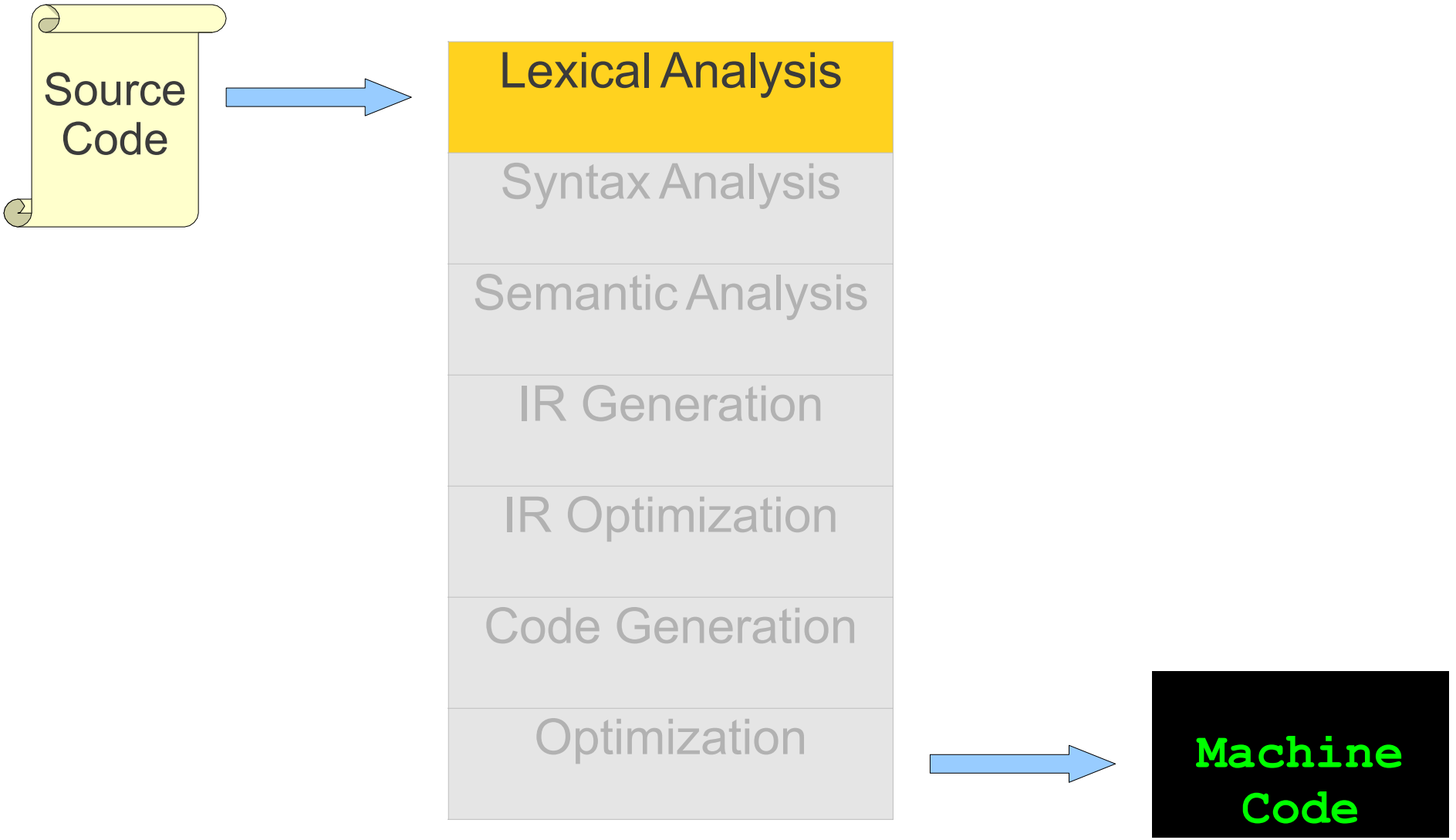
بسم الله الرحمن الرحيم

Lexical Analysis (2)

Review

Where We Are


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

Scanner

- function getNextToken() returns
  - type of next token
  - attribute of the token (e.g. integer constant, comparison type, …)

Scanning a Source File

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

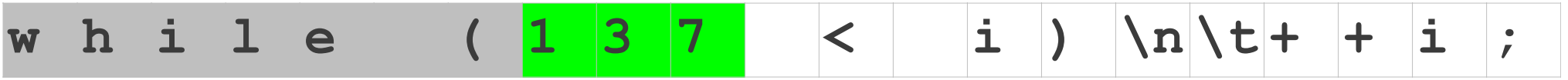
This is called a **token**. You can think of it as an enumerated type representing what logical entity we read out of the source code.

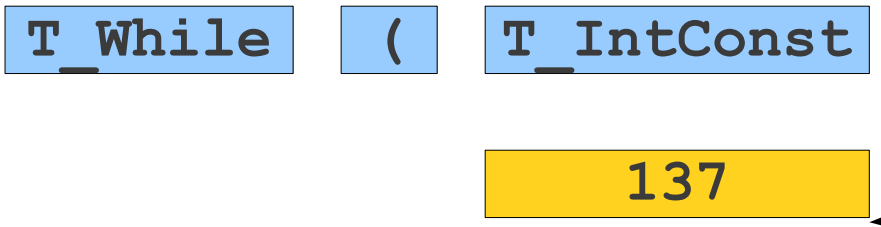
Scanning a Source File

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





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

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
```

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

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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

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-
-

Challenges in Scanning

- How do we determine which lexemes are associated with each token?
-
-

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?
