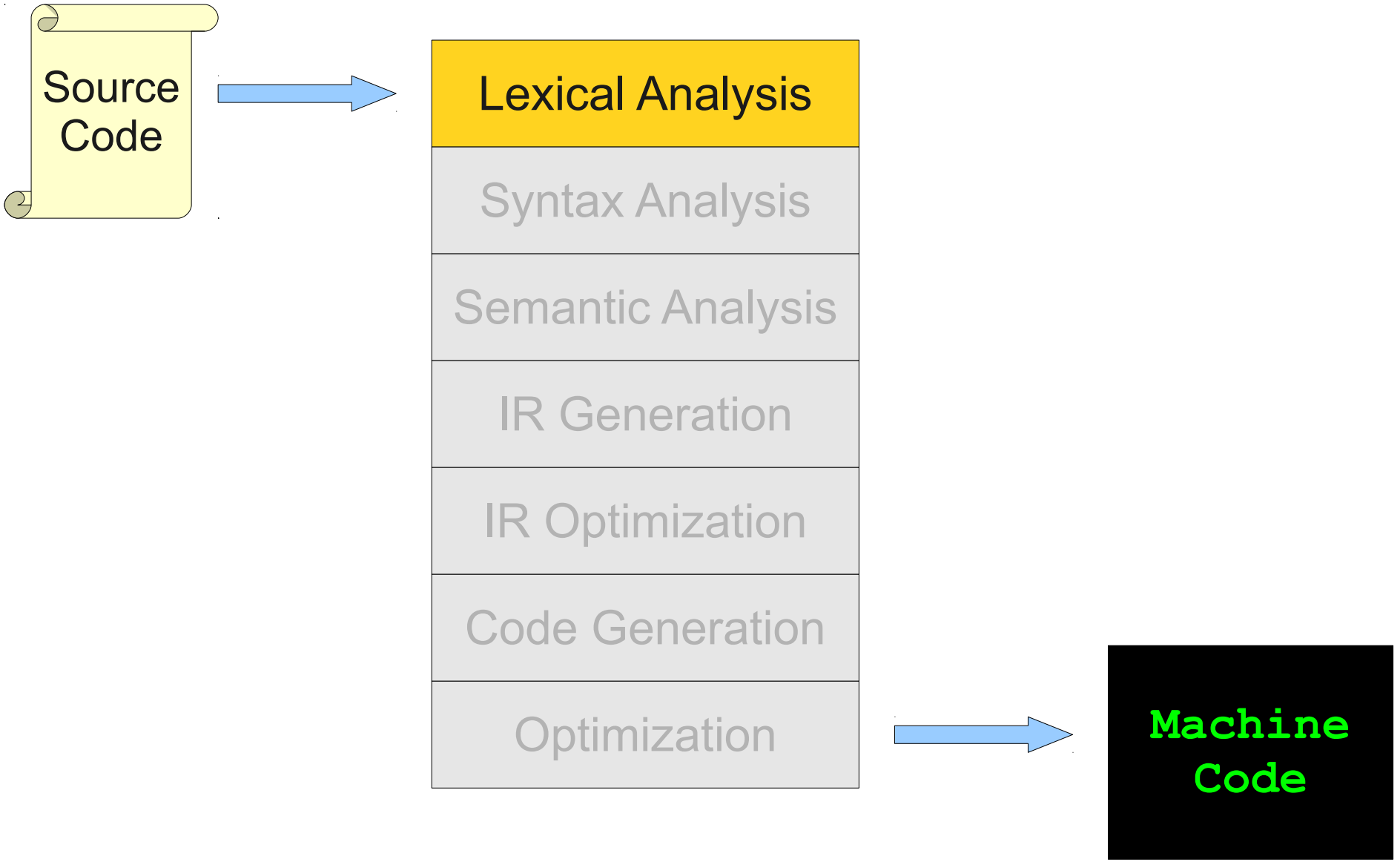
Lexical Analysis

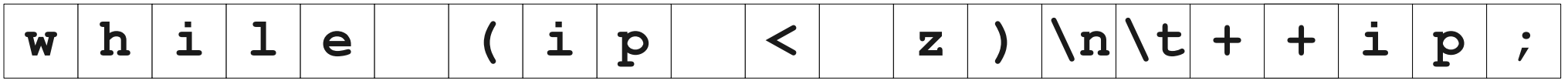
Announcements

- **Programming Assignment 1 Out**
  - Due Friday, July 1 at 11:59 PM.
- Check the website for readings:
  - Decaf Specification
  - Lexical Analysis
  - Intro to **`flex`**
  - Programming Assignment 1

Where We Are


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

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

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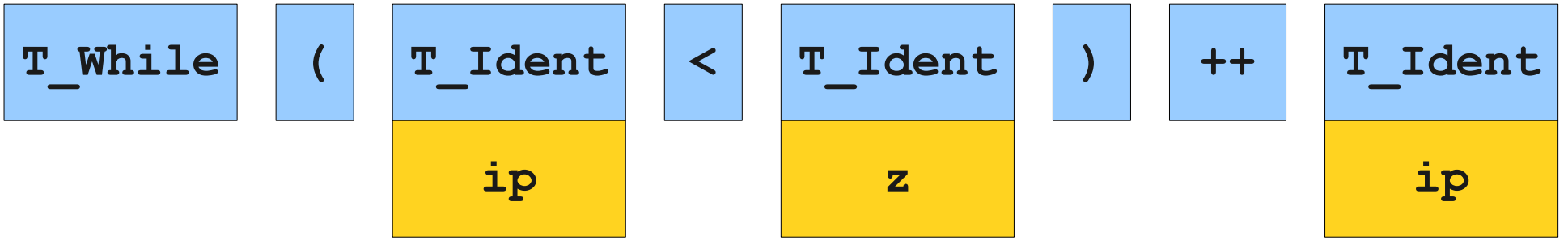

w	h	i	l	e		(	i	p		<		z	)	\n	\t	+	+	i	p	;

```
while (ip < z)
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```

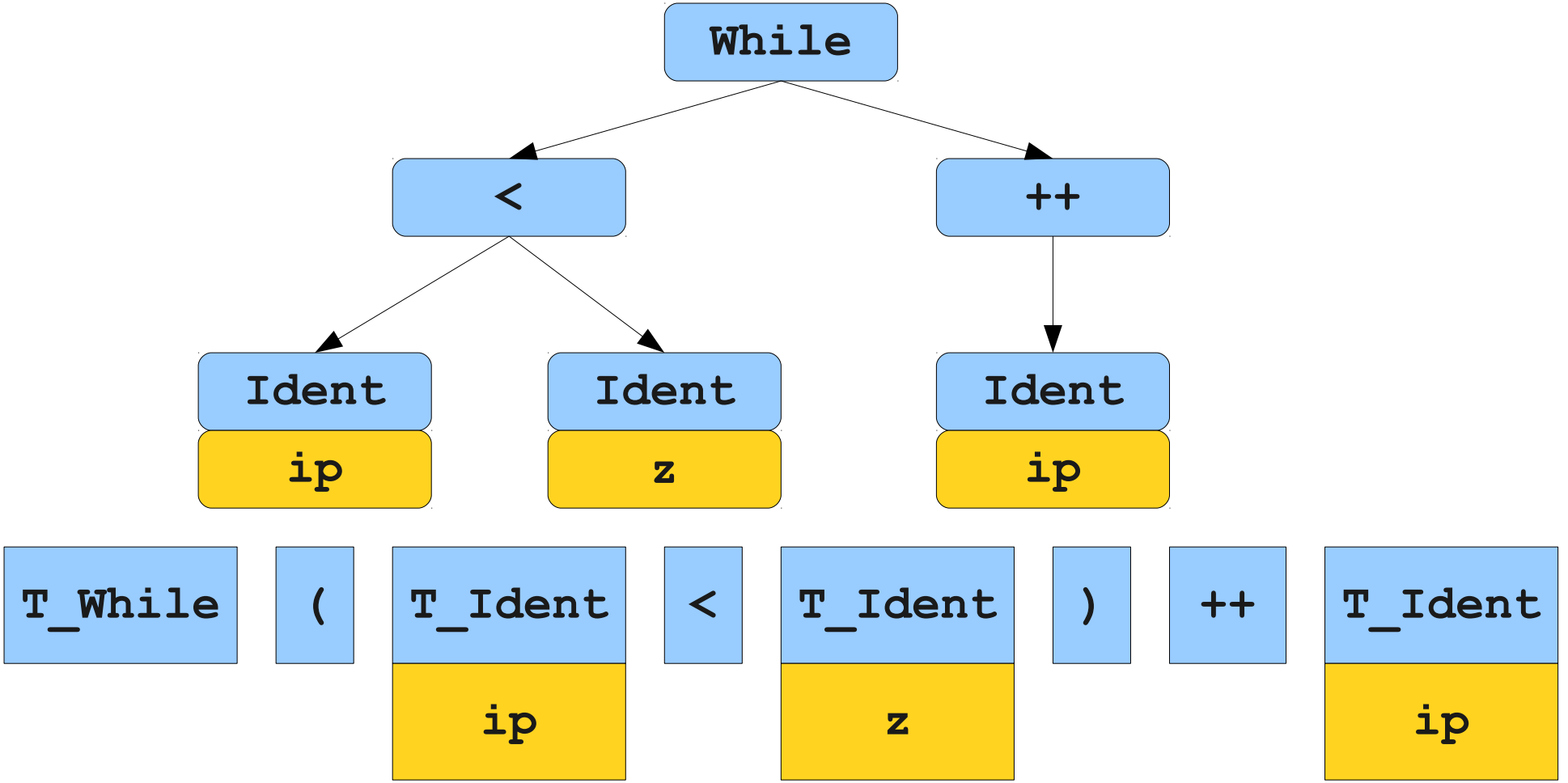

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```
do[for] = new 0;
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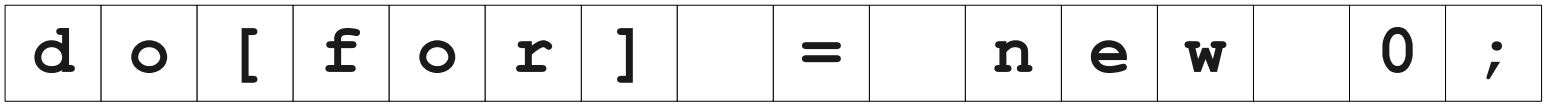


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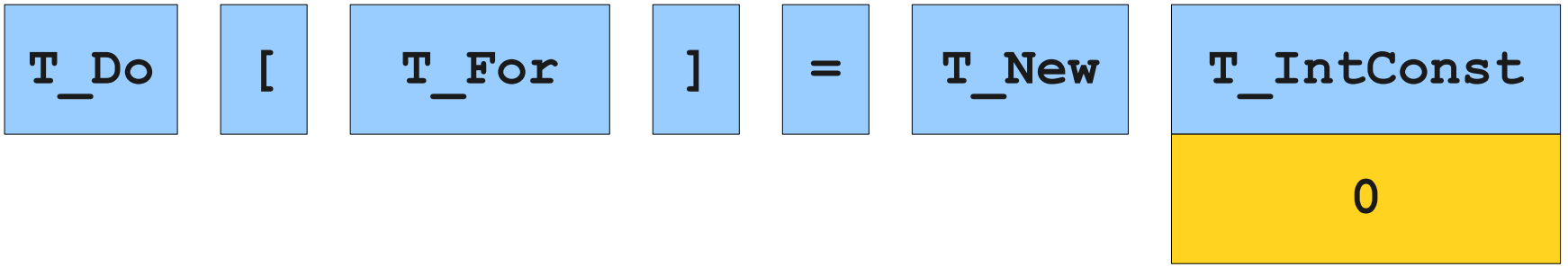
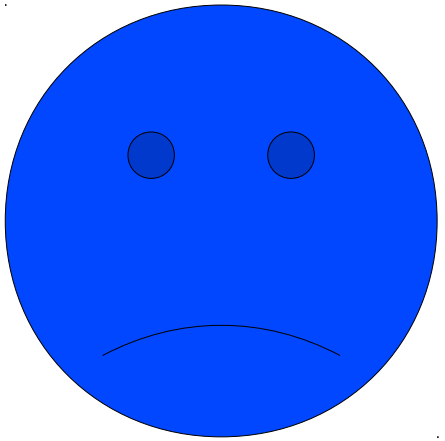


d	o	[	f	o	r	]		=		n	e	w		0	;

```
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;
```

Why do Lexical Analysis?

- Dramatically simplify parsing.
  - Eliminate whitespace.
  - Eliminate comments.
  - Convert data early.
- Separate out logic to read source files.
  - Potentially an issue on multiple platforms.
  - Can optimize reading code independently of parser.
  - An extreme example...

I am having some difficulty compiling a C++ program that I've written.

This program is very simple and, to the best of my knowledge, conforms to all the rules set forth in the C++ Standard. [...]

The program is as follows:

Source:
http://stackoverflow.com/questions/5508110/why-is-this-program-erroneously-rejected-by-three-c-compilers

I am having some difficulty compiling a C++ program that I've written.

This program is very simple and, to the best of my knowledge, conforms to all the rules set forth in the C++ Standard. [...]

The program is as follows:

```
#include <iostream>

int main(int argc, char** argv)
{
    std::cout << "Hello World!" << std::endl;
    return 0;
}
```

Source:
http://stackoverflow.com/questions/5508110/why-is-this-program-erroneously-rejected-by-three-c-compilers

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The program is as follows:

```
#include <iostream>

int main(int argc, char** argv)
{
    std::cout << "Hello World!" << std::endl;
    return 0;
}
```

```
c:\dev>g++ helloworld.png
helloworld.png: file not recognized: File format not recognized
collect2: ld returned 1 exit status
```

Source:
http://stackoverflow.com/questions/5508110/why-is-this-program-erroneously-rejected-by-three-c-compilers

Goals of Lexical Analysis

- Convert from physical description of a program into sequence of of **tokens**.
- Each token is associated with a **lexeme**.
- Each token may have optional **attributes**.
- The token stream will be used in the parser to recover the program structure.

Challenges in Lexical Analysis

- How to partition the program into lexemes?
- How to label each lexeme correctly?

Not-so-Great Moments in Scanning

- FORTRAN: Whitespace is irrelevant

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

Thanks to Prof. Alex Aiken

Not-so-Great Moments in Scanning

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DO 5 I = 1,25
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Not-so-Great Moments in Scanning

- 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

Not-so-Great Moments in Scanning

- C++: Nested template declarations

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

Thanks to Prof. Alex Aiken

Not-so-Great Moments in Scanning

- C++: Nested template declarations

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

Thanks to Prof. Alex Aiken

Not-so-Great Moments in Scanning

- C++: Nested template declarations

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

Thanks to Prof. Alex Aiken

Not-so-Great Moments in Scanning

- C++: Nested template declarations

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

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

Thanks to Prof. Alex Aiken

Not-so-Great Moments in Scanning

- C++: Types nested in templates

Not-so-Great Moments in Scanning

- C++: Types nested in templates

```
template <typename T>
void MyFunction(T val) {
    T::iterator itr;
}
```

Not-so-Great Moments in Scanning

- C++: Types nested in templates

```
template <typename T>
void MyFunction(T val) {
    typename T::iterator itr;
}
```

Not-so-Great Moments in Scanning

- C++: Types nested in templates

```
template <typename T>
void MyFunction(T val) {
    typename T::iterator itr;
}
```

- Can be hard to label tokens correctly.

Not-so-Great Moments in Scanning

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

Thanks to Prof. Alex Aiken

Not-so-Great Moments in Scanning

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

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

Thanks to Prof. Alex Aiken

Not-so-Great Moments in Scanning

- 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

Defining a Lexical Analysis

- Define a set of tokens.
- Define the set of lexemes associated with each token.
- Define an algorithm for resolving conflicts that arise in the lexemes.

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;
}
```

T_For	**{**
T_IntConstant	**}**
T_Int	**<<**
T_Identifier	**;**
=	**<**
(	**[**
)	**]**
++	

Choosing Good Tokens

- Very much dependent on the language.
- Typically:
  - Give keywords their own tokens.
  - Give different punctuation symbols their own tokens.
  - Discard irrelevant information (whitespace, comments)

Defining Sets of Strings

String Terminology

- An **alphabet** Σ is a set of characters.
- A **string** over Σ is a finite sequence of elements from Σ.
- Example:
  - Σ = { ☺ , ☼ }
  - Valid strings include ☺ , ☺ ☺ , ☺☼, ☺ ☺☼, etc.
- The **empty string** of no characters is denoted ε.

Languages

- A **language** is a set of strings.
- Example: Even numbers
  - Σ = {0, 1, 2, 3, 4, 5, 6, 7, 8, 9}
  - L = {0, 2, 4, 6, 8, 10, 12, 14, … }
- Example: C variable names
  - Σ = ASCII characters
  - L = {a, b, c, …, A, B, C, …, _, aa, ab, … }
- Example: L = {static}

Regular Languages

- A subset of all languages that can be defined by **regular expressions**.
- Small subset of all languages, but surprisingly powerful in practice:
  - Capture a useful class of languages.
  - Can be implemented efficiently (more on that later).

Regular Expressions

- Any character is a regular expression matching itself.
- ε is a regular expression matching the empty string.
- If R_1 and R_2 are regular expressions, then
  - R_1R_2 is a regular expression matching the **concatenation** of the languages.
  - $R_1 \mid R_2$ is a regular expression matching the **disjunction** of the languages.
  - R_1^* is a regular expression matching the **Kleene closure** of the language.
  - (R) is a regular expression matching R.

Regular Expressions In Action

- Example: Even Numbers

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

Regular Expressions In Action

- Example: Even Numbers

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

- Notational simplification: Definitions

  Sign = + | -

  OptSign = Sign | ε

  Digit = 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

  EvenDigit = 0 | 2 | 4 | 6 | 8

  EvenNumber = OptSign Digit* EvenDigit

Regular Expressions In Action

- Example: Even Numbers

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

- Notational simplification: Multi-Way Disjunction

  Sign = + | -

  OptSign = Sign | ε

  Digit = **[0123456789]**

  EvenDigit = **[02468]**

  EvenNumber = OptSign Digit* EvenDigit

Regular Expressions In Action

- Example: Even Numbers

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

- Notational simplification: Ranges

  Sign = + | -

  OptSign = Sign | ε

  Digit = **[0-9]**

  EvenDigit = [02468]

  EvenNumber = OptSign Digit* EvenDigit

Regular Expressions In Action

- Example: Even Numbers

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

- Notational simplification: Zero-or-One

  Sign = + | -

  OptSign = Sign**?**

  Digit = [0-9]

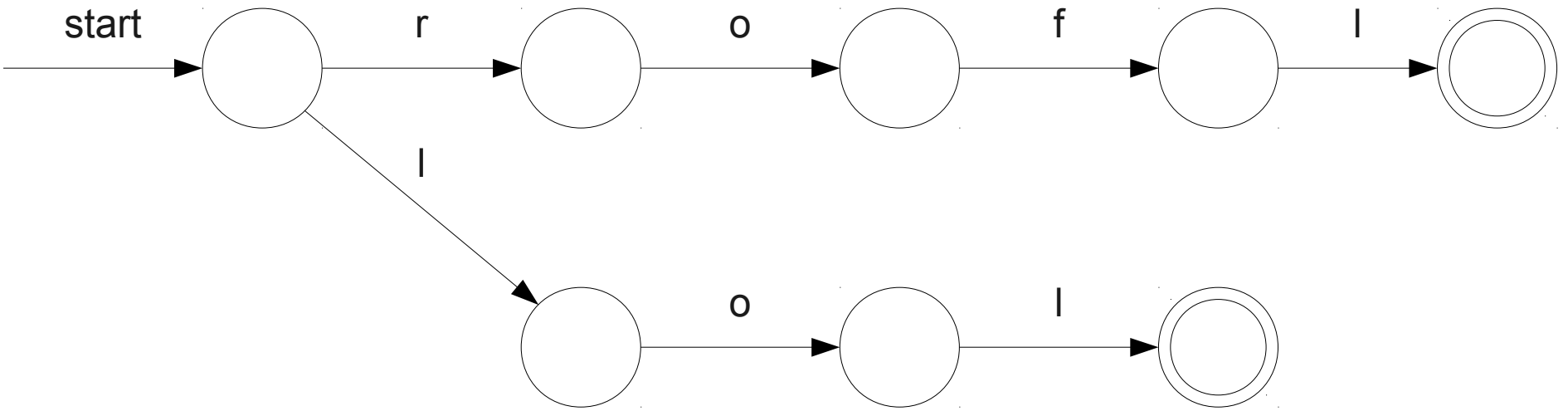
  EvenDigit = [02468]

  EvenNumber = OptSign Digit* EvenDigit

Implementing Regular Expressions

- Regular expressions can be implemented using **finite automata**.
- There are two 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 NFA



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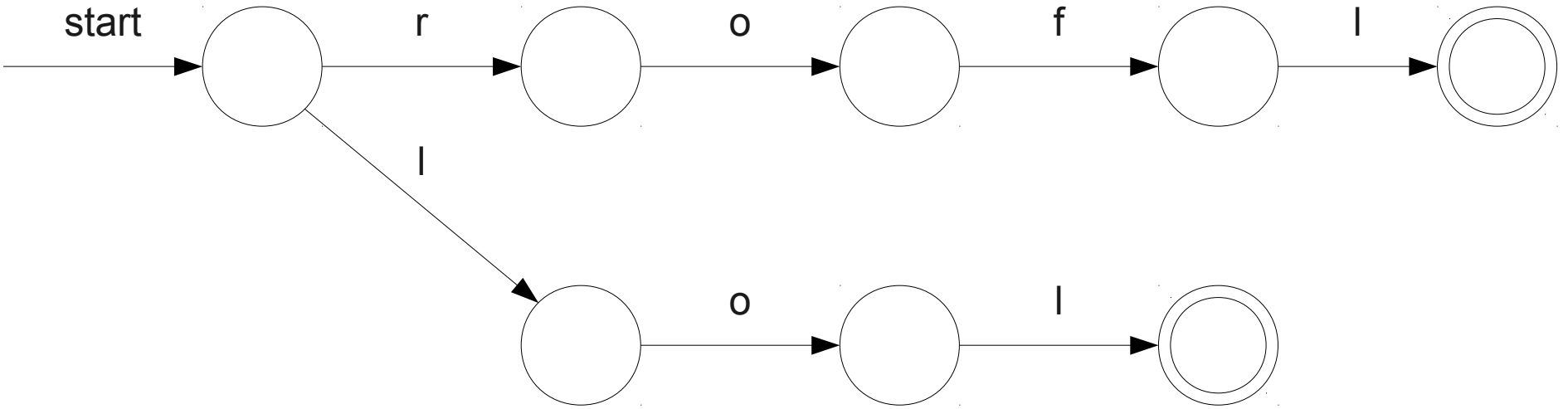

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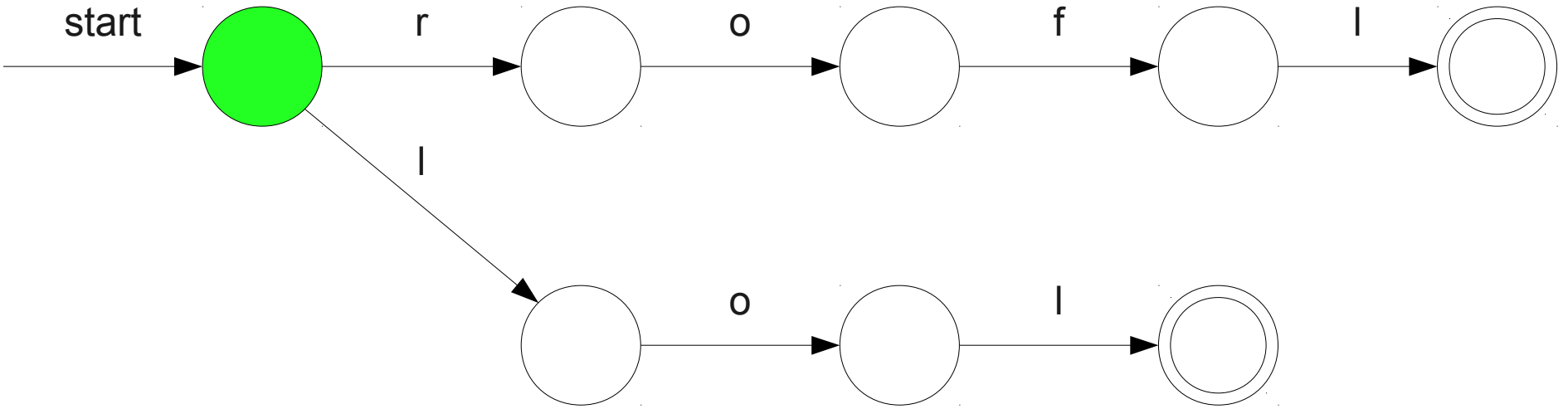

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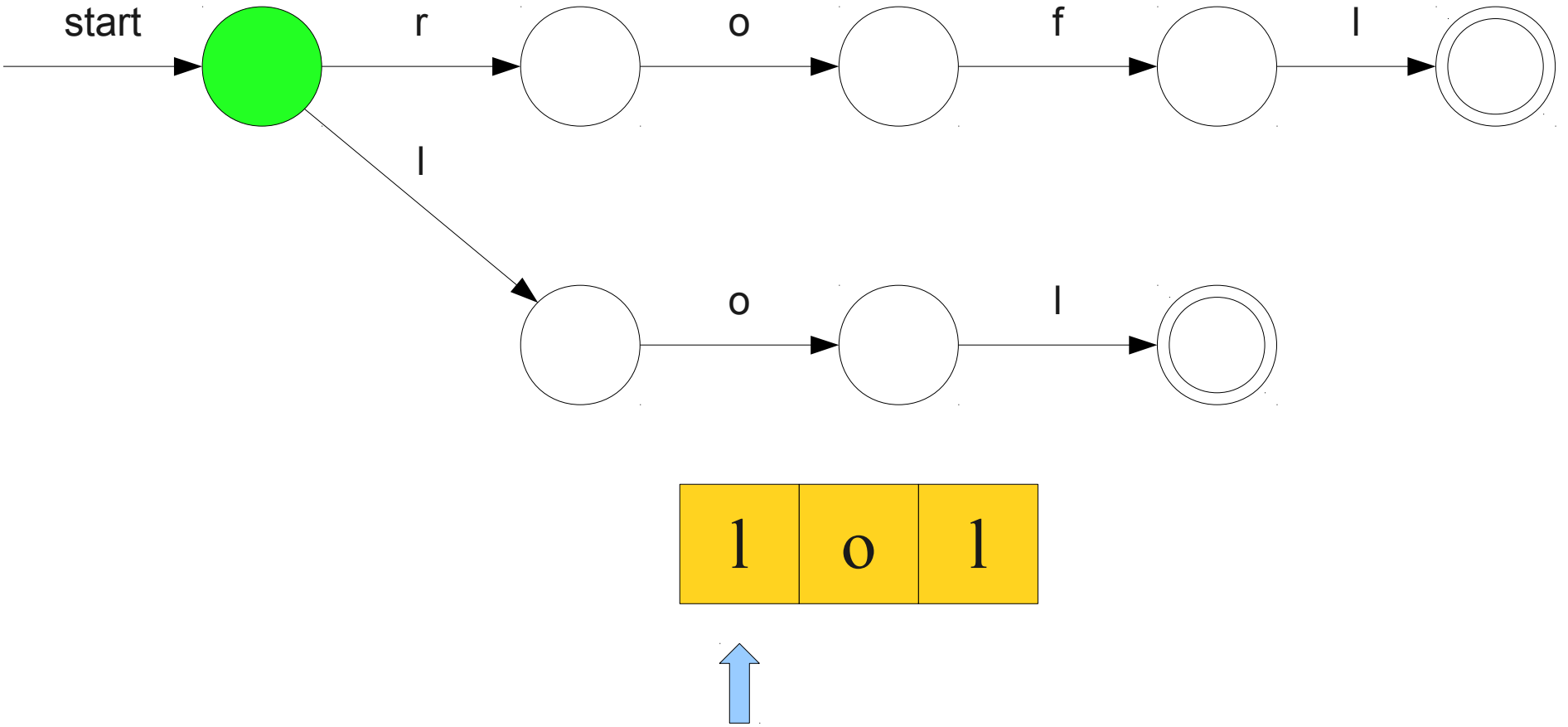

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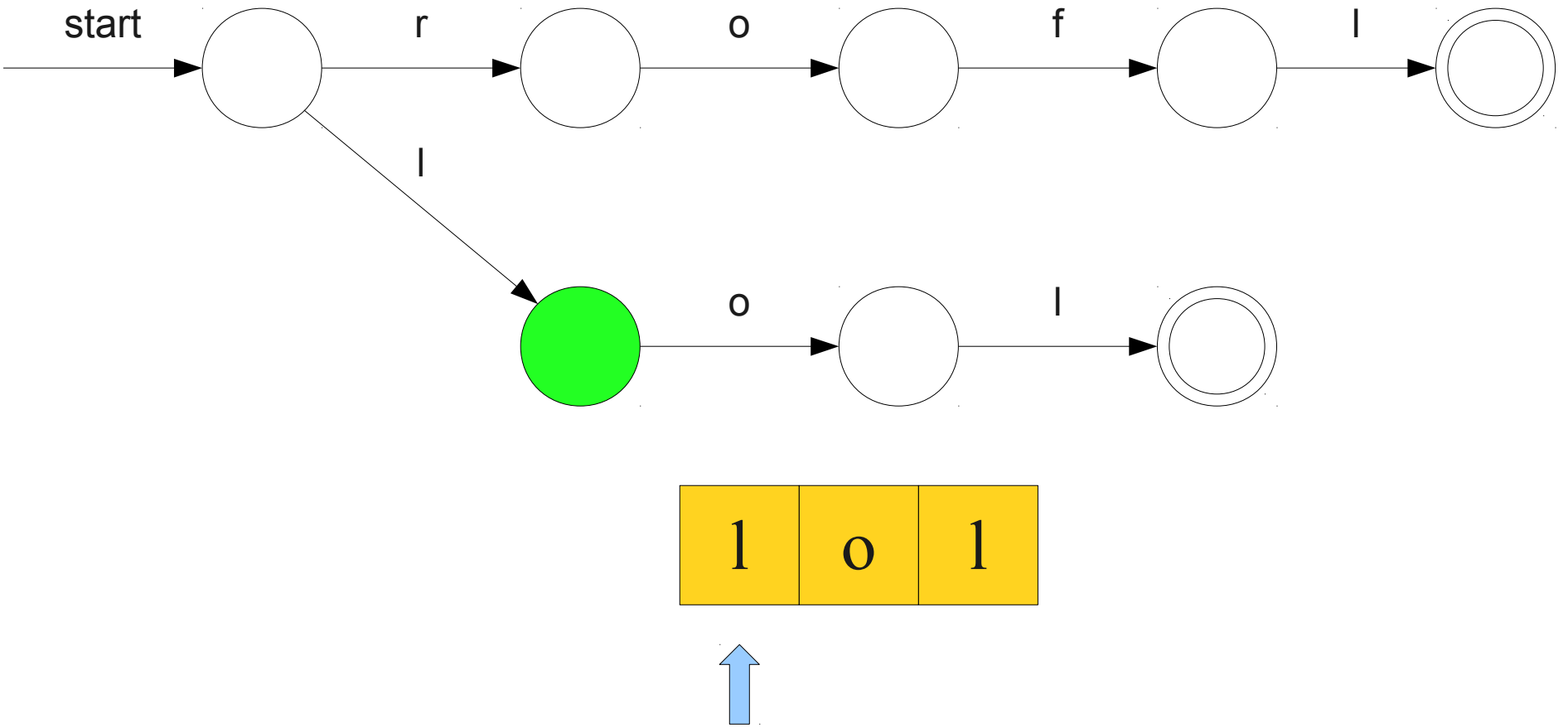

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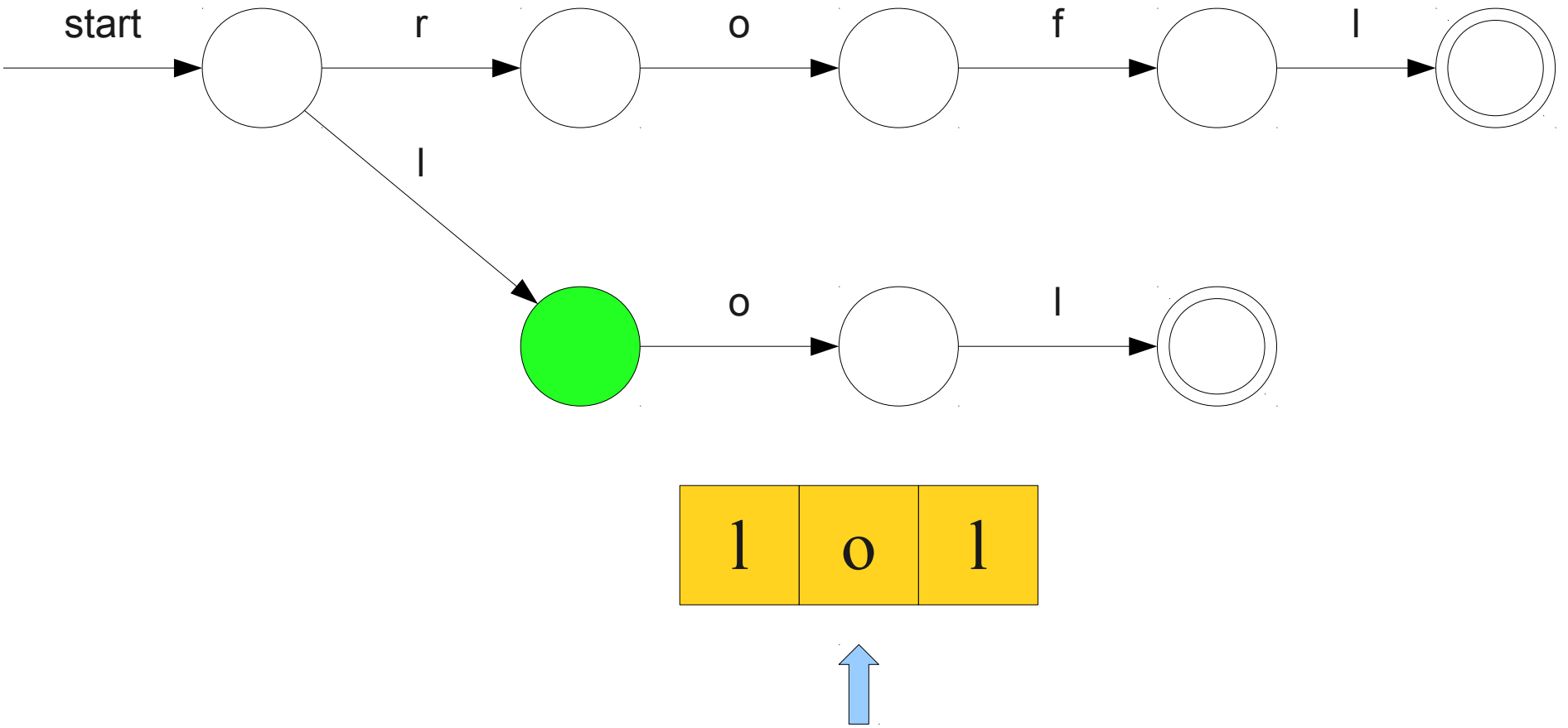

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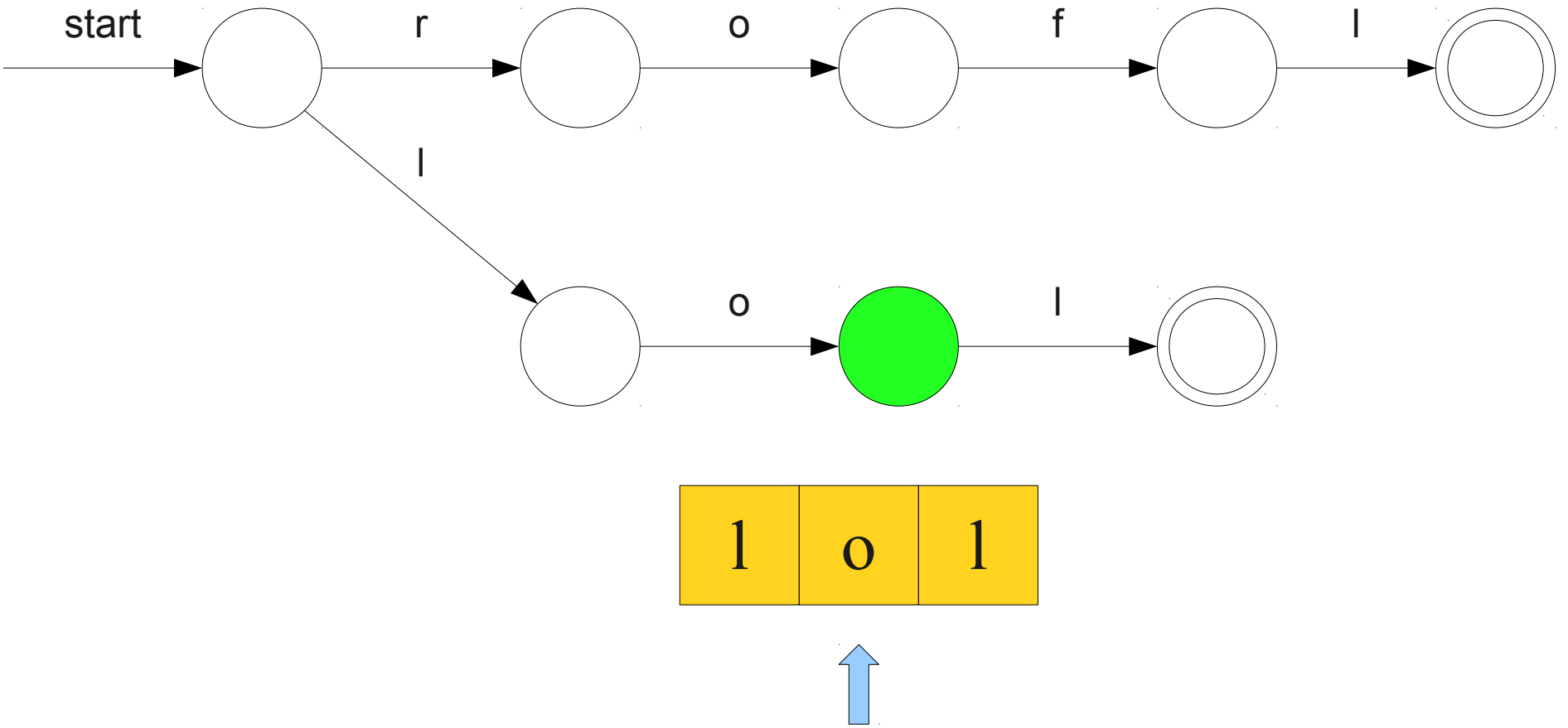

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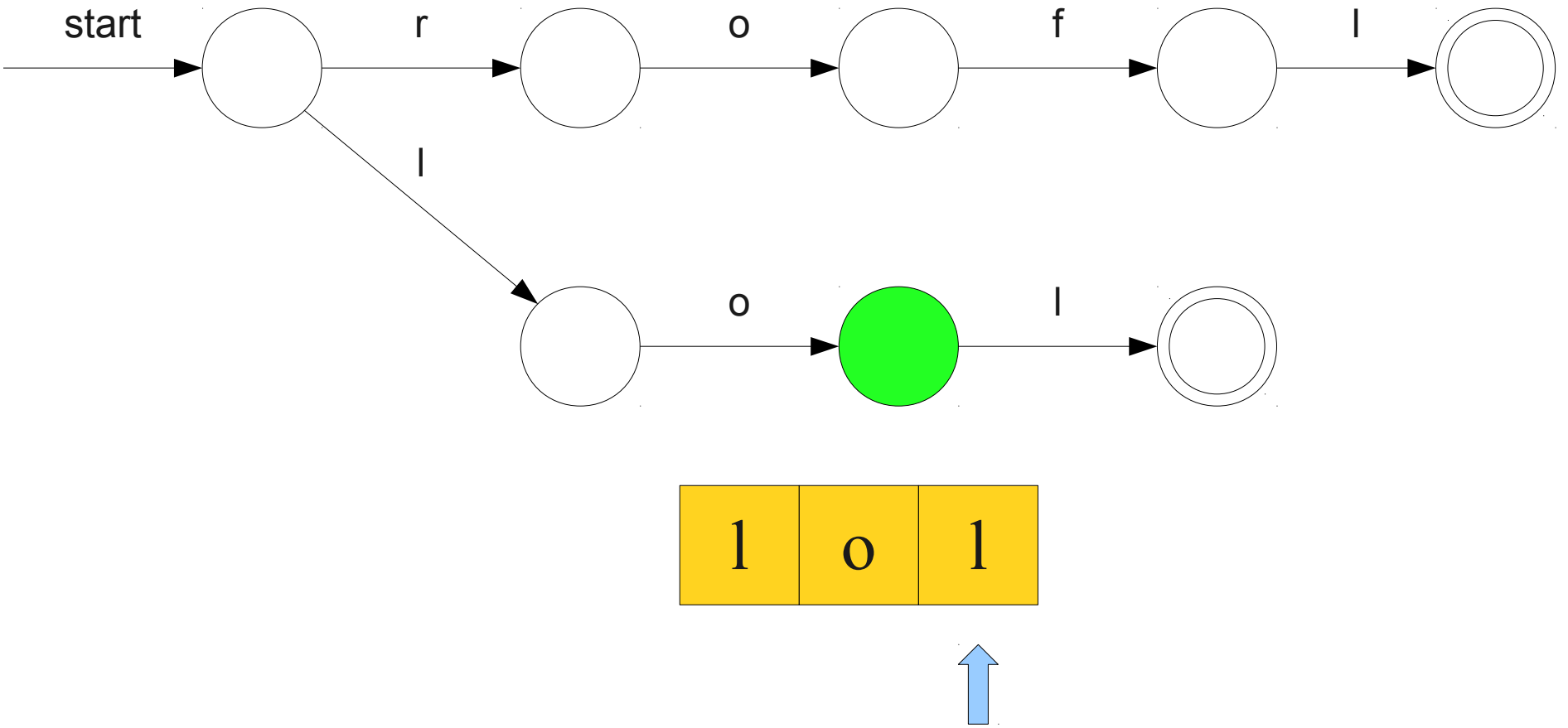

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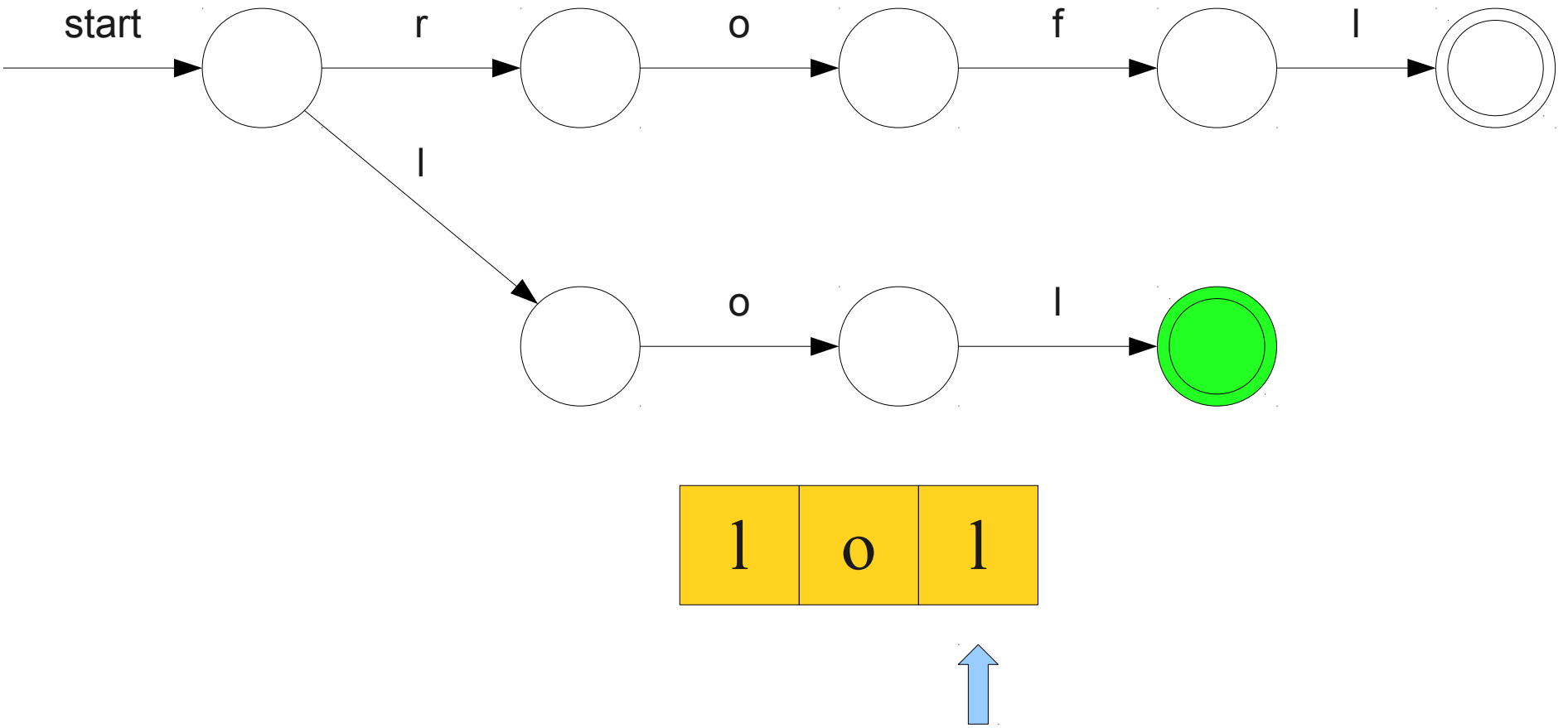

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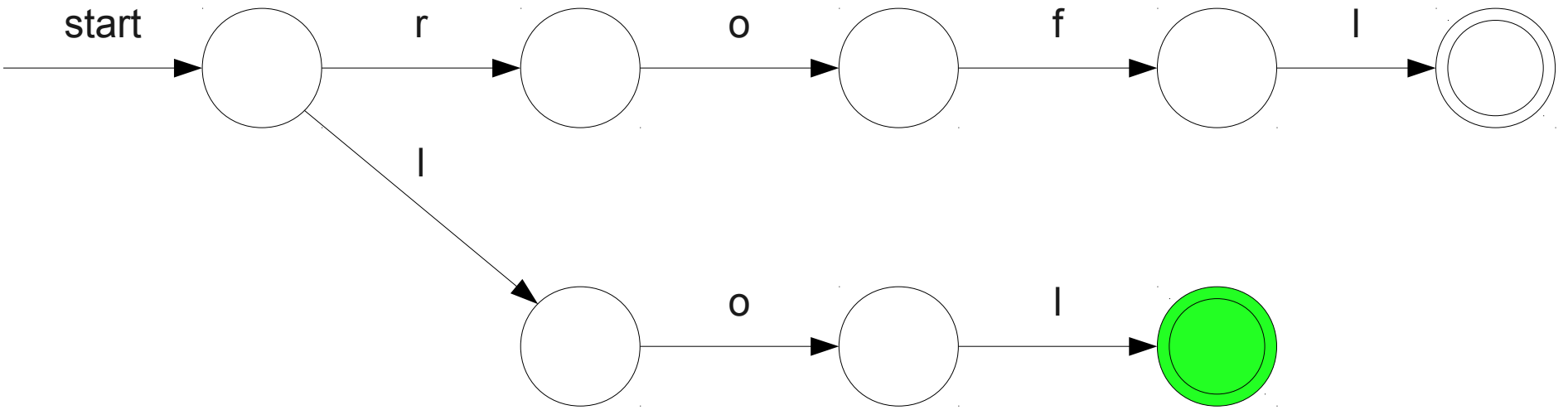

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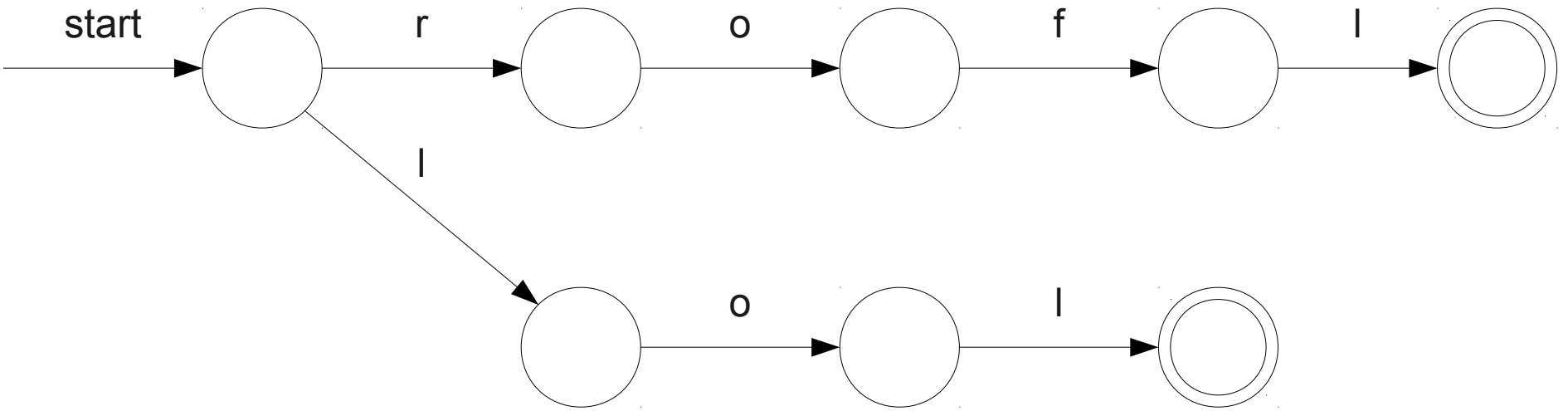

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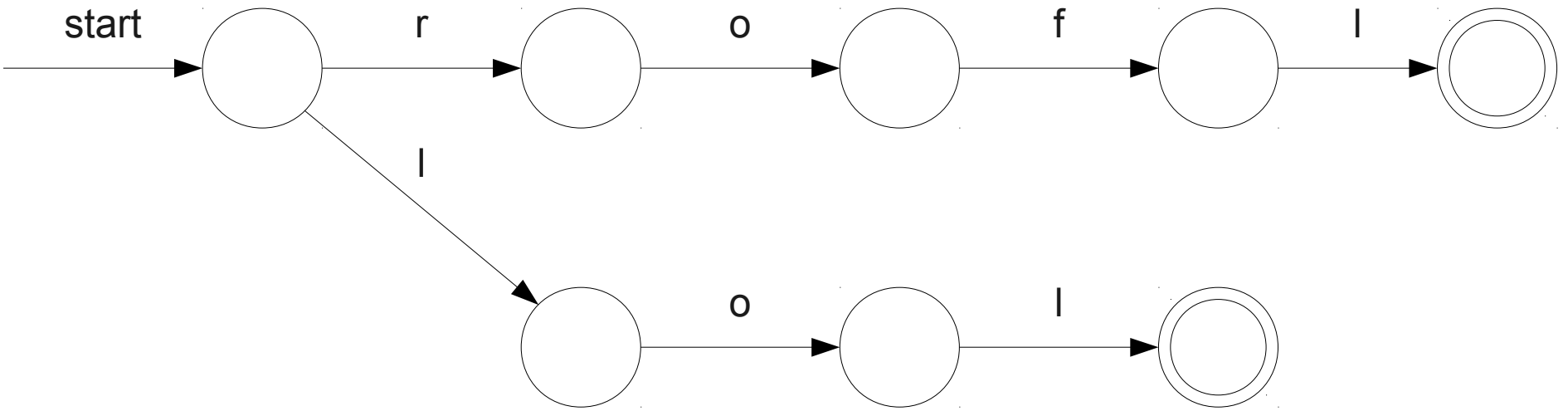

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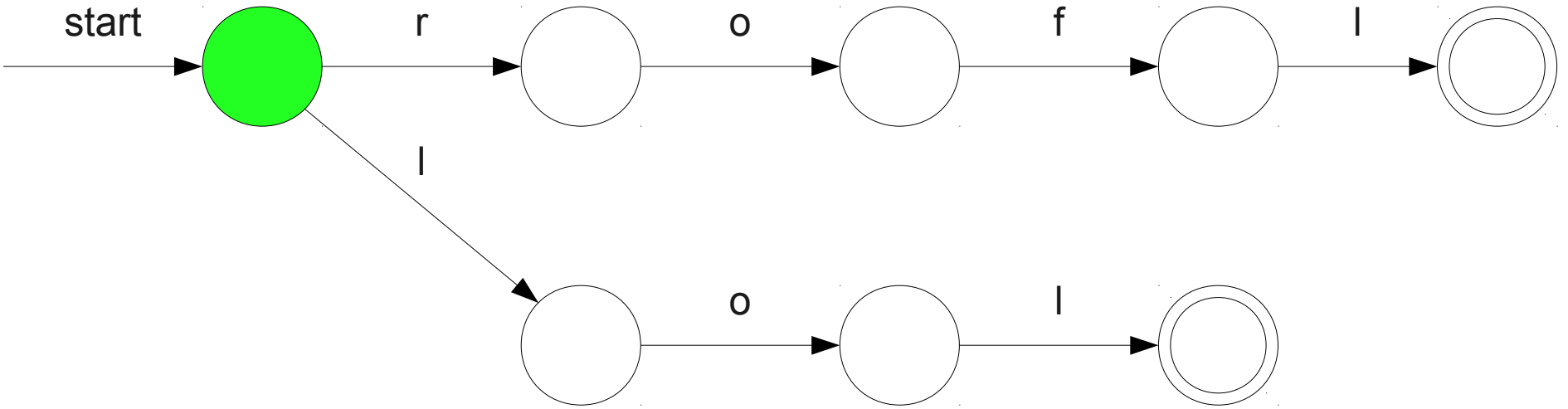

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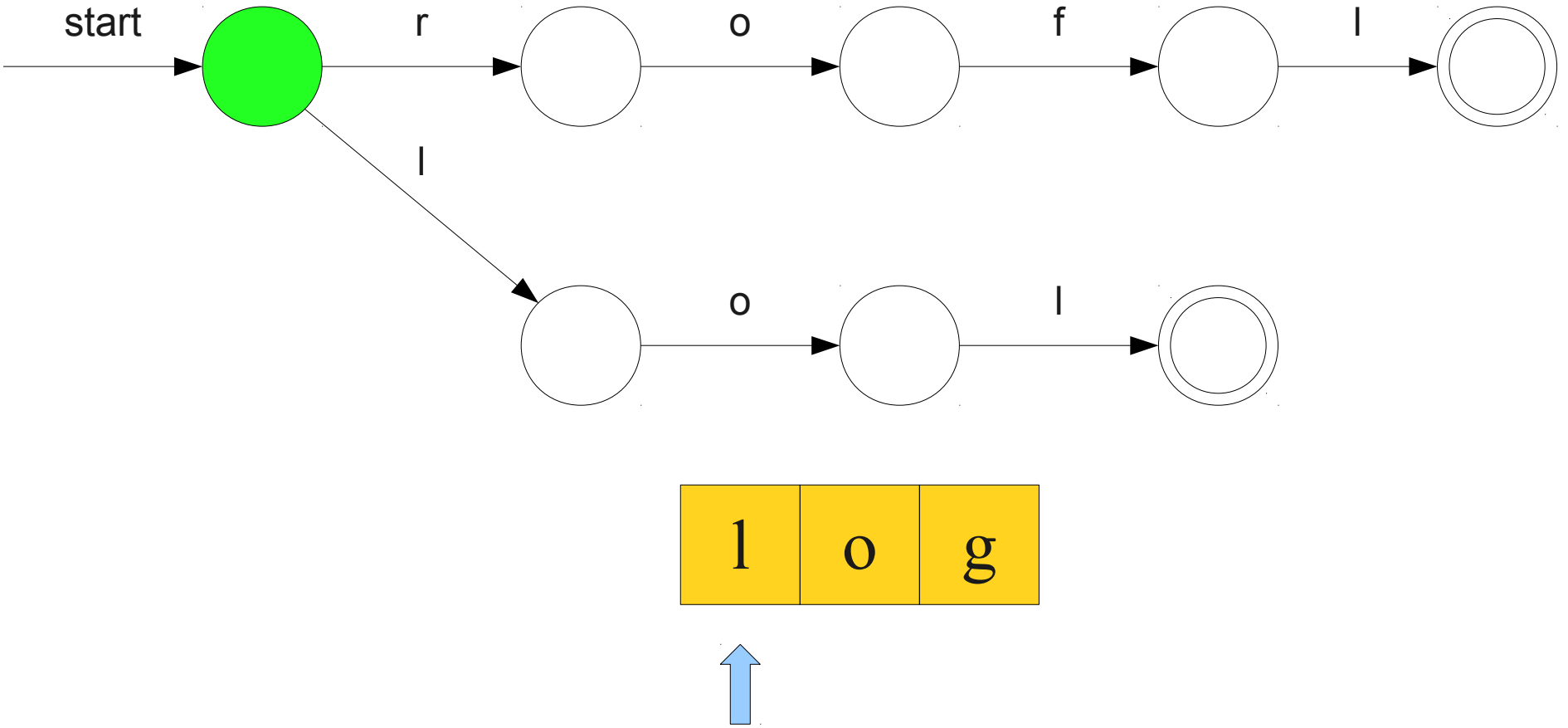

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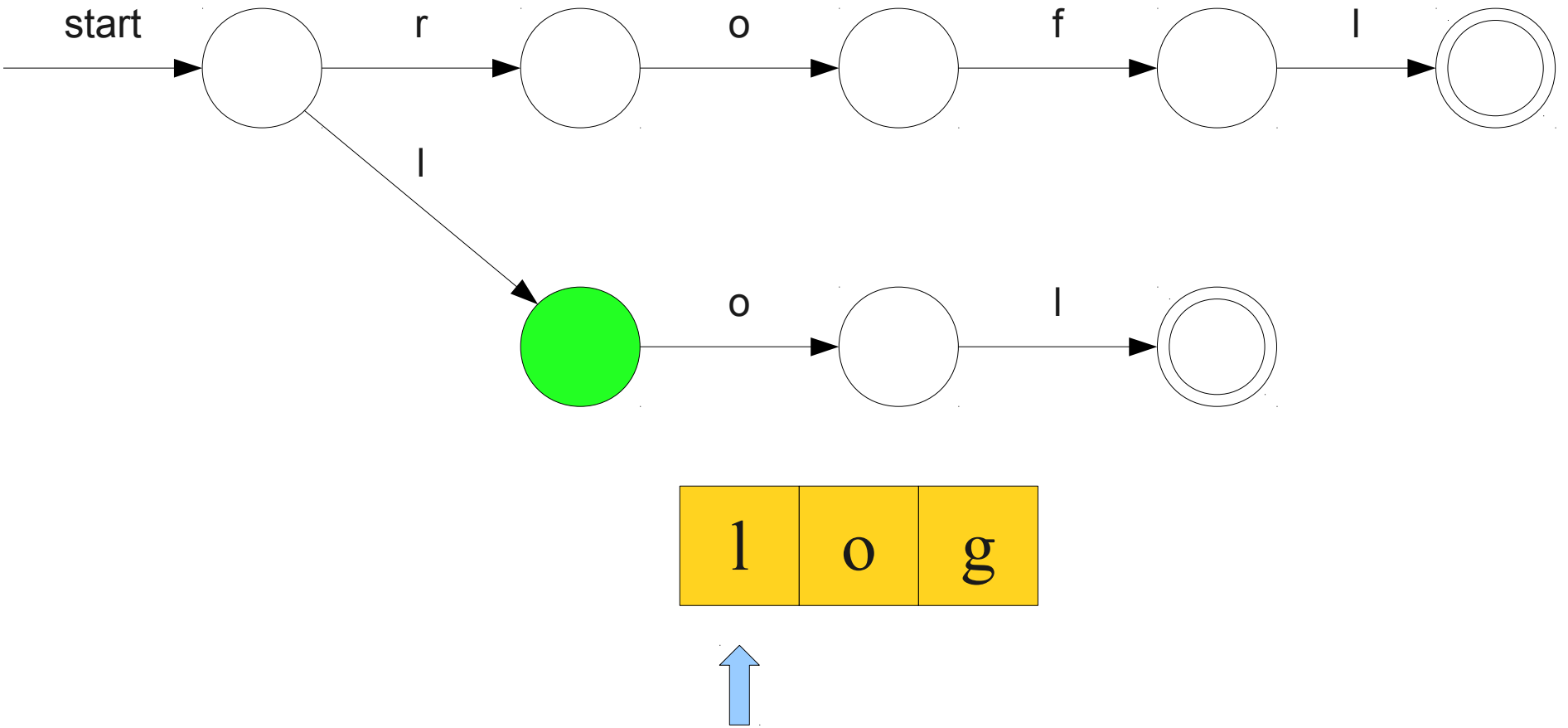

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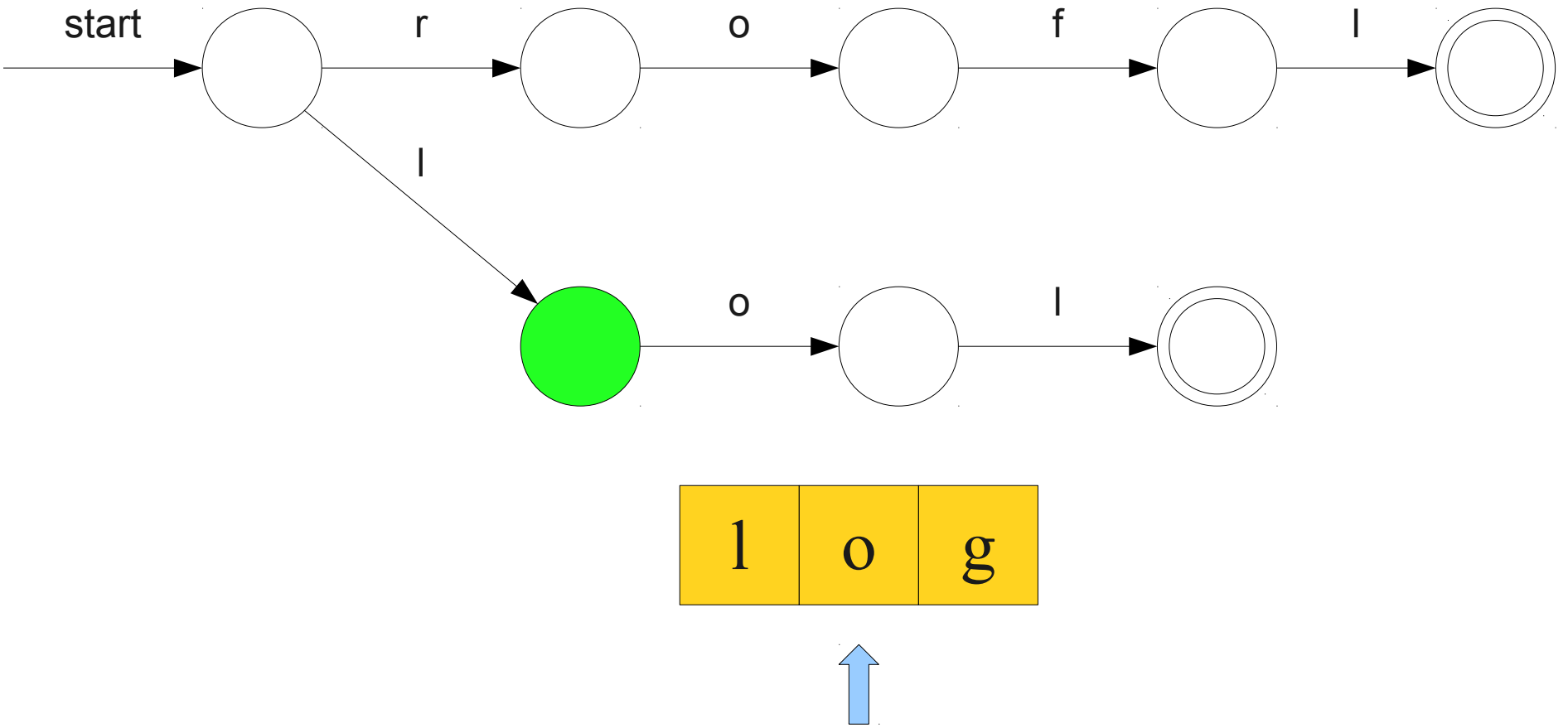

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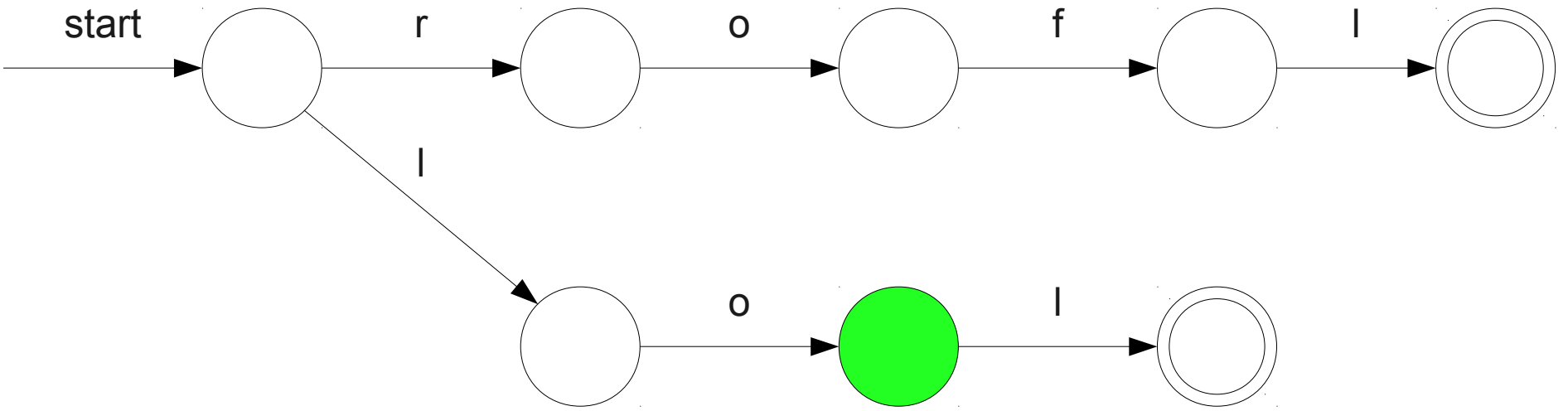

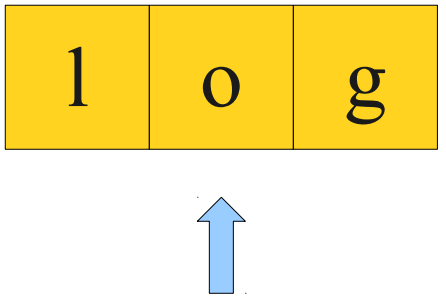

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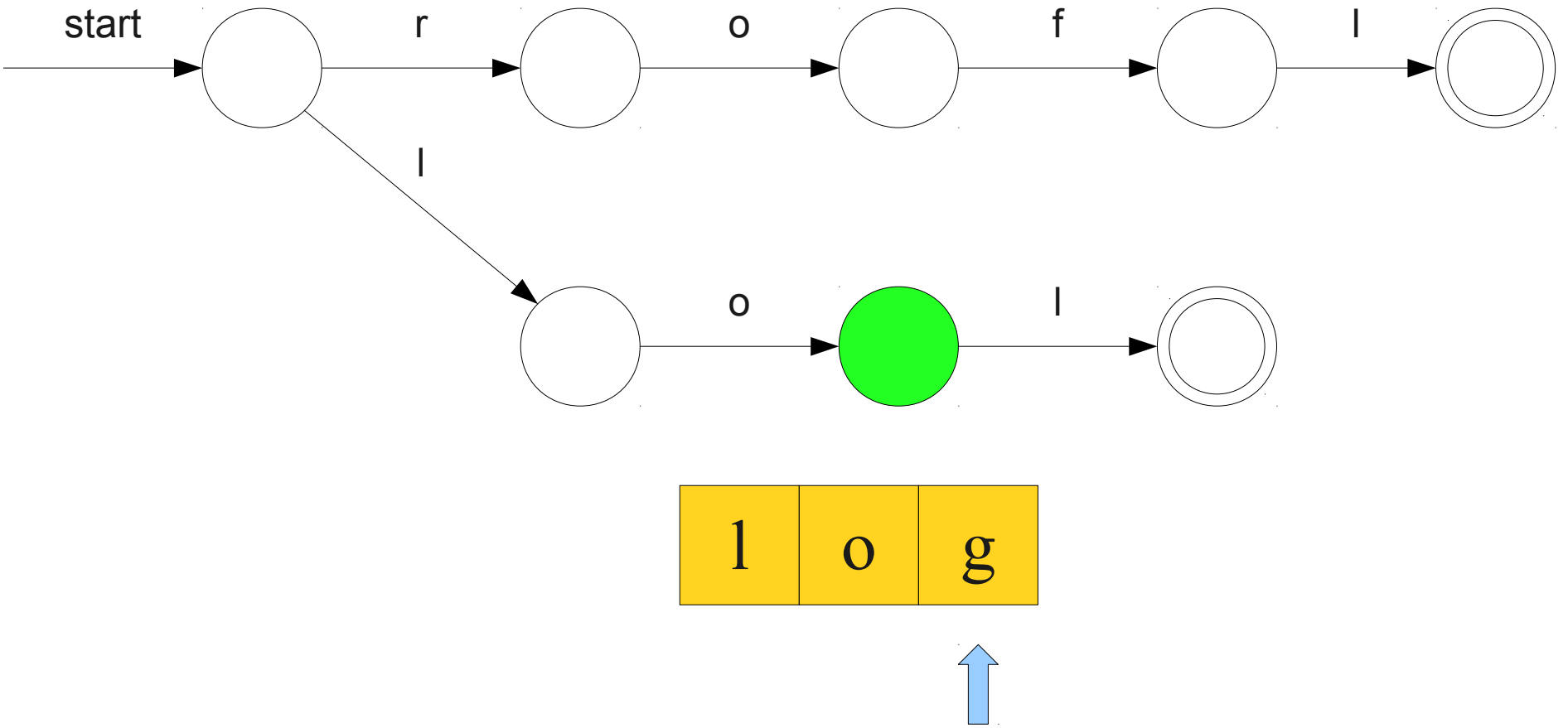

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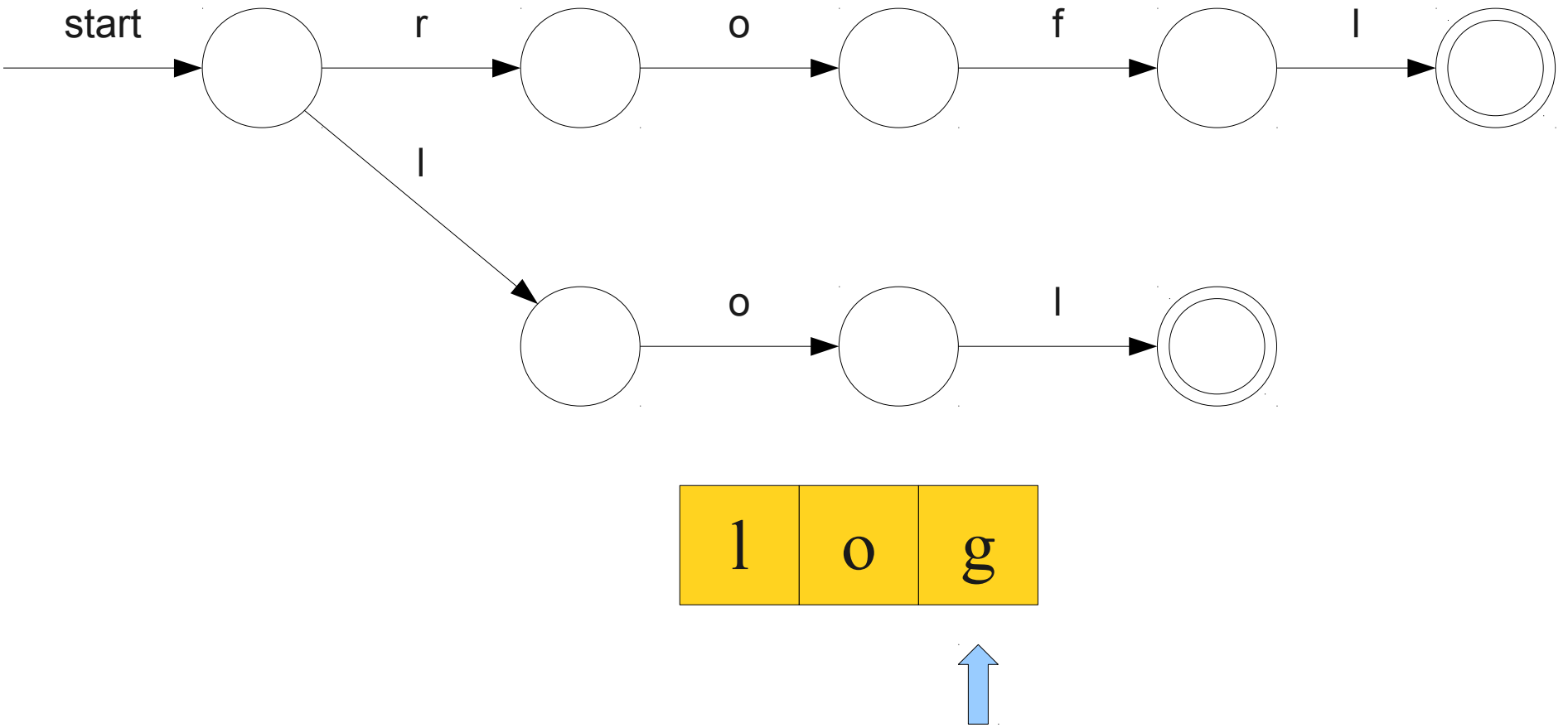

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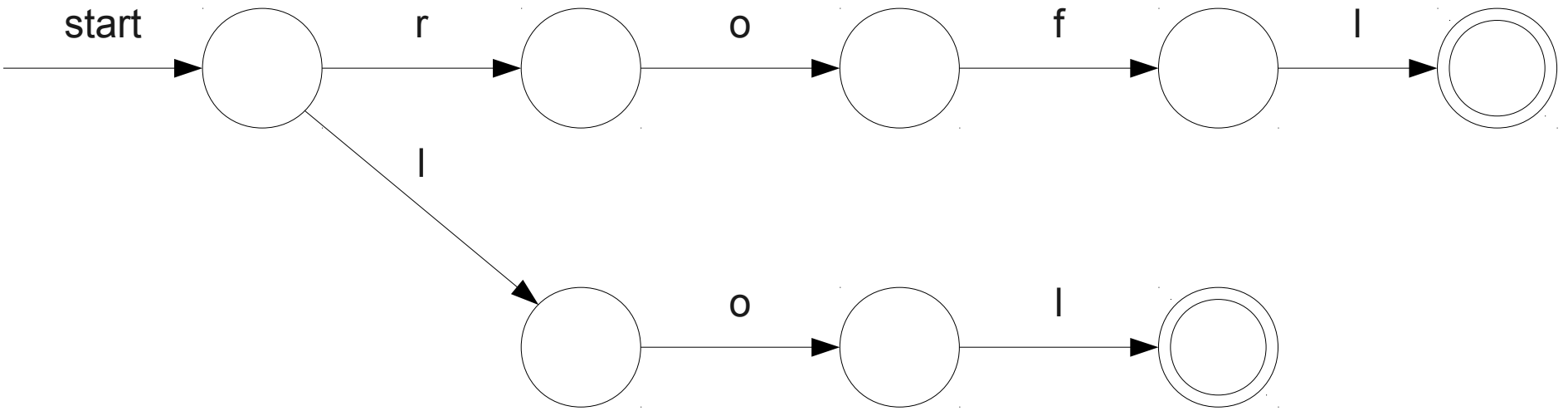

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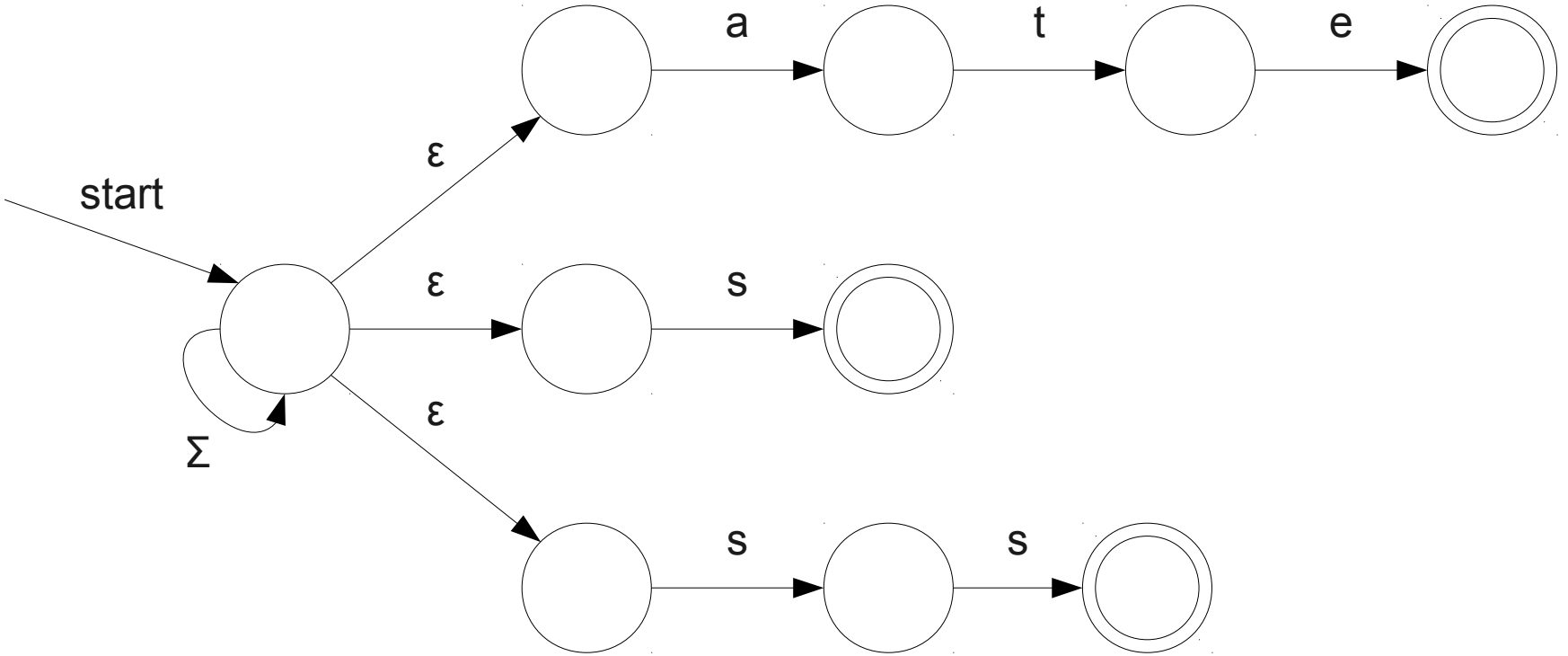

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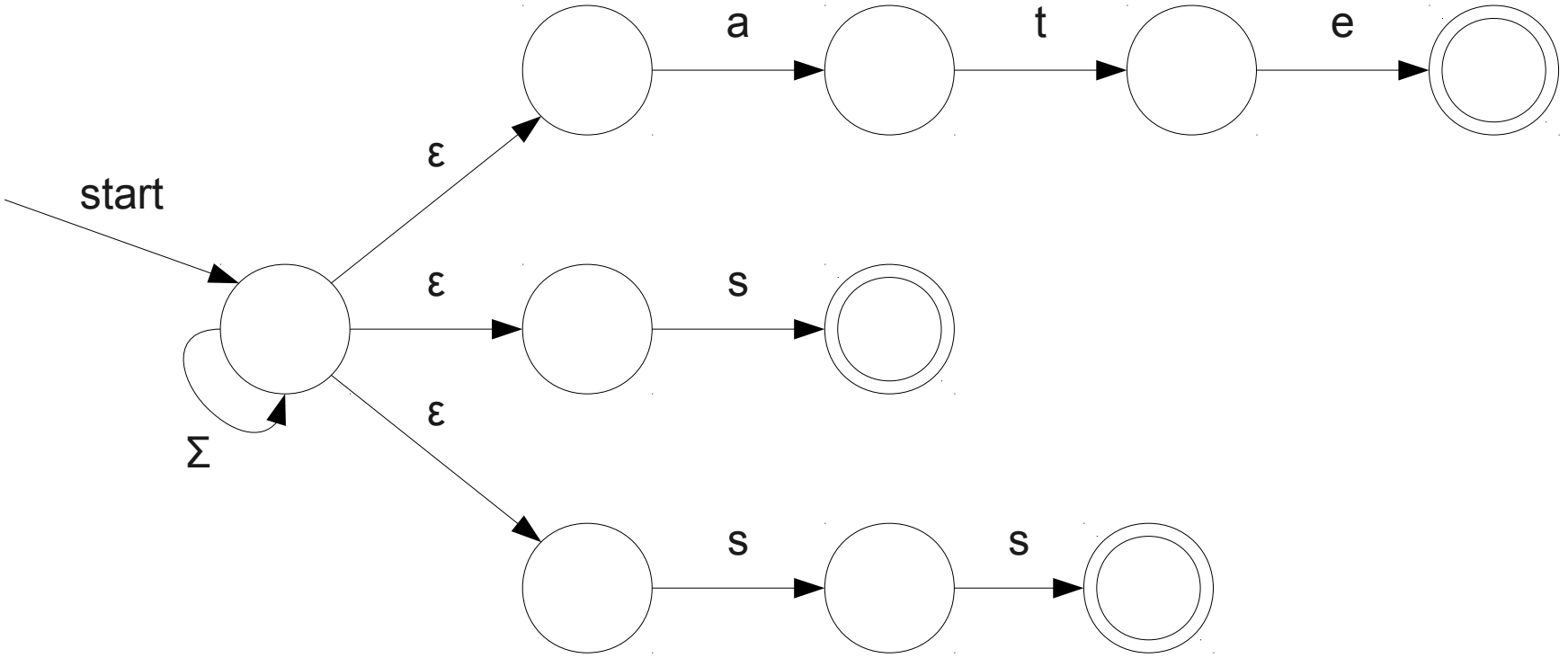

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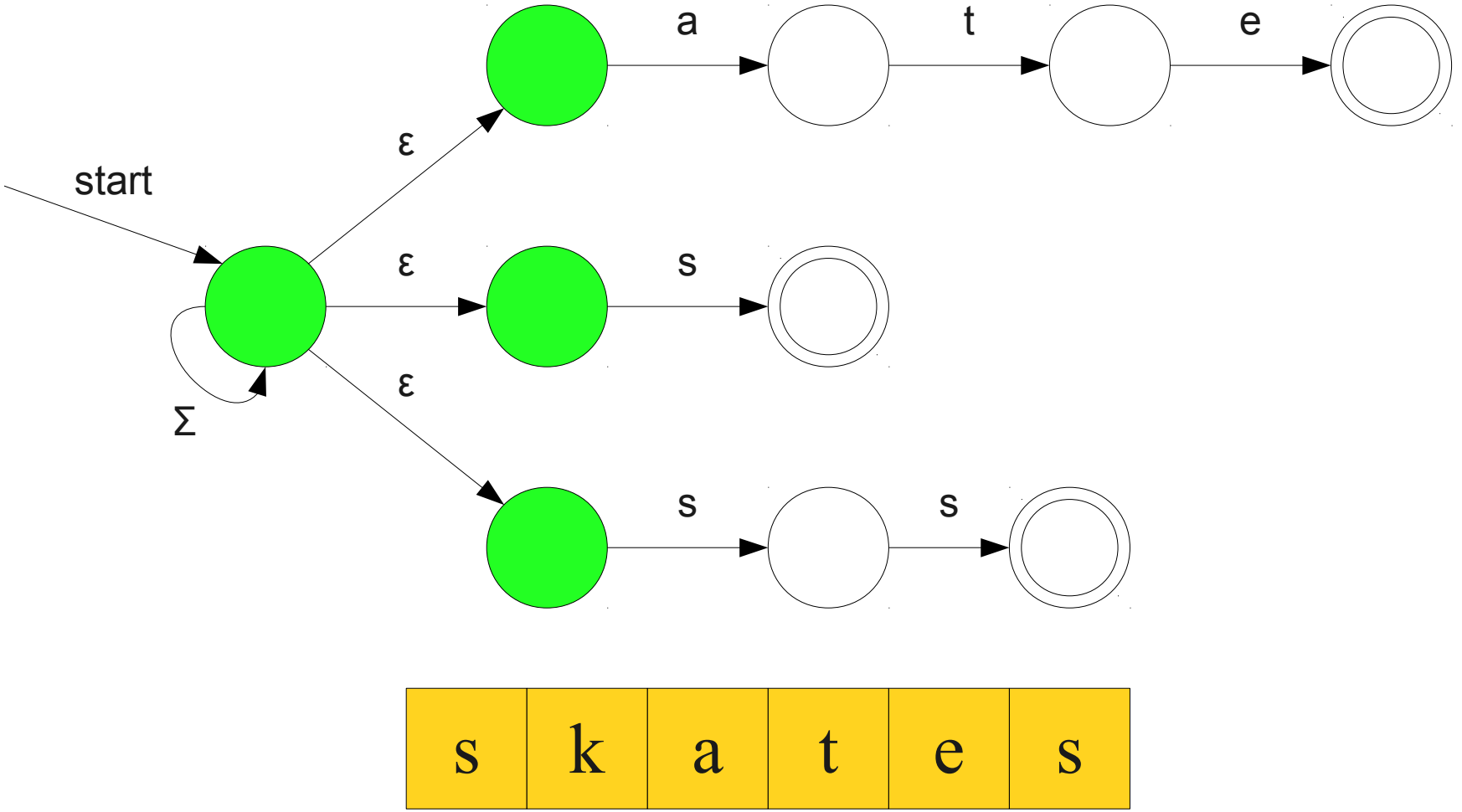

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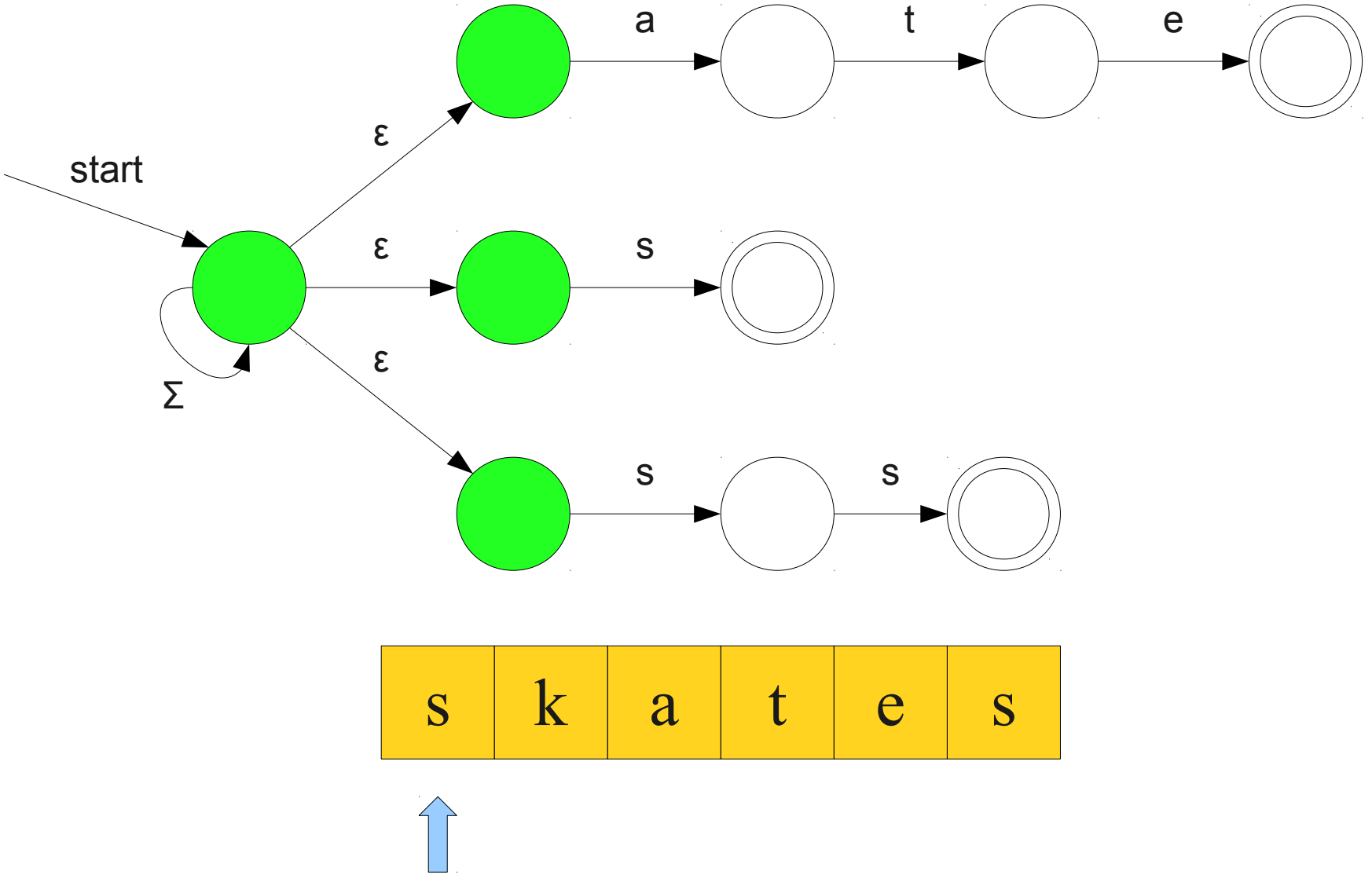

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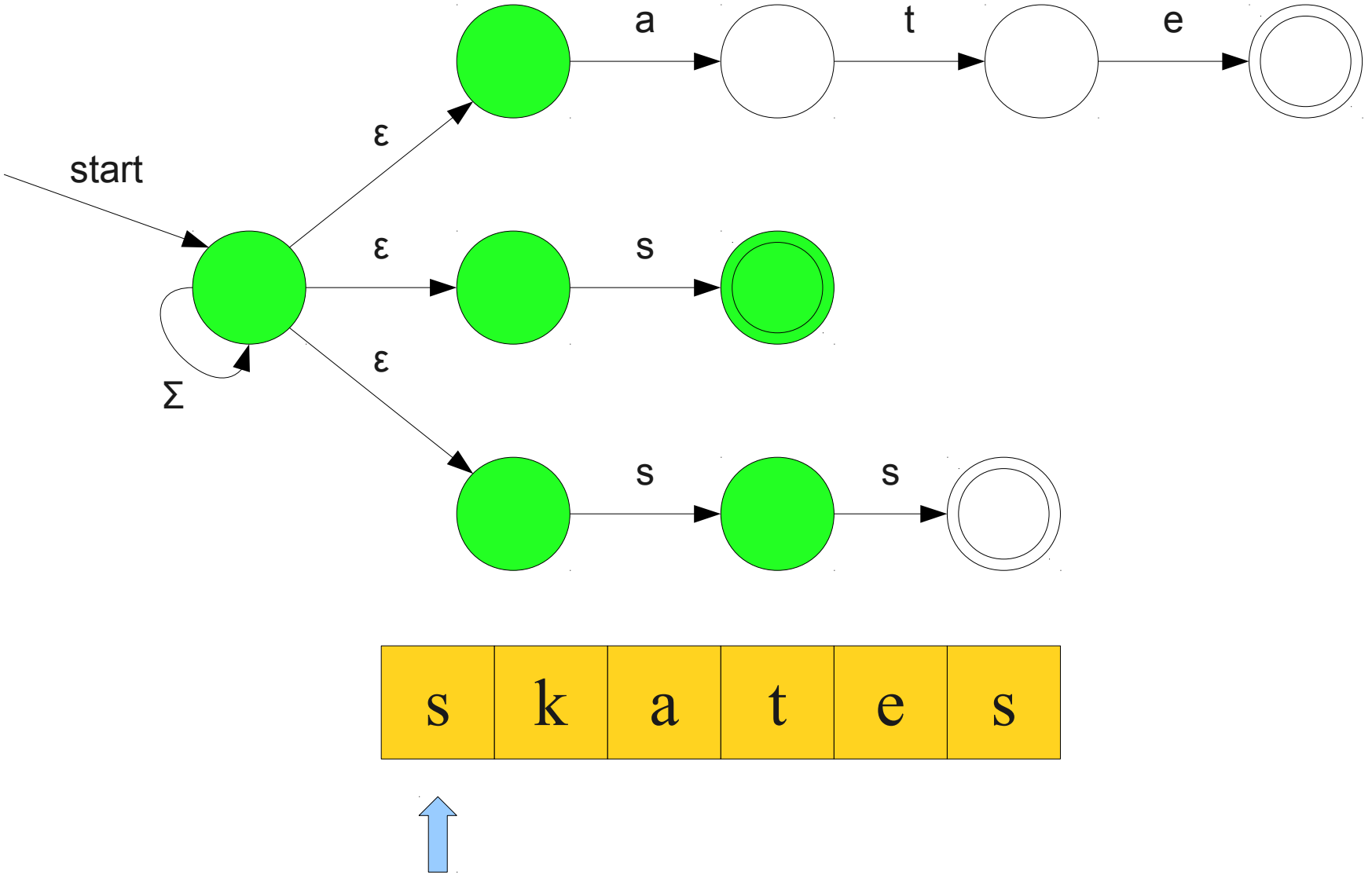

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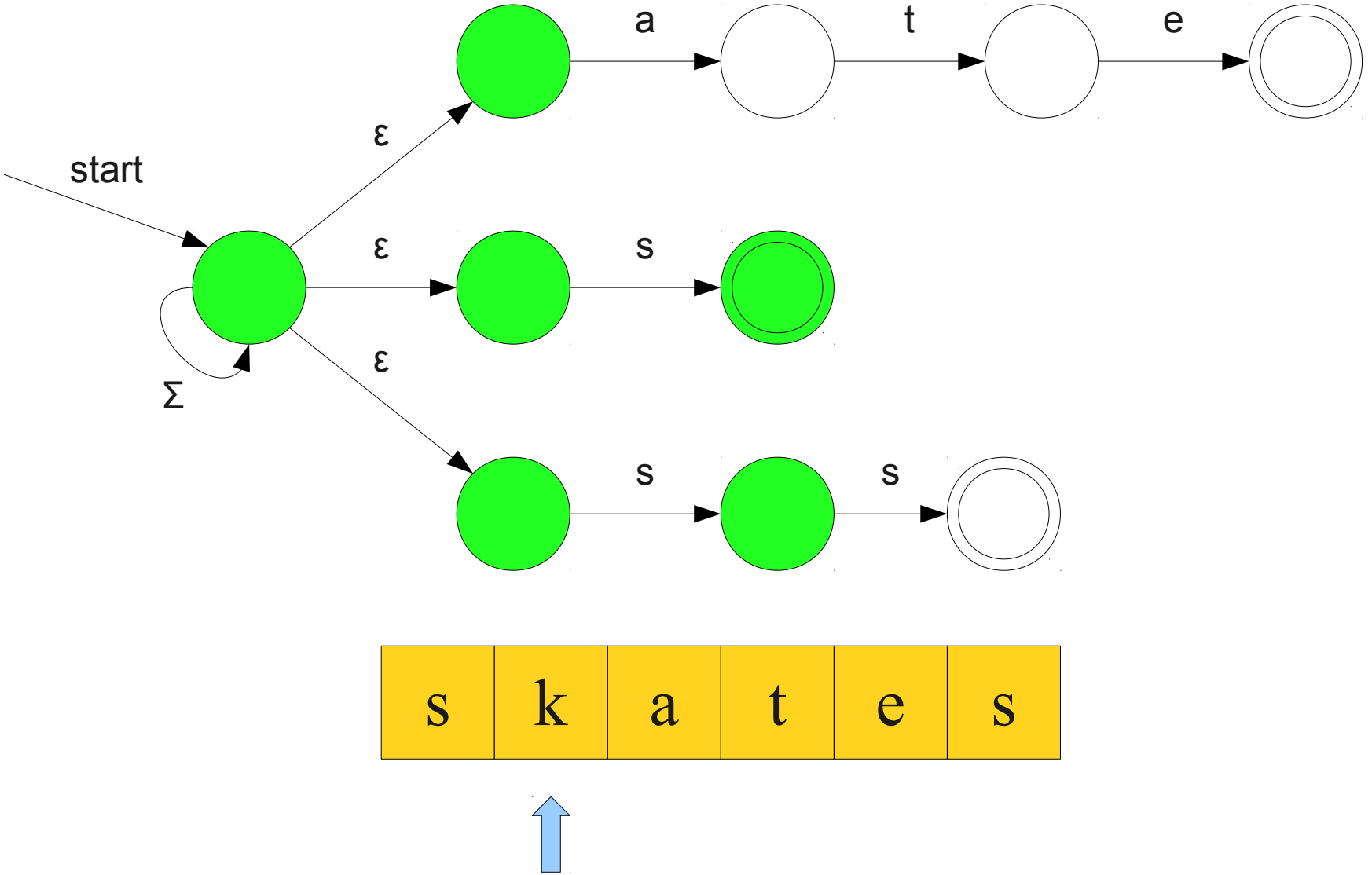

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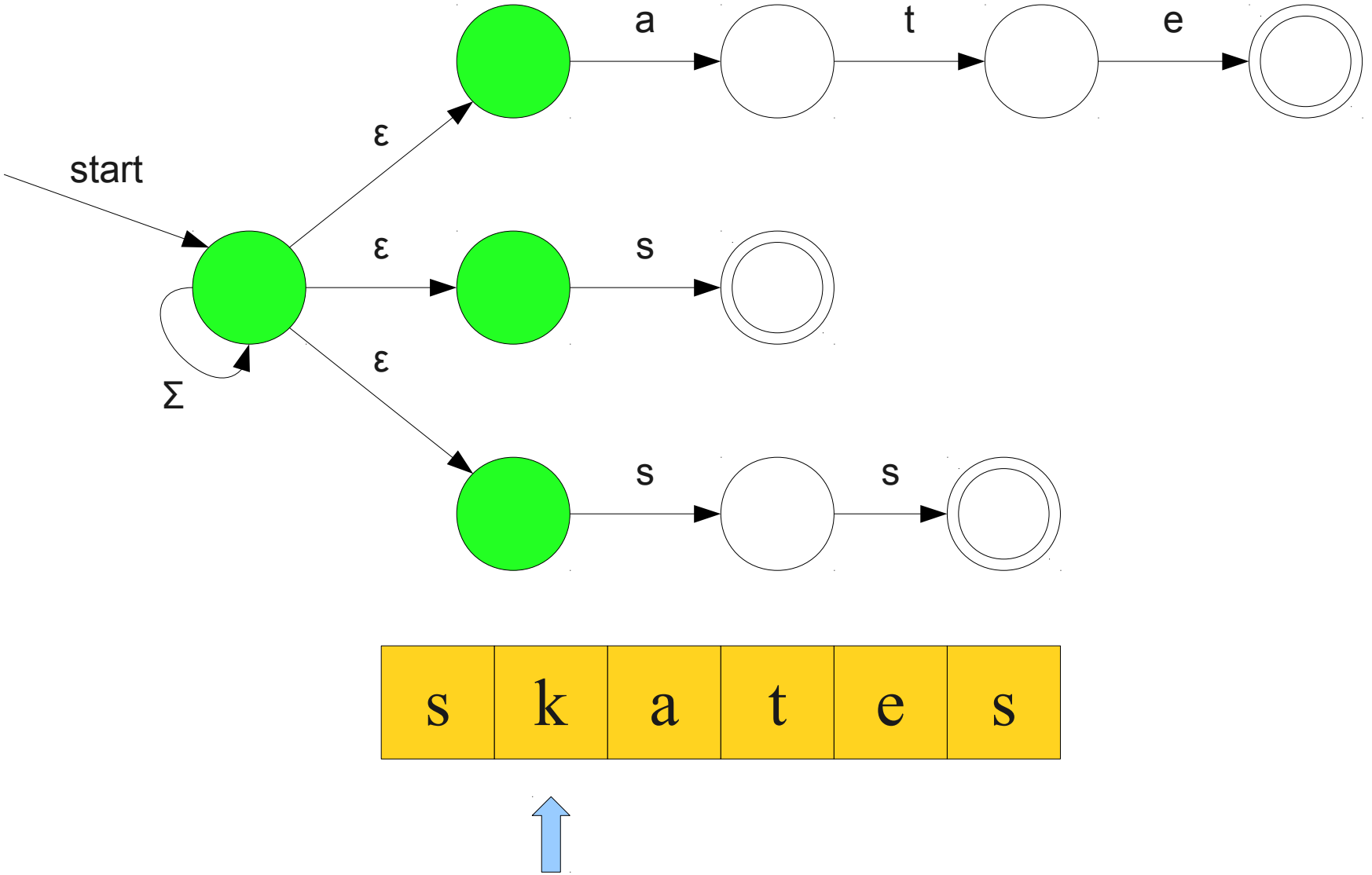