-

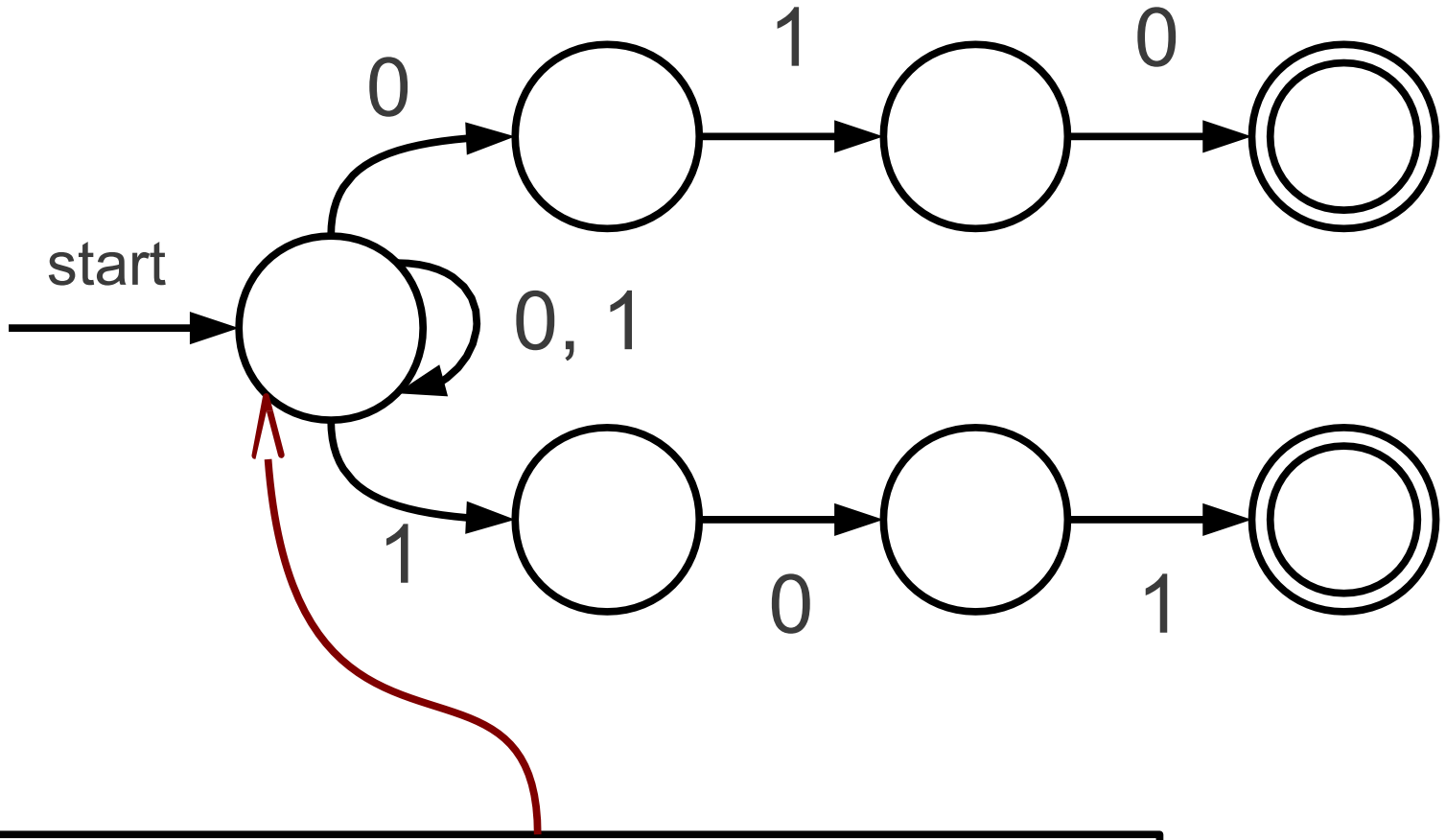
Challenges in Scanning

- 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?

Idea:

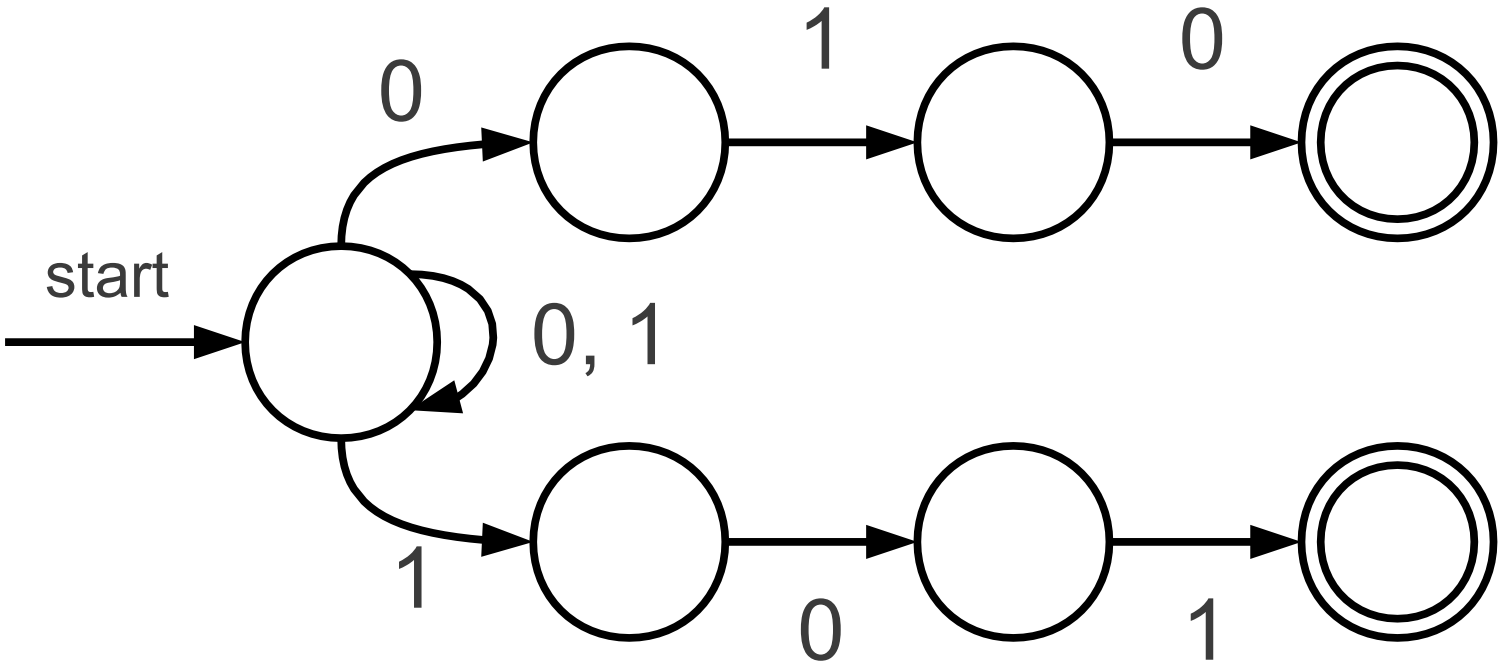
- To each token, assign a regular language
  - = regular expression

A More Complex Automaton



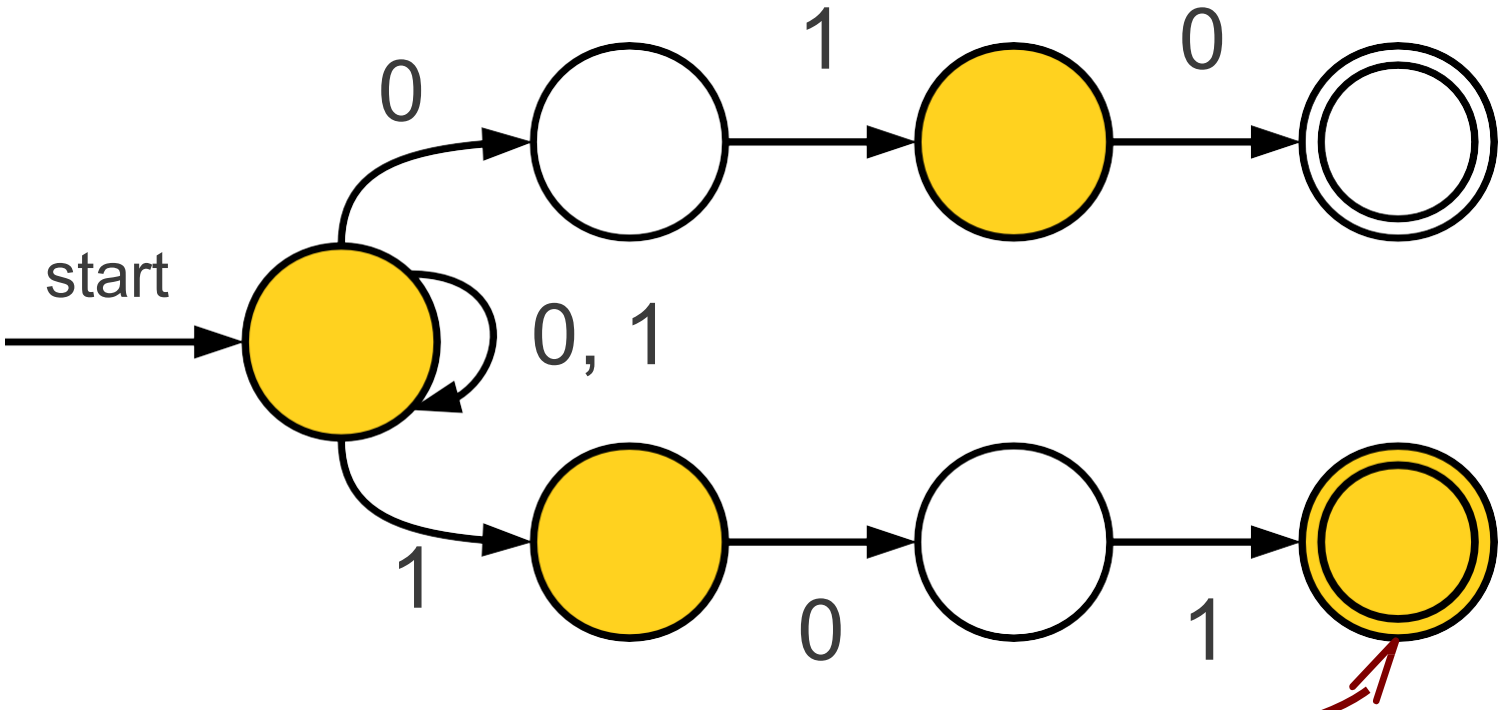
Notice that there are multiple transitions defined here on 0 and 1. If we read a 0 or 1 here, we follow *both* transitions and enter multiple states.