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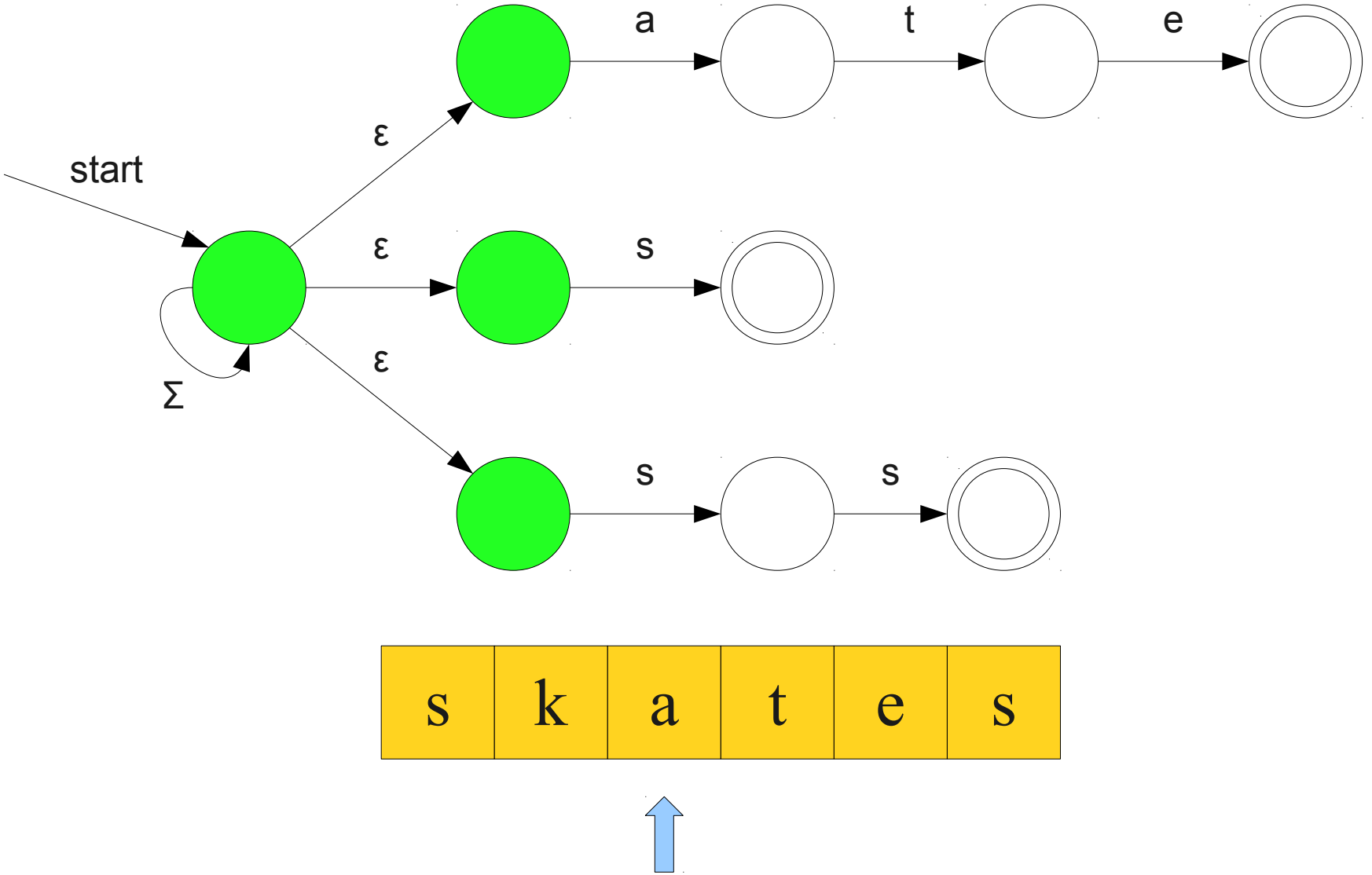
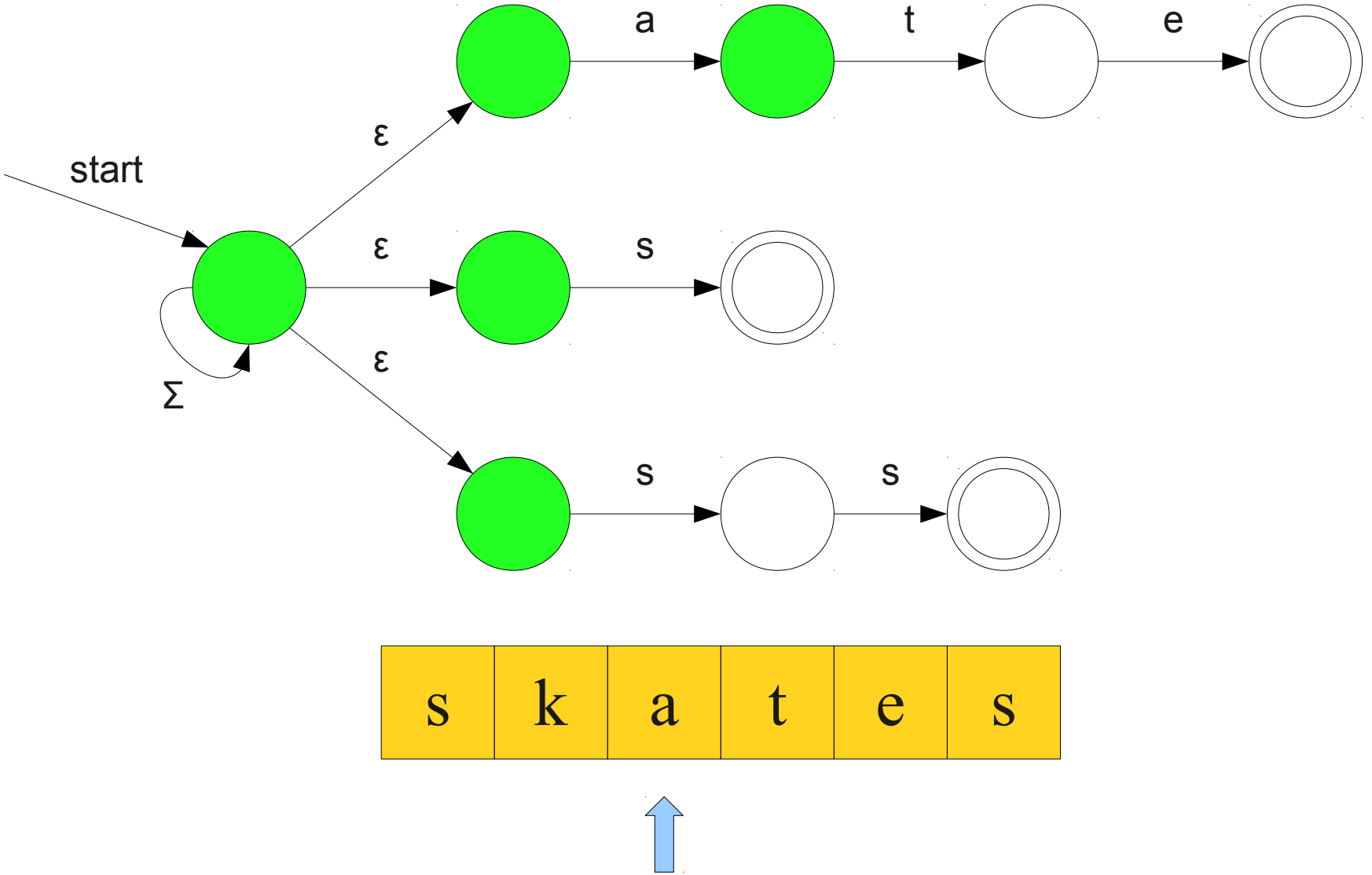
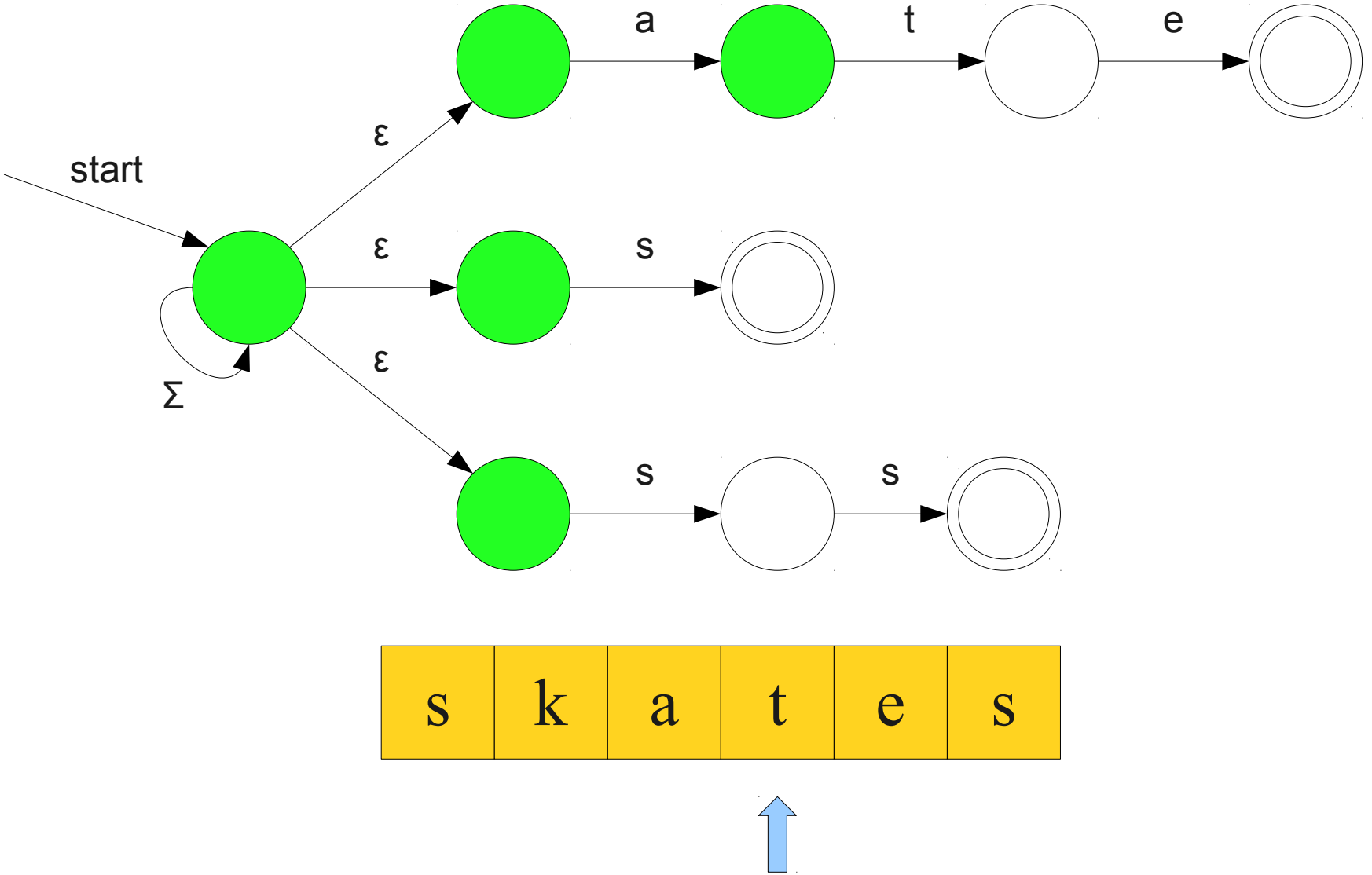


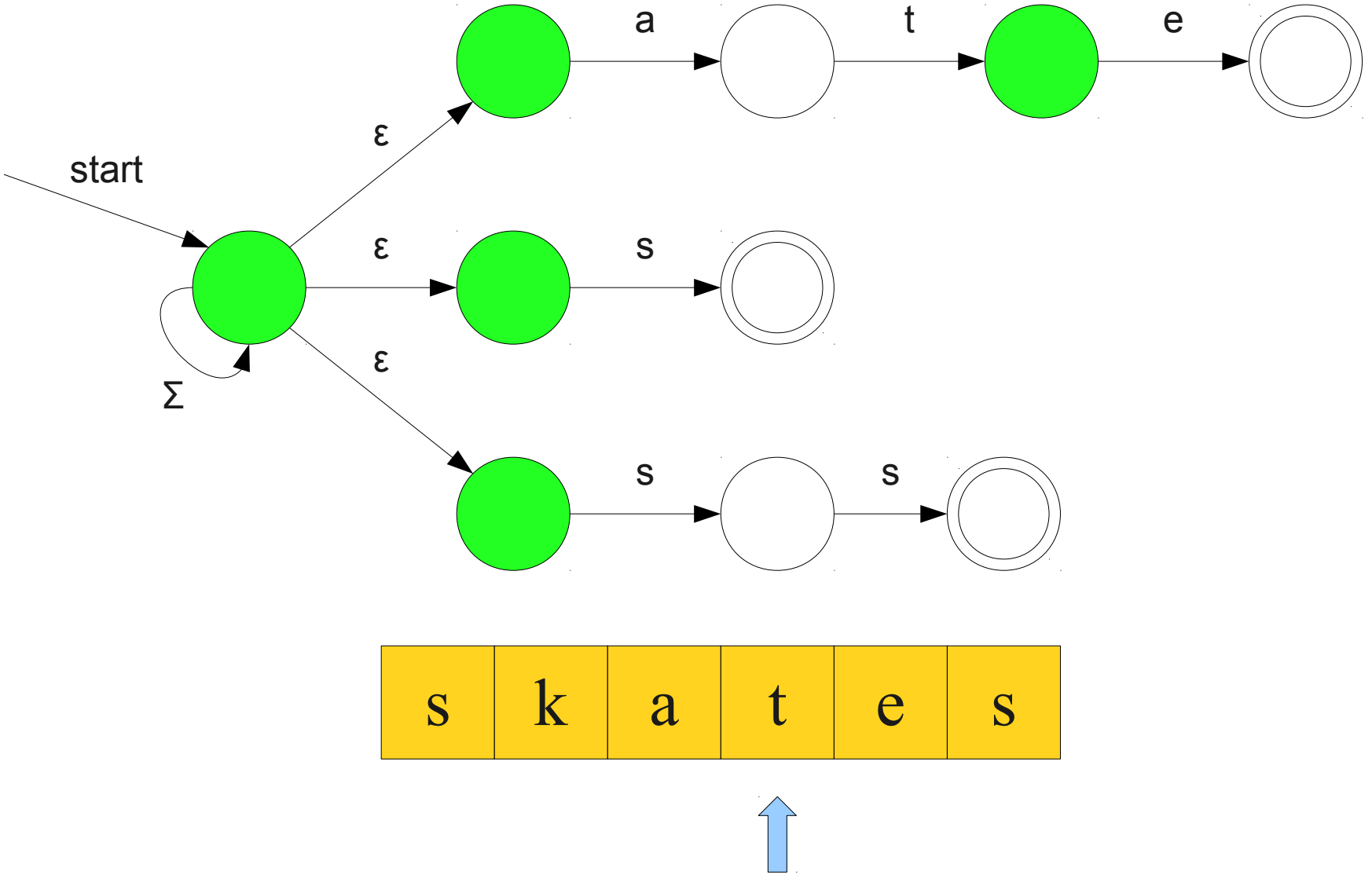
A More Complex NFA



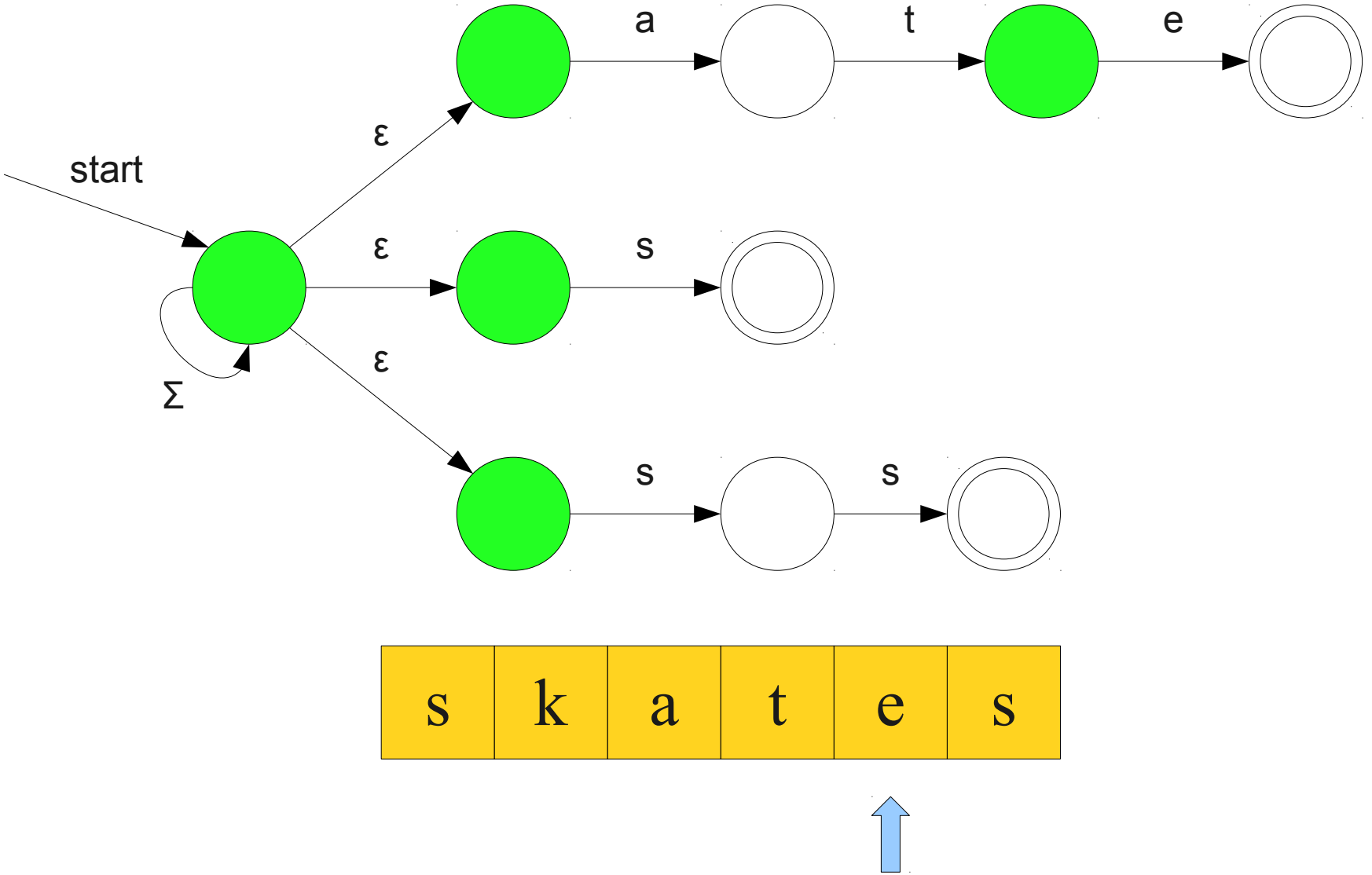
A More Complex NFA



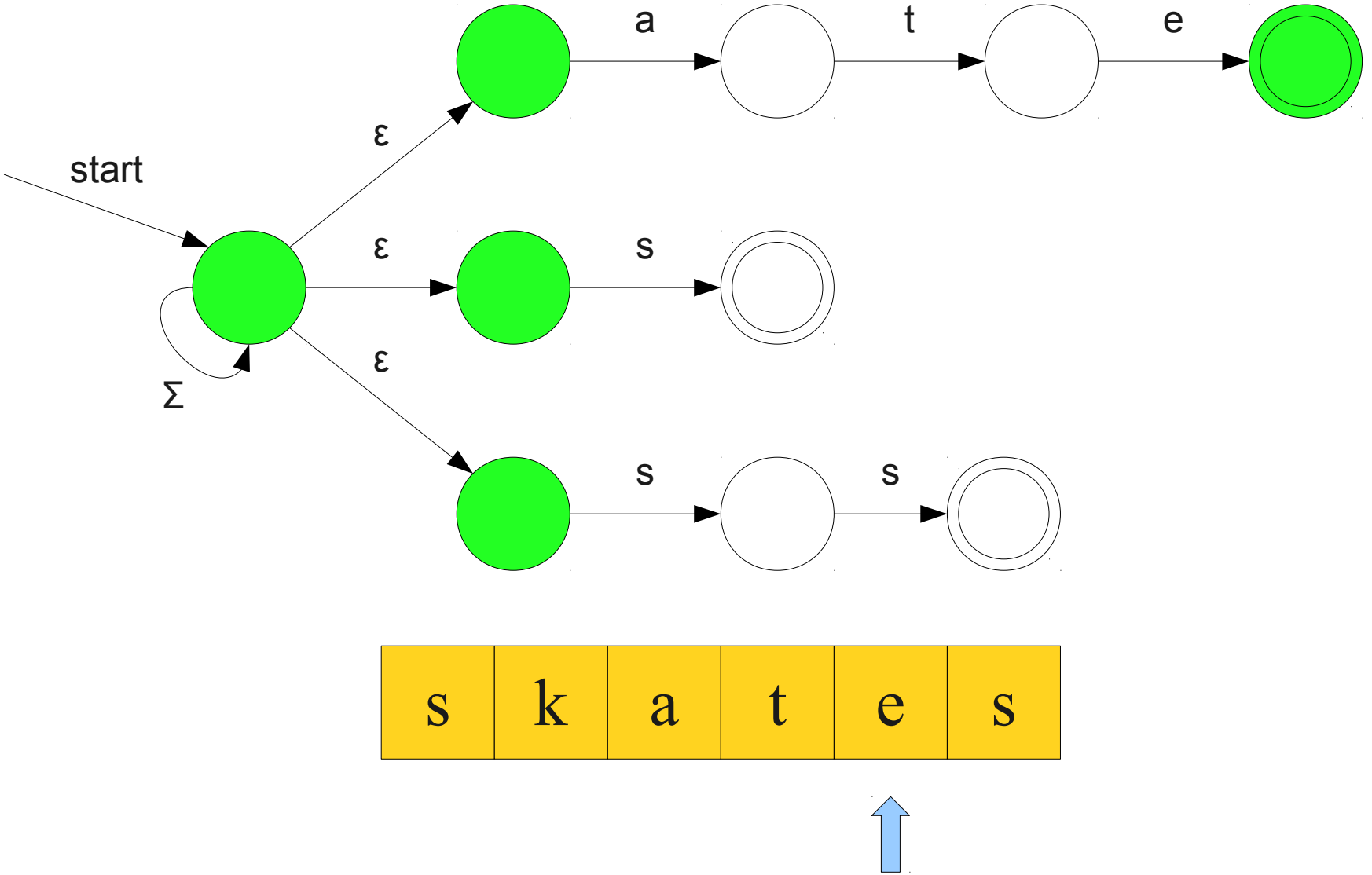
A More Complex NFA



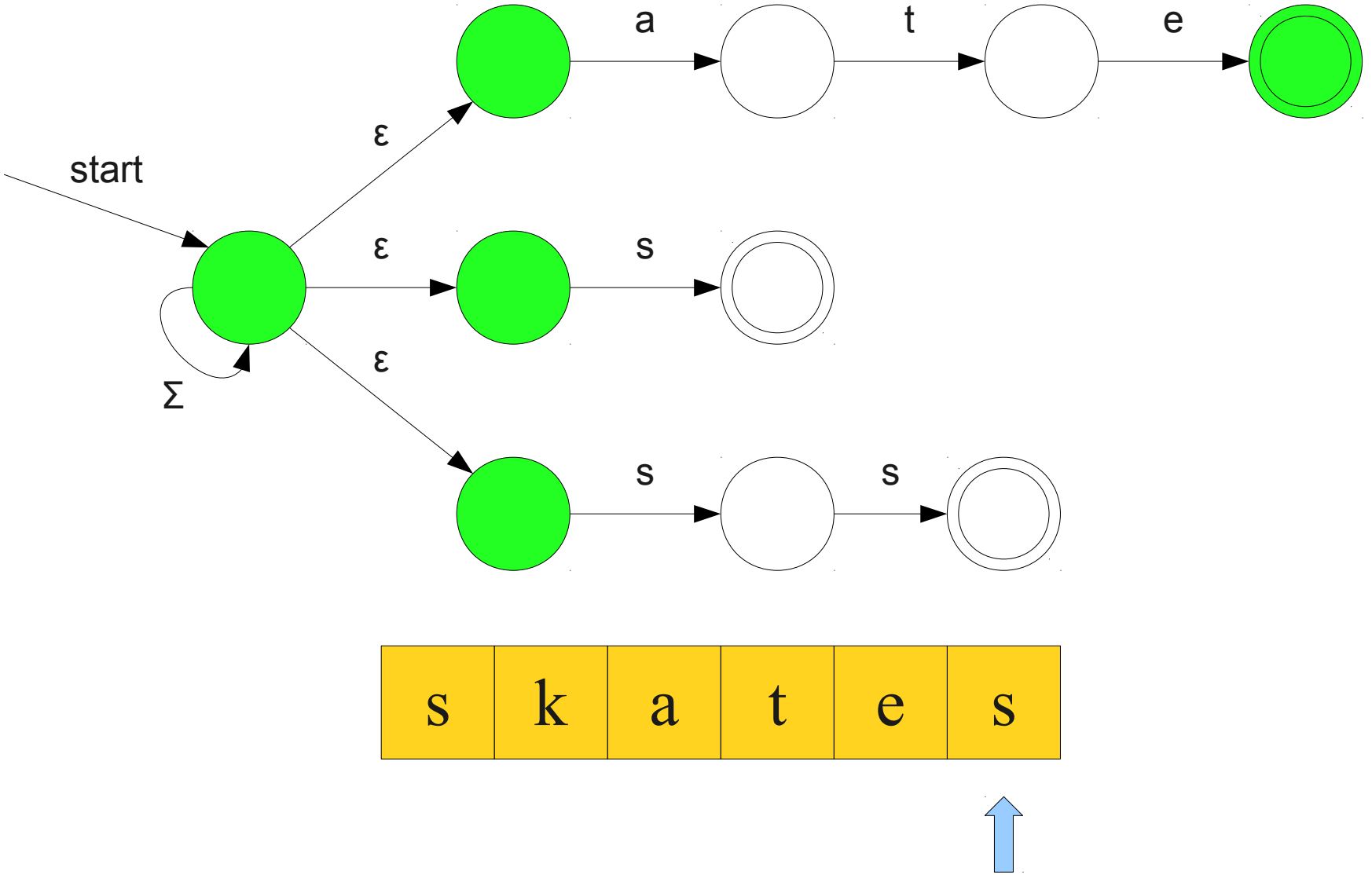
A More Complex NFA



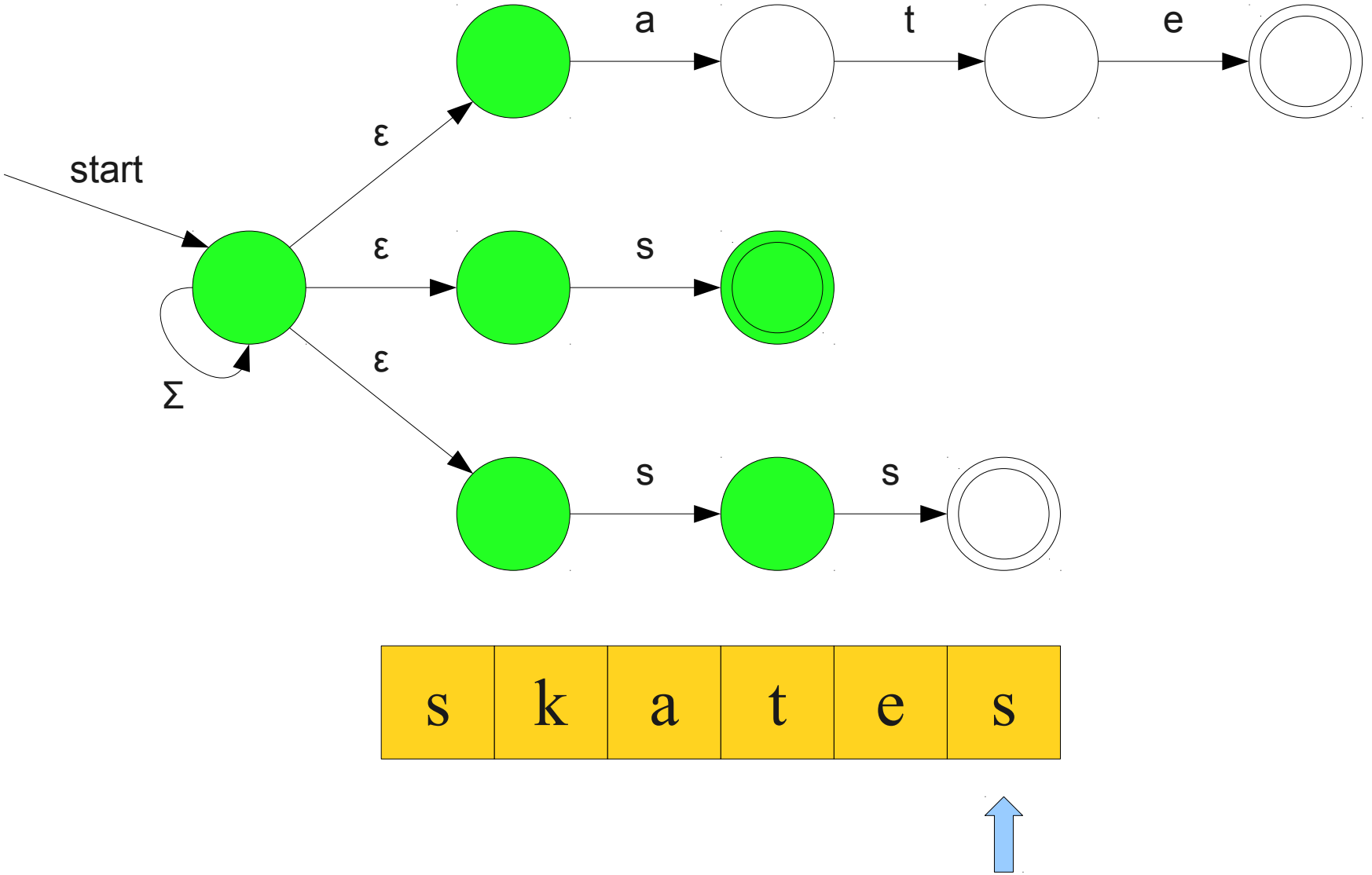
A More Complex NFA



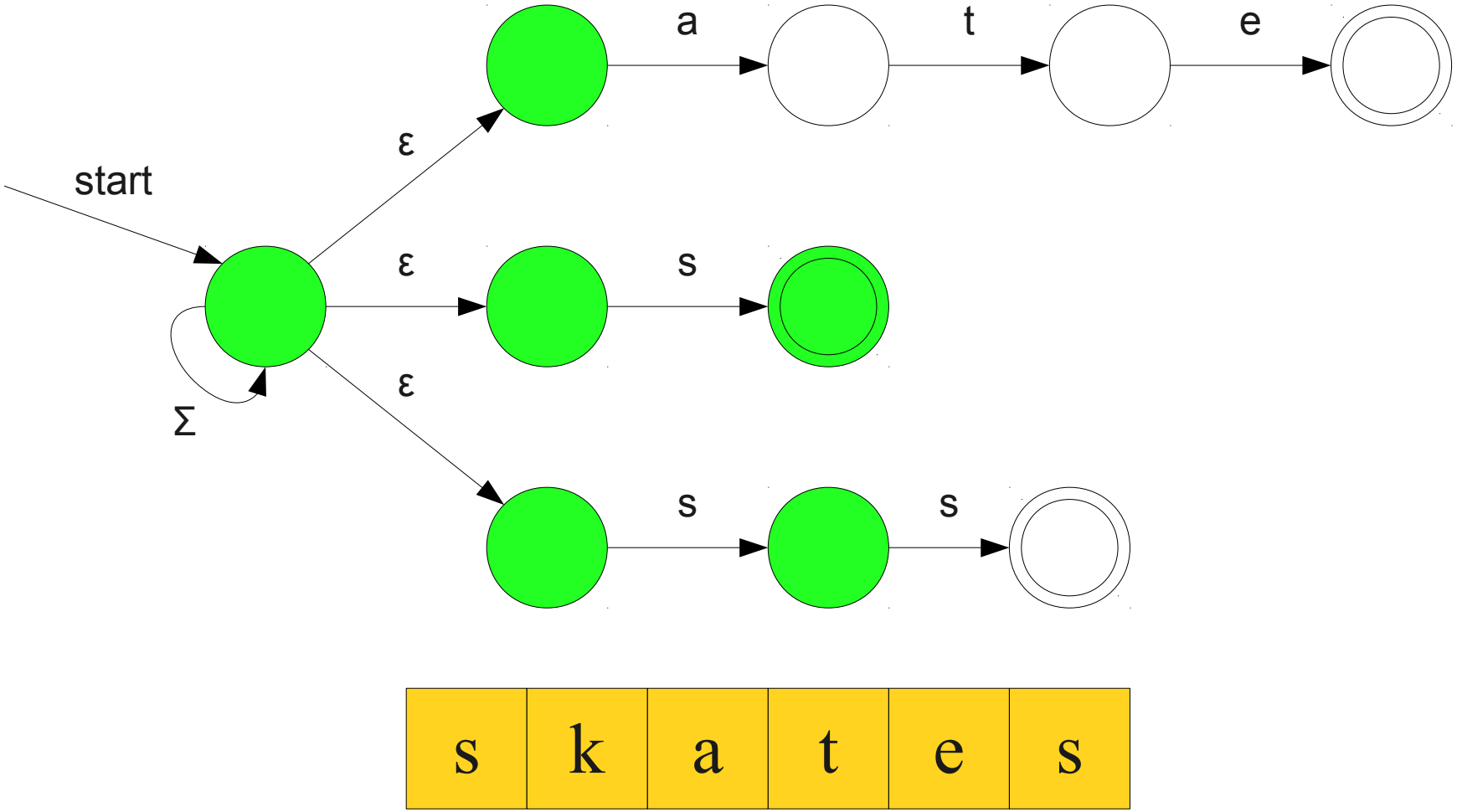
A More Complex NFA



A More Complex NFA



A More Complex NFA

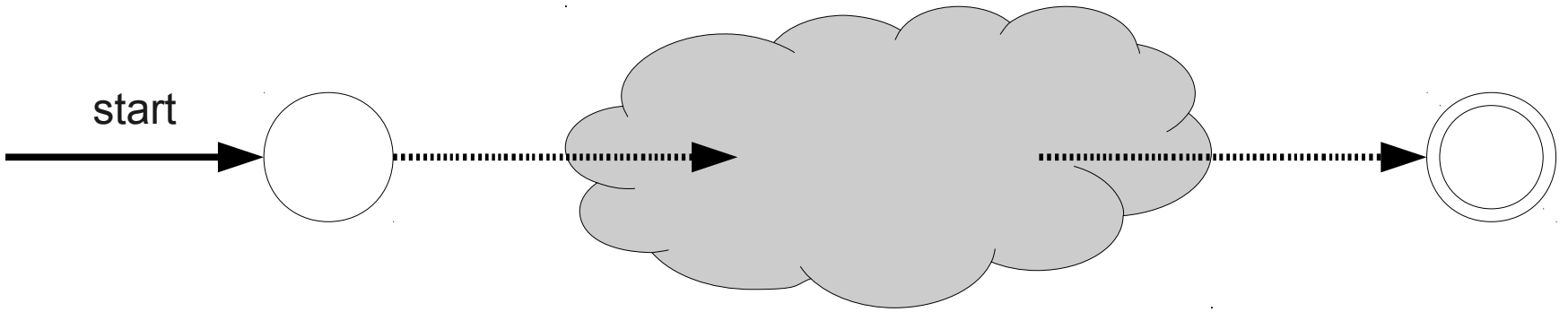


Simulating an NFA

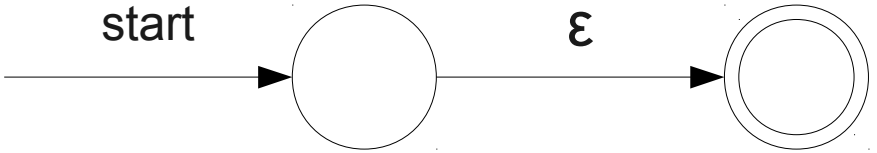
- Keep track of a set of states, initially the start state and everything reachable by ε-moves.
- For each character in the input:
  - Maintain a set of next states, initially empty.
  - For each current state:
    - Follow all transitions labeled with the current letter.
    - Add these states to the set of new states.
  - Add every state reachable by an ε-move to the set of next states.
- Accept if at least one state in the set of states is accepting.
- Complexity: $O(|S||Q|^2)$ for strings of length |S| and |Q| states.

From Regular Expressions to NFAs

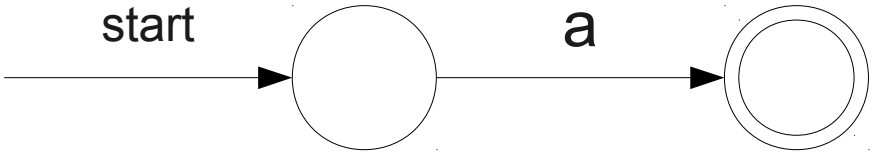
- There is a (beautiful!) procedure from converting a regular expression to an NFA.
- Associate each regular expression with an NFA with the following properties:
  - There is exactly one accepting state.
  - There are no transitions out of the accepting state.
  - There are no transitions into the starting state.



Base Cases



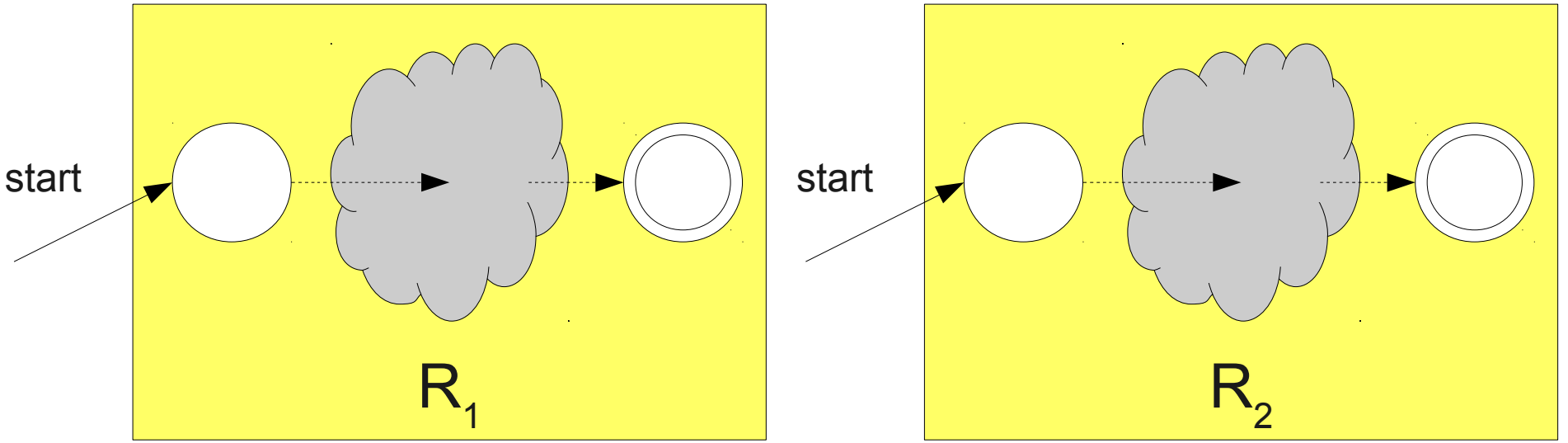
Automaton for ε



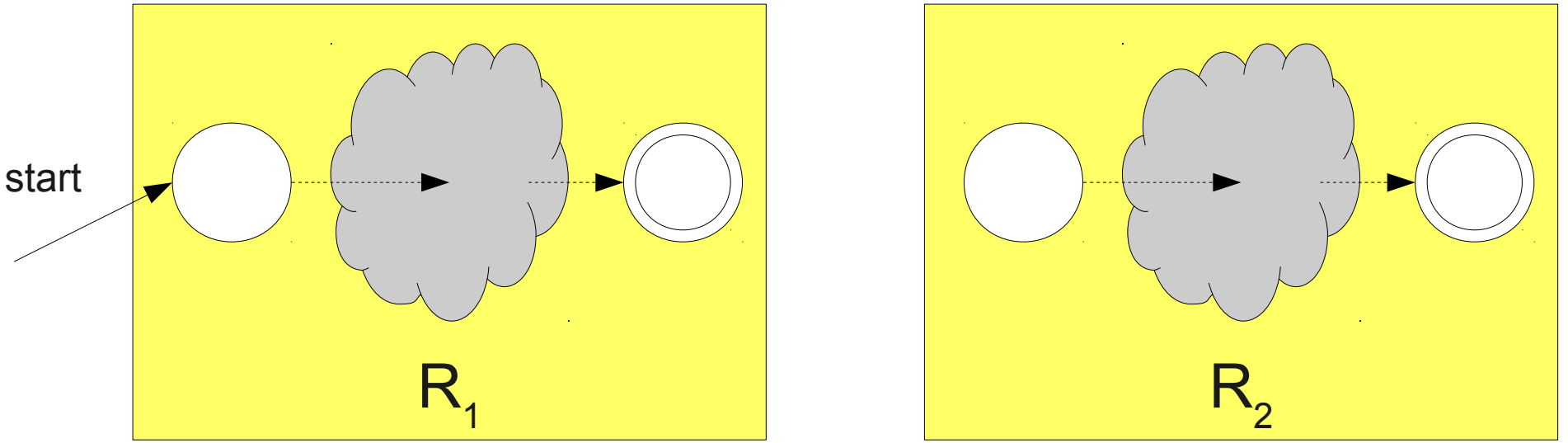
Automaton for single character **`a`**

Construction for R_1R_2

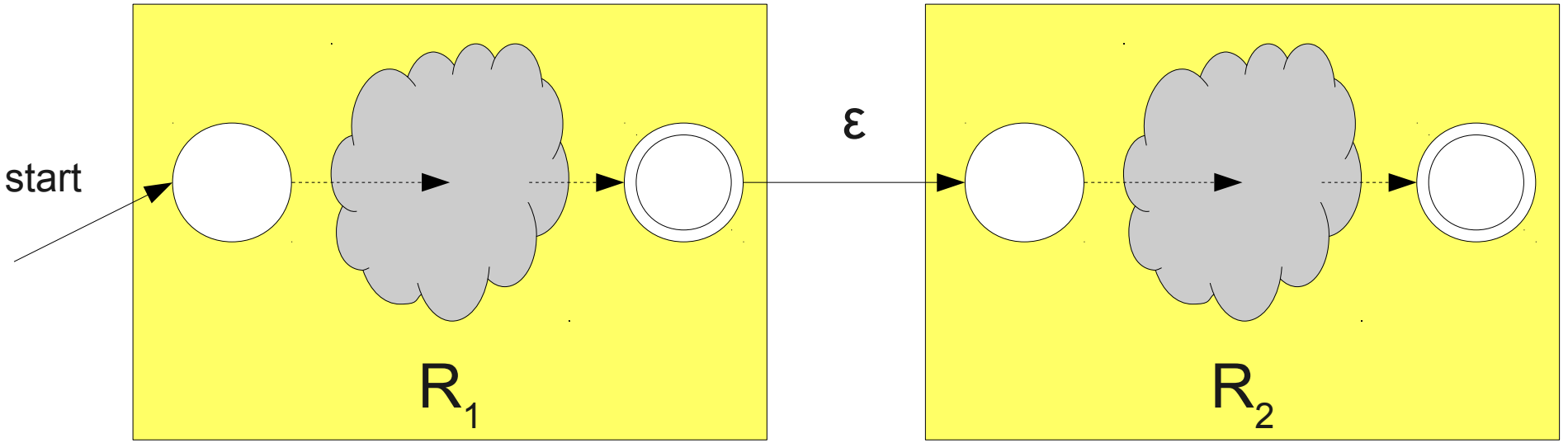
Construction for R_1R_2



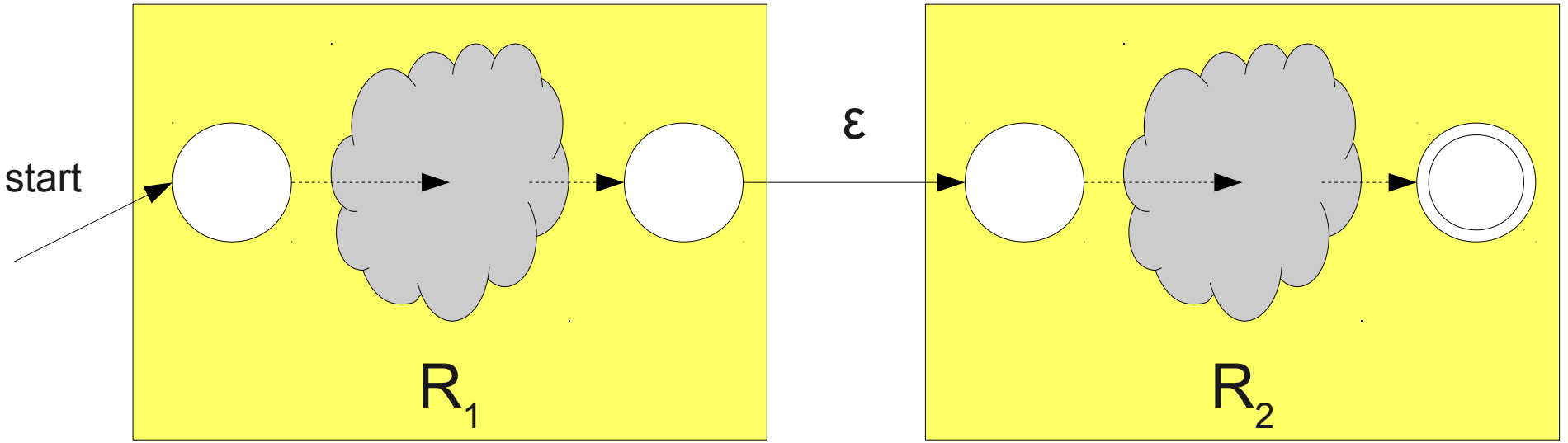
Construction for R_1R_2



Construction for R_1R_2

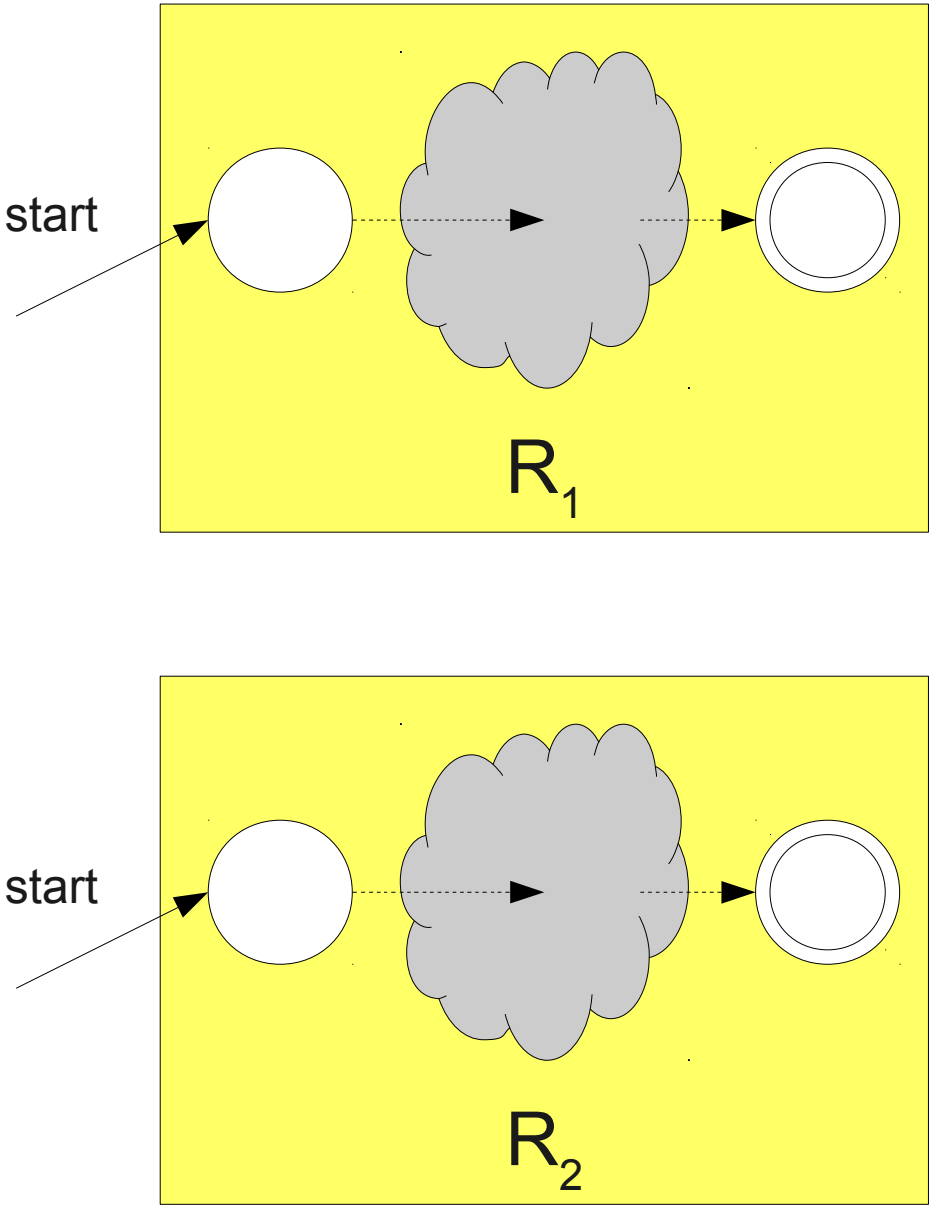


Construction for R_1R_2

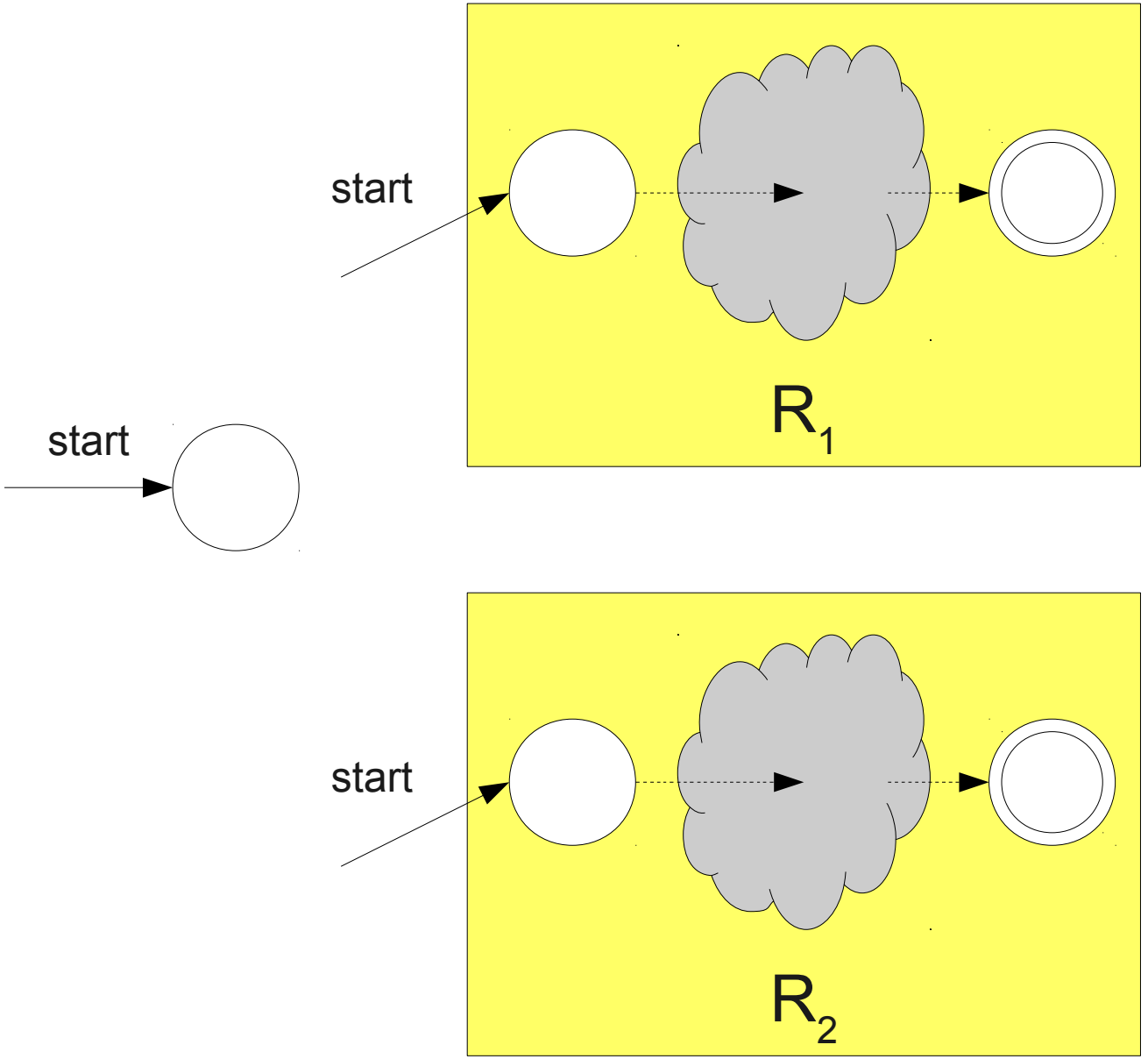


Construction for $R_1 \mid R_2$

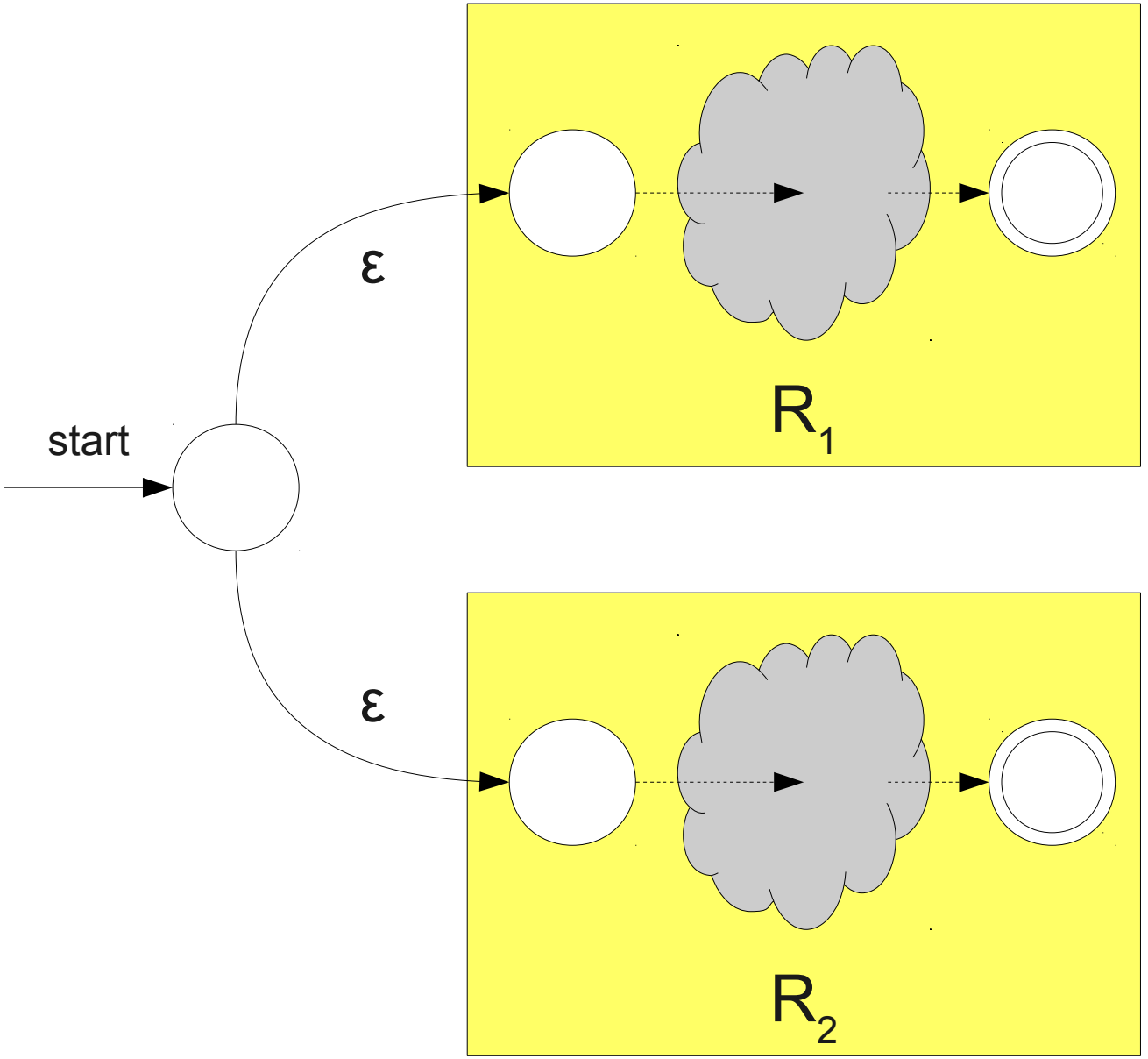
Construction for $R_1 \mid R_2$



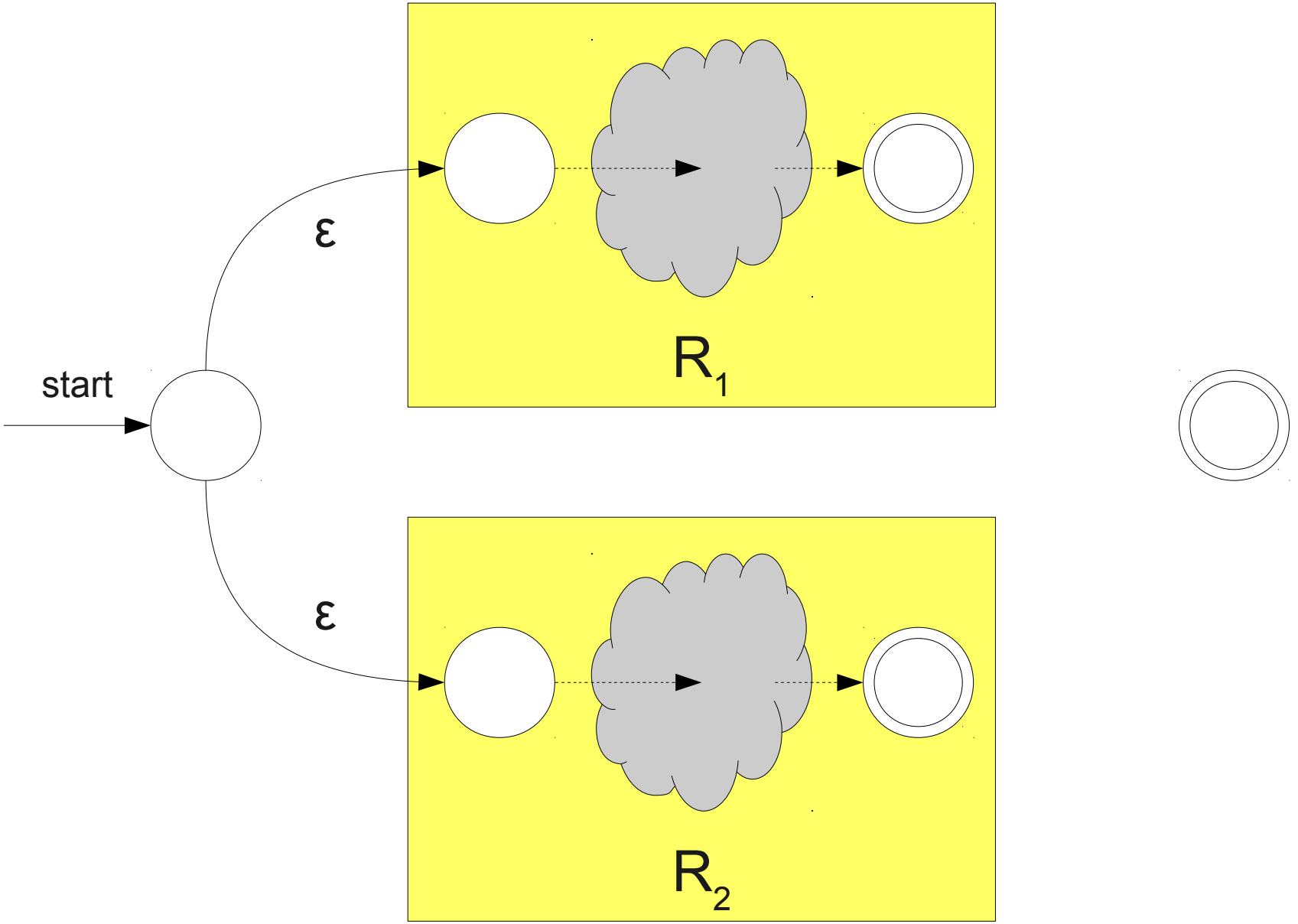
Construction for $R_1 \mid R_2$



Construction for $R_1 \mid R_2$



Construction for $R_1 \mid R_2$



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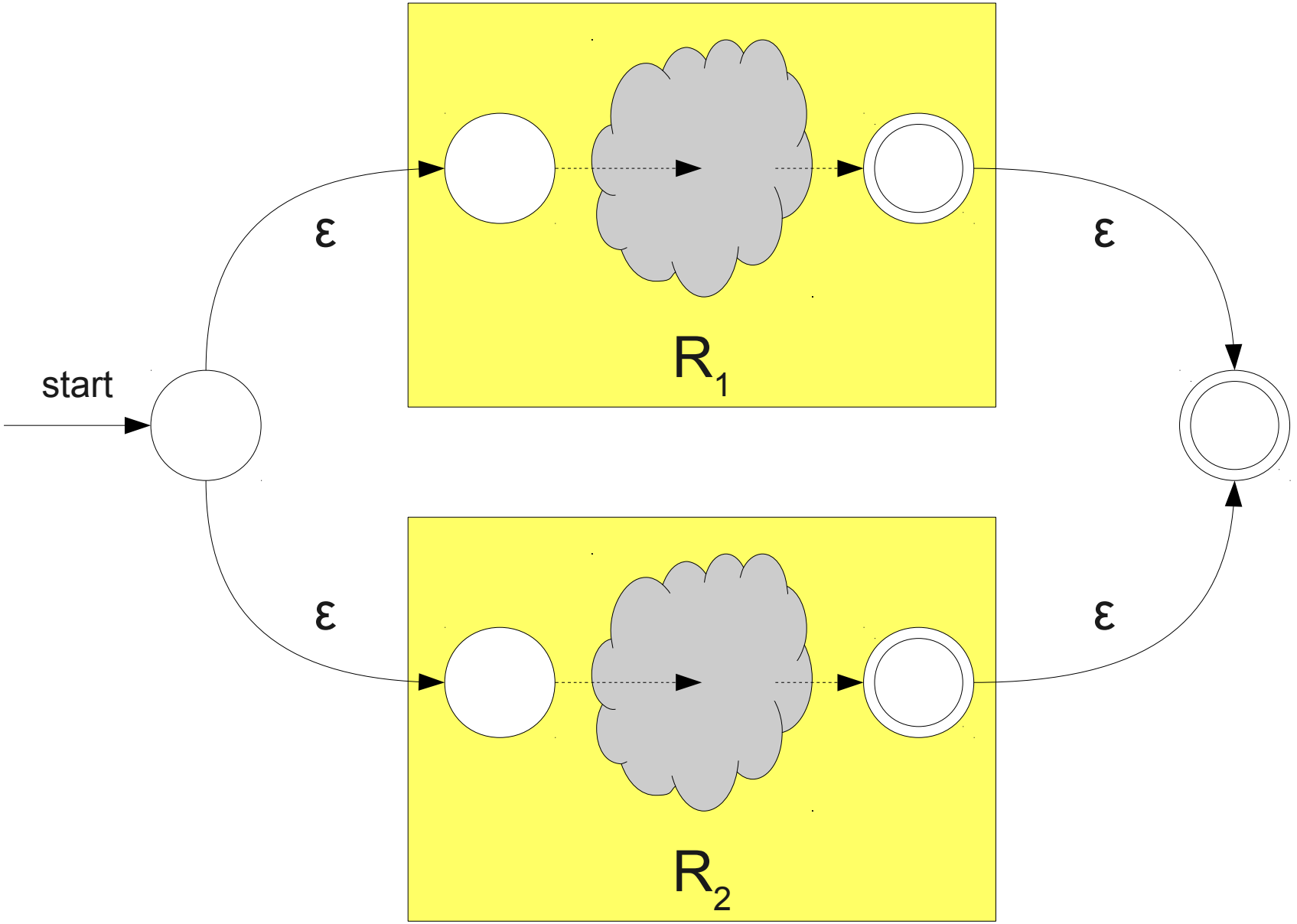
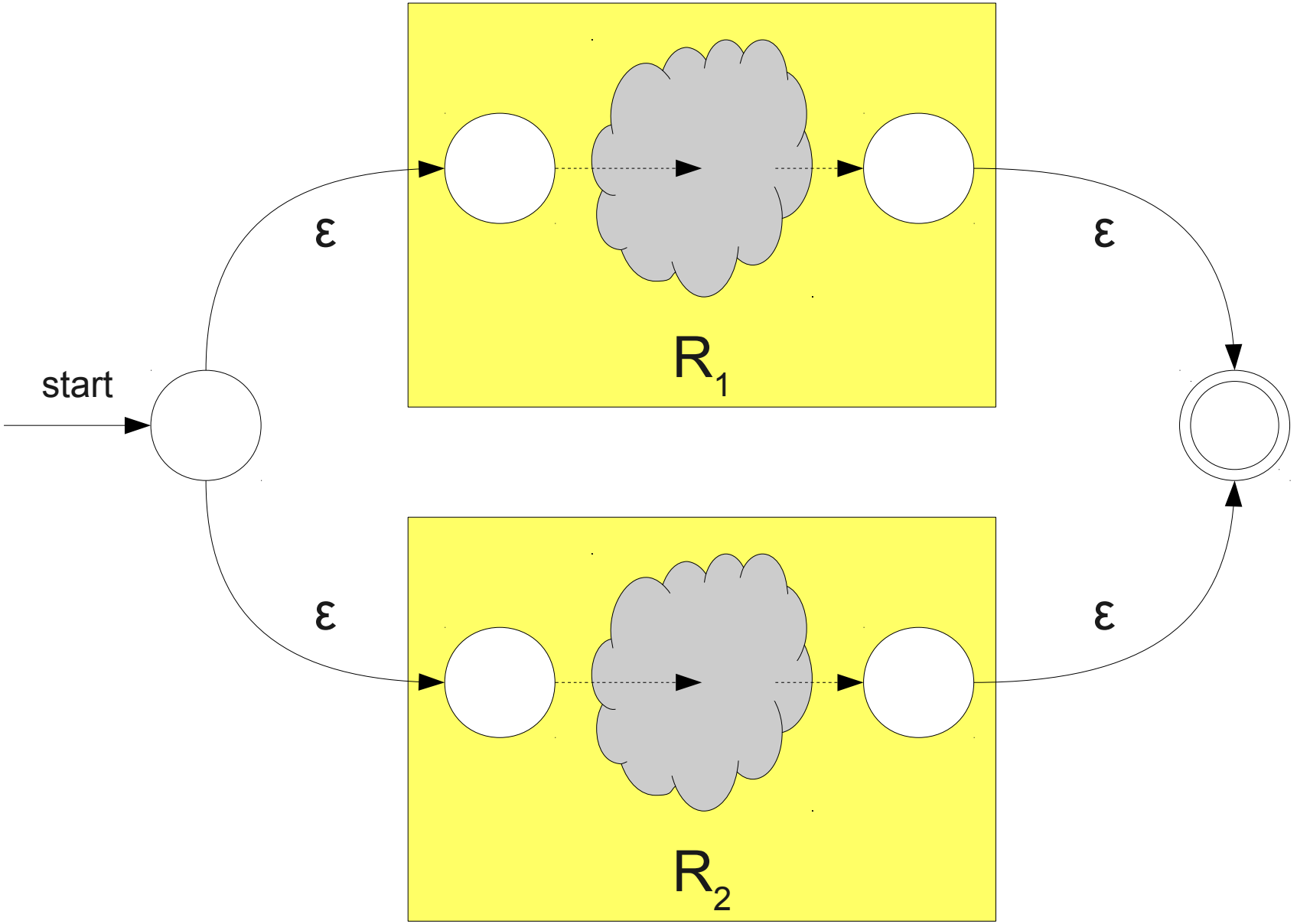
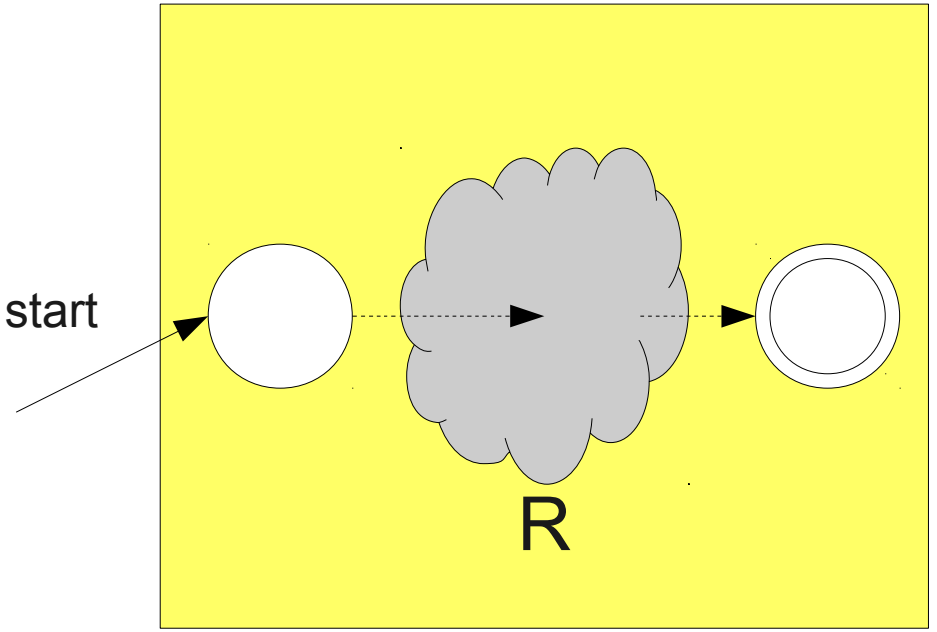


Construction for $R_1 \mid R_2$

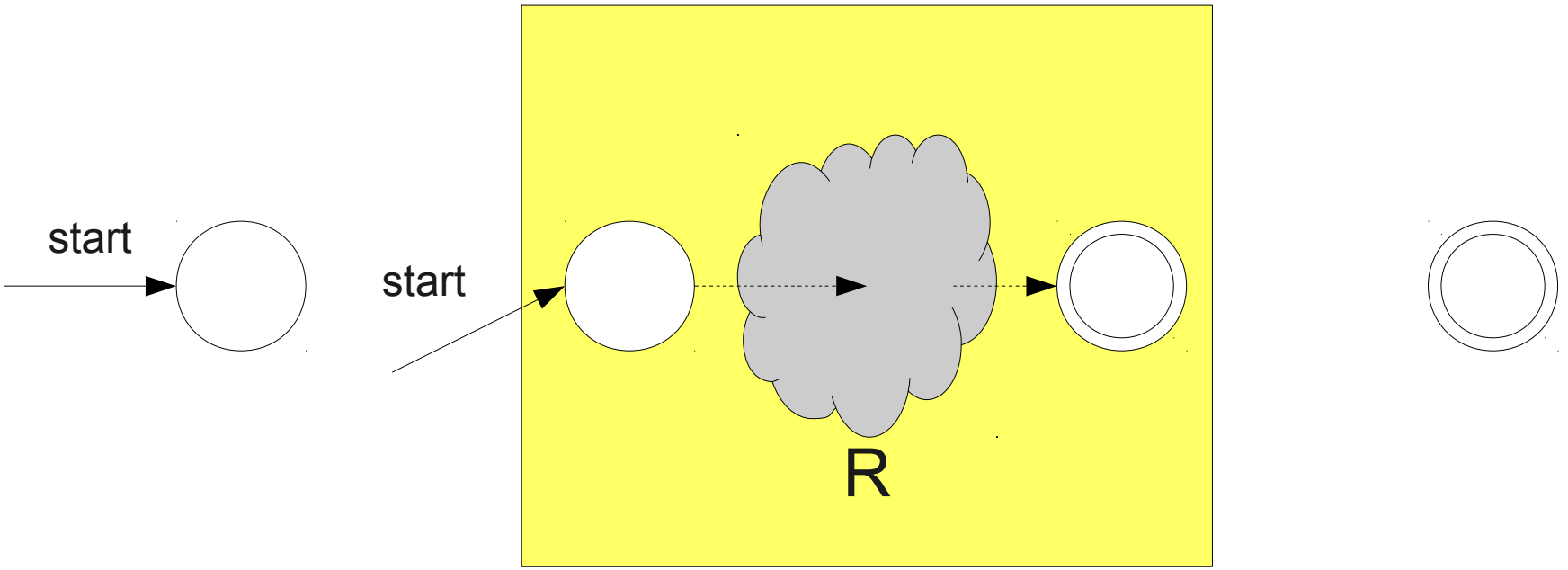


Construction for R*

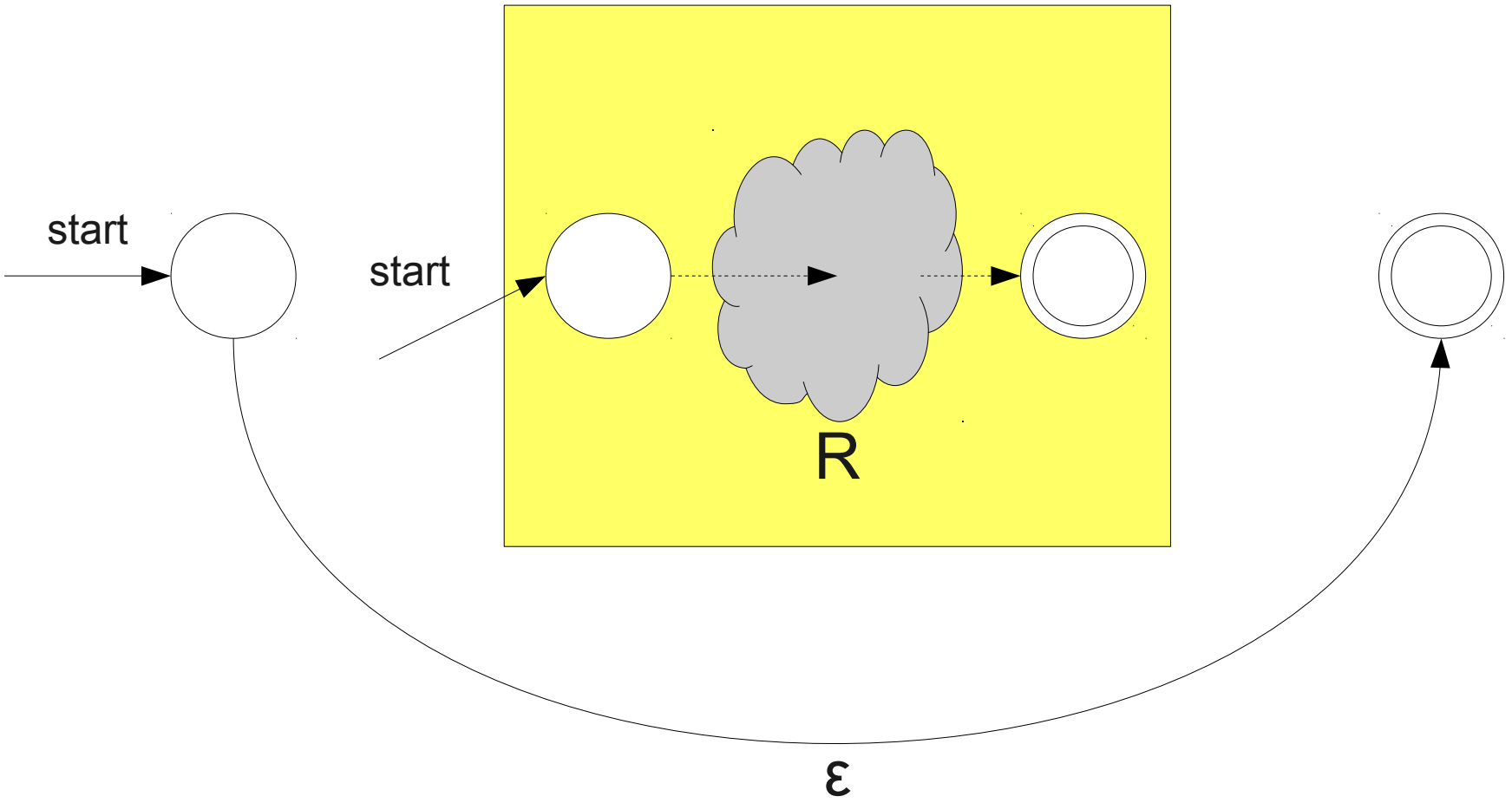
Construction for R*



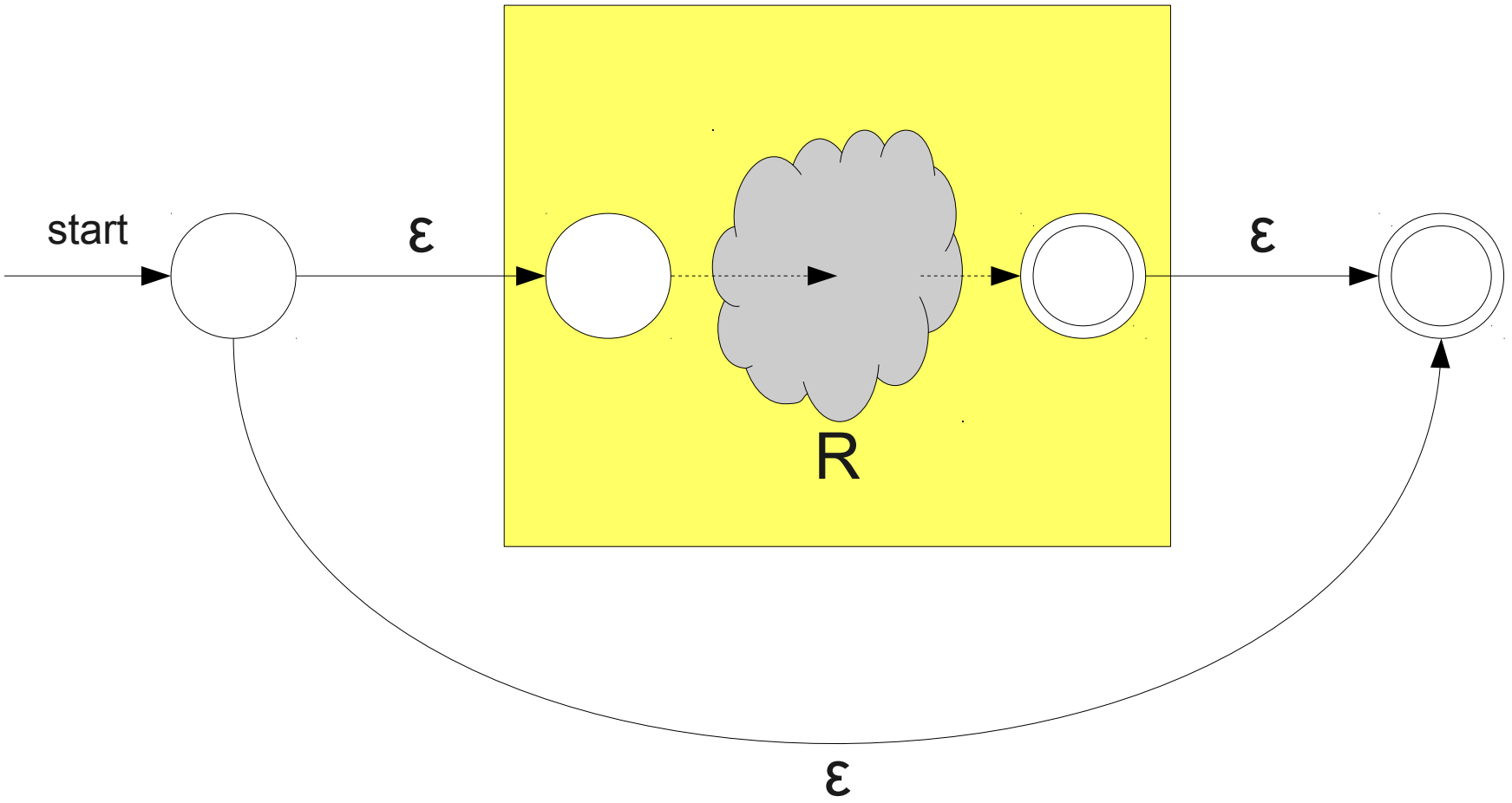
Construction for R*



Construction for R*



Construction for R*



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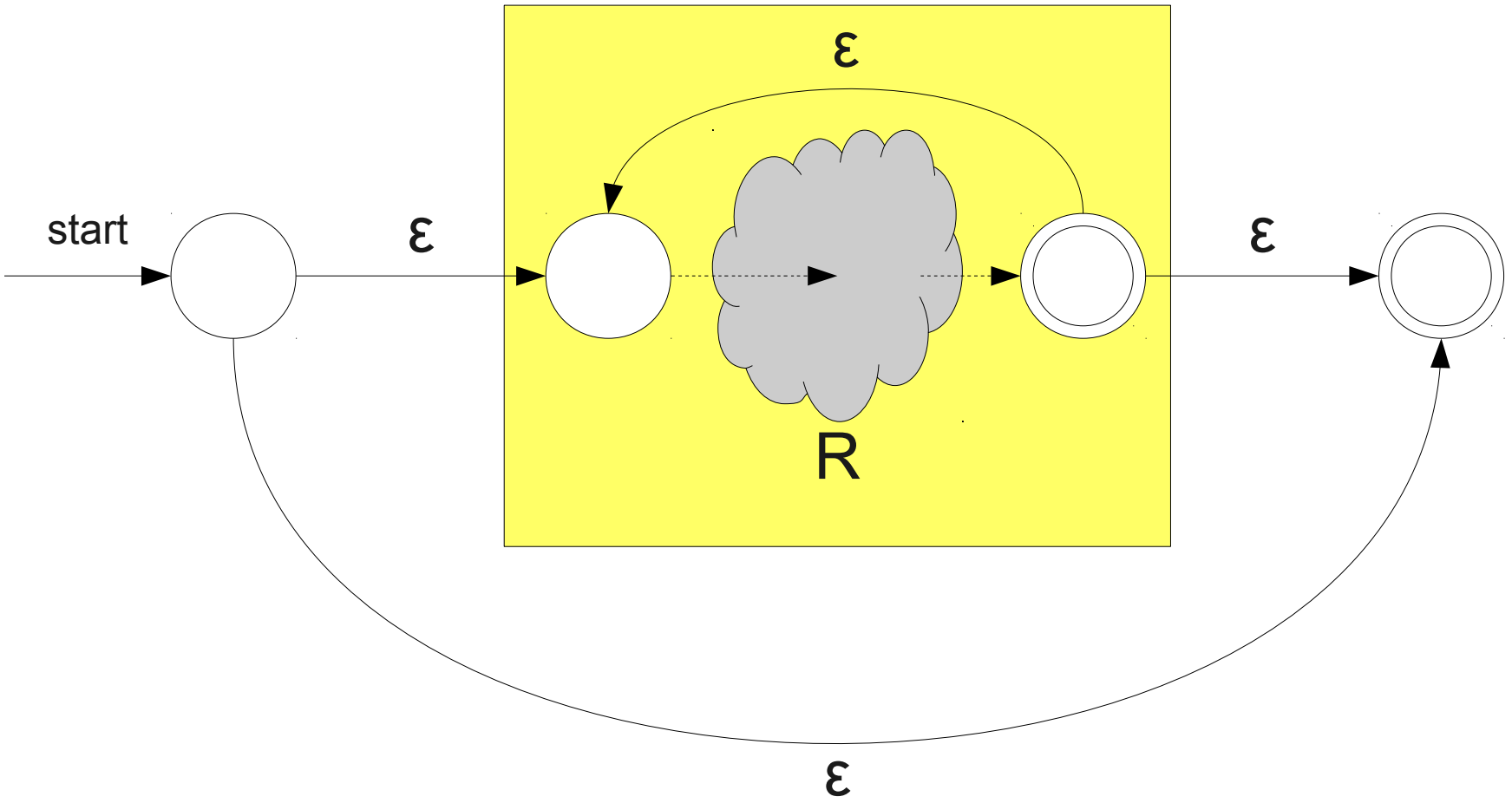
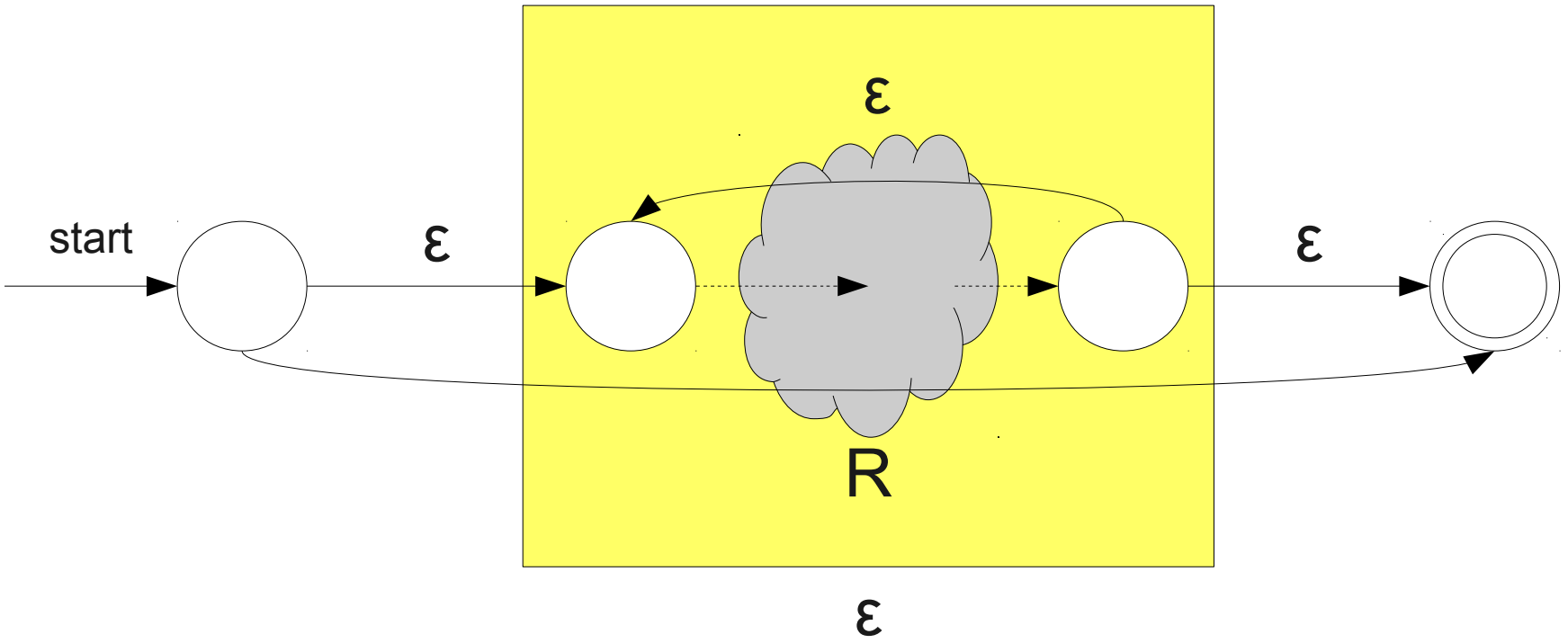


Construction for R*



Overall Result

- Any regular expression of length n can be converted into an NFA with O(n) states.
- Can determine whether a string matches a regular expression in $O(|S|n^2)$, where |S| is the length of the string.
- We'll see how to make this O(|S|) later.

The Story so Far

- We have a way of describing sets of strings for each token using regular expressions.
- We have an implementation of regular expressions using NFAs.
- How do we cut apart the input text?

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_]*
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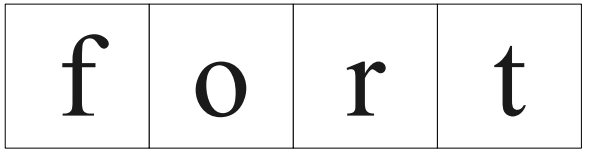

Lexing Ambiguities

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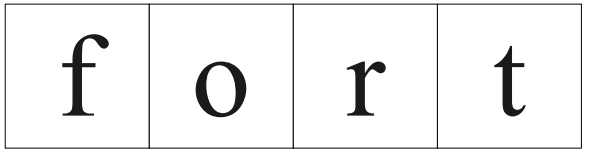
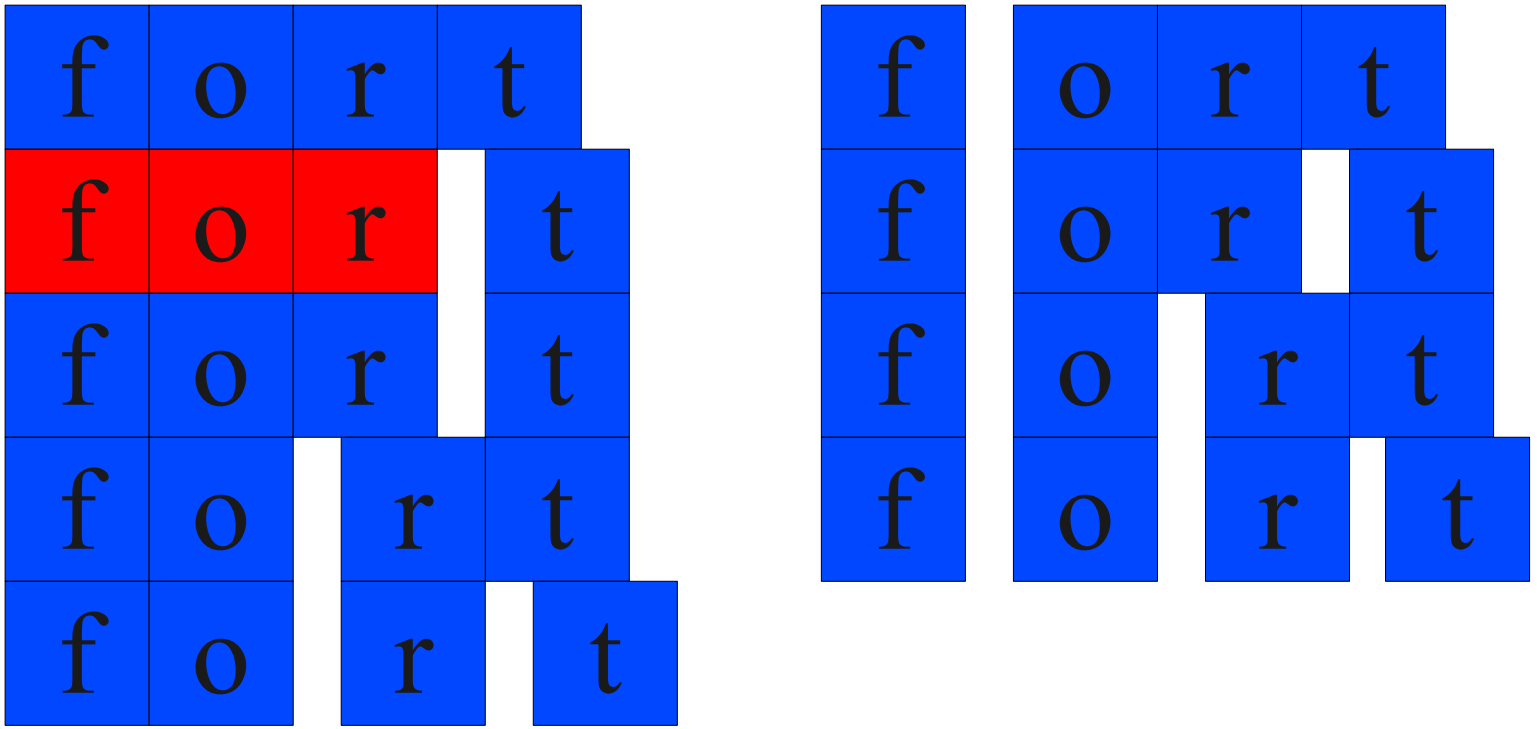
T_Identifier         [A-Za-z_][A-Za-z0-9_]*
```



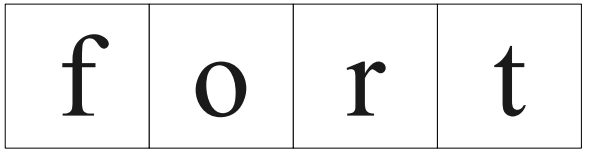


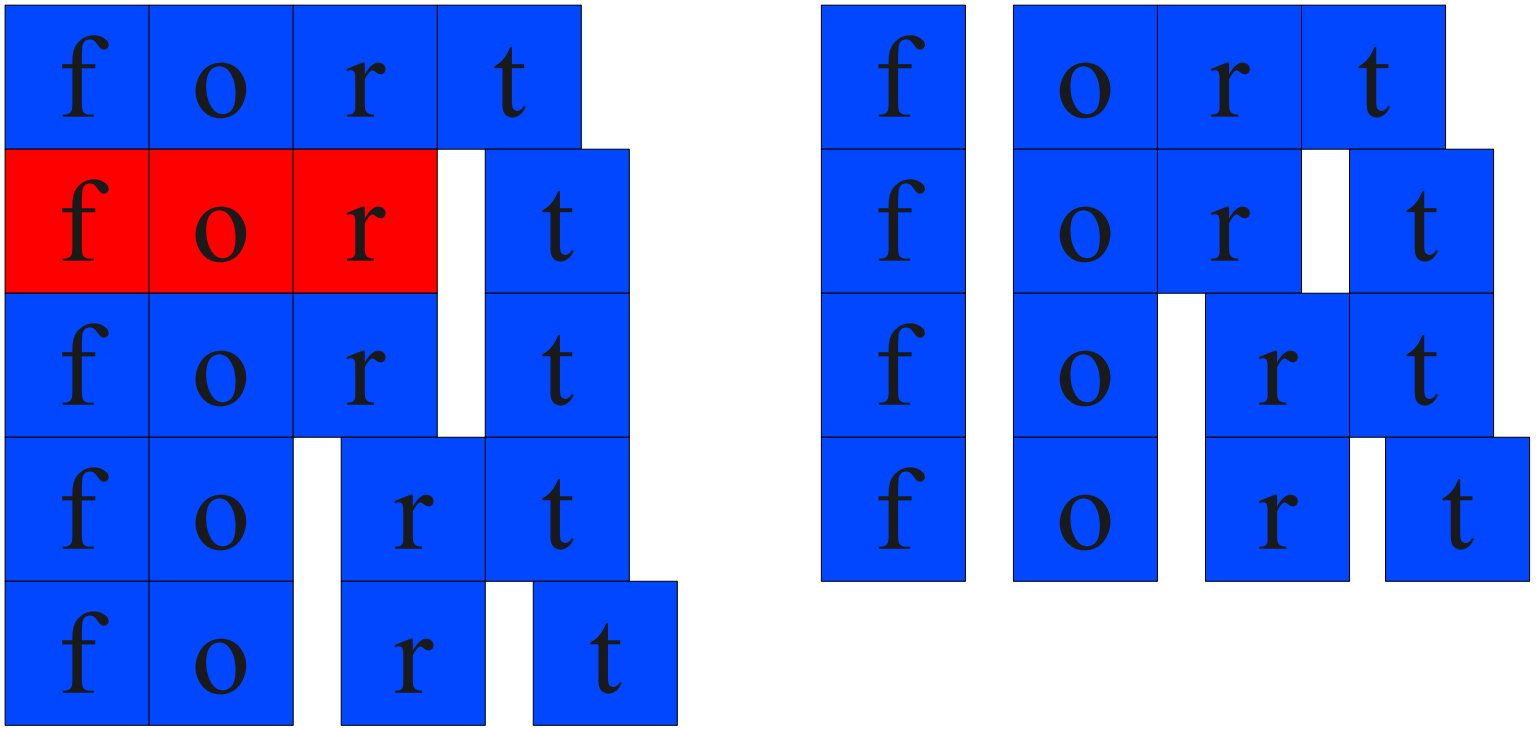
Conflict Resolution

- 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_]*
```





Lexing Ambiguities

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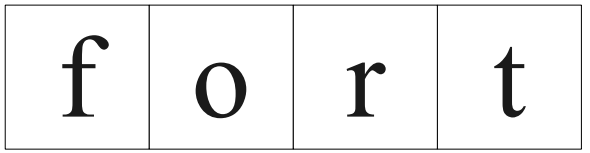
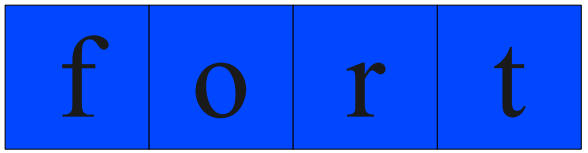




Implementing Maximal Munch

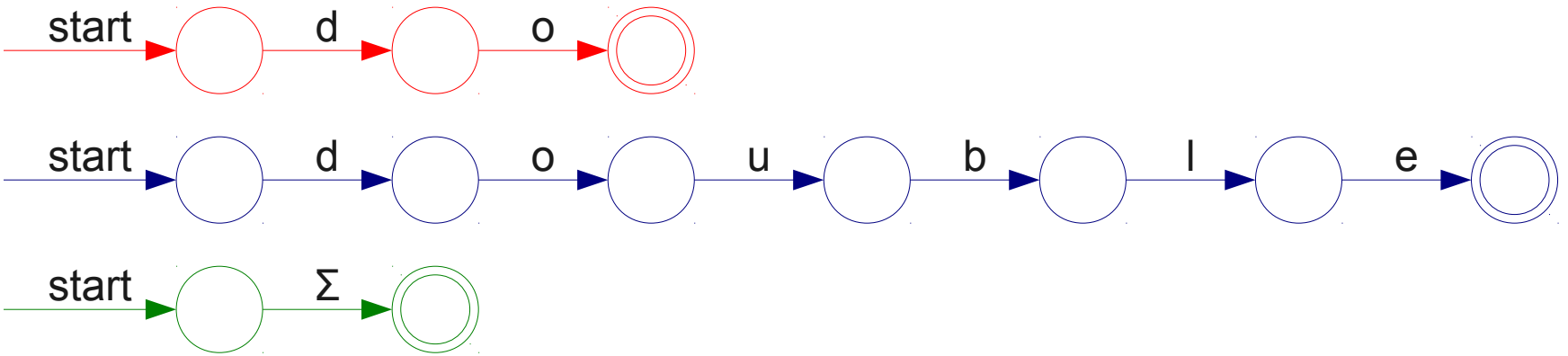
- Given a set of regular expressions, how can we use them to implement maximum munch?
- Idea:
  - Convert expressions to NFAs.
  - Run all NFAs in parallel, keeping track of the last match.
  - When all automata get stuck, report the last match and restart the search at that point.