A More Complex Automaton



0	1	1	1	0	1

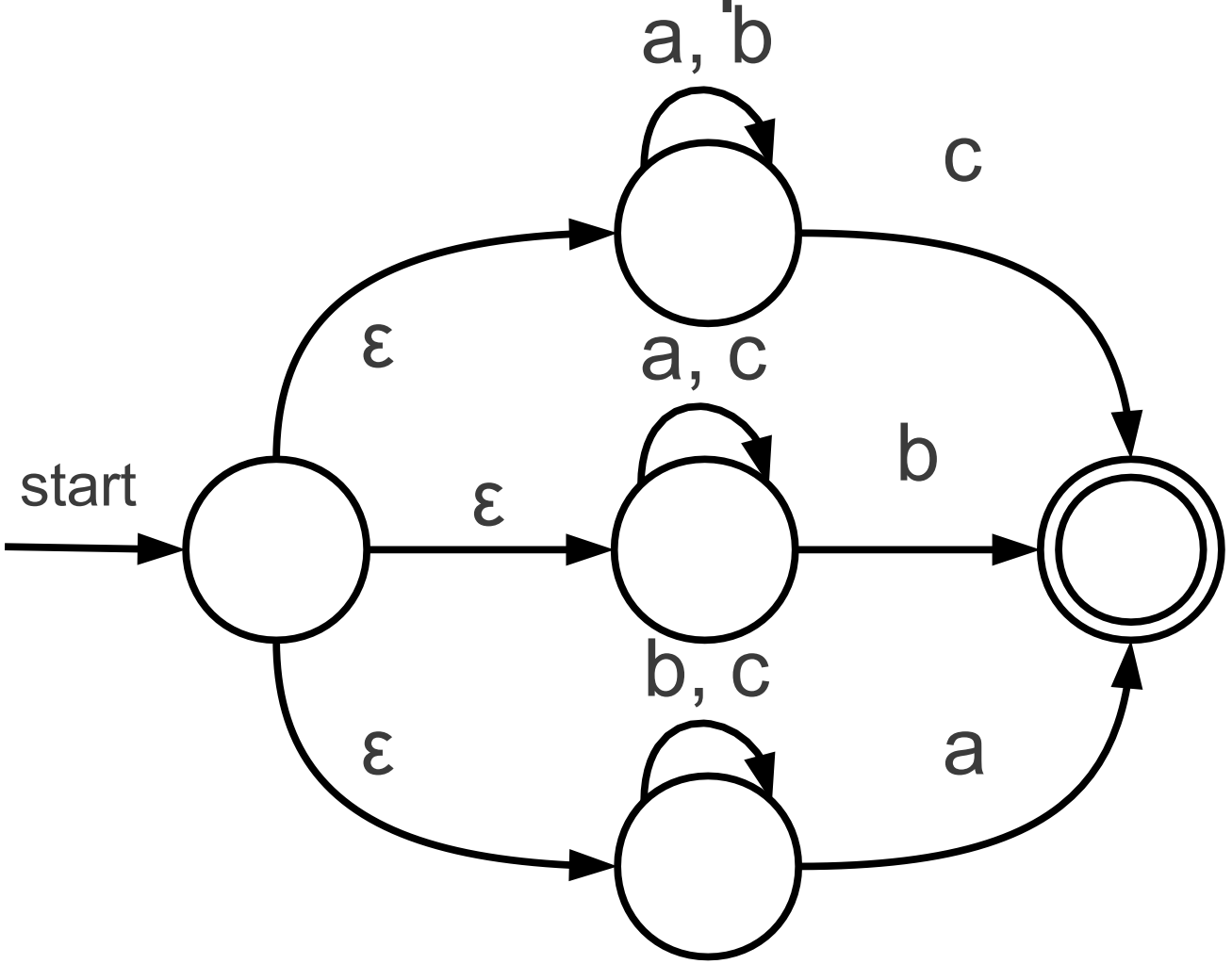
A More Complex Automaton



0	1	1	1	0	1

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

An Even More Complex Automaton



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