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
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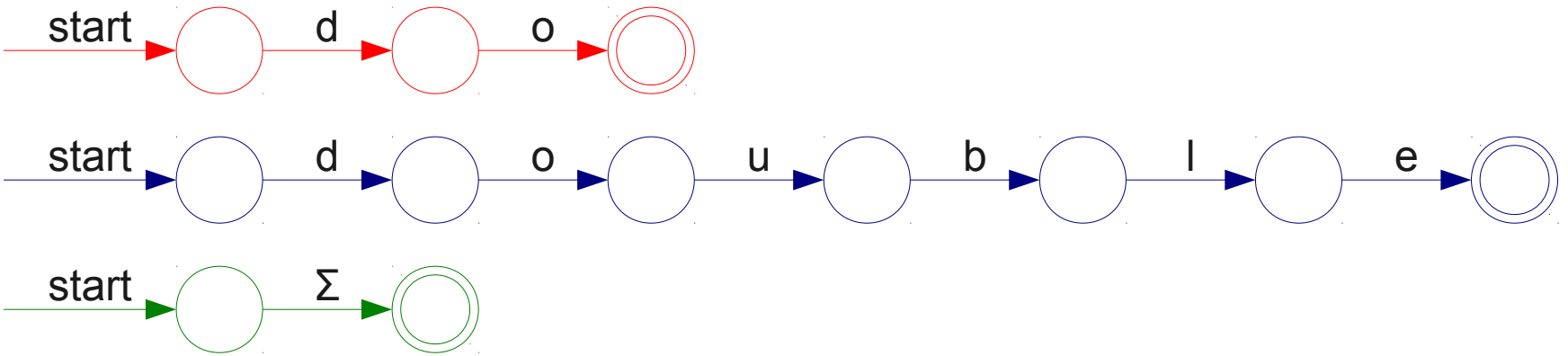
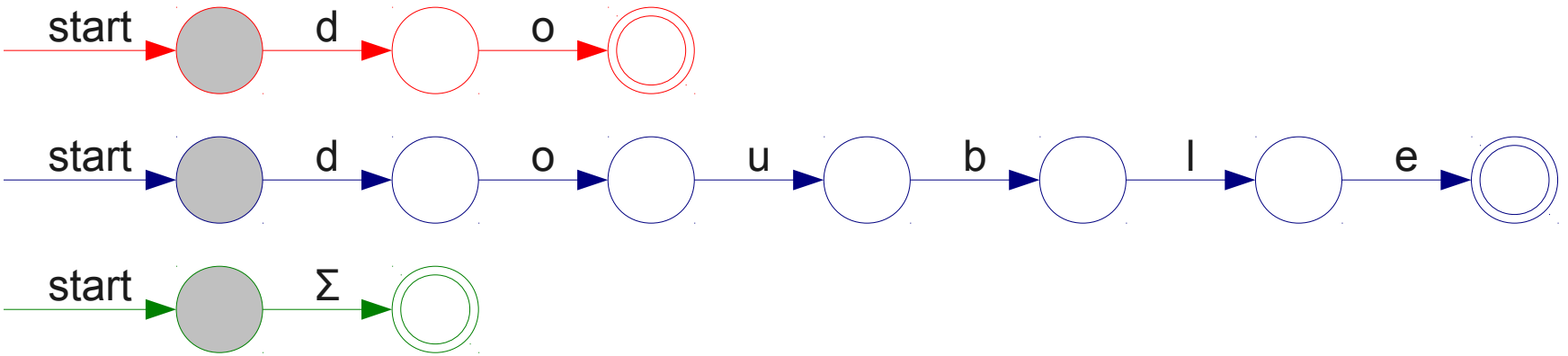
T_Mystery     [A-Za-z]
```



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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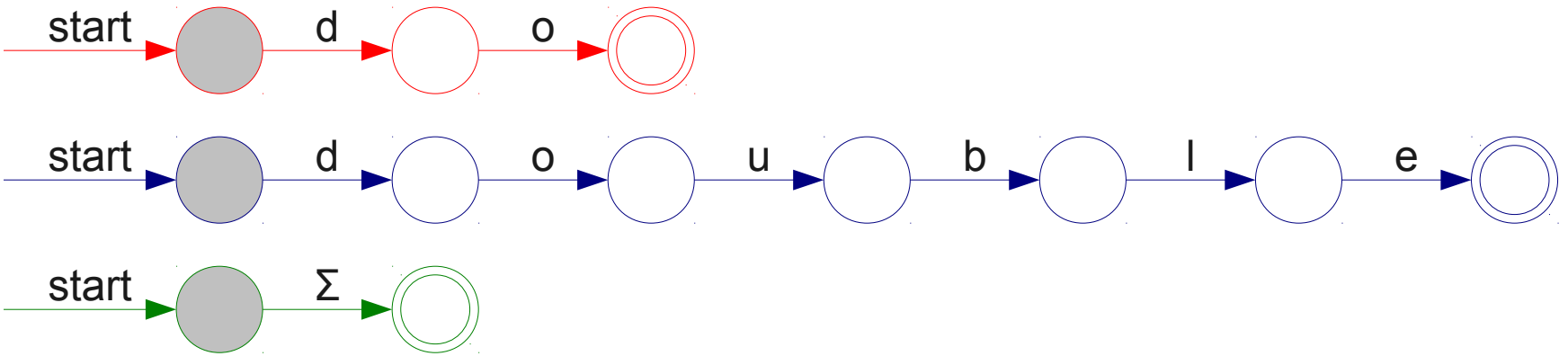

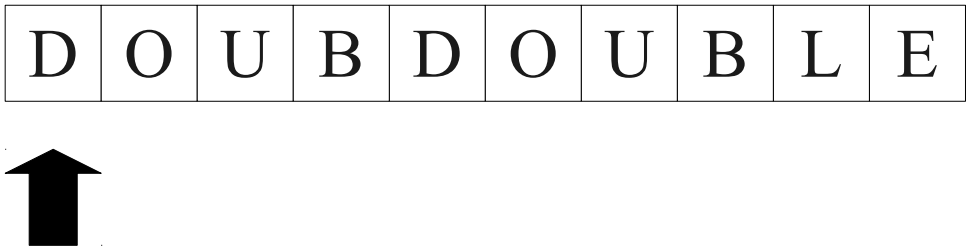

Implementing Maximal Munch

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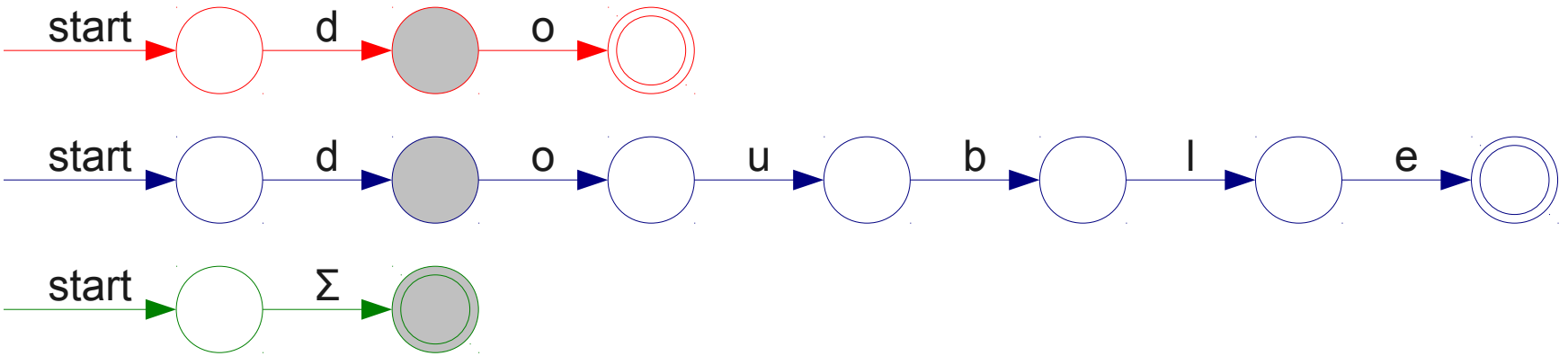

D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

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T_Mystery     [A-Za-z]
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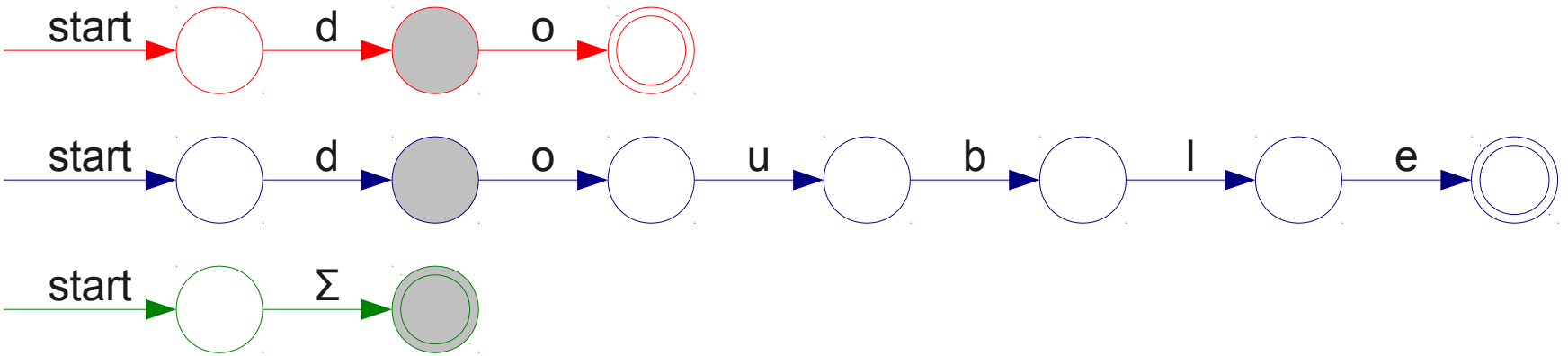

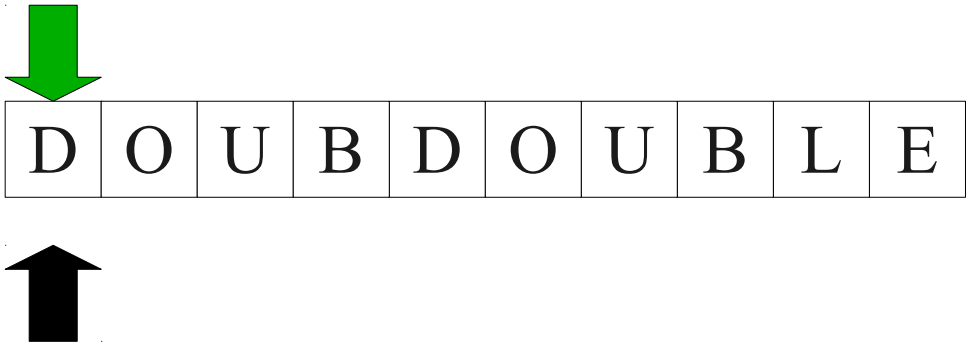

Implementing Maximal Munch

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T_Mystery     [A-Za-z]
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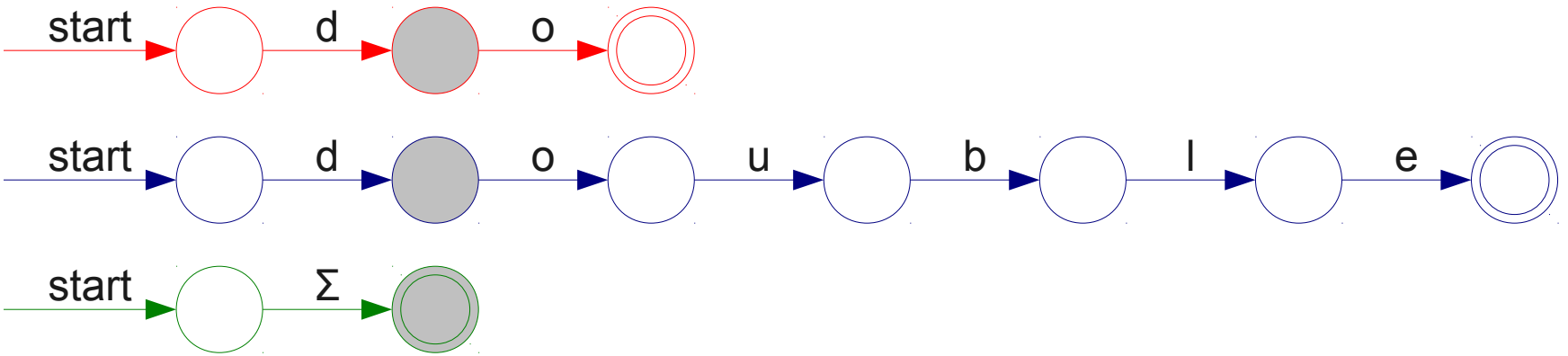

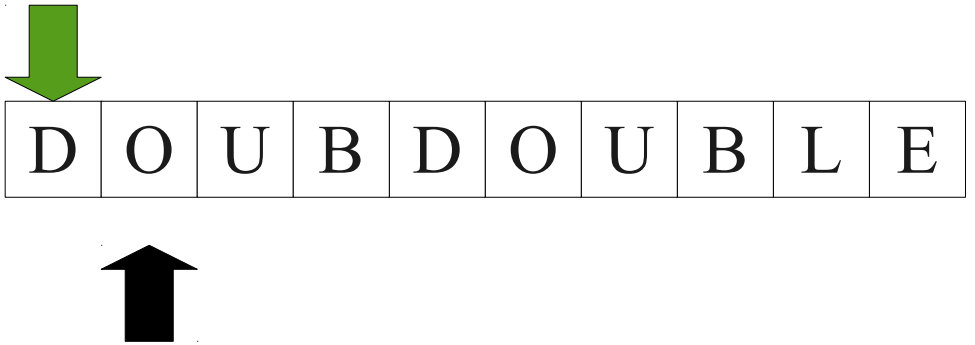

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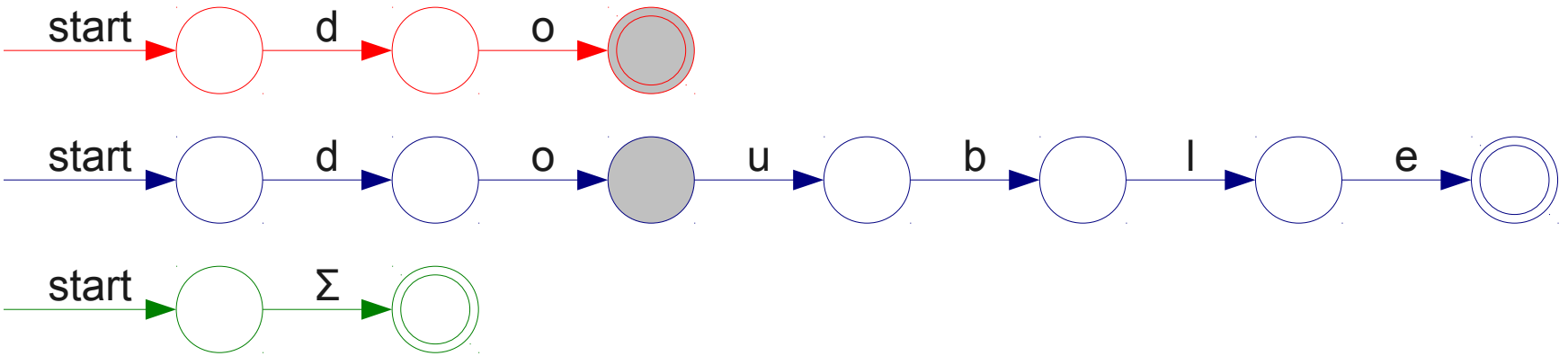

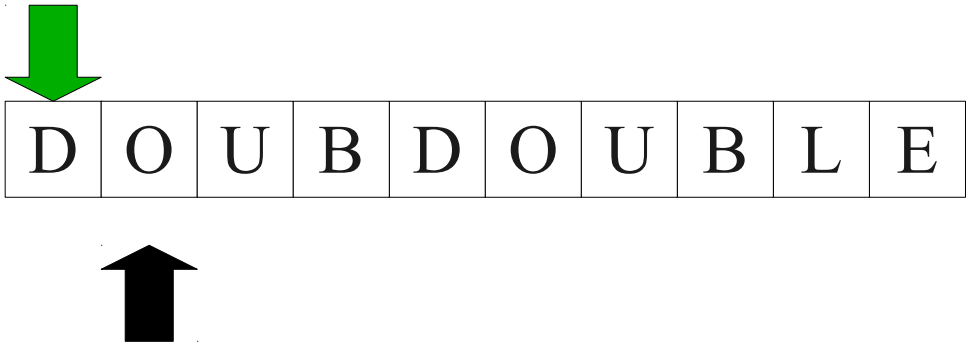

Implementing Maximal Munch

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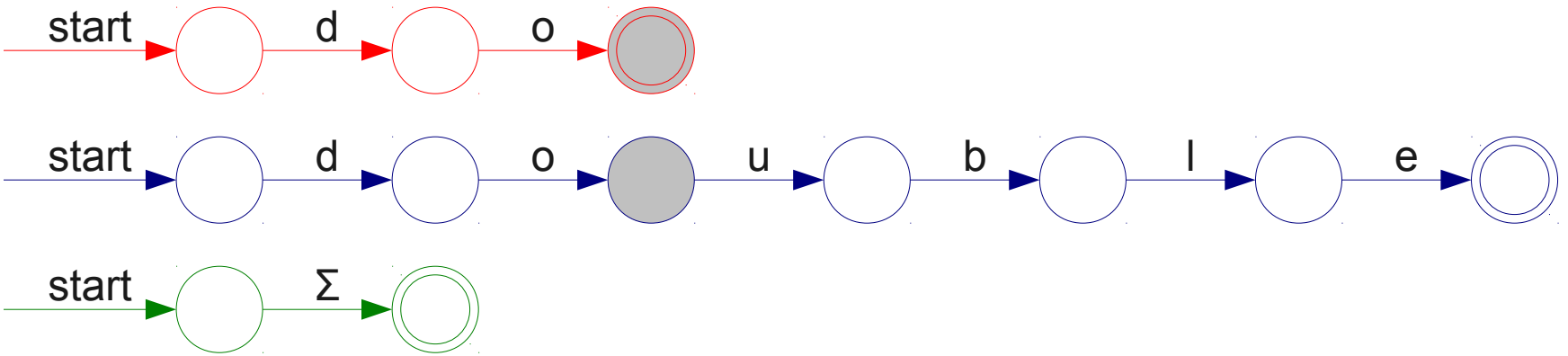

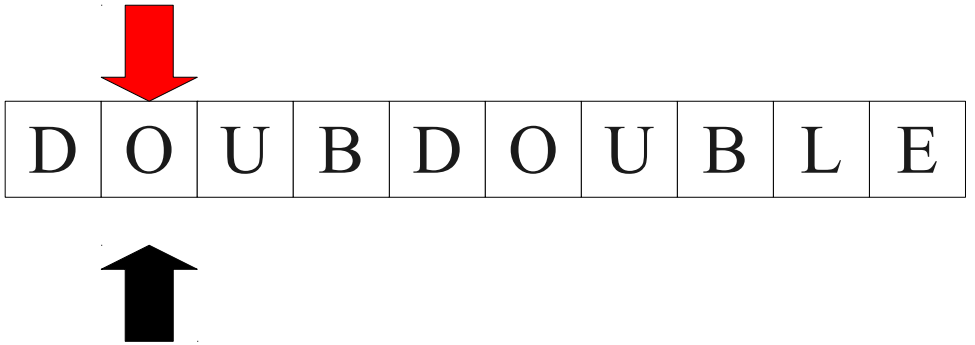

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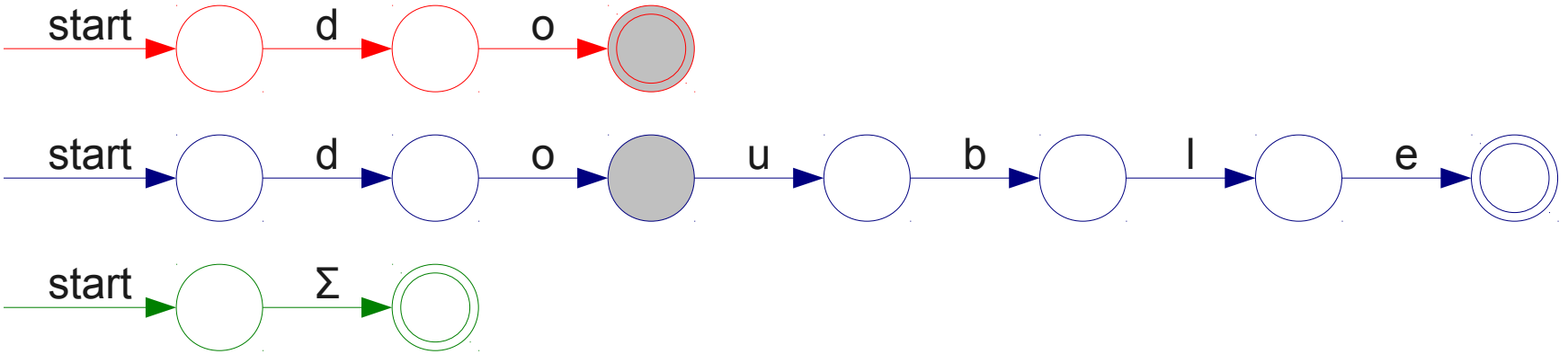

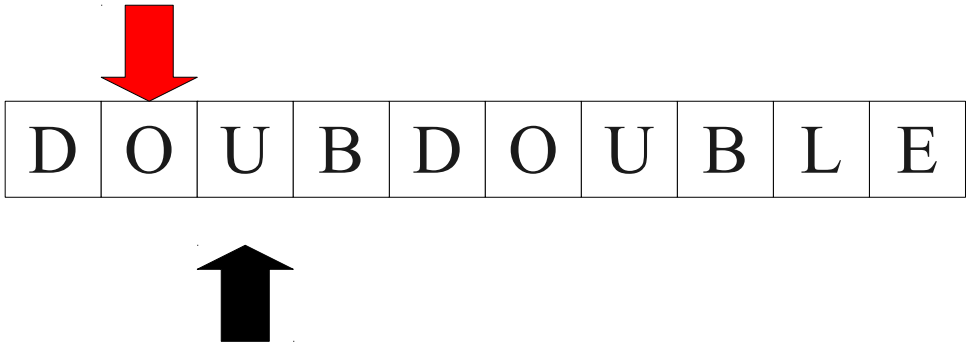

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T_Mystery     [A-Za-z]
```
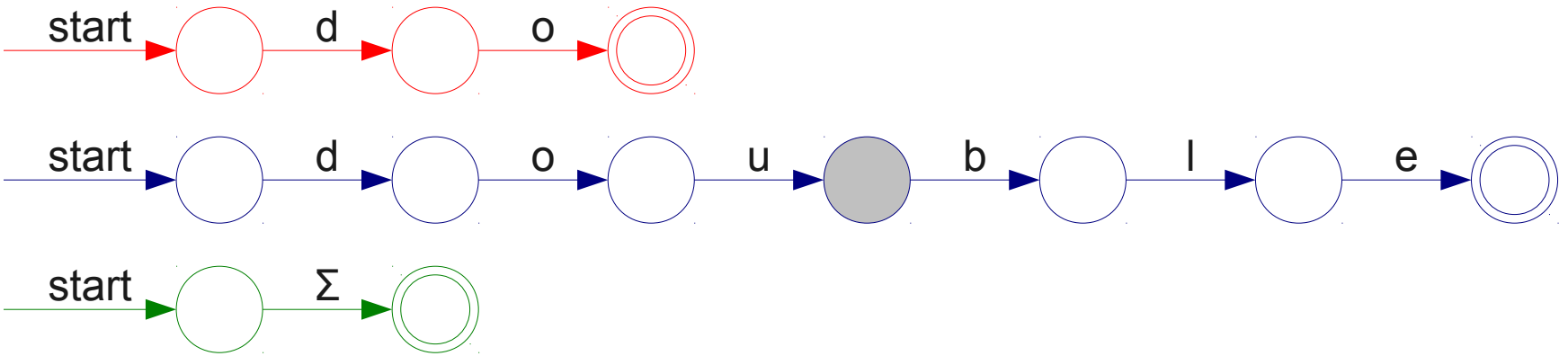
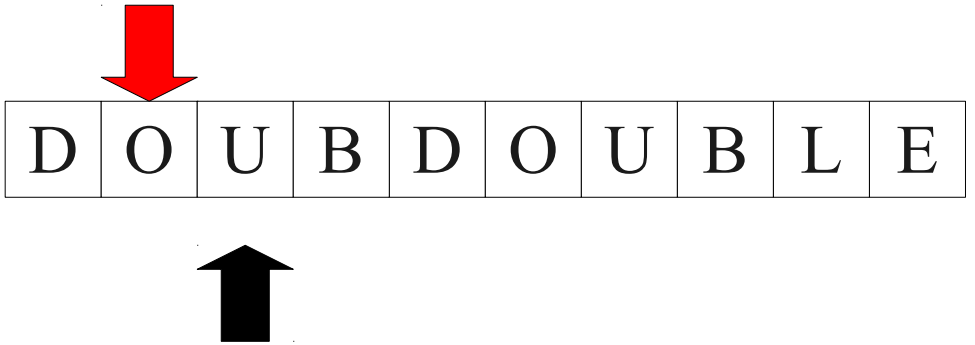
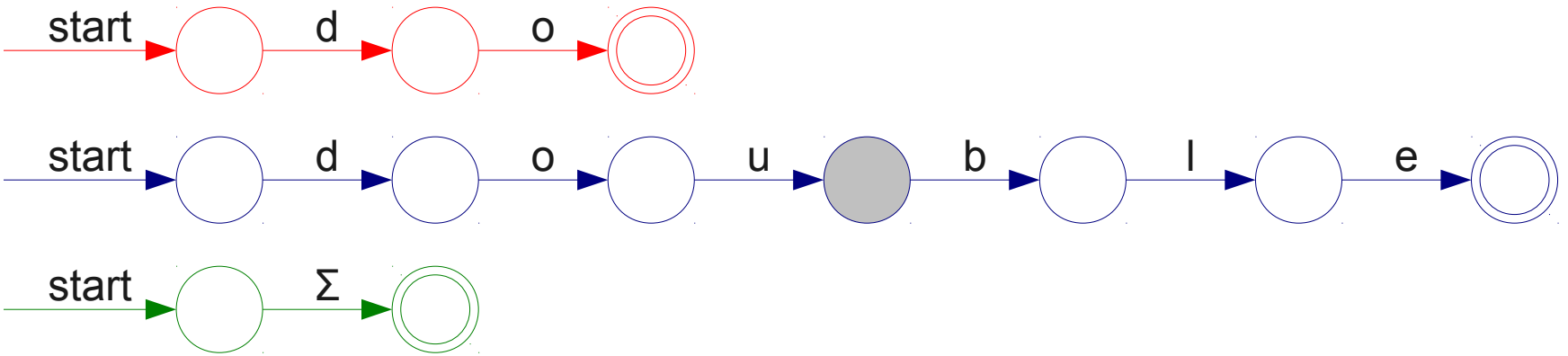
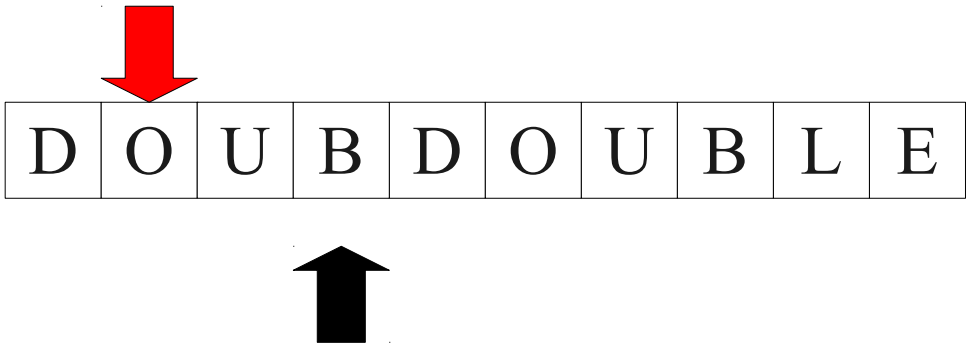





Implementing Maximal Munch

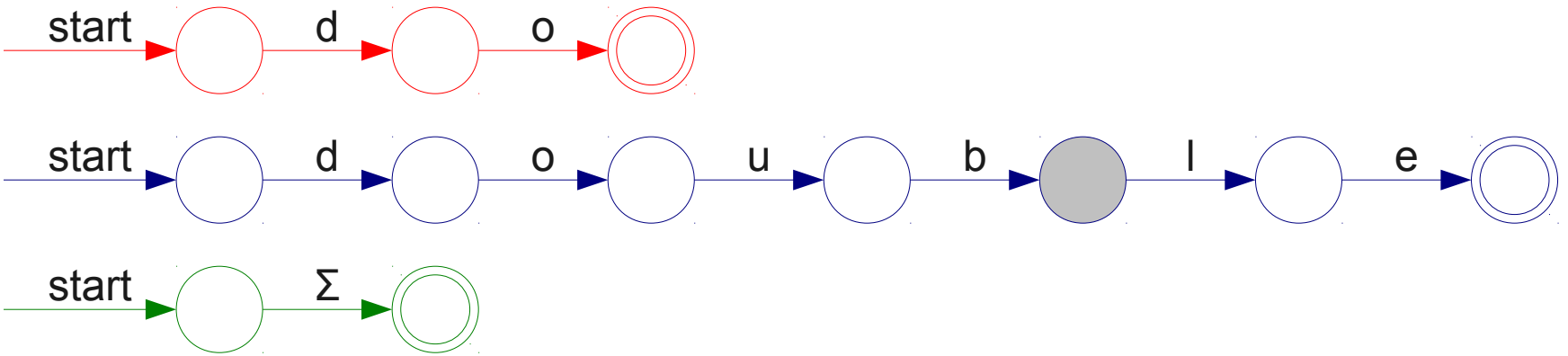
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

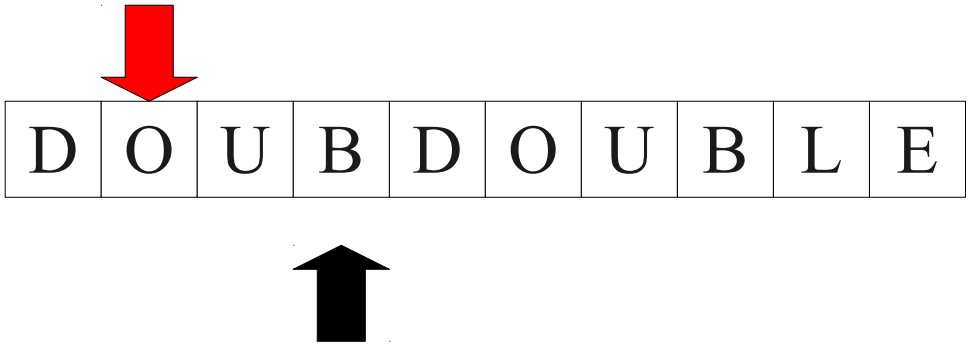




Implementing Maximal Munch

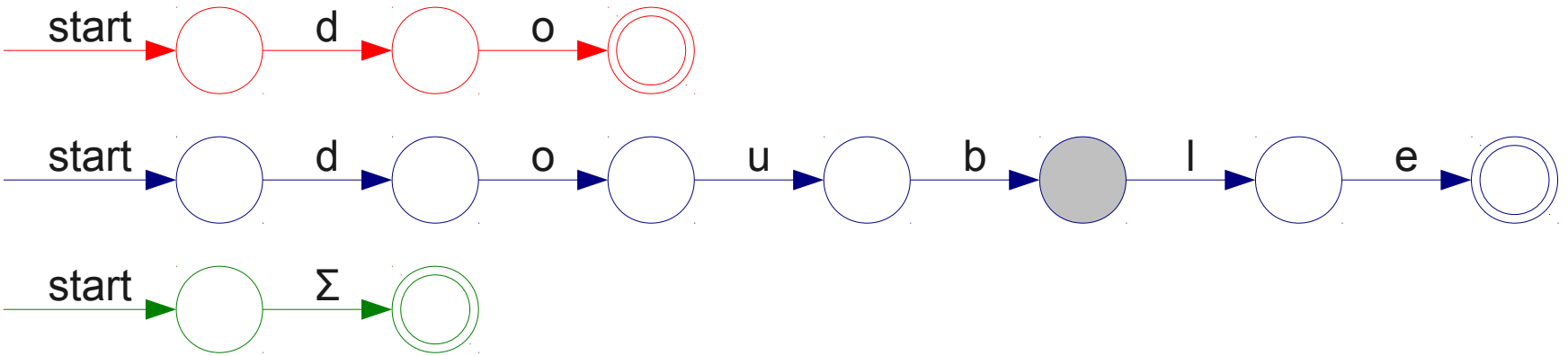
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

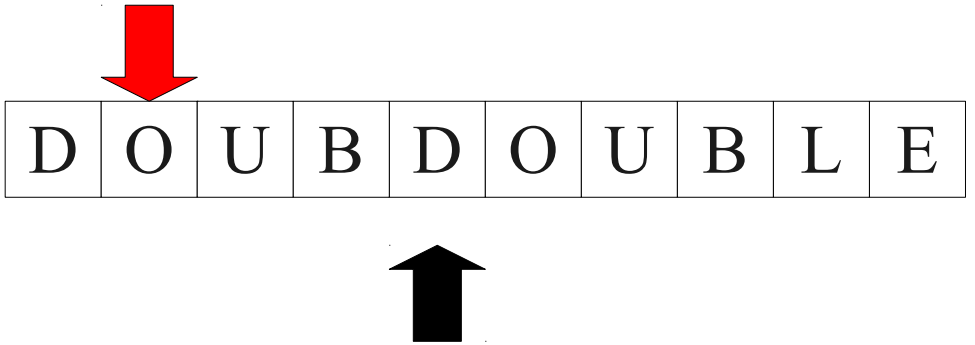




Implementing Maximal Munch

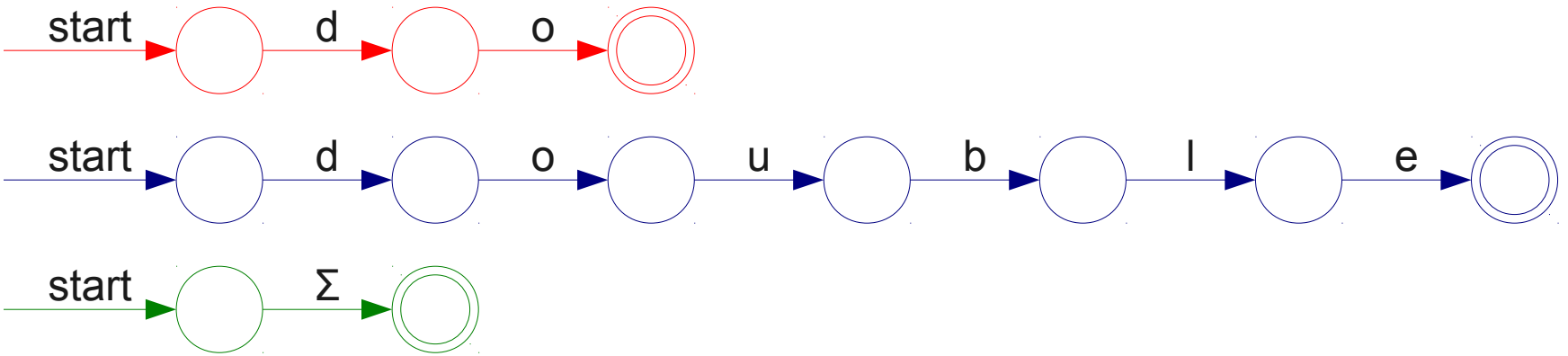
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

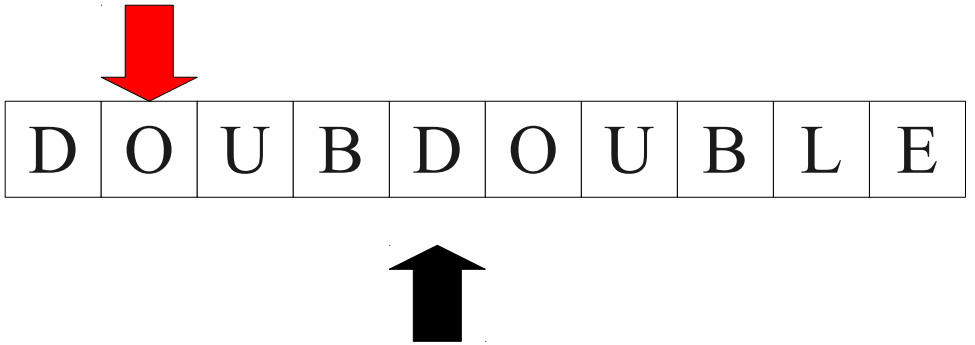




Implementing Maximal Munch

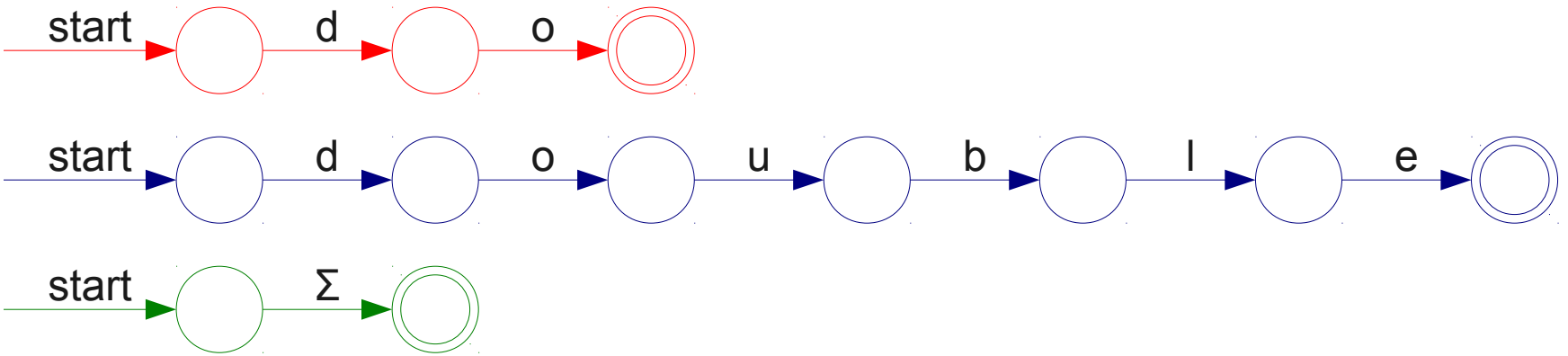
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

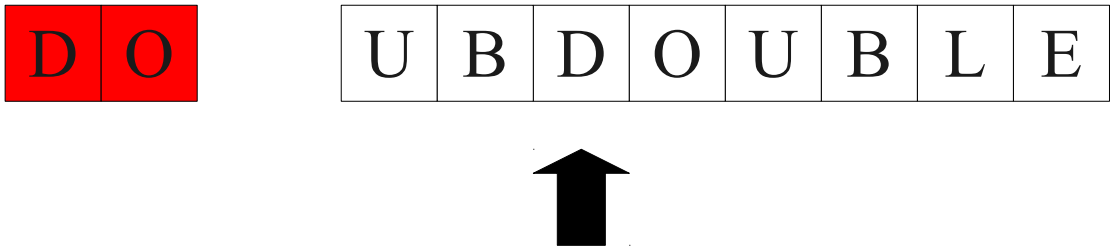




Implementing Maximal Munch

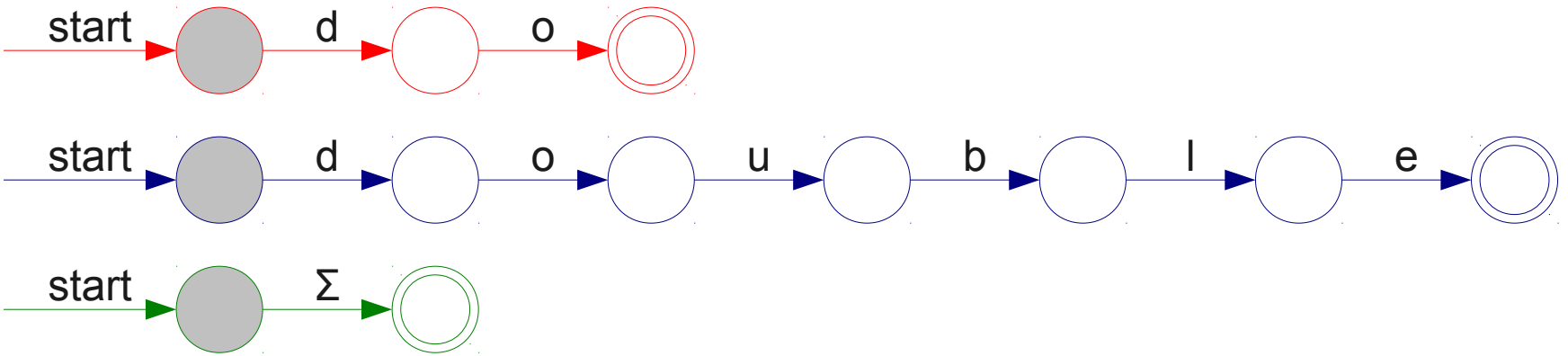
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

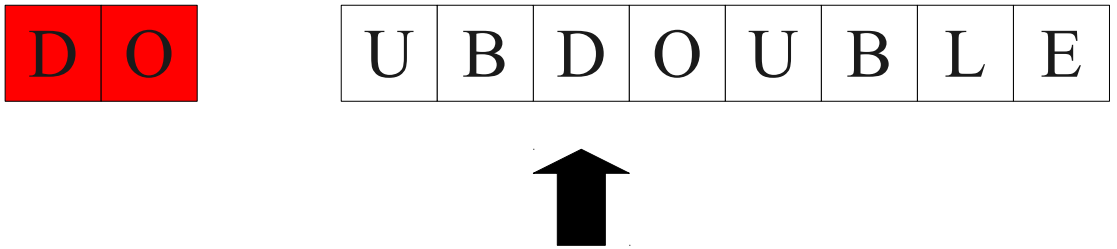




Implementing Maximal Munch

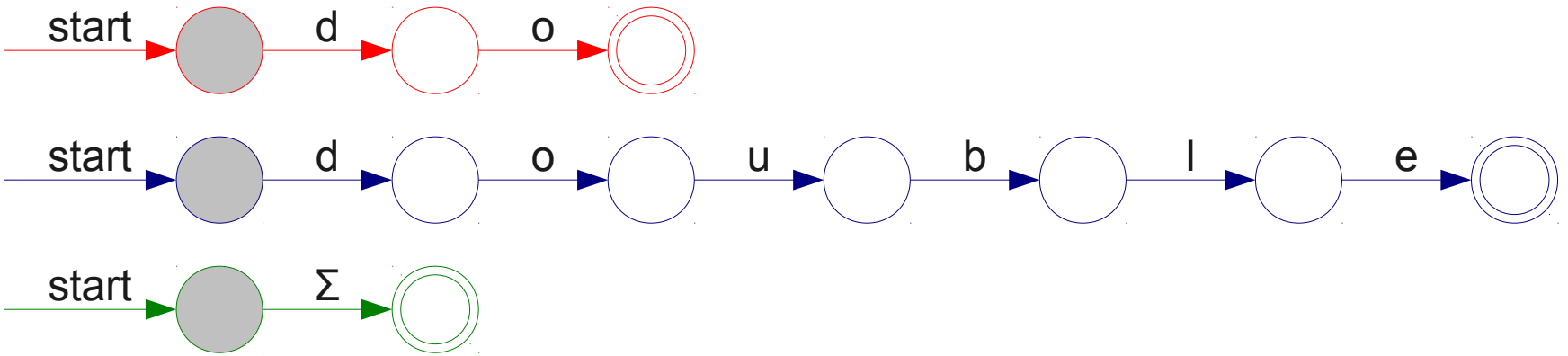
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

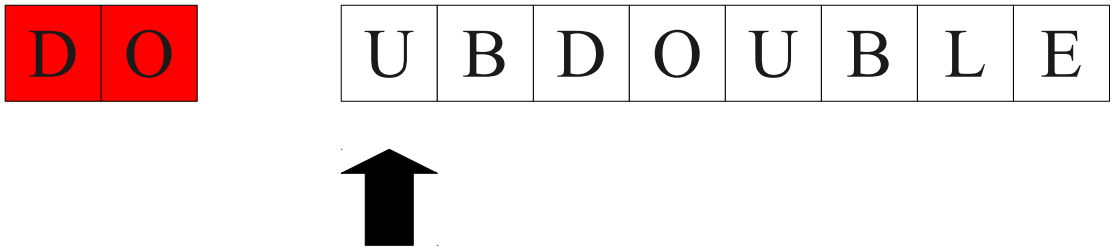




Implementing Maximal Munch

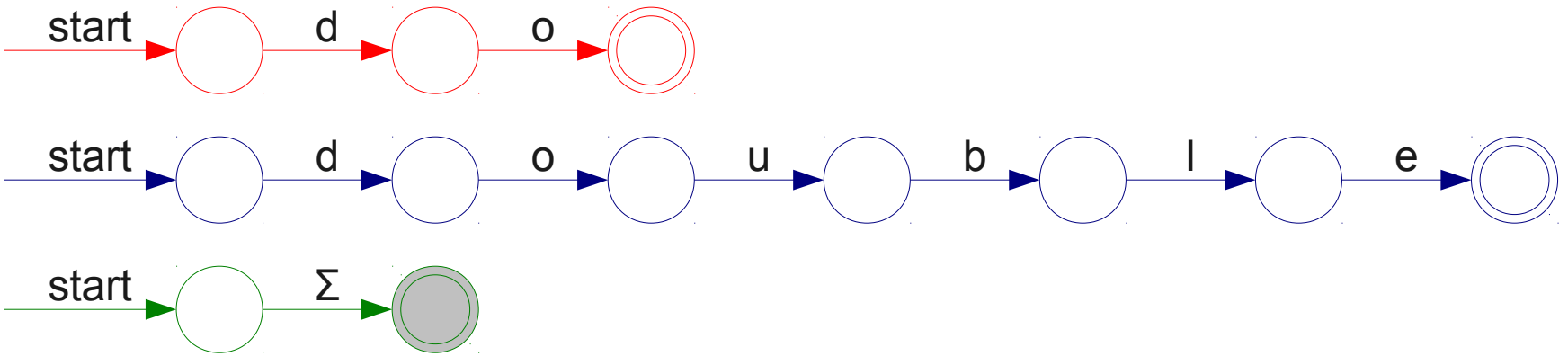
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

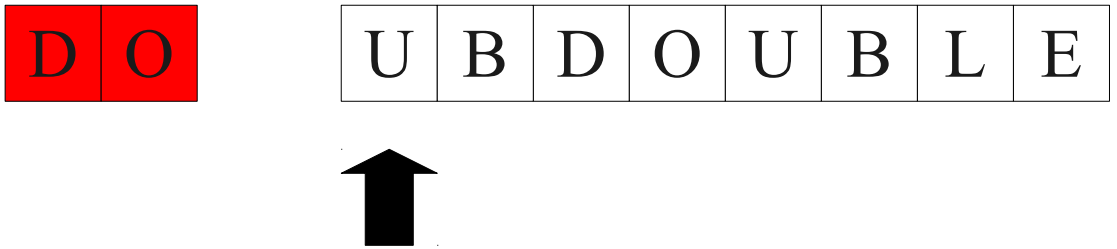




Implementing Maximal Munch

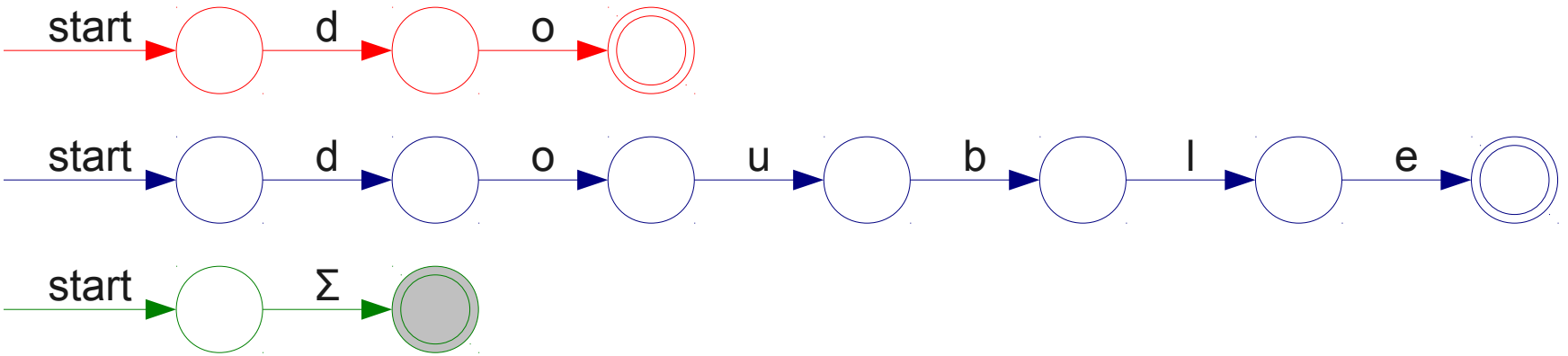
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

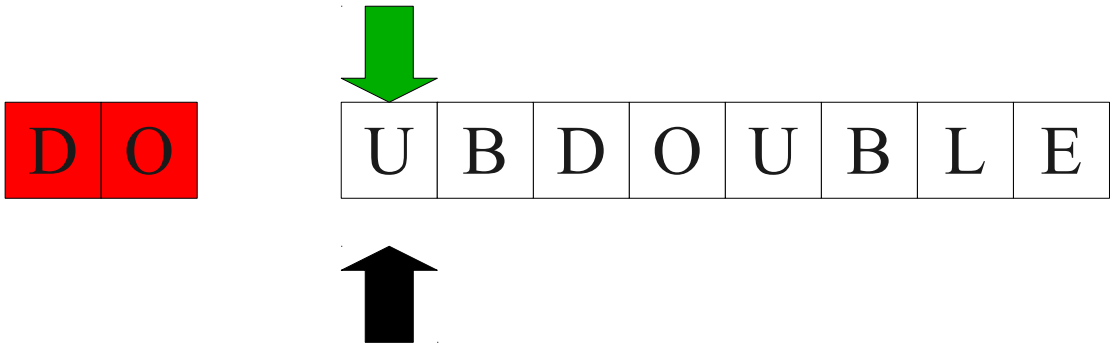




Implementing Maximal Munch

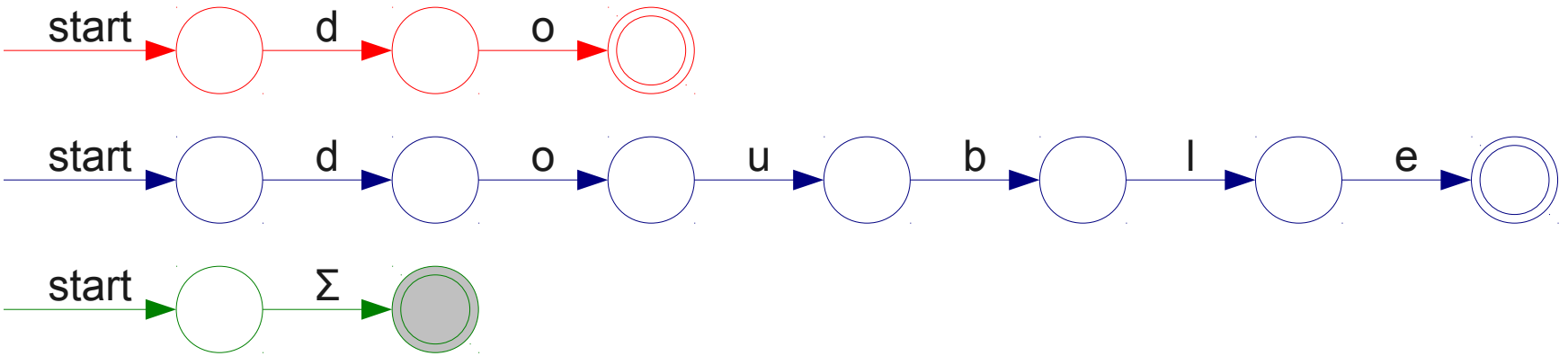
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

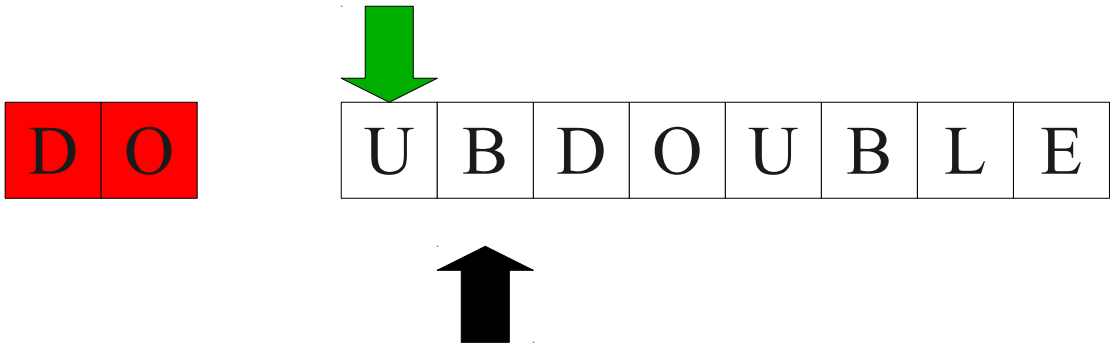




Implementing Maximal Munch

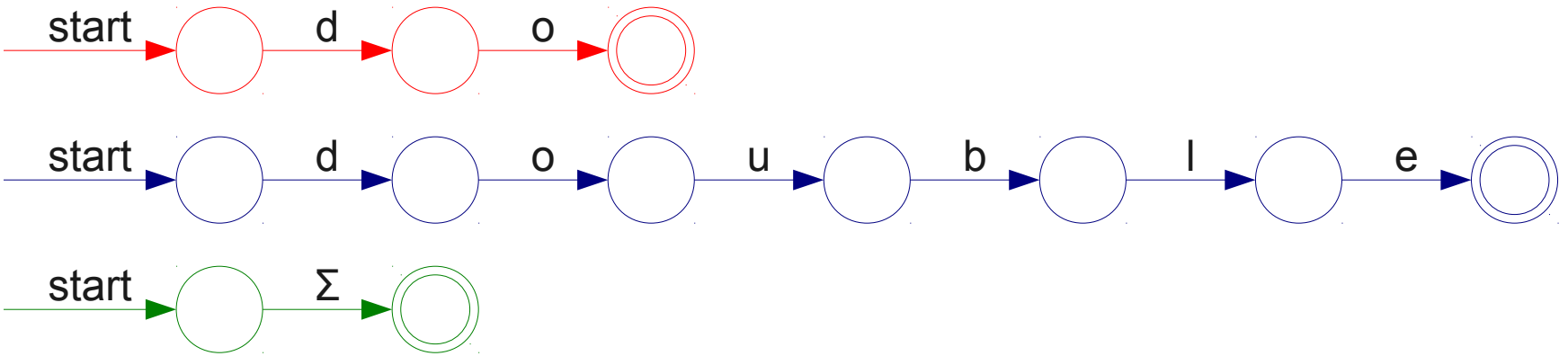
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

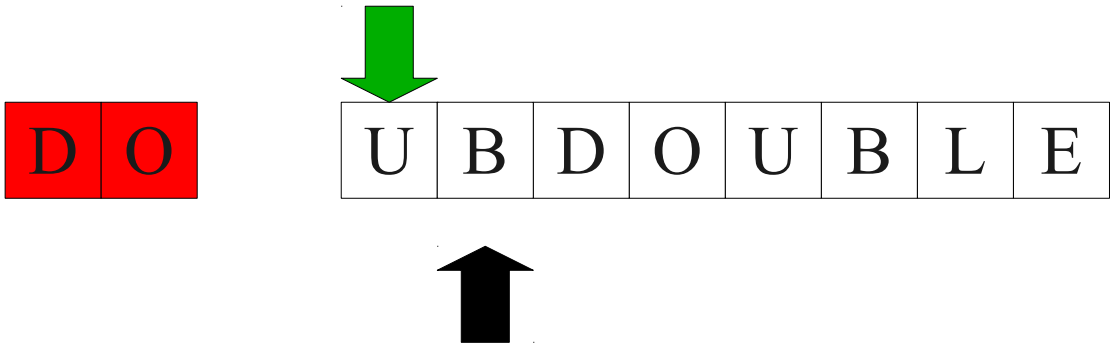




Implementing Maximal Munch

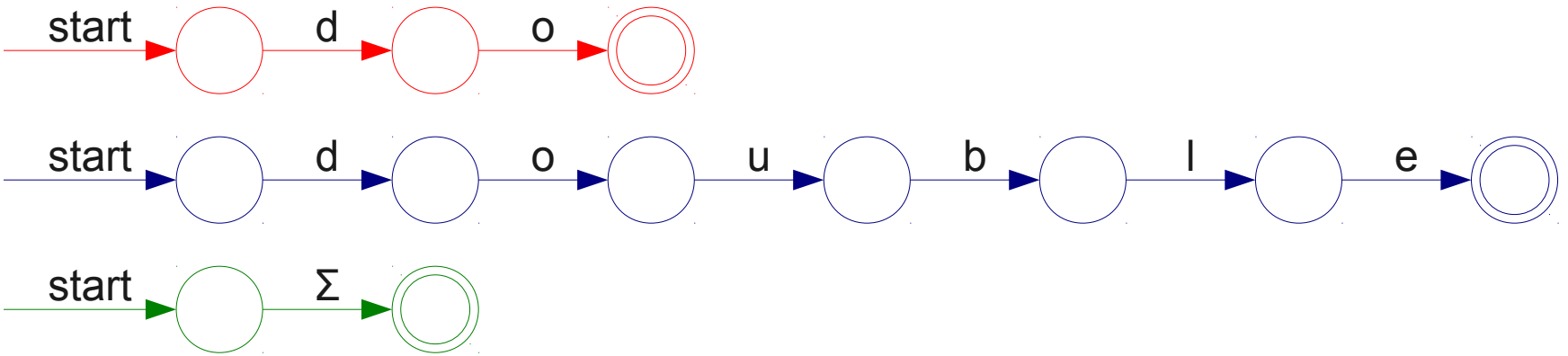
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

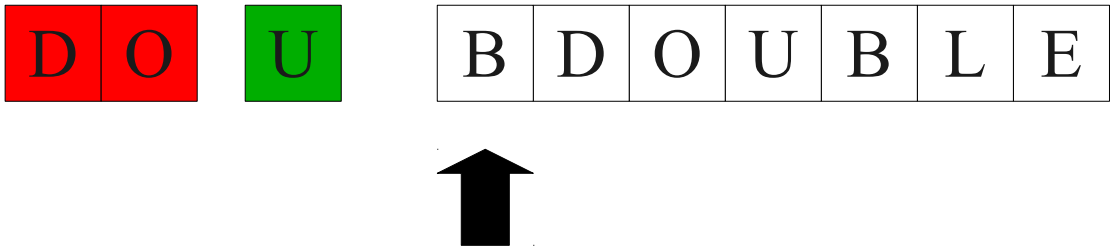




Implementing Maximal Munch

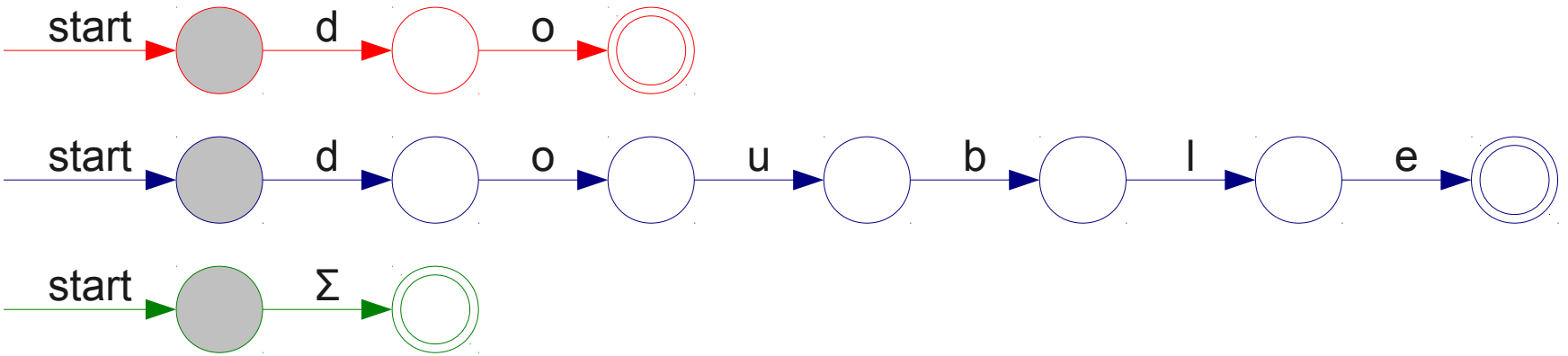
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

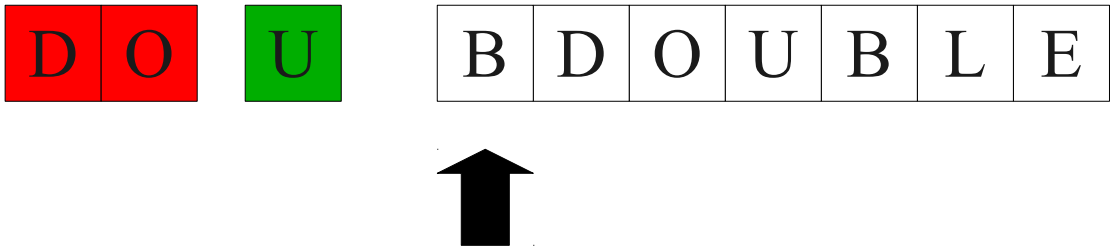




Implementing Maximal Munch

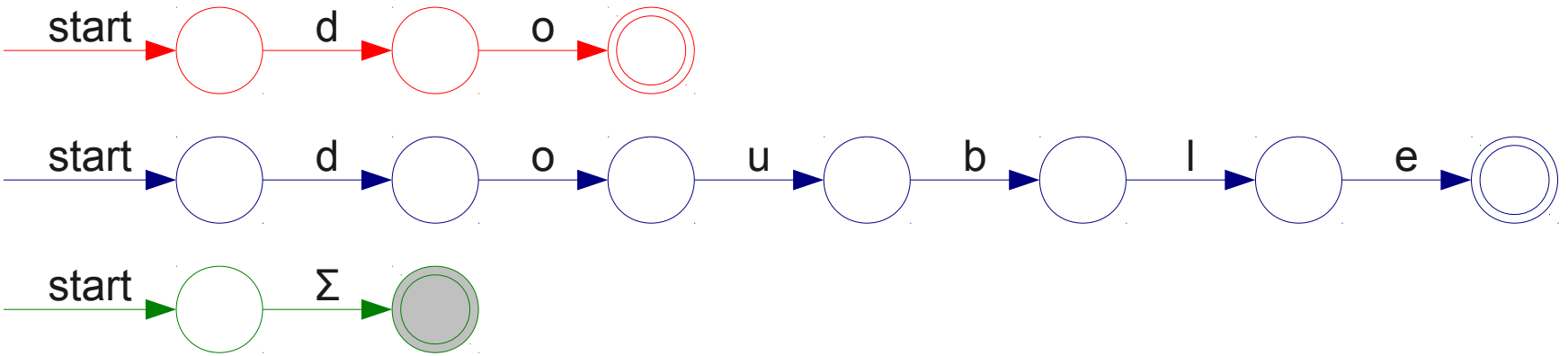
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

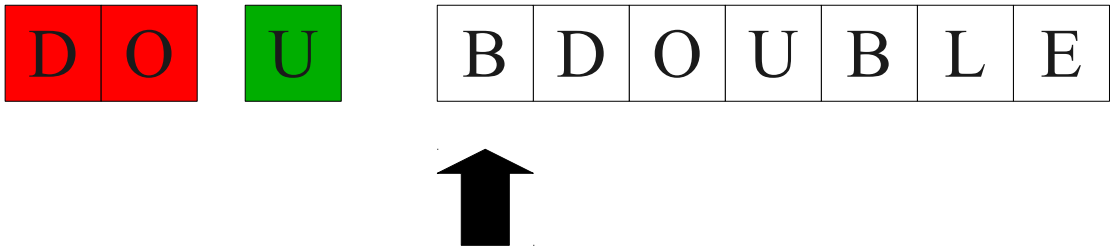




Implementing Maximal Munch

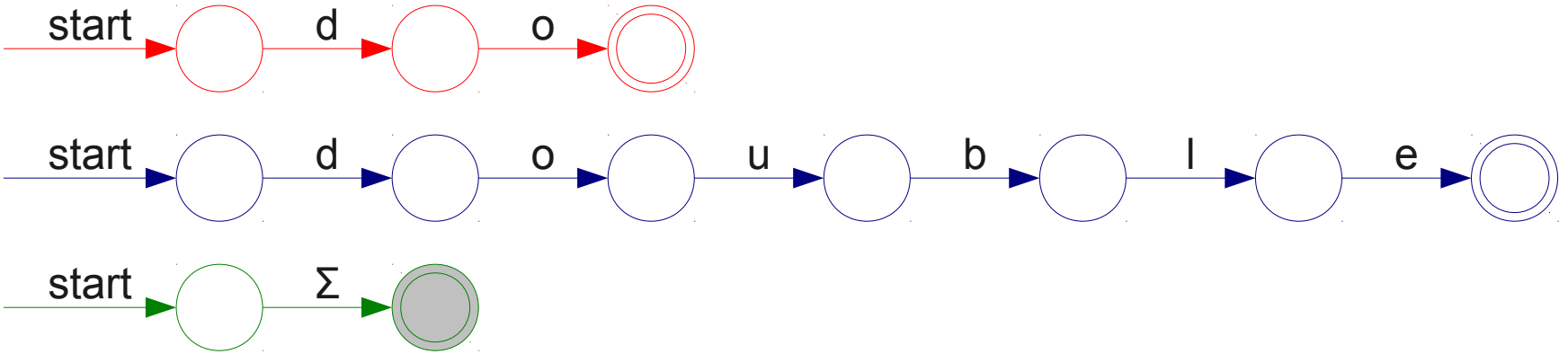
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

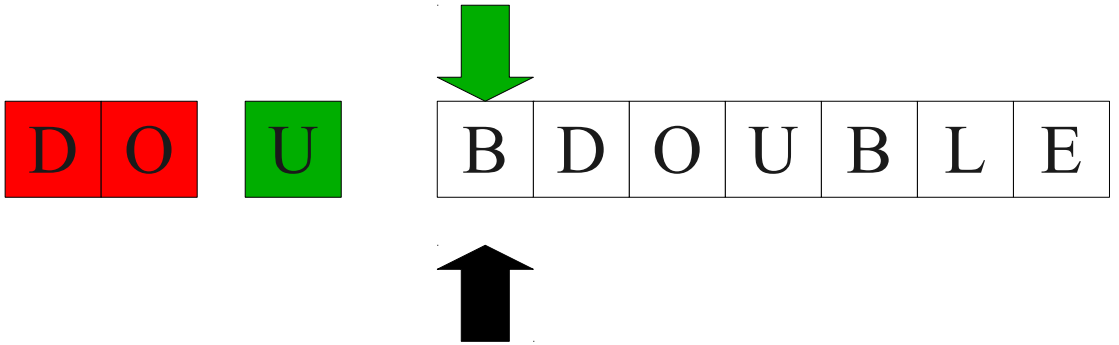




Implementing Maximal Munch

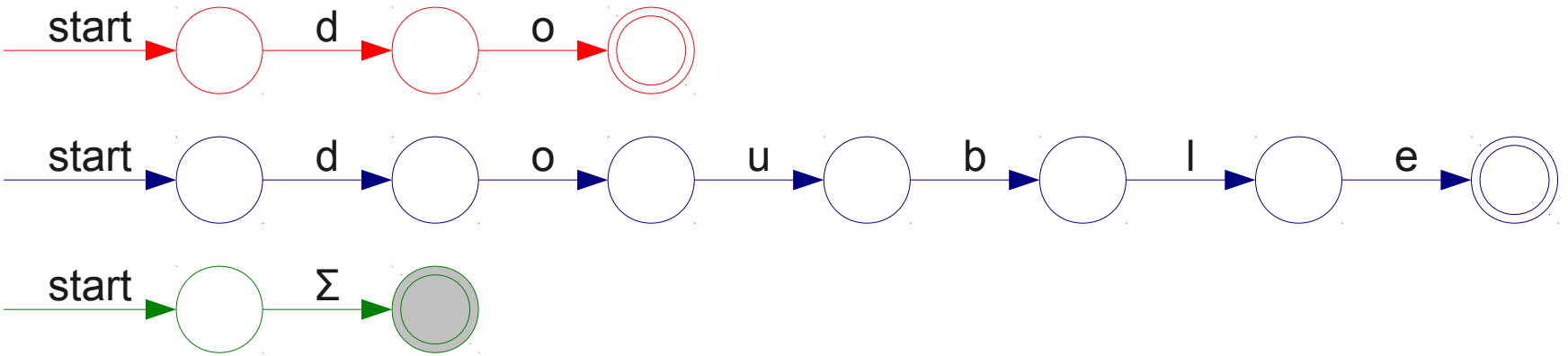
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

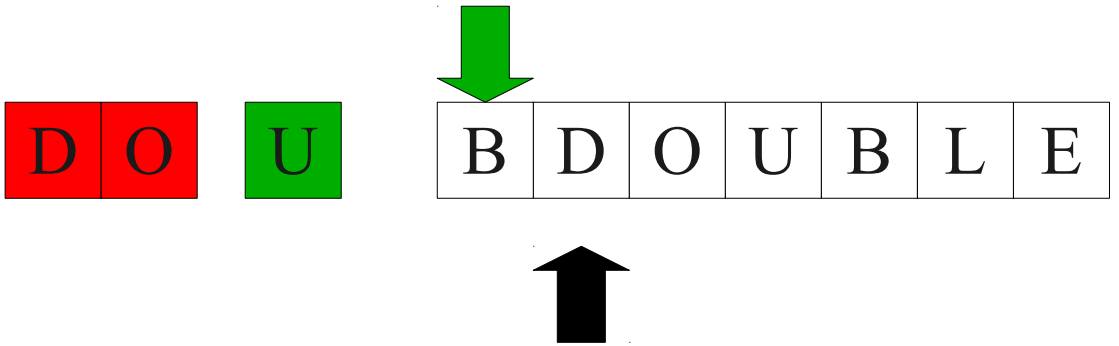




Implementing Maximal Munch

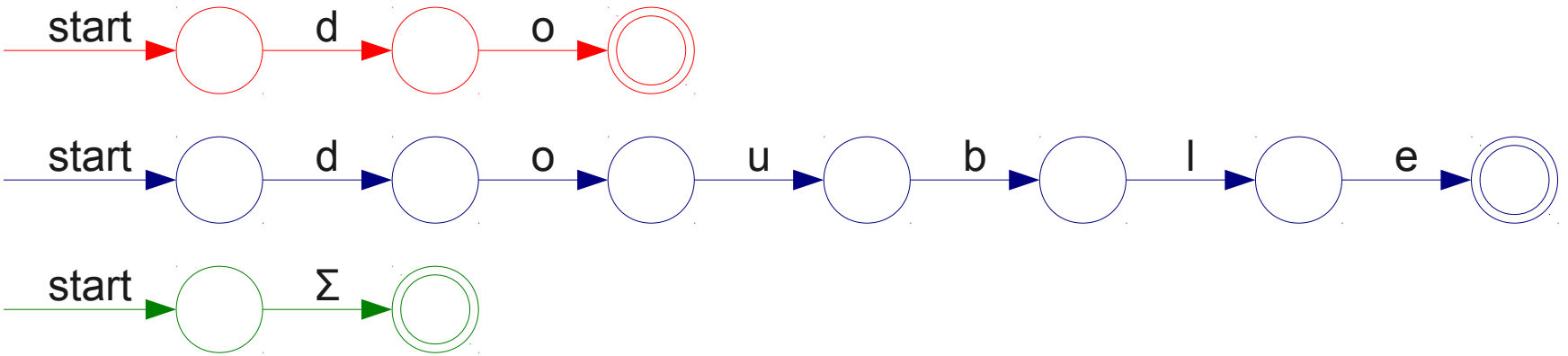
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

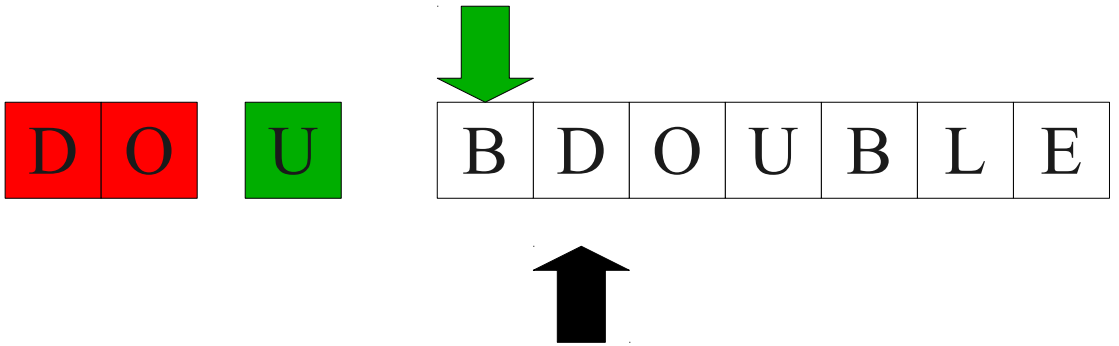




Implementing Maximal Munch

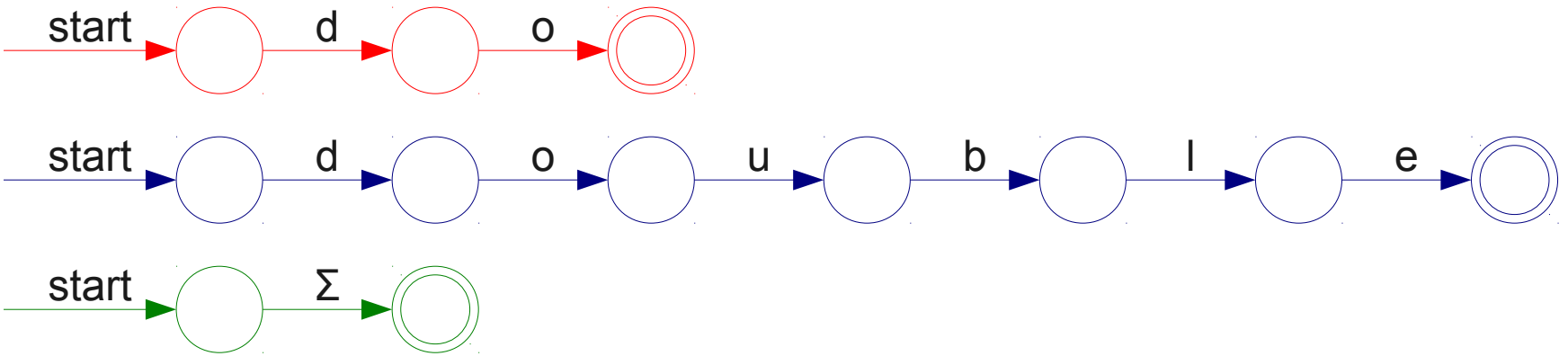
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

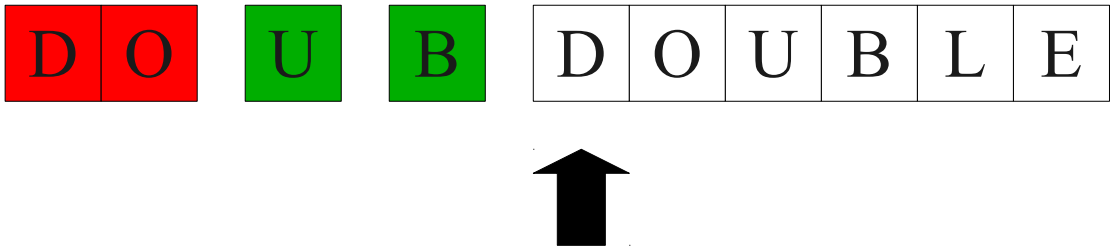




Implementing Maximal Munch

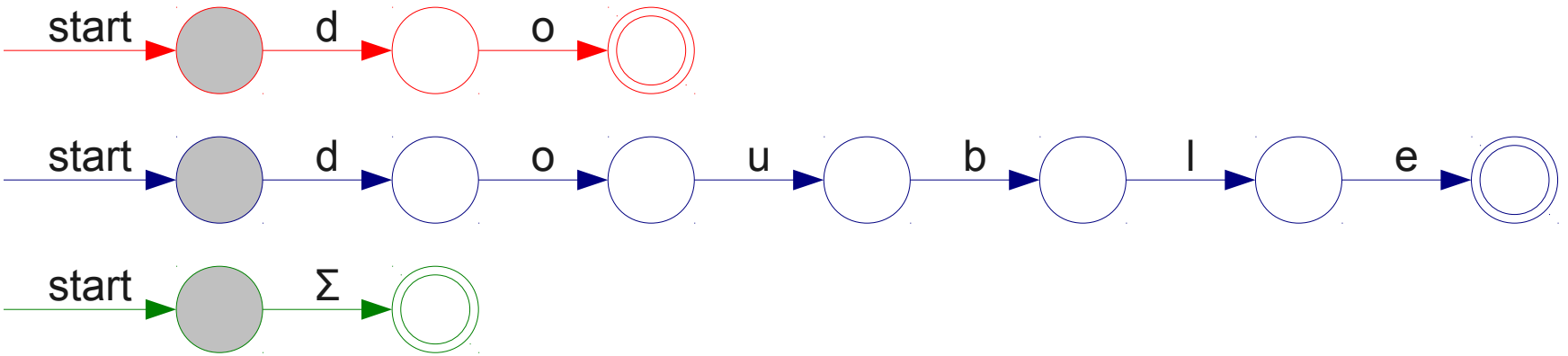
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

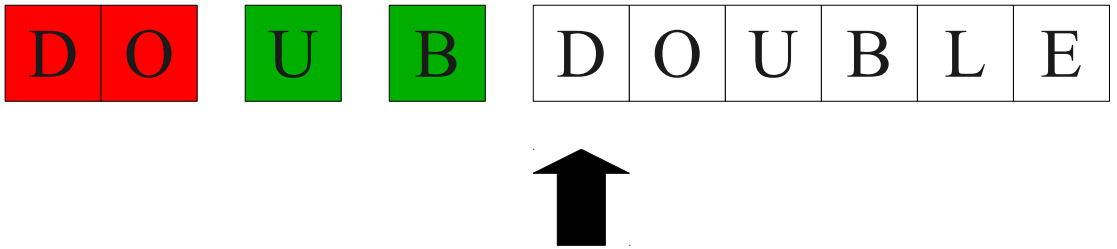




Implementing Maximal Munch

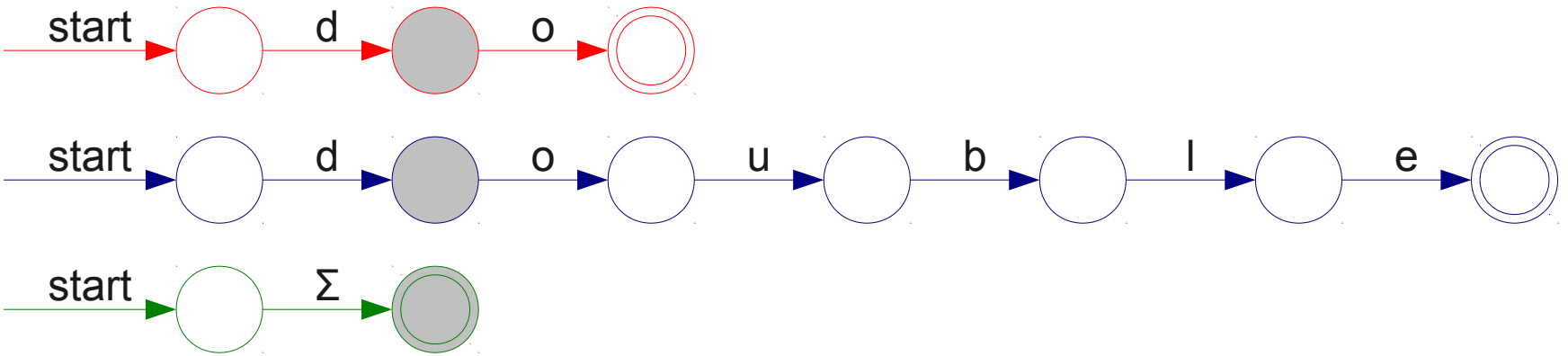
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

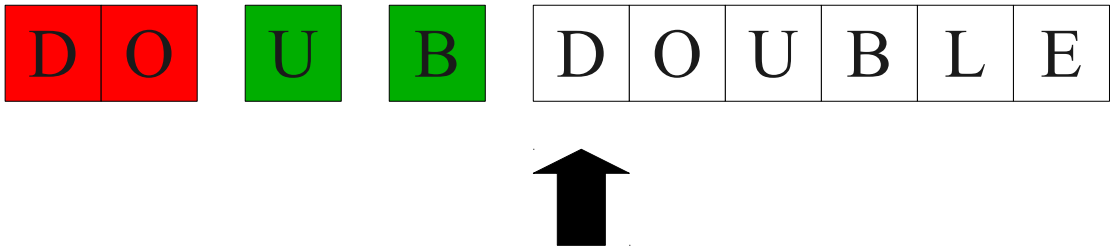




Implementing Maximal Munch

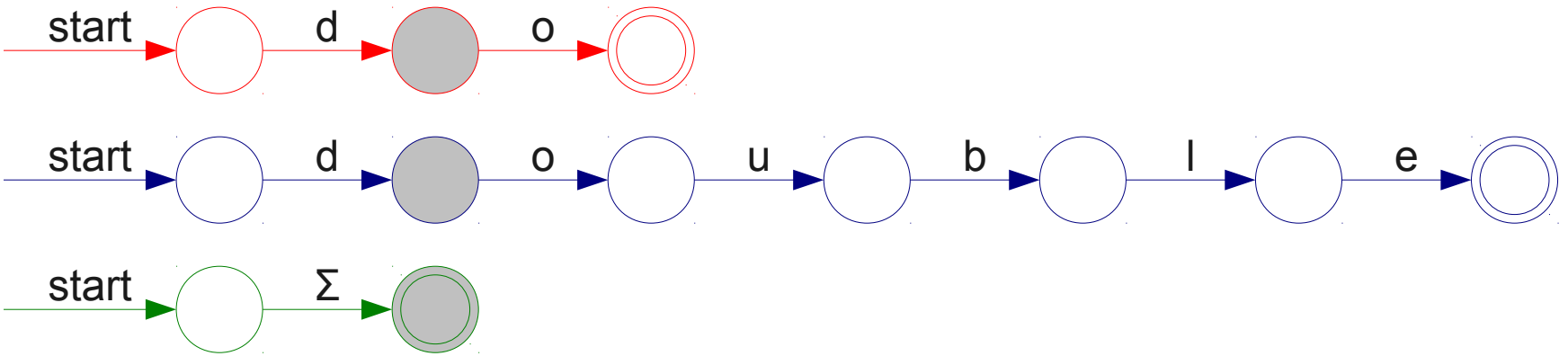
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

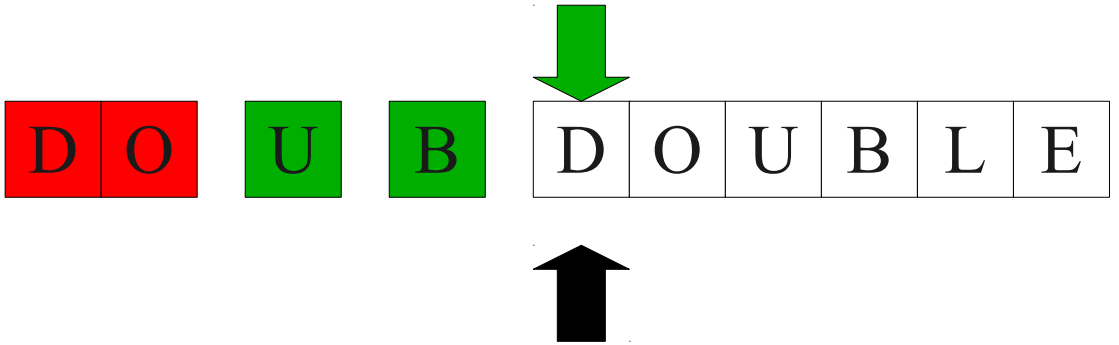




Implementing Maximal Munch

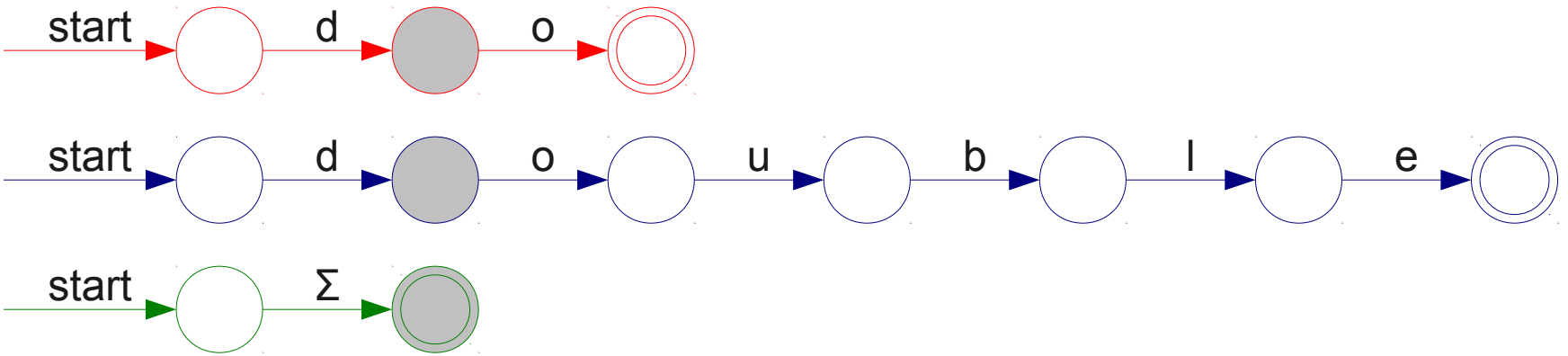
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

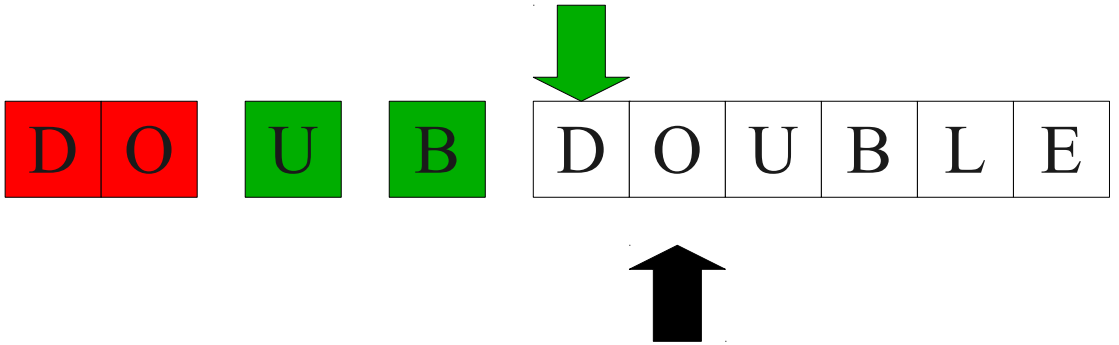




Implementing Maximal Munch

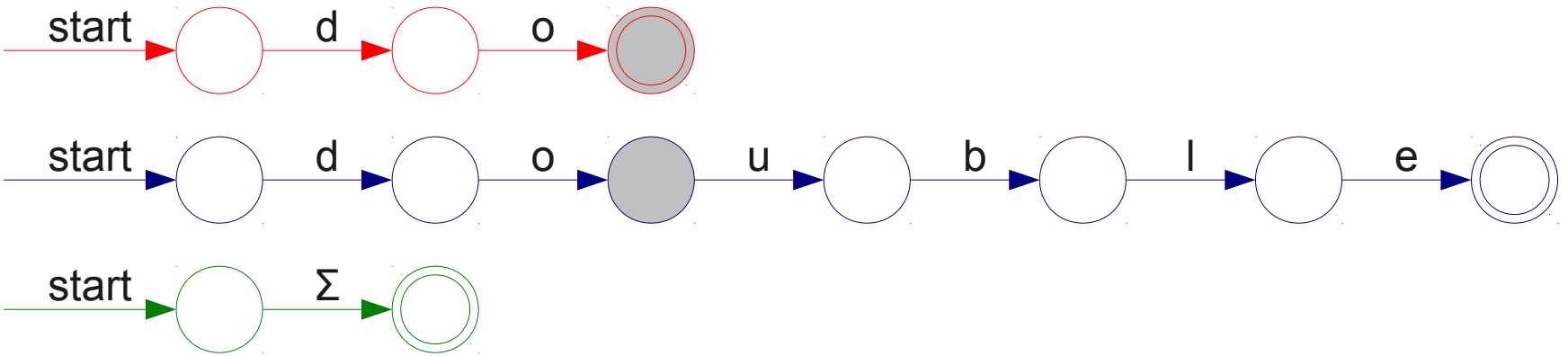
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

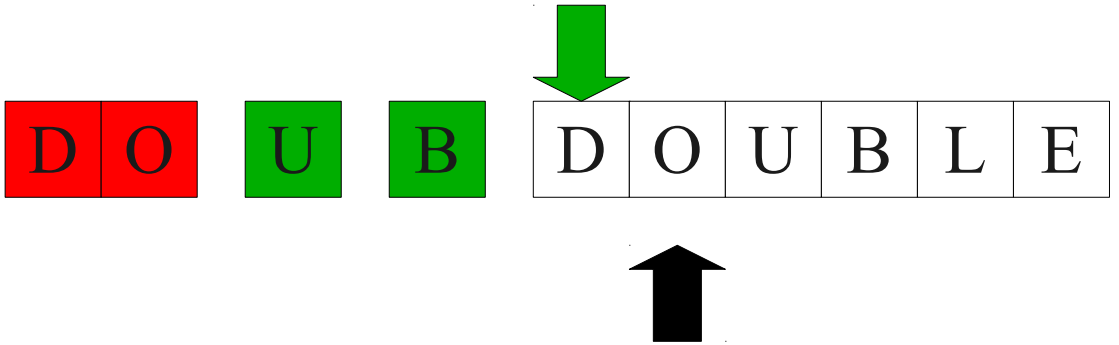




Implementing Maximal Munch

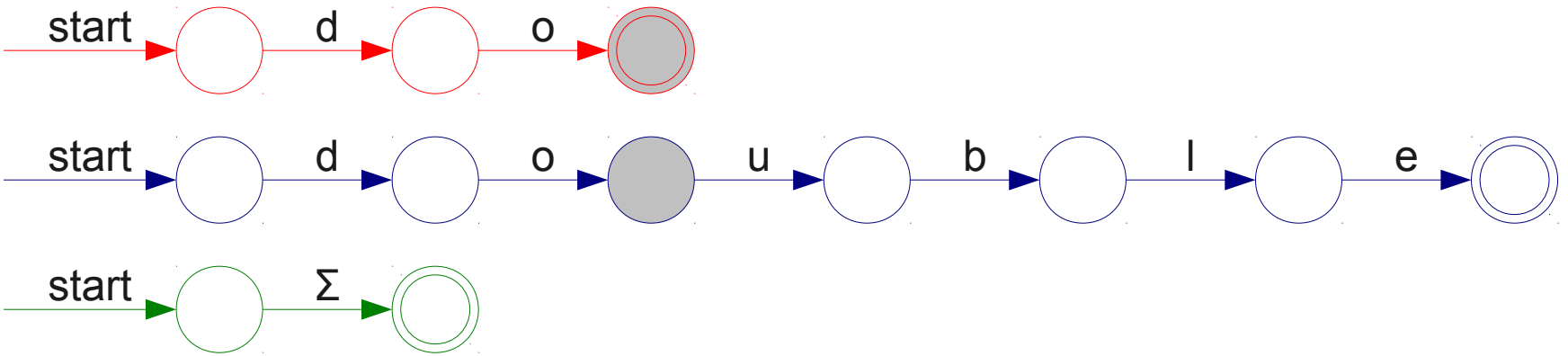
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

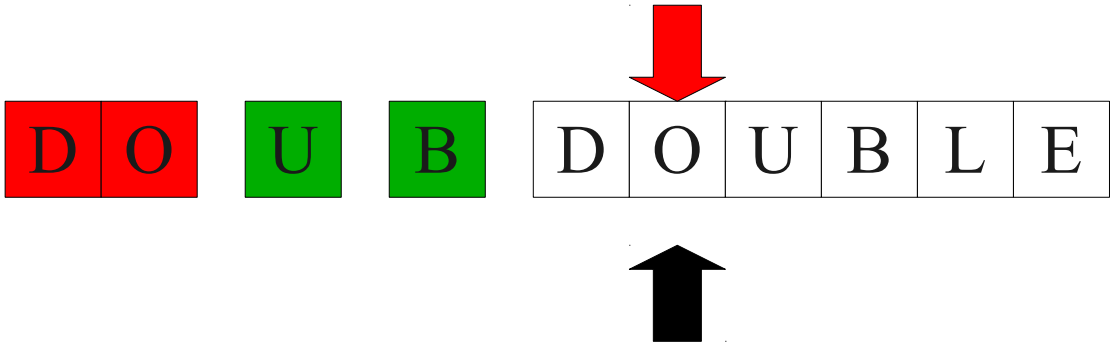




Implementing Maximal Munch

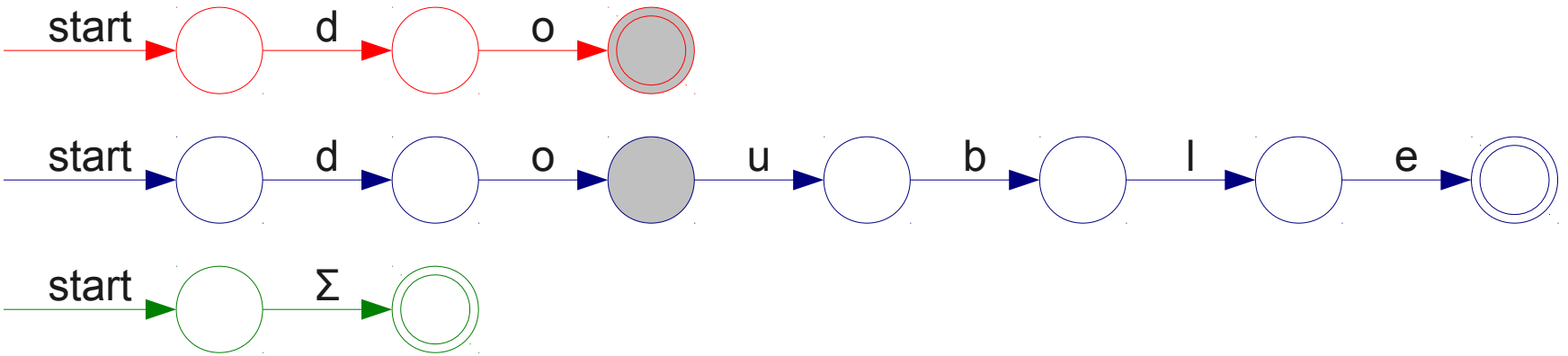
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

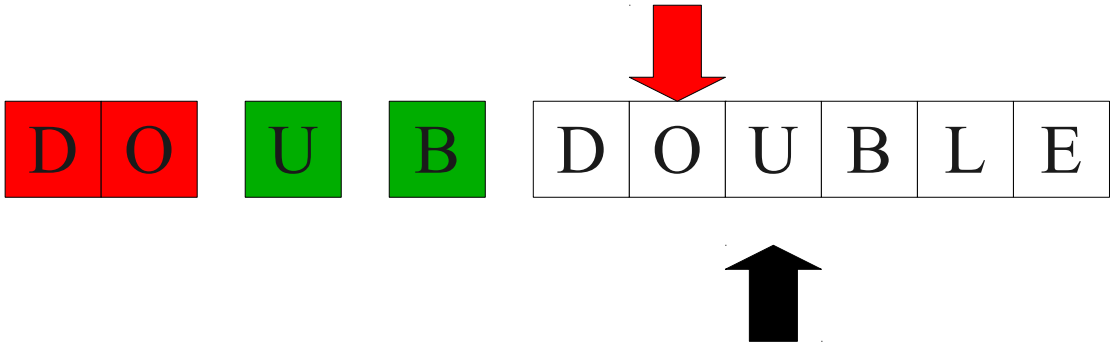




Implementing Maximal Munch

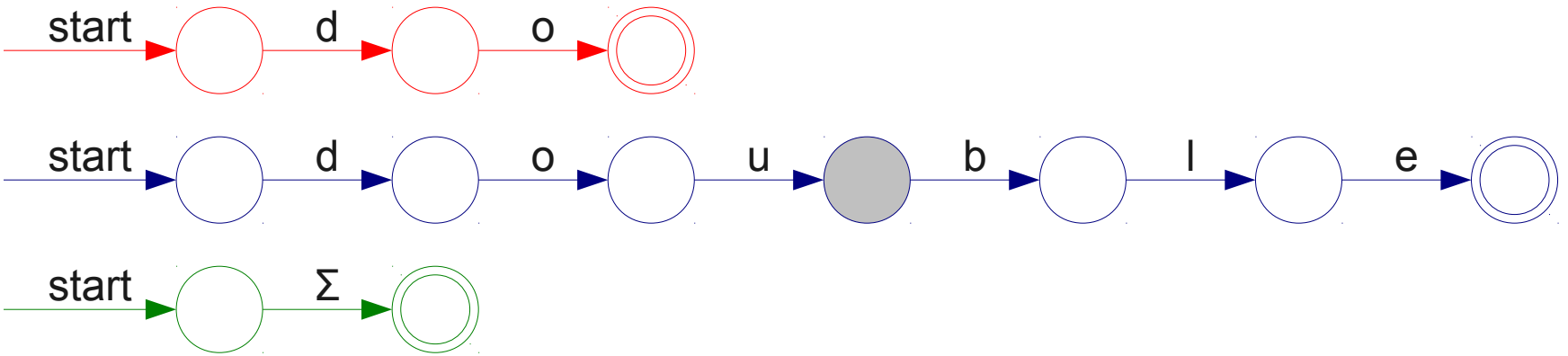
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

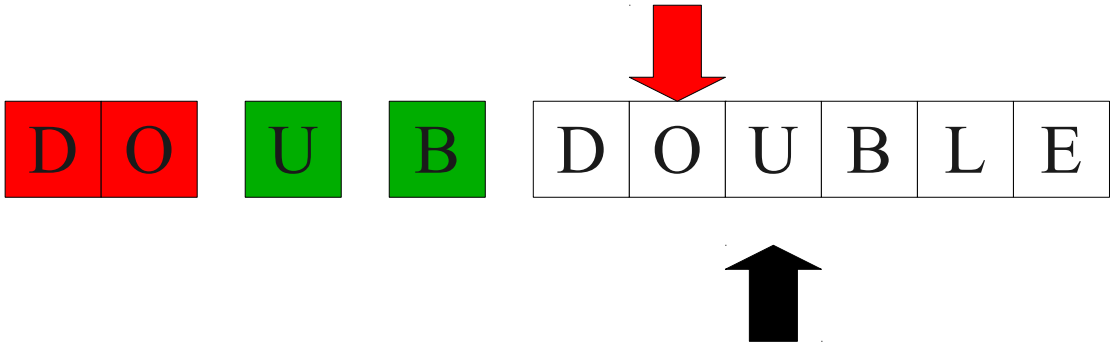




Implementing Maximal Munch

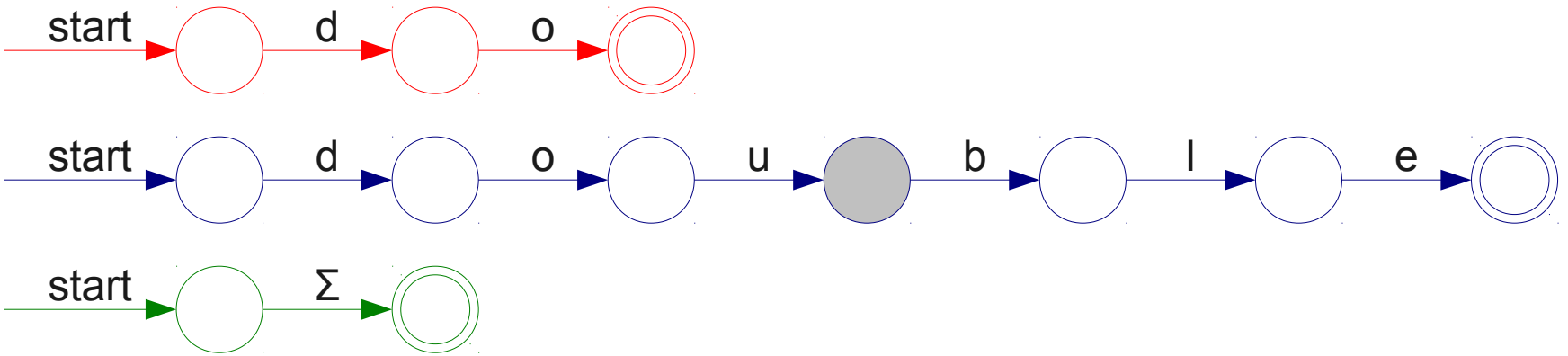
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

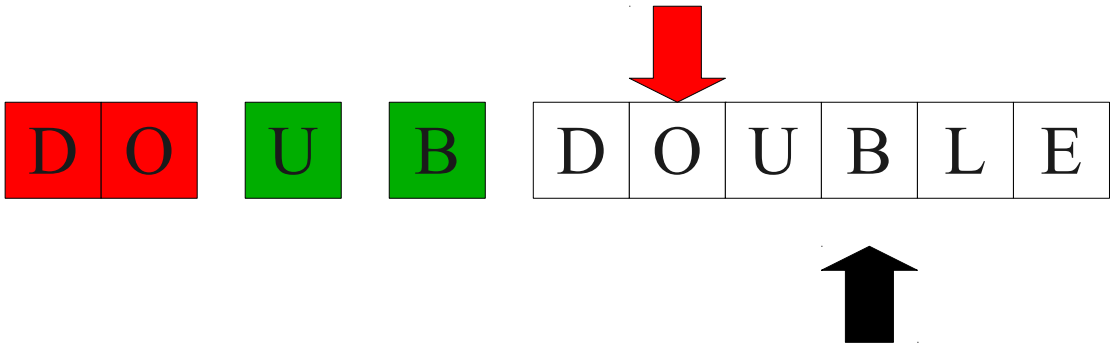




Implementing Maximal Munch

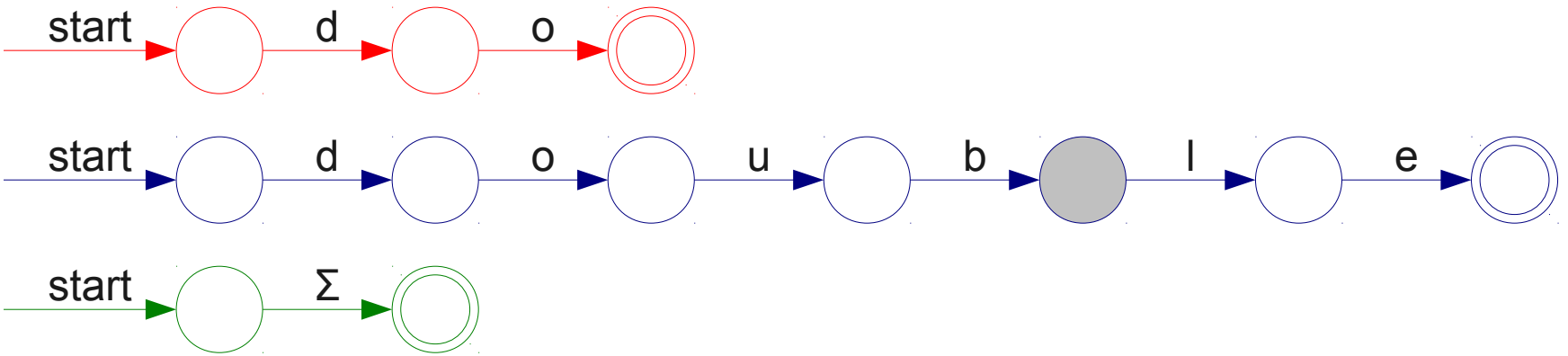
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