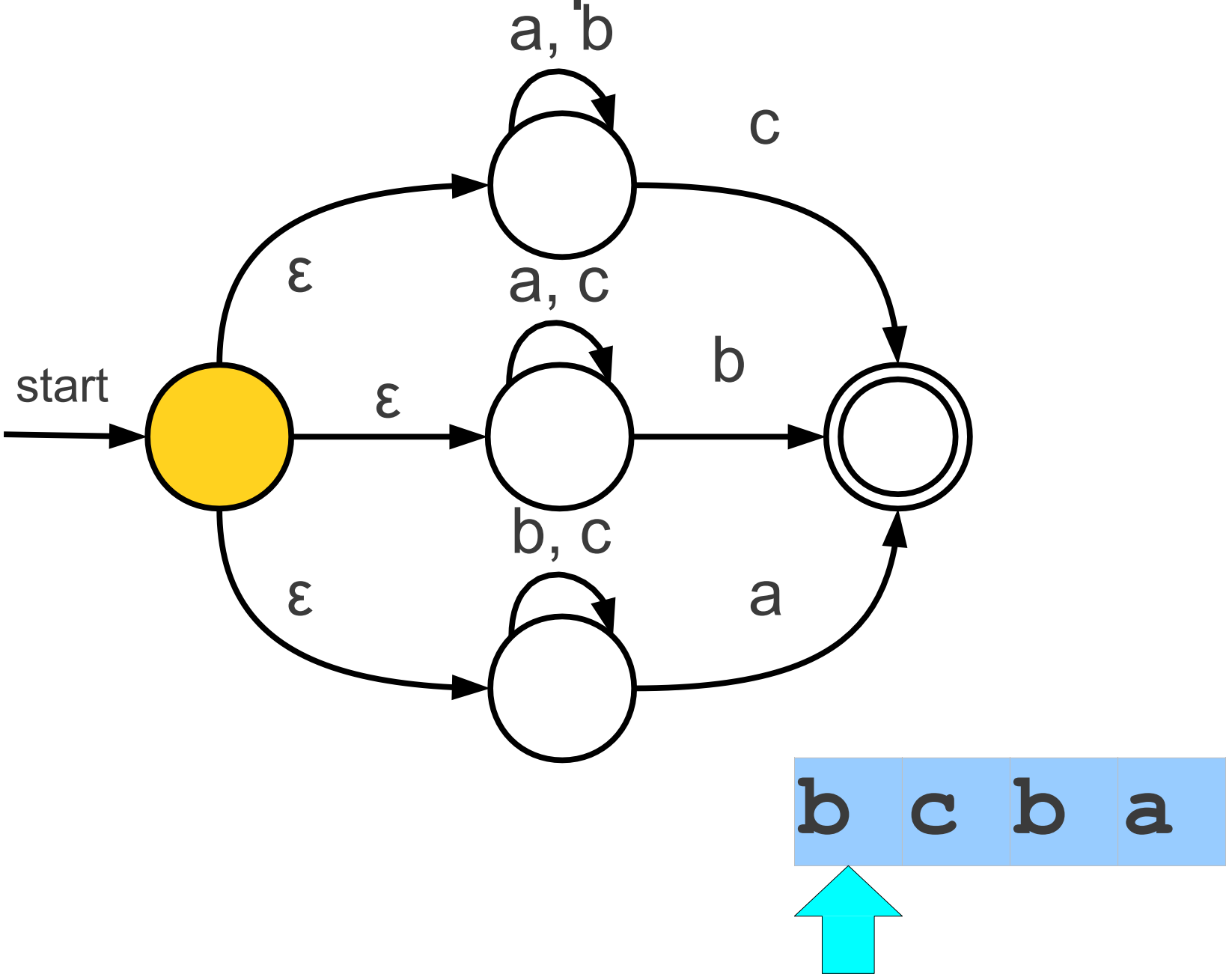

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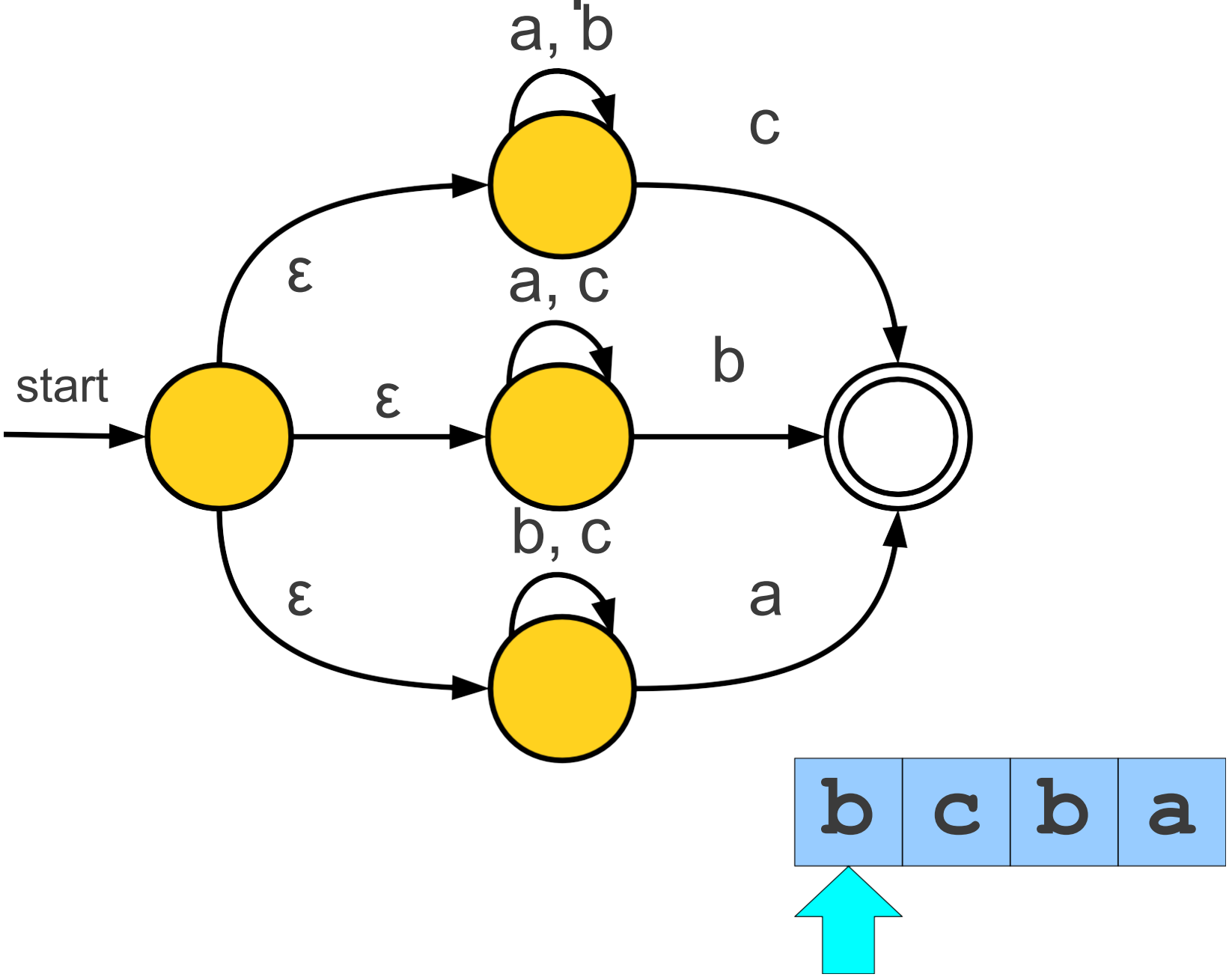
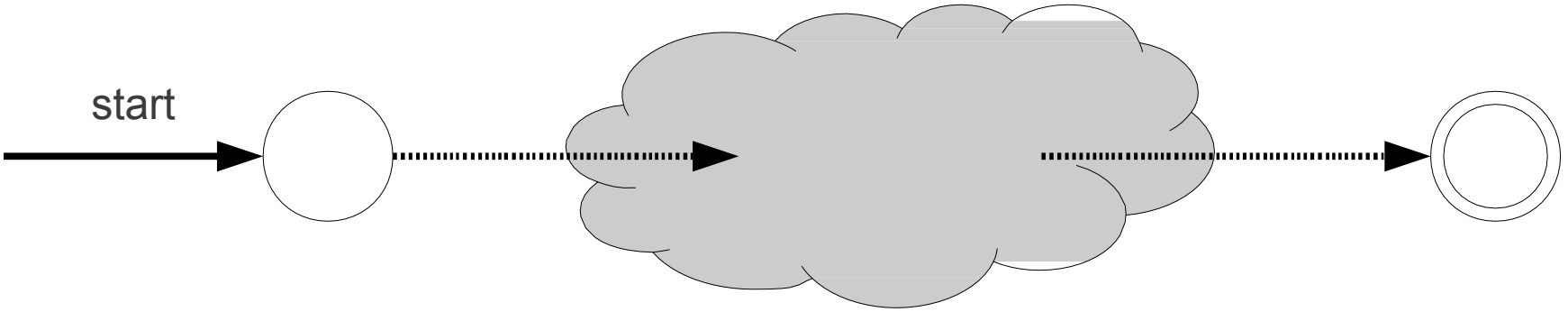
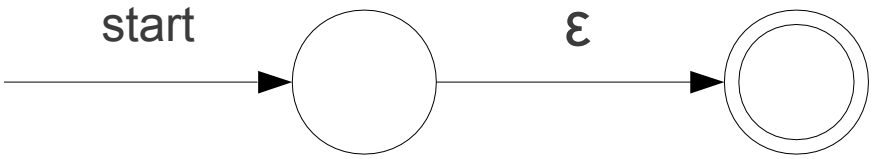


From Regular Expressions to NFAs