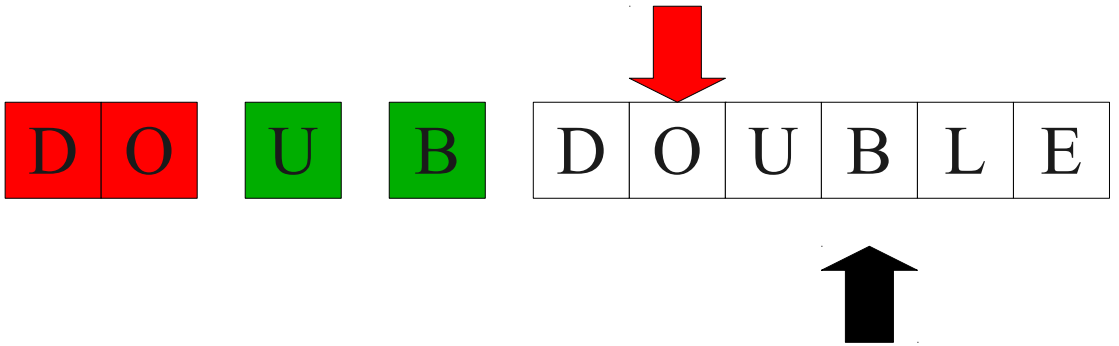




Implementing Maximal Munch

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





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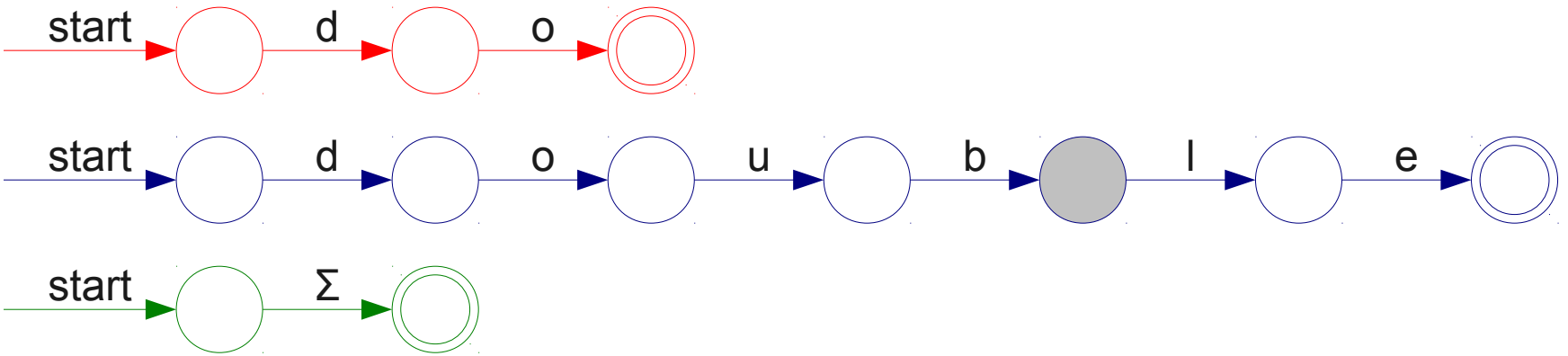

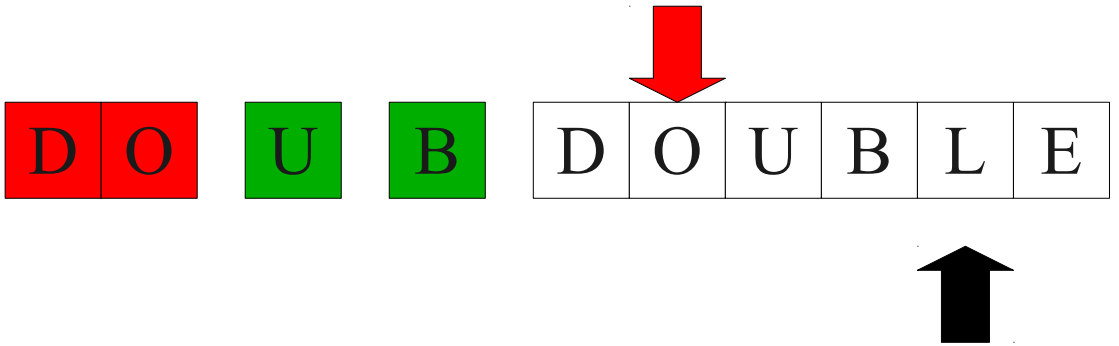

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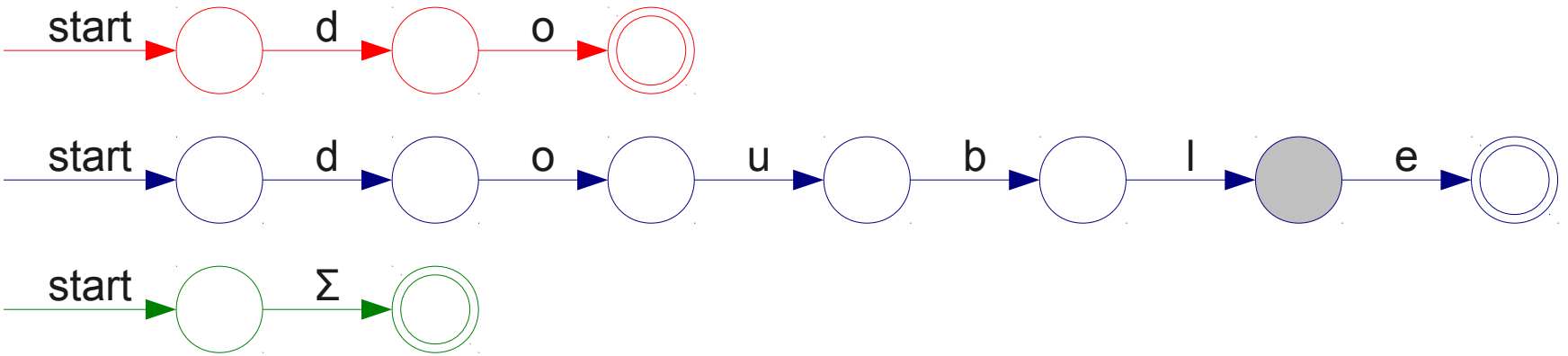

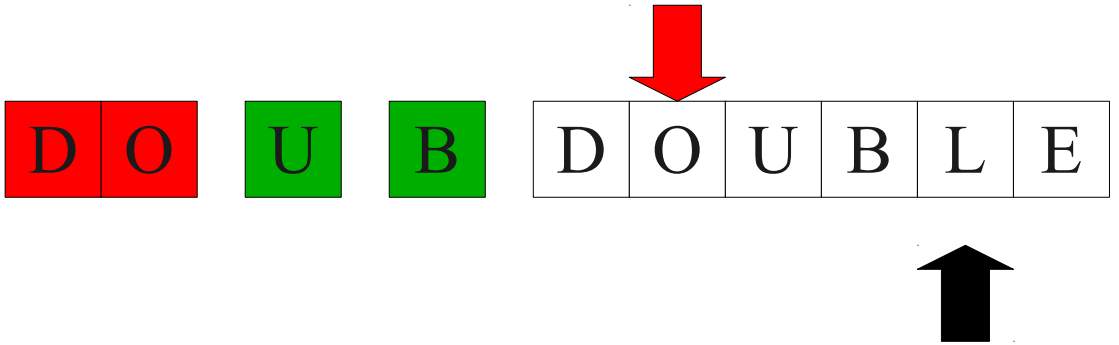

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T_Mystery       [A-Za-z]
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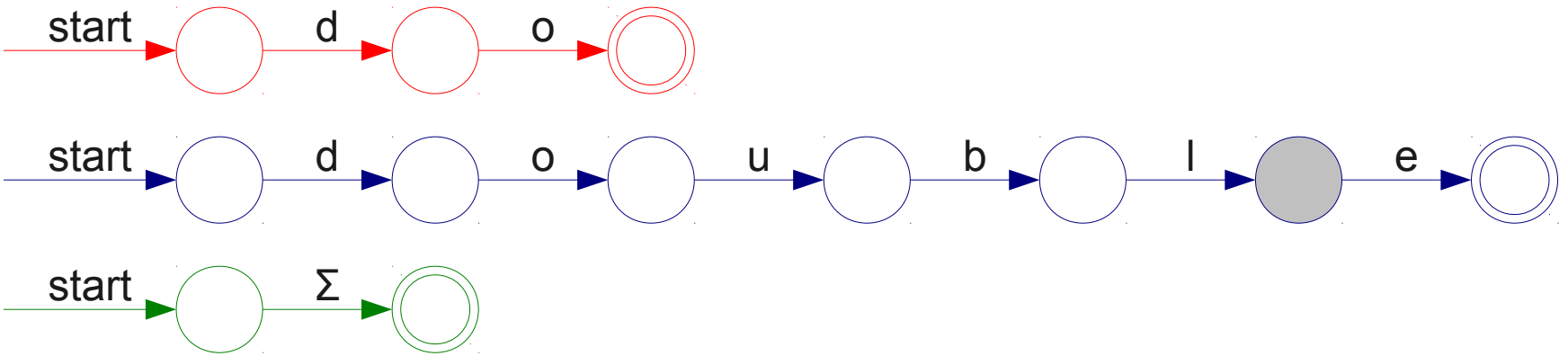

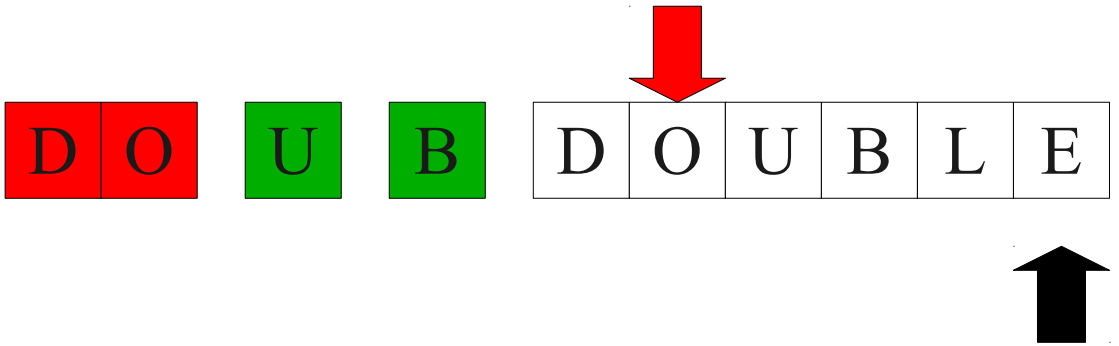

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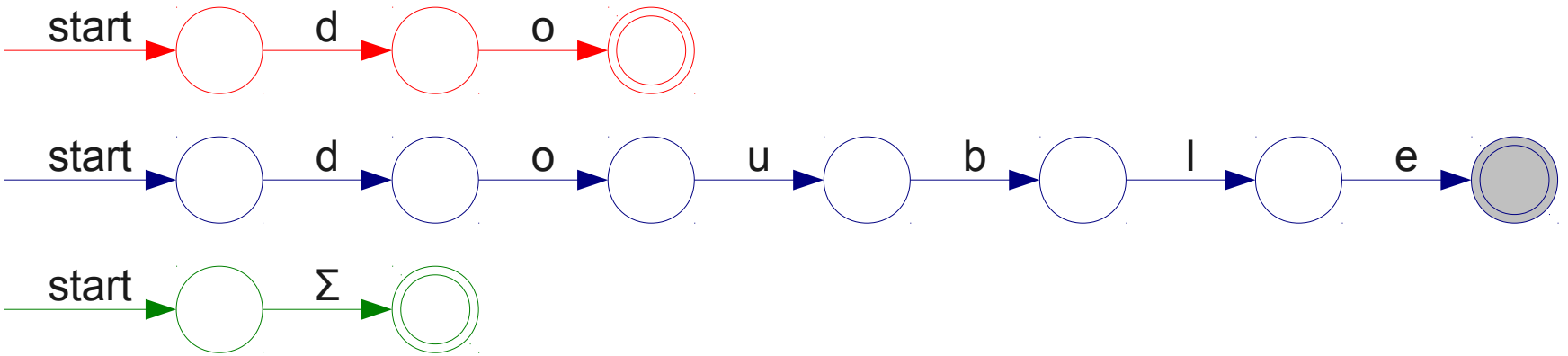

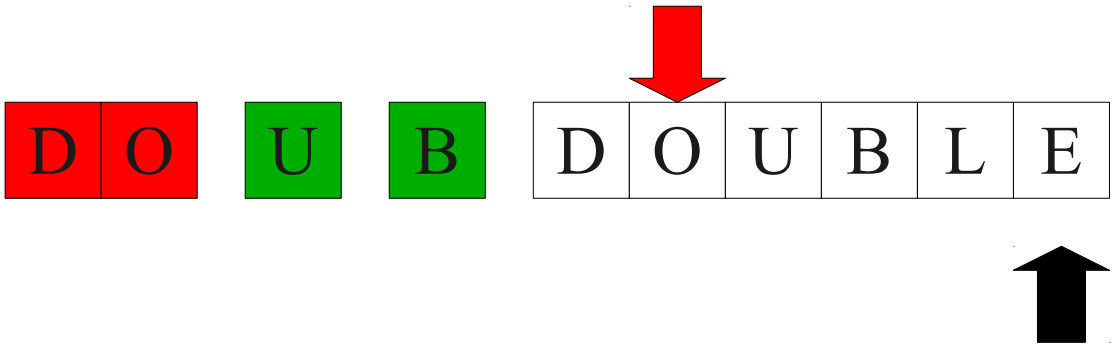

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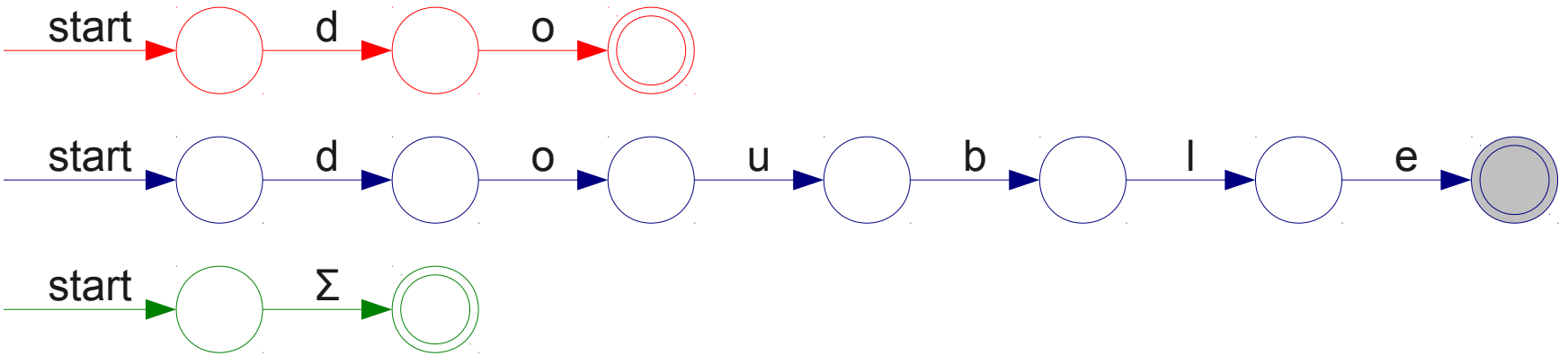

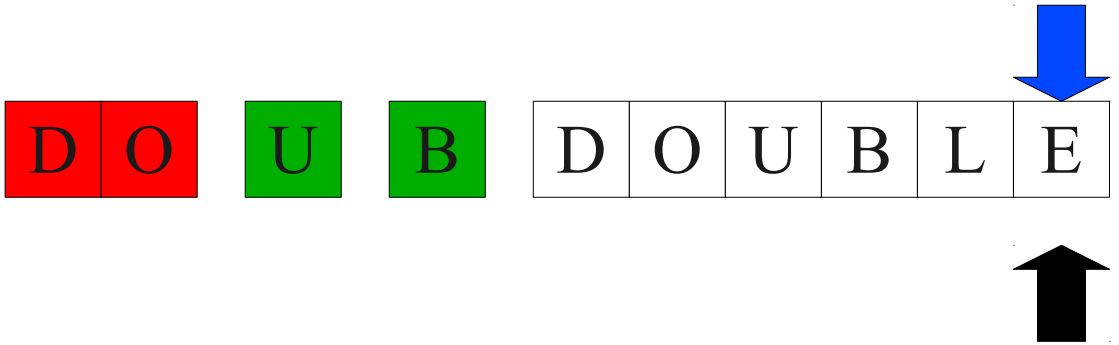

Implementing Maximal Munch

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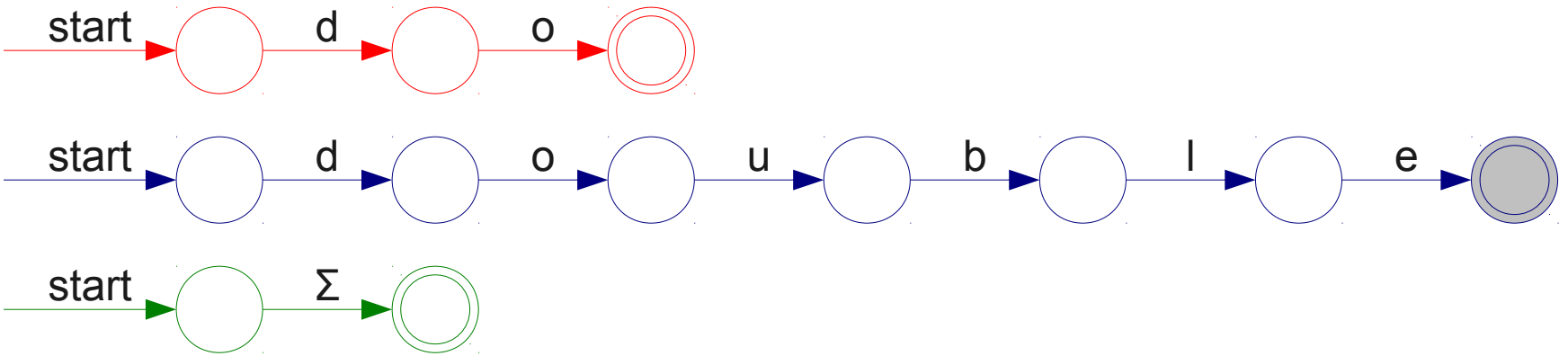
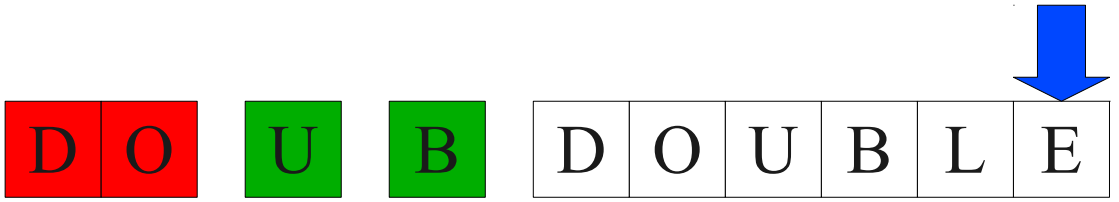
T_Double        double
T_Mystery       [A-Za-z]
```





Implementing Maximal Munch

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T_Mystery       [A-Za-z]
```
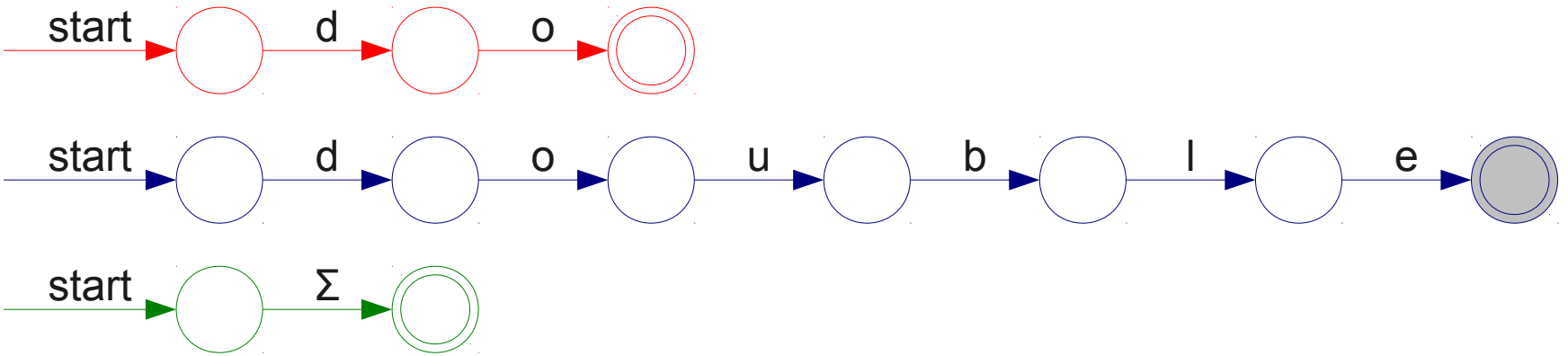
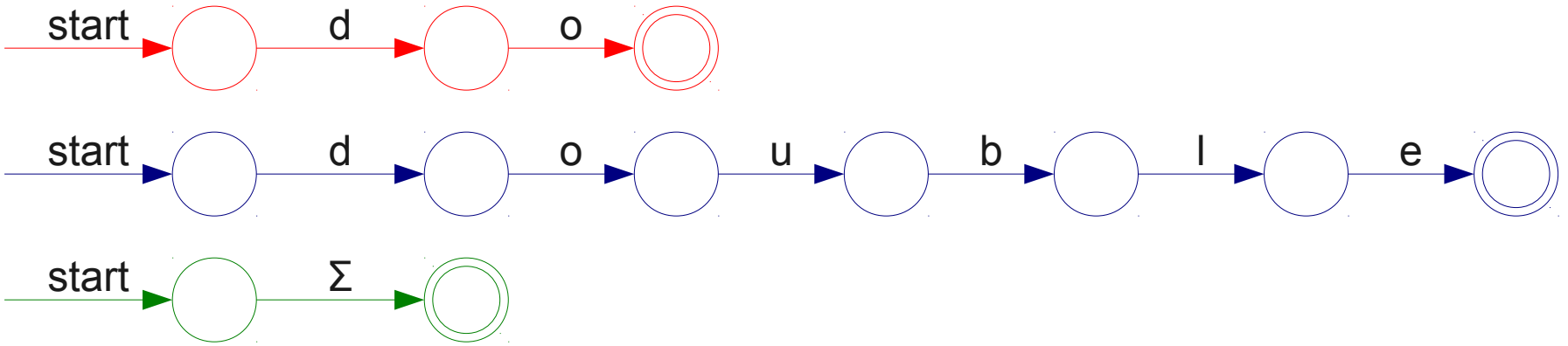



A Minor Simplification

A Minor Simplification



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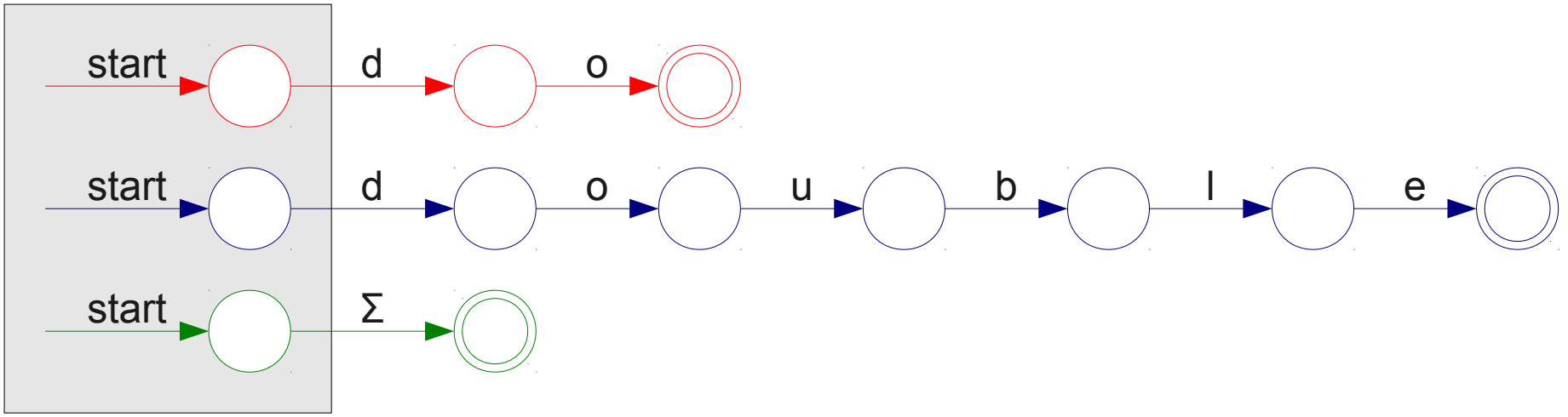

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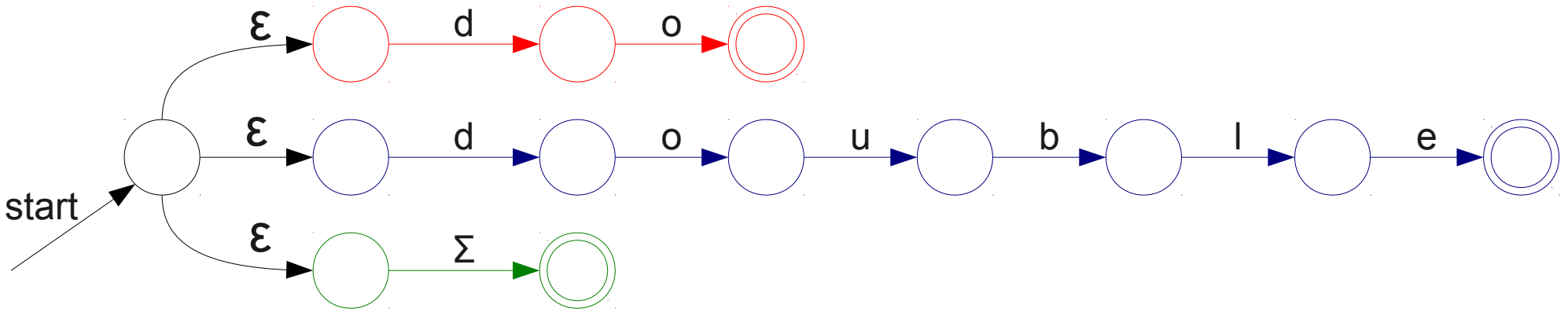
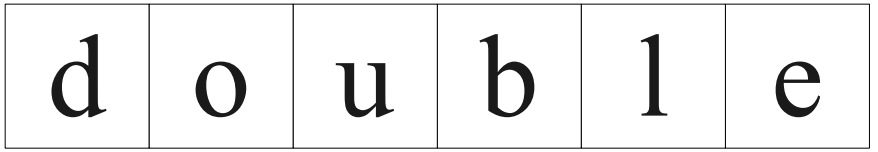


Other Conflicts

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

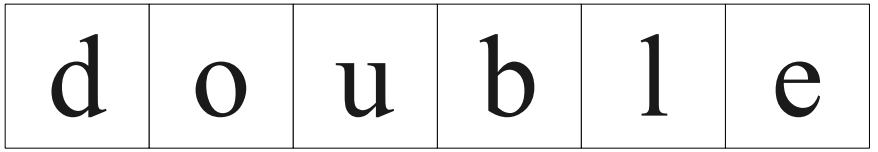
Other Conflicts

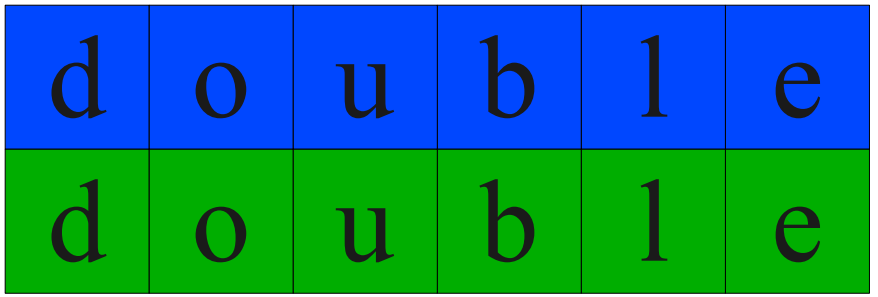
```
T_Do           do
T_Double       double
T_Identifier [A-Za-z_][A-Za-z0-9_]*
```



Other Conflicts

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



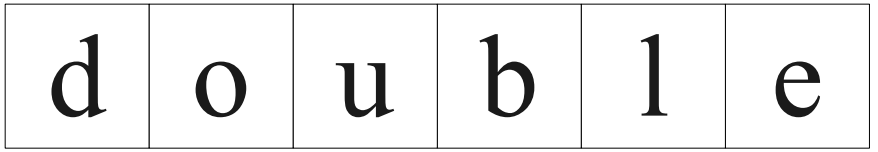


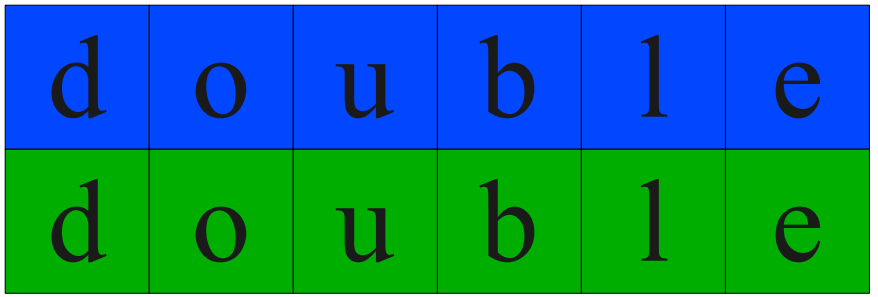
More Tiebreaking

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

Other Conflicts

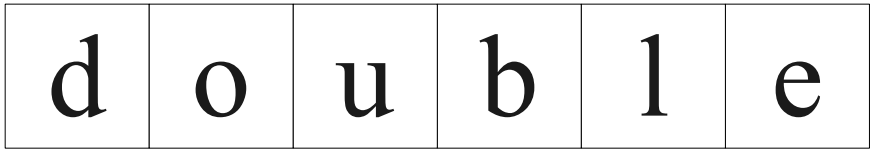
```
T_Do            do
T_Double        double
T_Identifier [A-Za-z_][A-Za-z0-9_]*
```

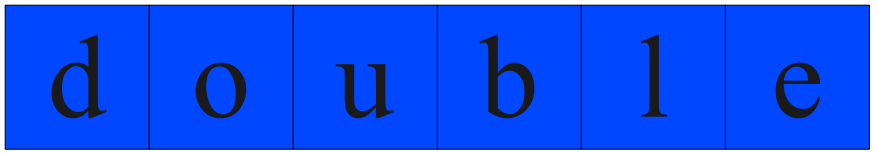




Other Conflicts

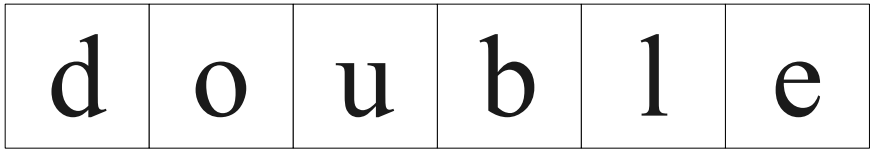
```
T_Do            do
T_Double        double
T_Identifier [A-Za-z_][A-Za-z0-9_]*
```

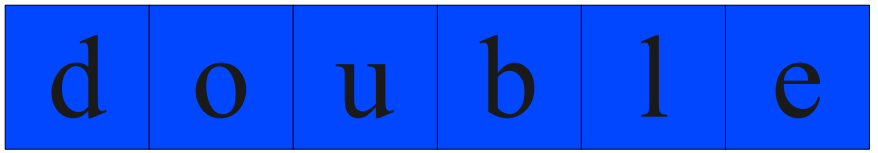




Other Conflicts

```
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.

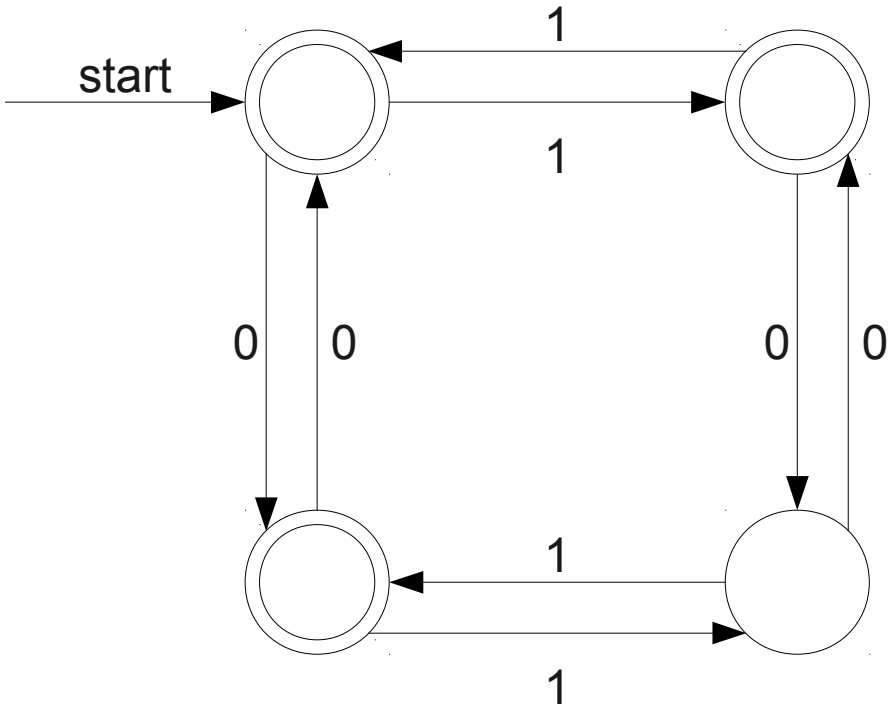
Speeding up the Scanner

DFAs

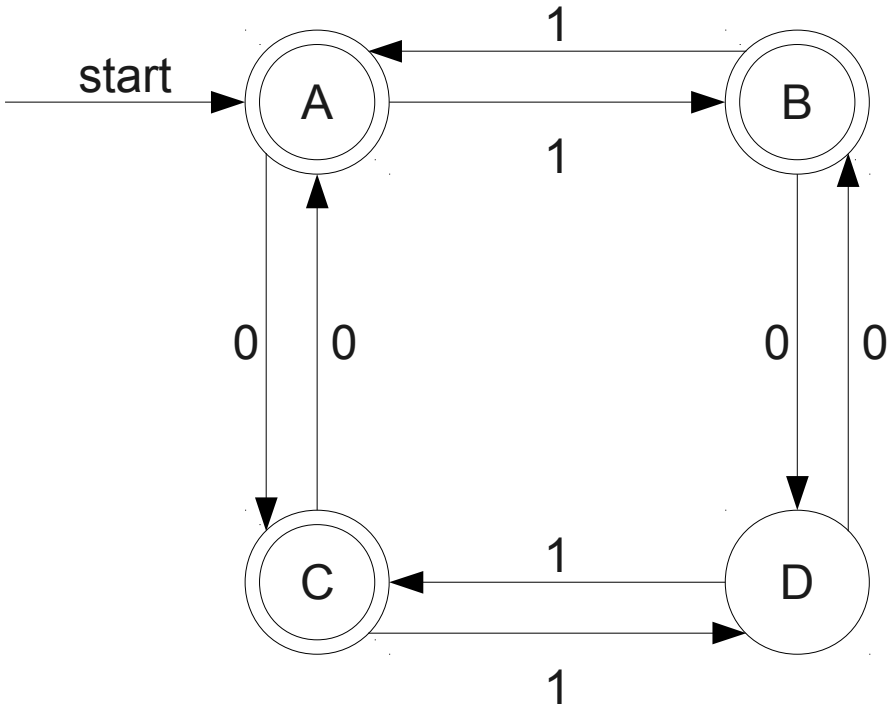
- The automata we've seen so far have all been NFAs.
- A **DFA** is like an NFA, but with tighter restrictions:
  - Every state must have **exactly one** transition defined for every letter.
  - ε-moves are not allowed.

A Sample DFA

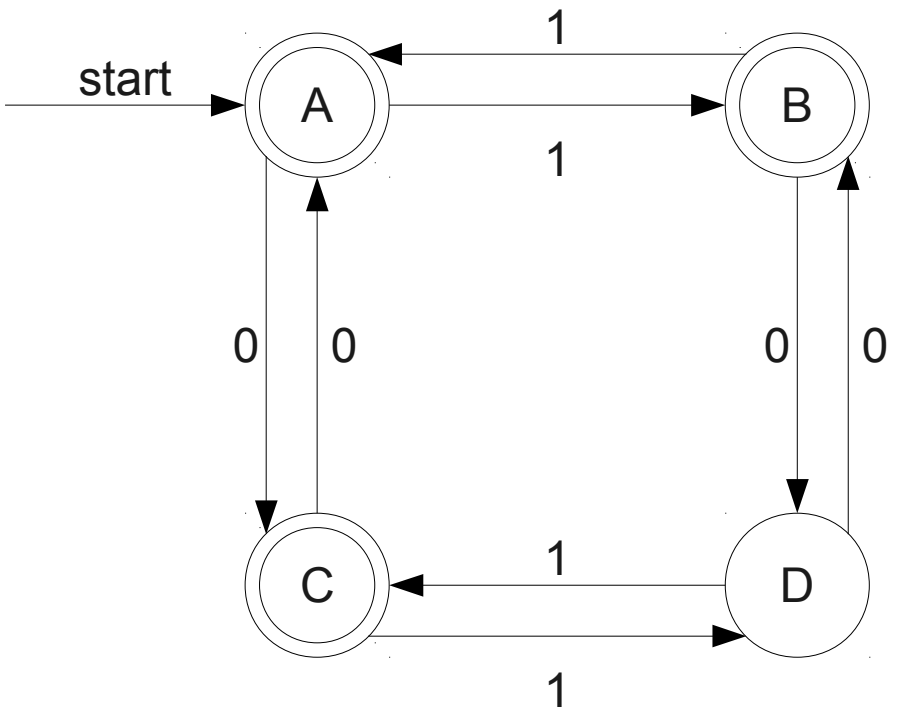
A Sample DFA



A Sample DFA



A Sample DFA



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

Simulating a DFA

- Begin in the start state.
- For each character of the input:
  - Follow the indicated transition to the next state.
- Assuming transitions are in a table, time to scan a string of length S is O(|S|).

Speeding up Matching

- In the worst-case, an NFA takes $O(|S||Q|^2)$ time to match a string.
- DFAs, on the other hand, take only $O(|S|)$.
- There is another (beautiful!) algorithm to convert NFAs to DFAs.

Subset Construction

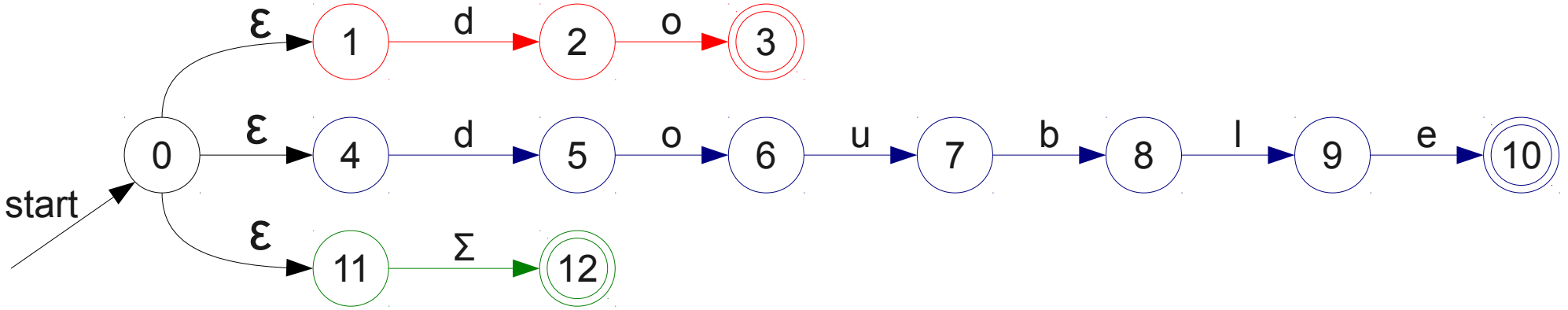
- NFAs can be in many states at once, while DFAs can only be in a single state at a time.
- Key idea: **Make the DFA simulate the NFA**.
- Have the states of the DFA correspond to the **sets of states** of the NFA.
- Transitions between states of DFA correspond to transitions between **sets of states**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

Formally...

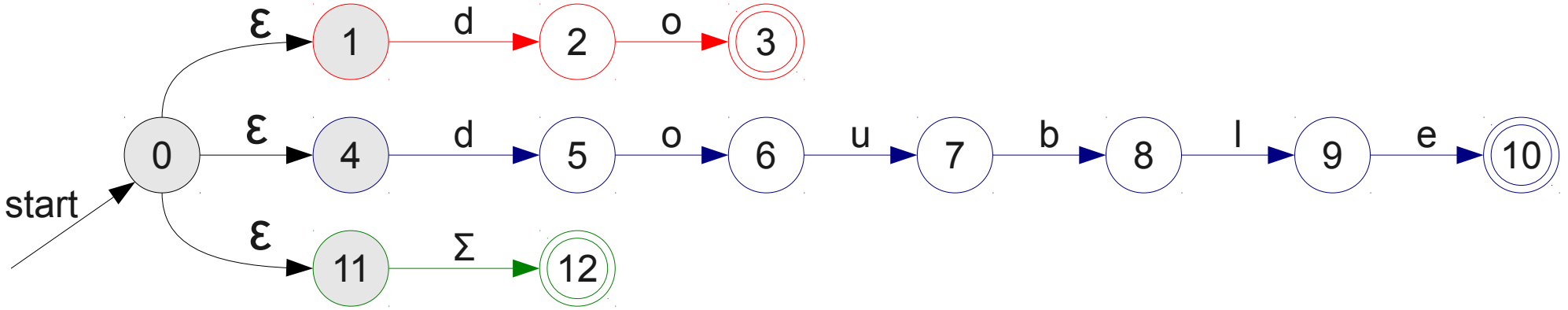
- Given an NFA $N = (\Sigma, Q, \delta, s, F)$, define the DFA $D = (\Sigma', Q', \delta', s', F')$ as follows:
  - $\Sigma' = \Sigma$
  - $Q' = 2^Q$
  - $\delta'(S, a) = \{\text{ECLOSE}(s') \mid s \in S \text{ and } \delta(s, a) = s'\}$
  - $s' = \text{ECLOSE}(s)$
  - $F' = \{ S \mid \exists\, s \in S.\ s \in F \}$
- Here, ECLOSE(s) is the set of states reachable from s via ε-moves.

From NFA to DFA

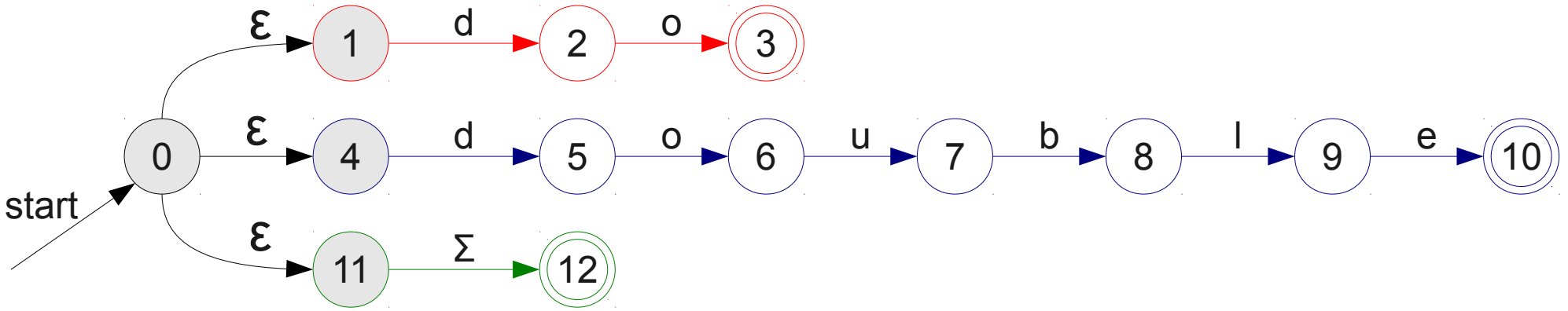
From NFA to DFA

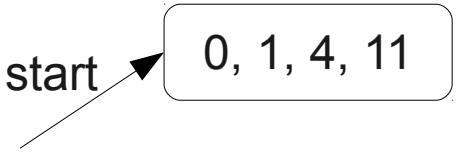


From NFA to DFA



From NFA to DFA





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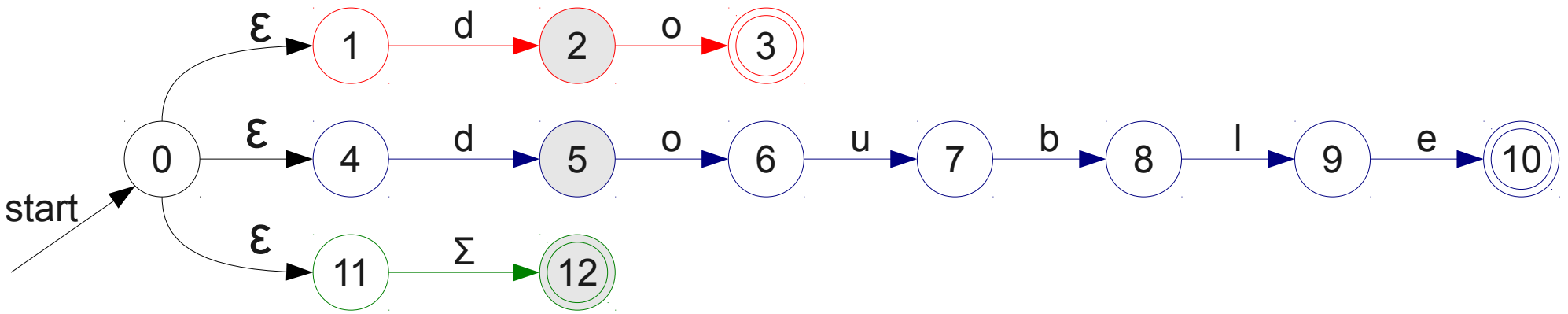

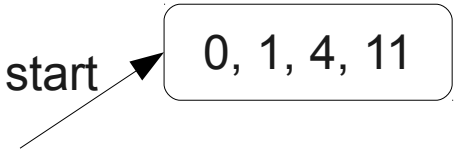

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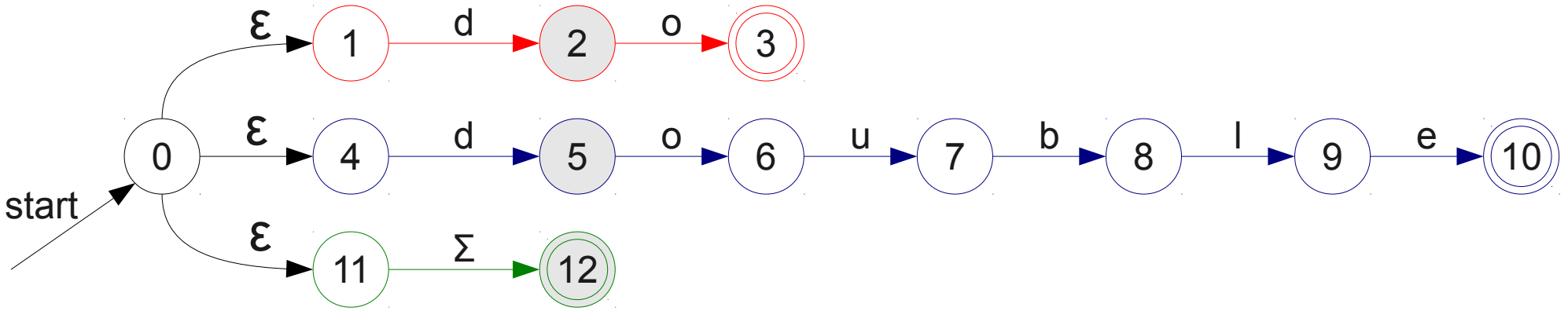

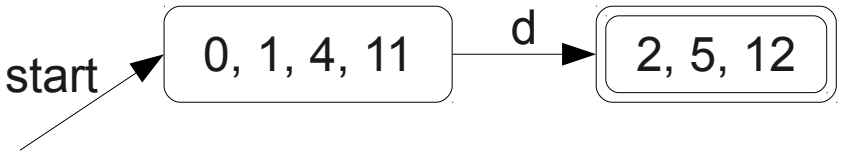

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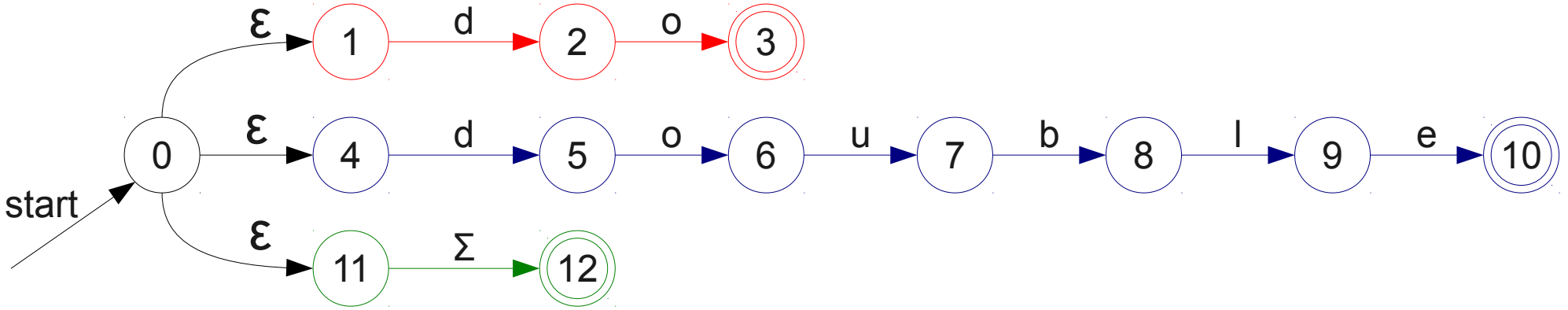

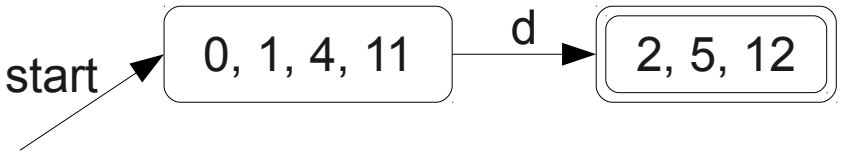

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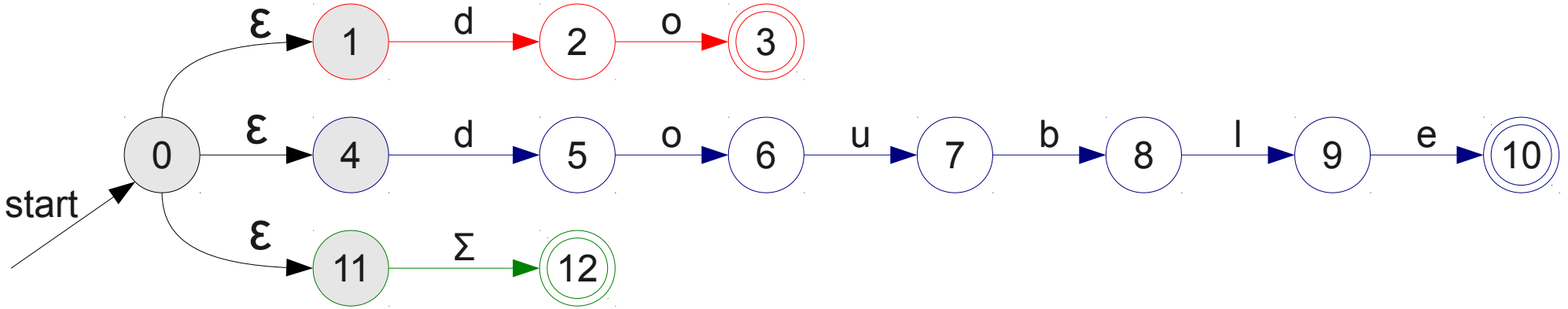

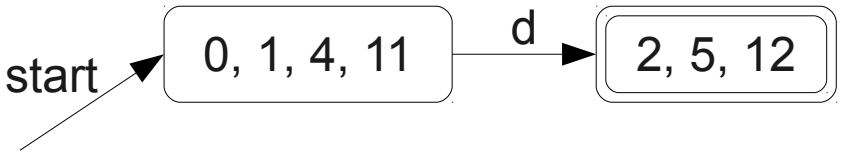

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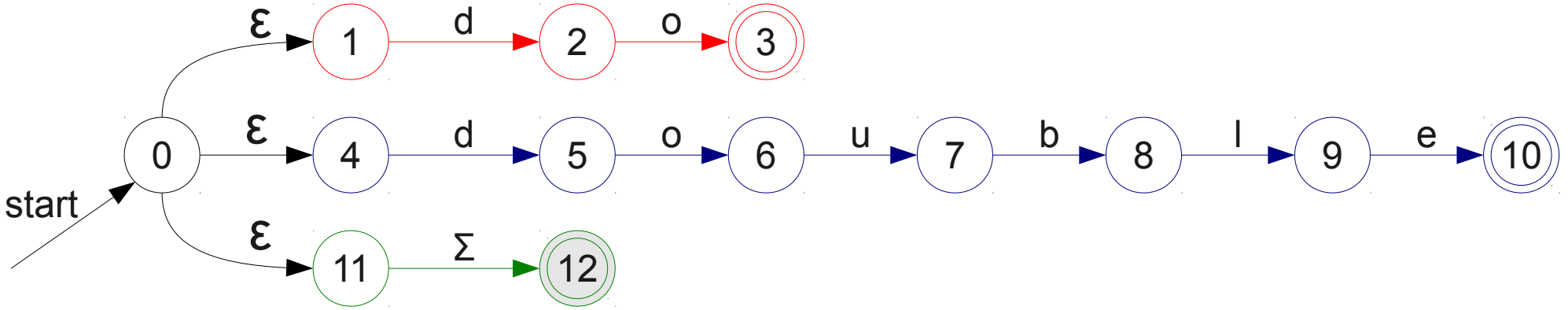

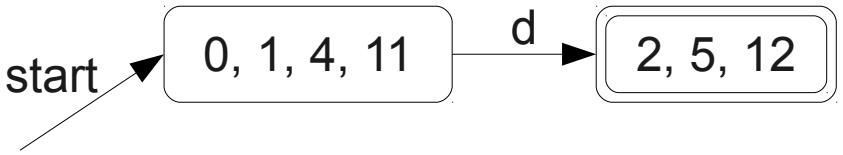

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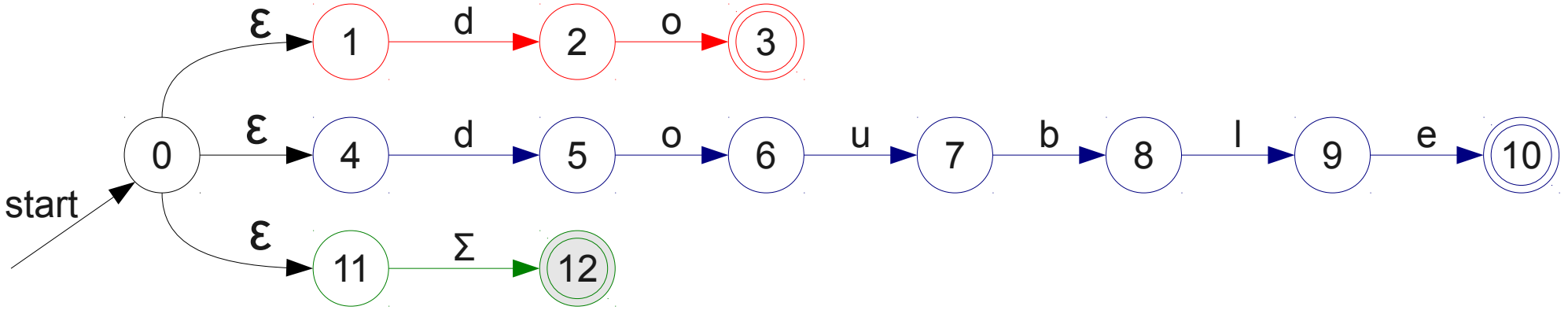

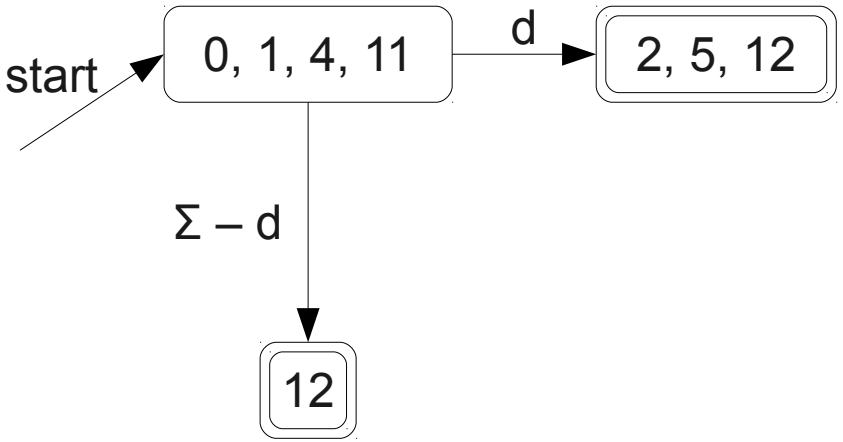

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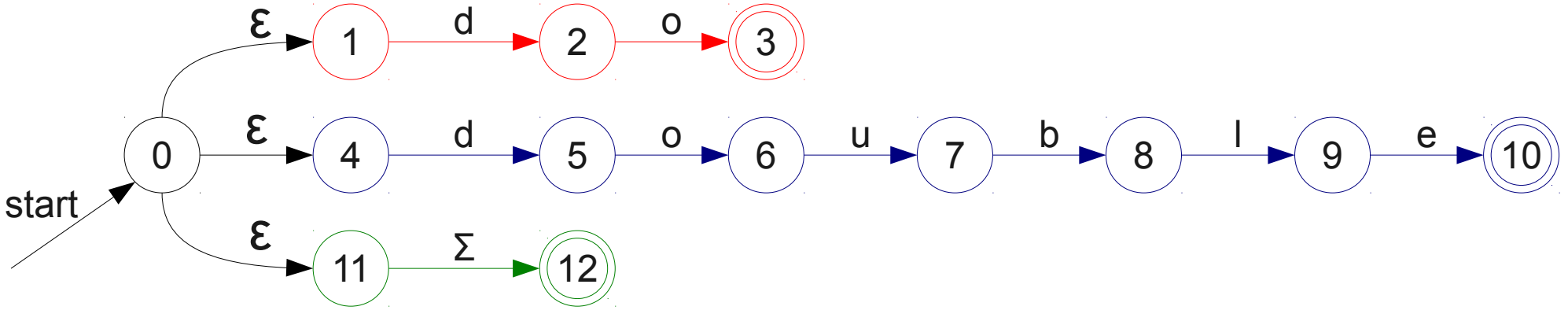
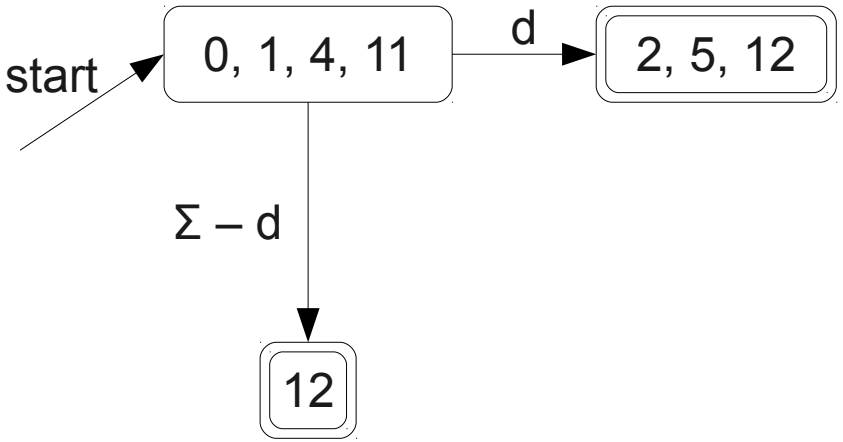
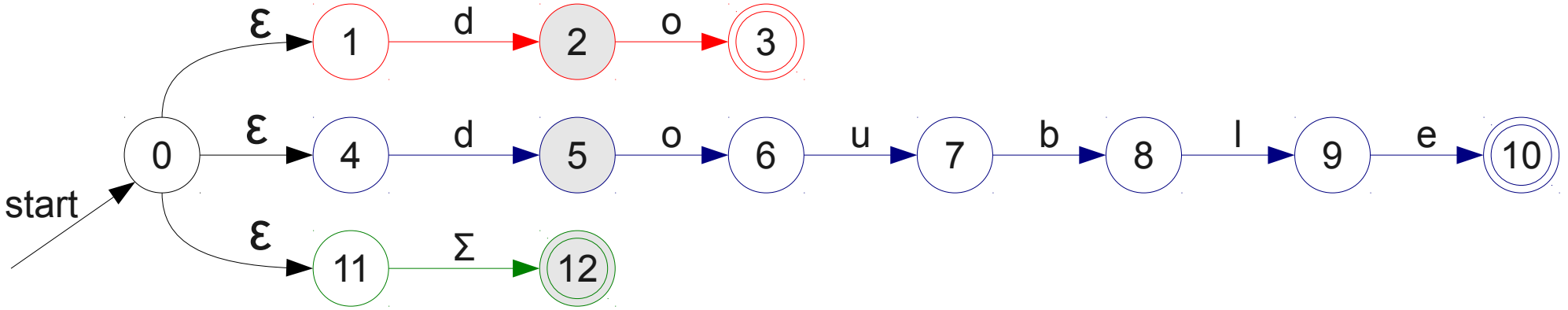
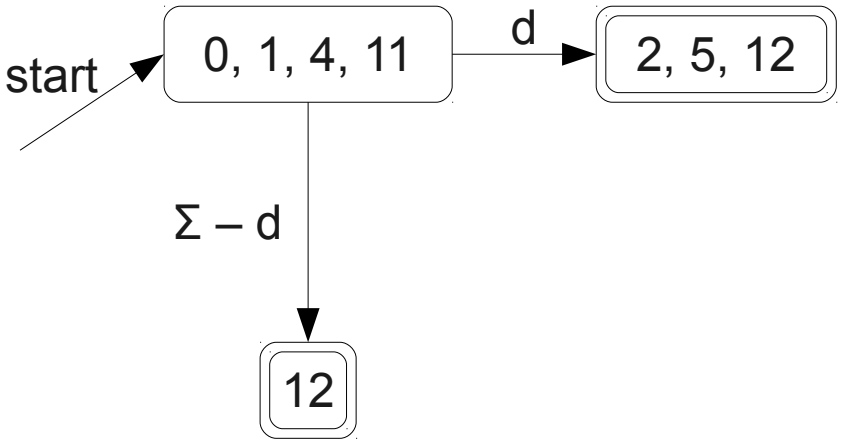


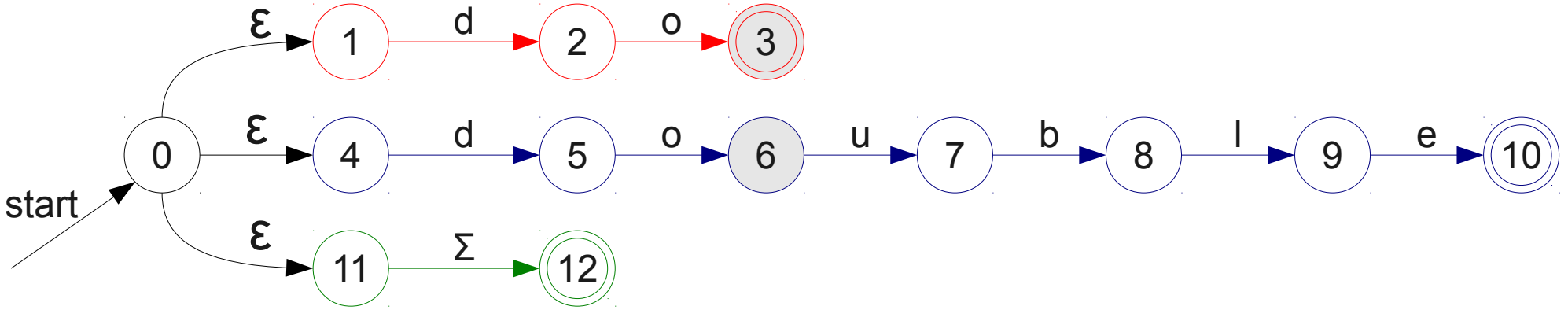


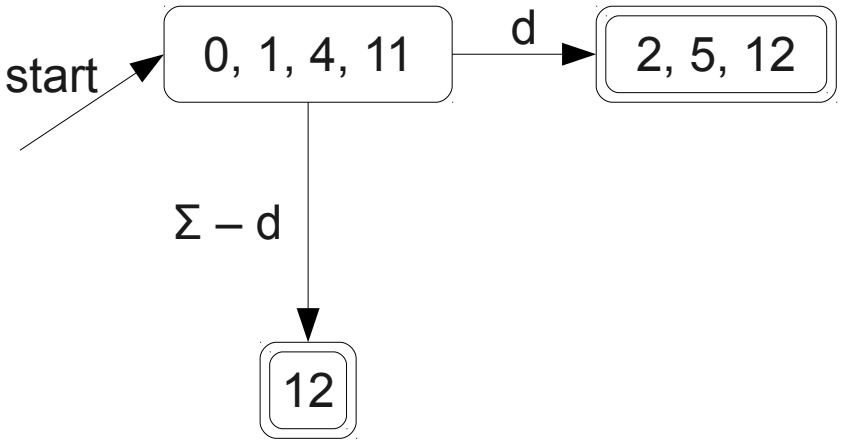
From NFA to DFA



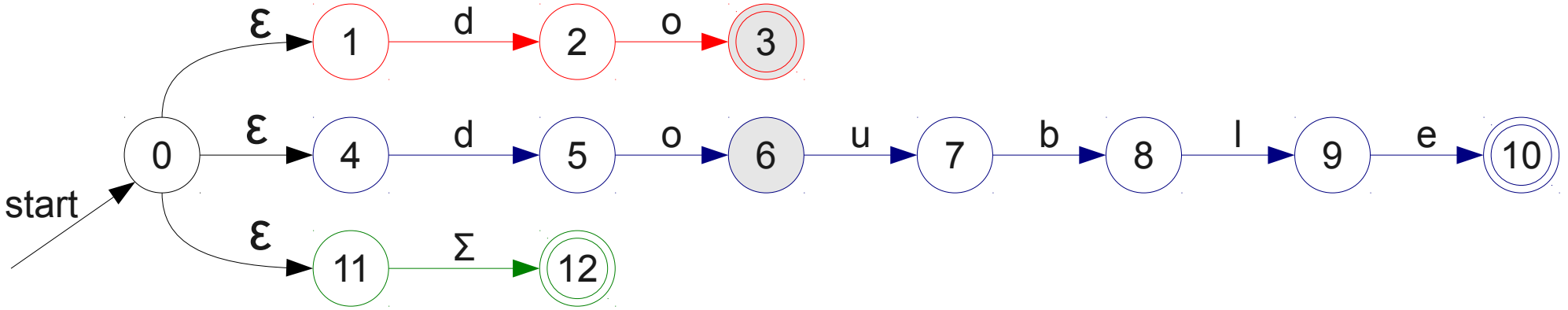


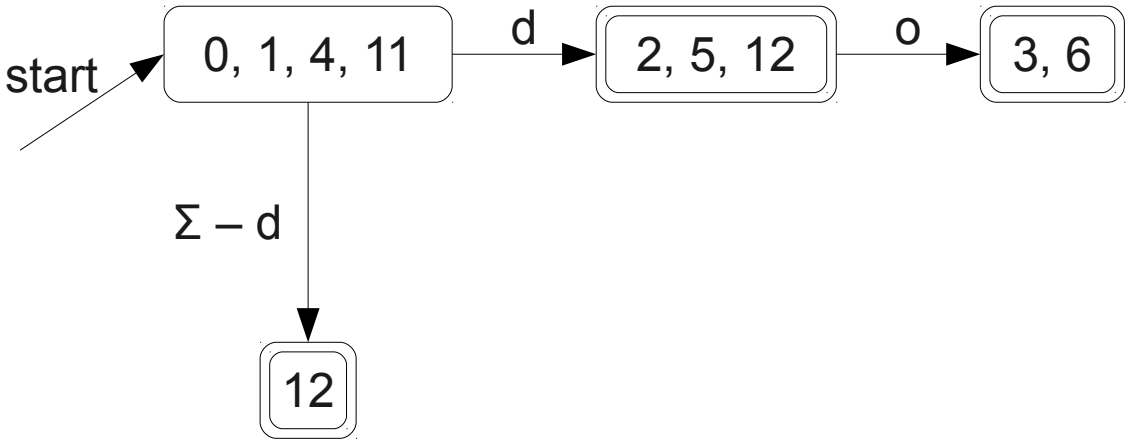
From NFA to DFA





From NFA to DFA





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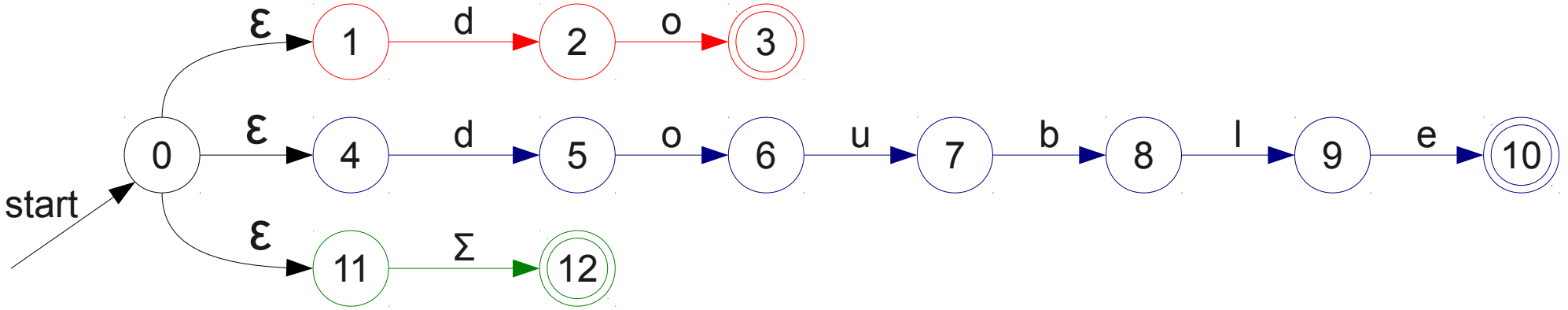

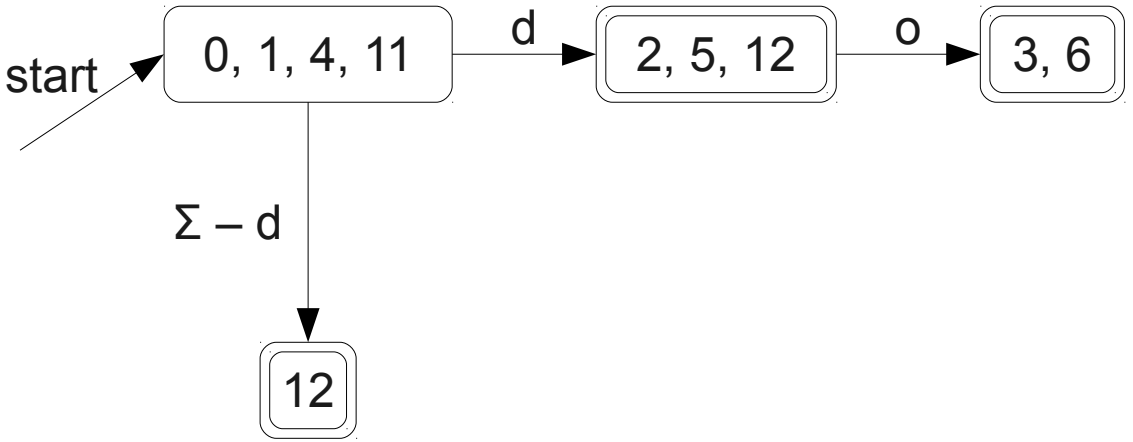

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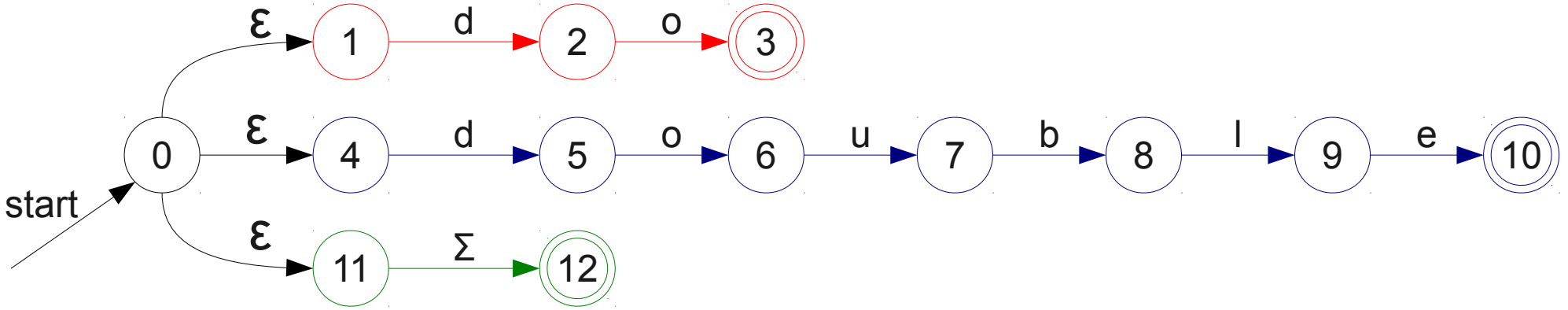

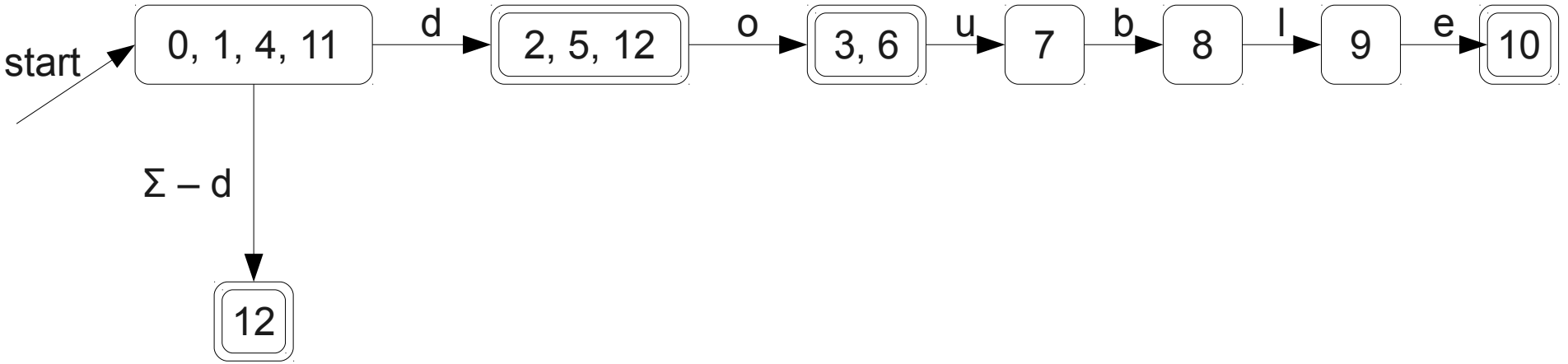

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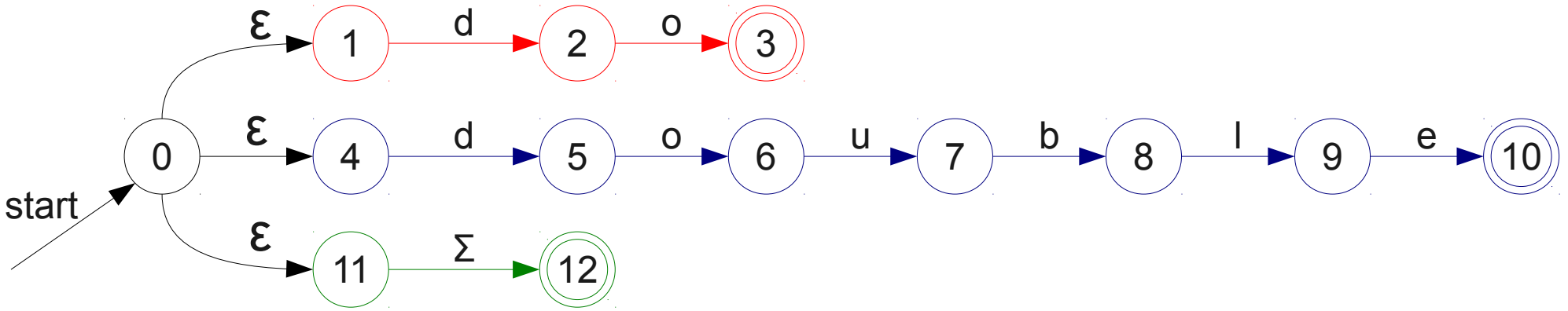
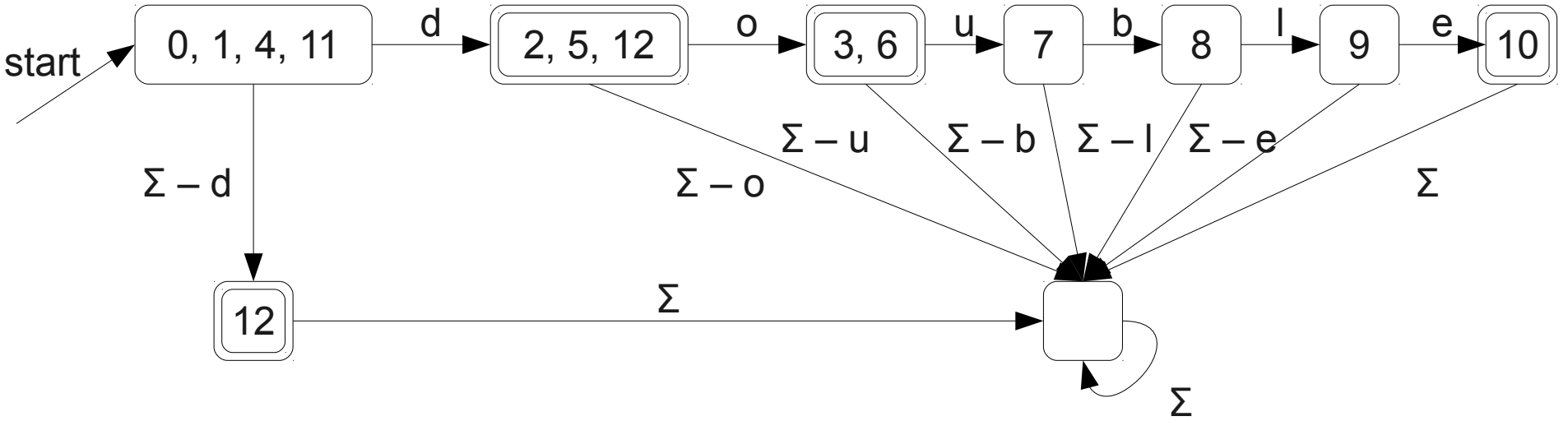
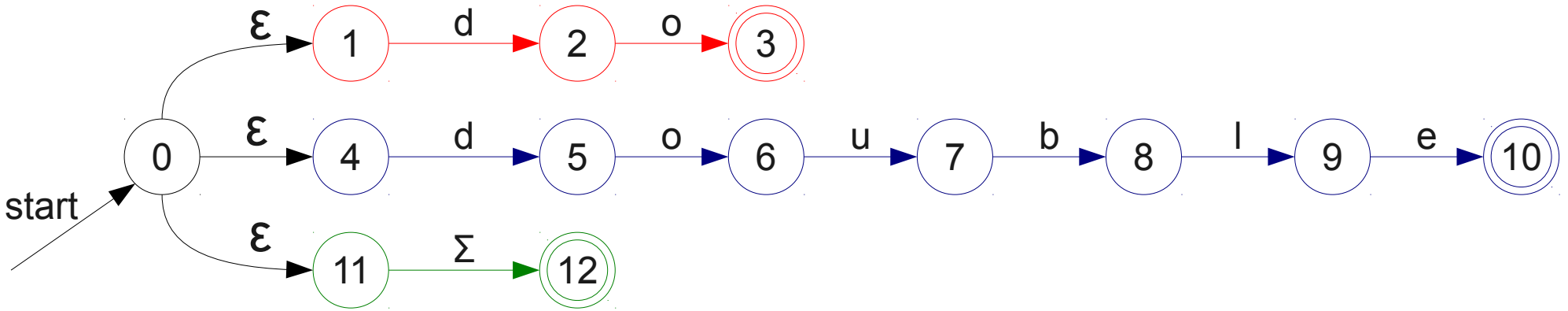
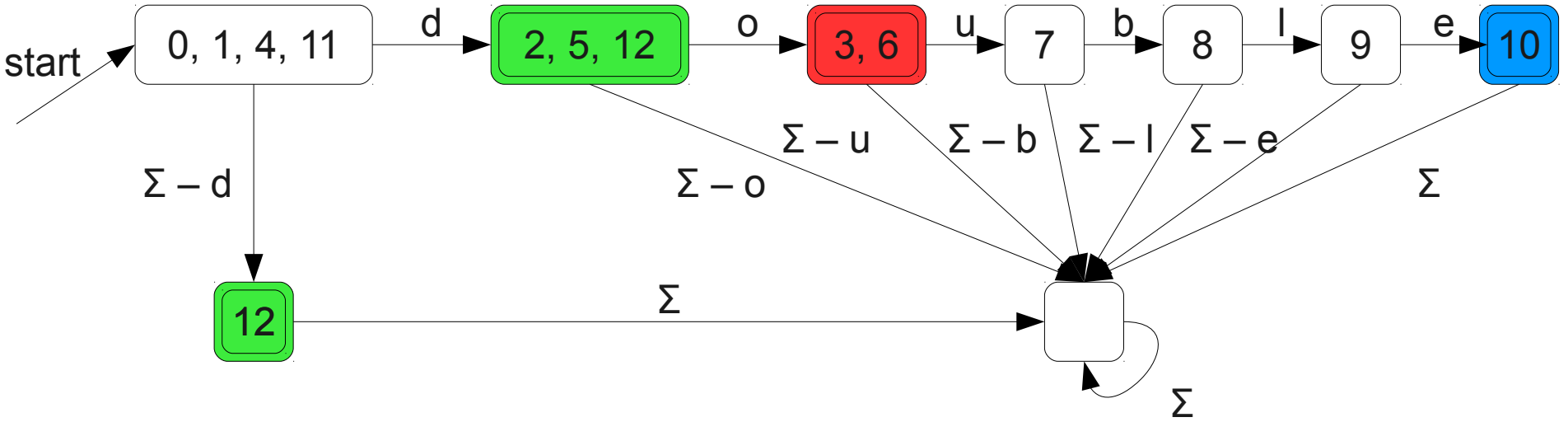




From NFA to DFA





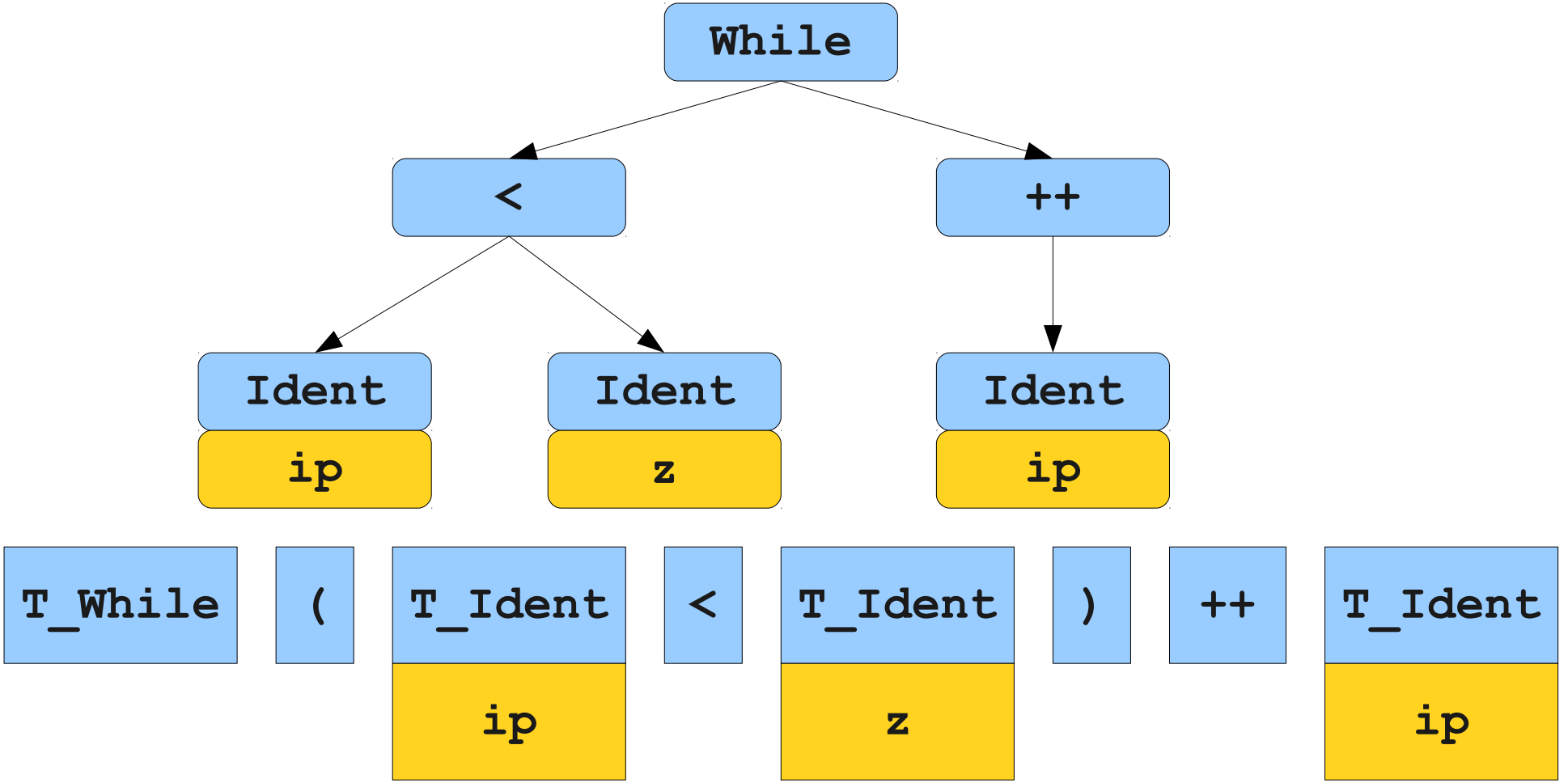
Modified Subset Construction

- 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
g = h
```

Scanning Python

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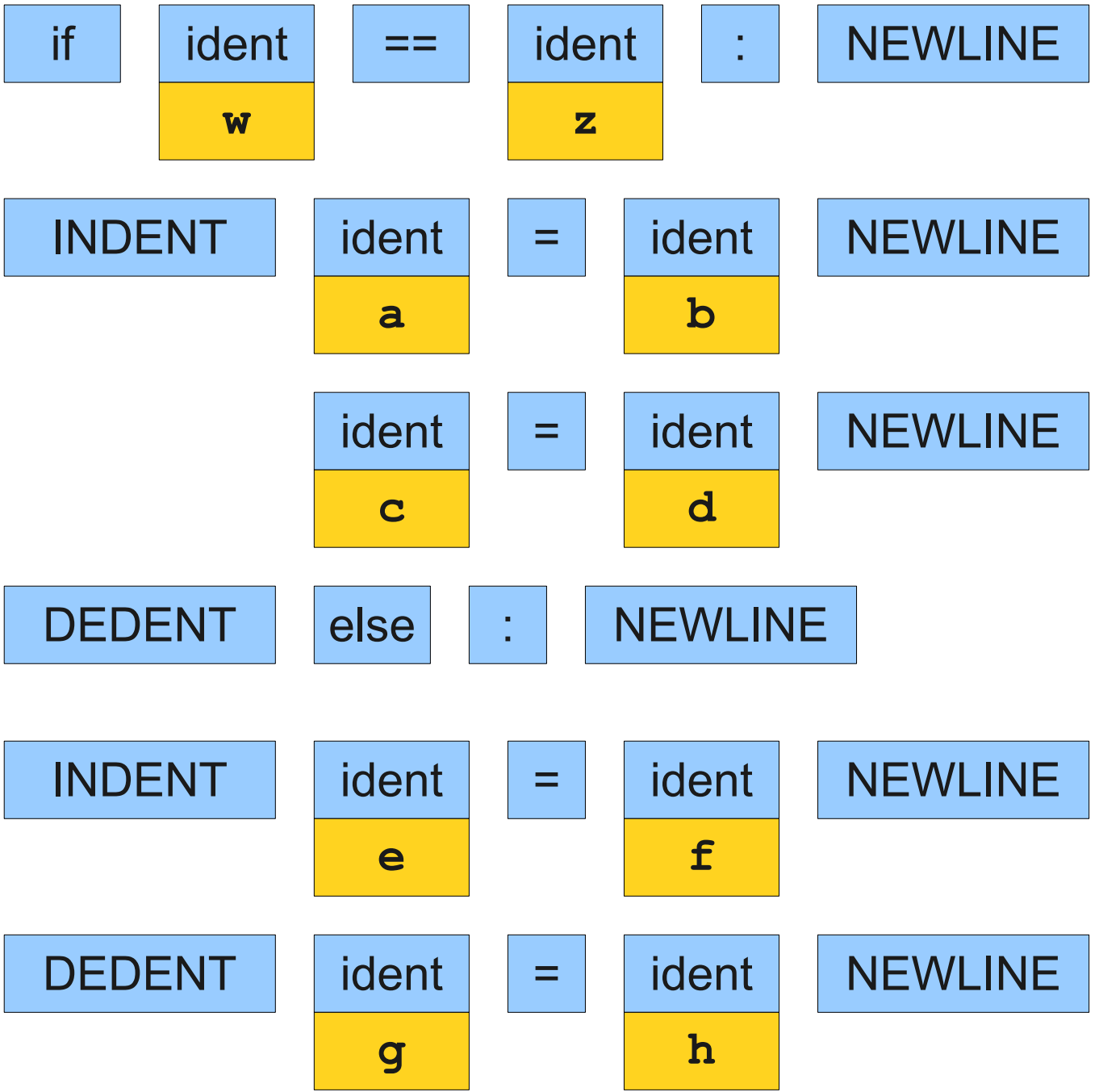
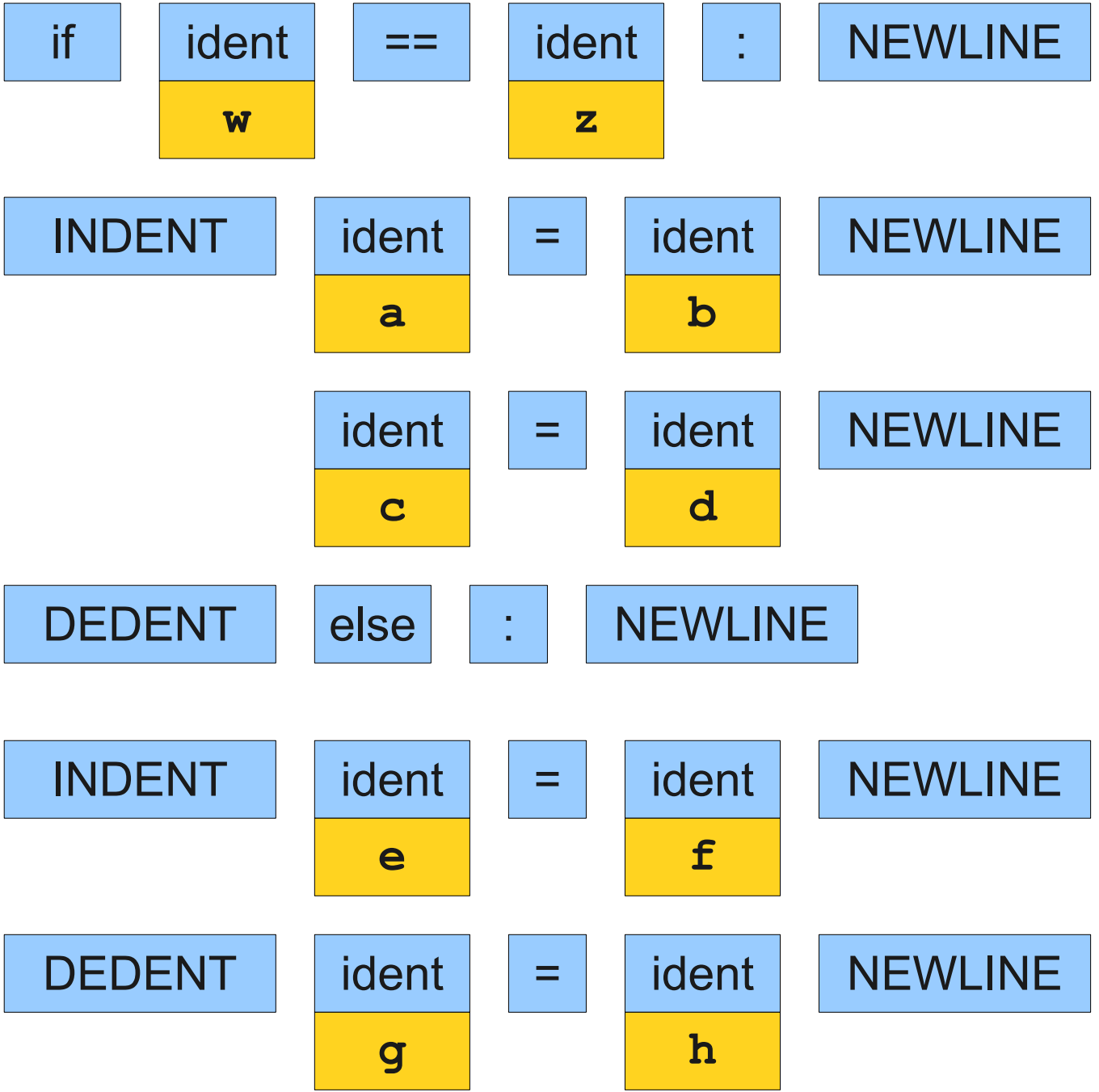



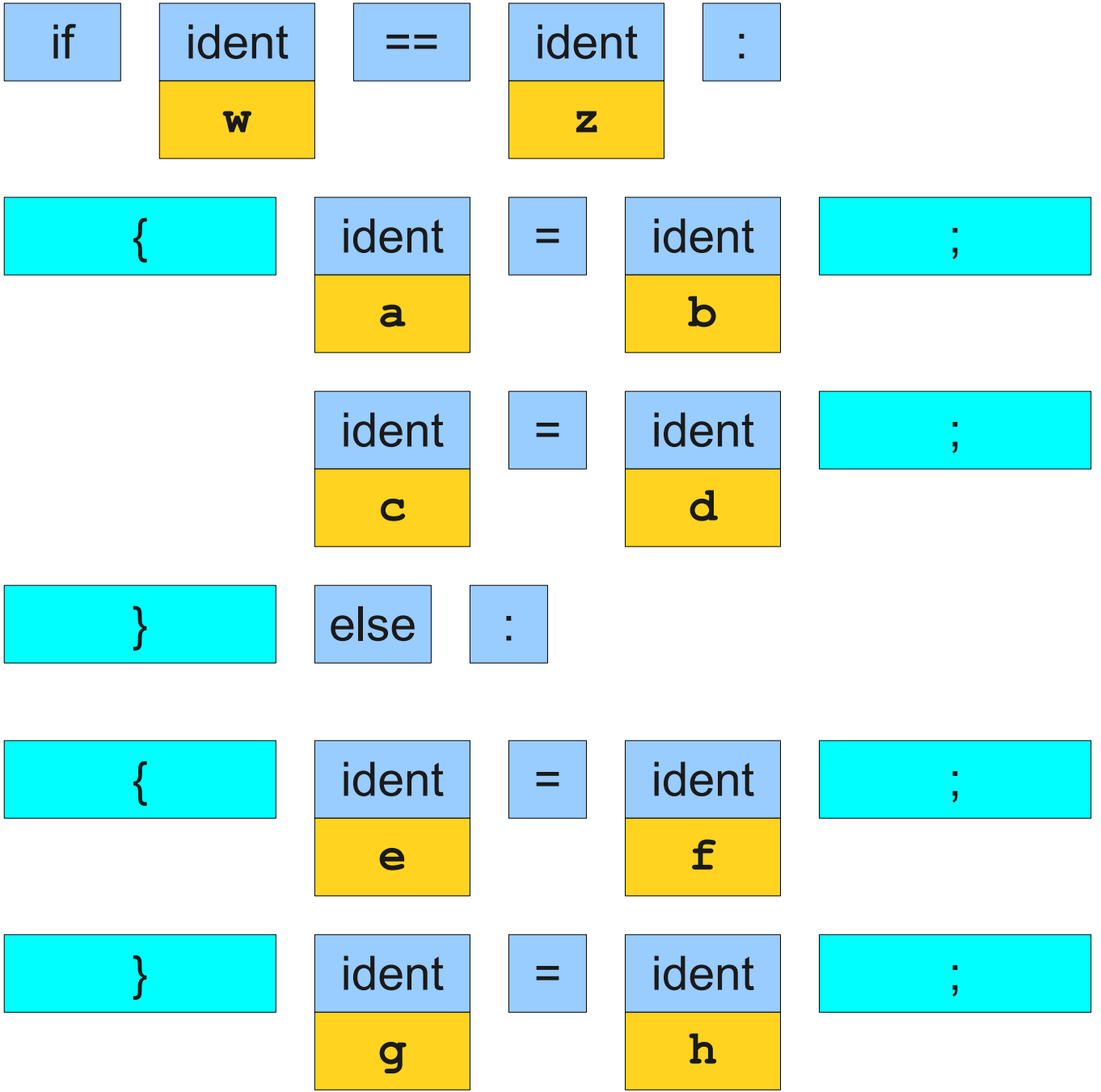
Scanning Python

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



Scanning Python

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

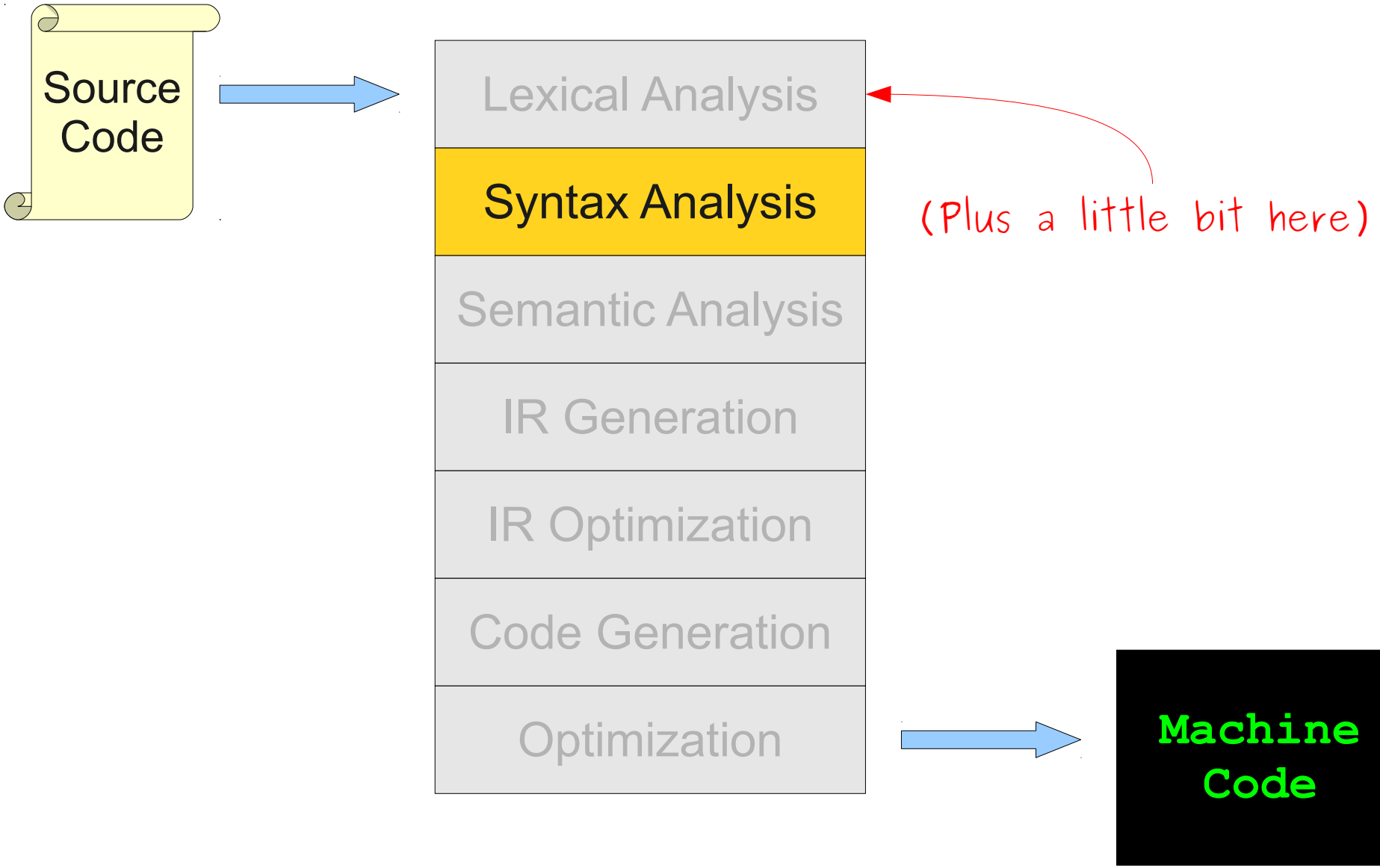
- Normally, more text on a line translates into more tokens.
- With DEDENT, **less** text on a line often means more tokens:

```
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