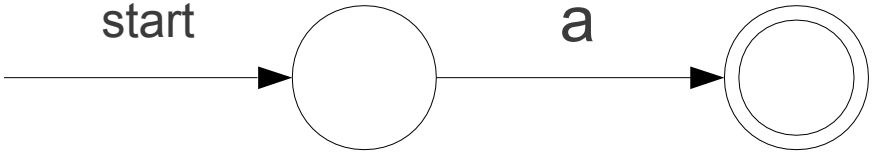
- There is a (beautiful!) procedure from converting a regular expression to an NFA.
- Associate each regular expression with an NFA with the following properties:
  - There is exactly one accepting state.
  - There are no transitions out of the accepting state. There are no transitions into the starting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



Base Cases



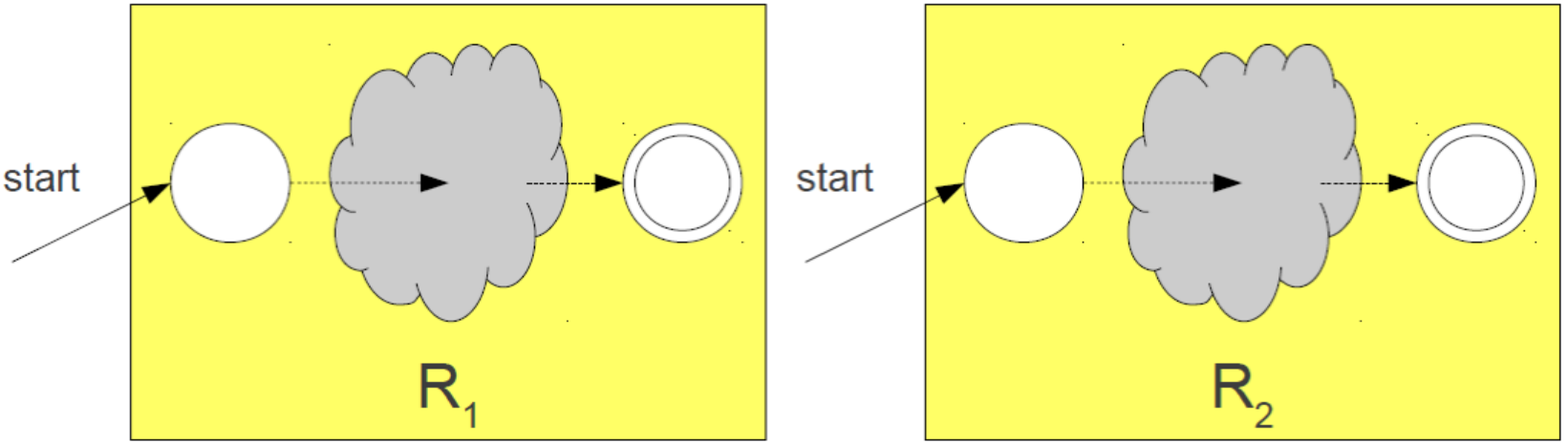
Automaton for ε



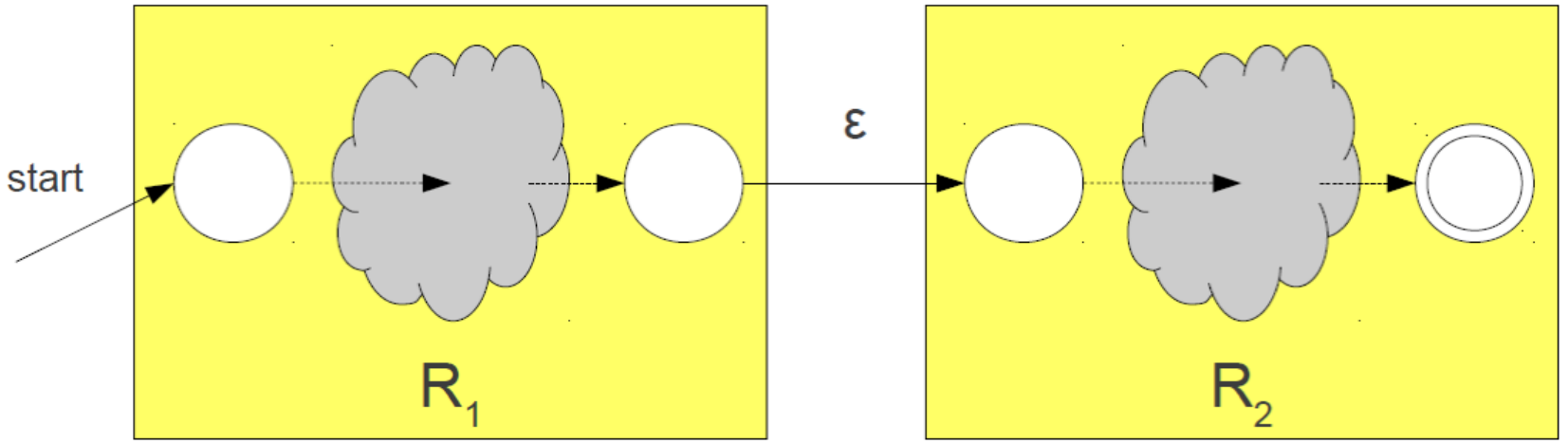
Automaton for single character **`a`**

Construction for R_1R_2

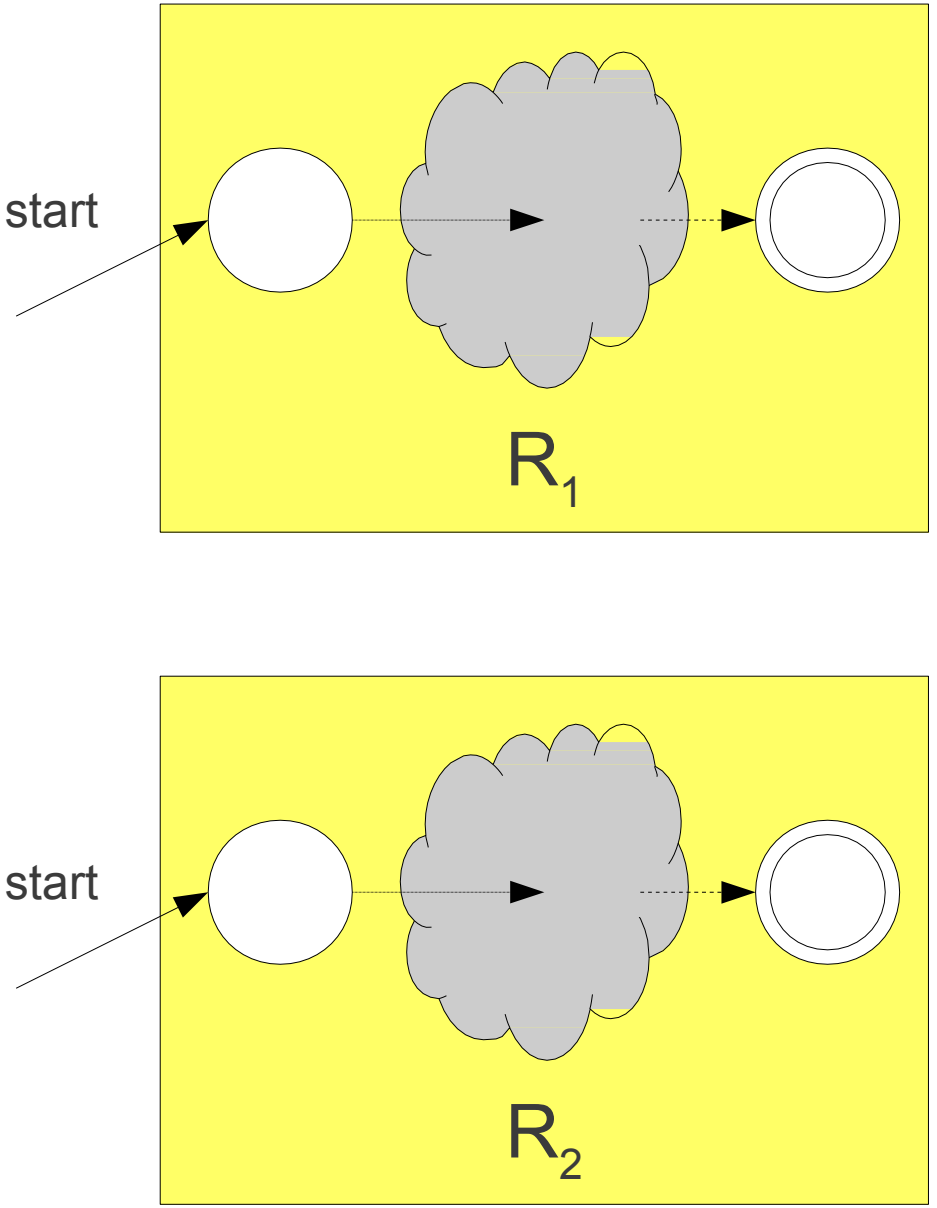
Construction for R_1R_2



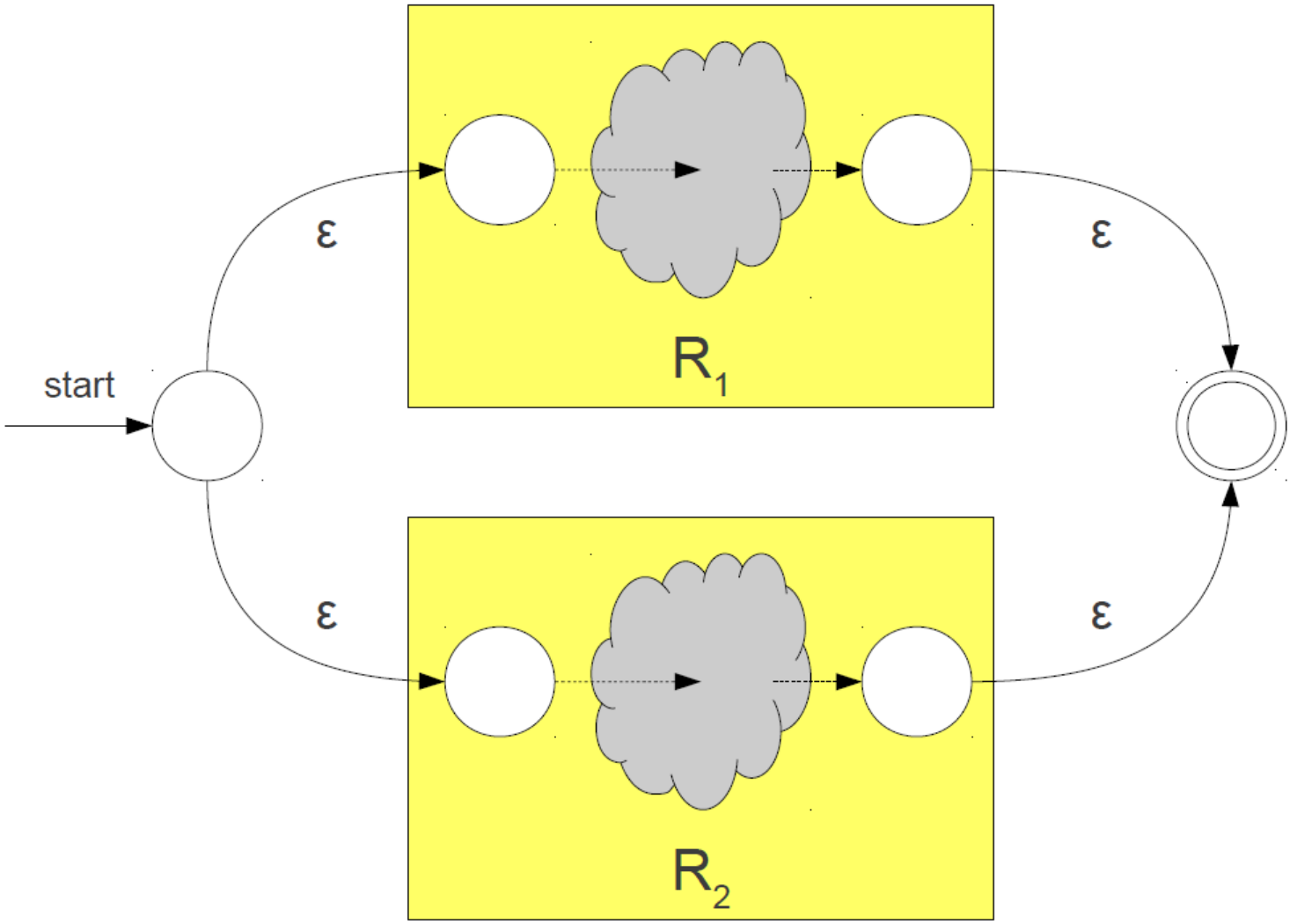
Construction for R_1R_2



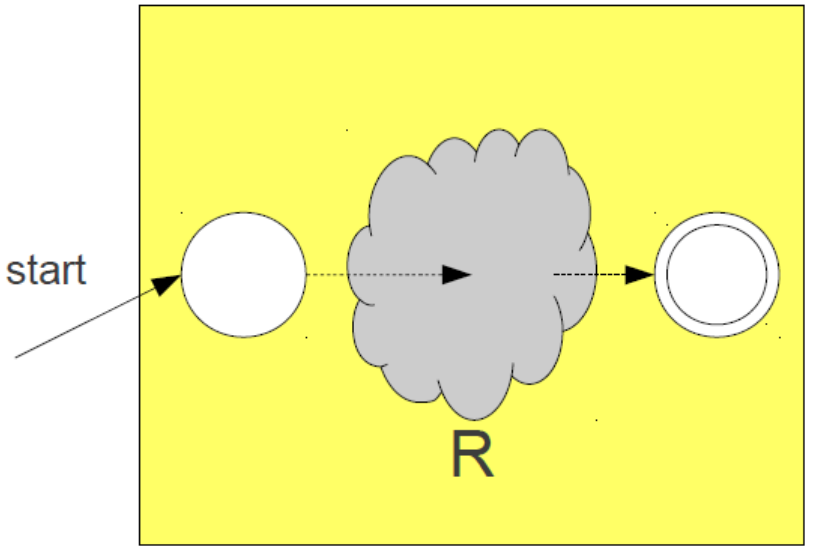
Construction for $R_1 \mid R_2$



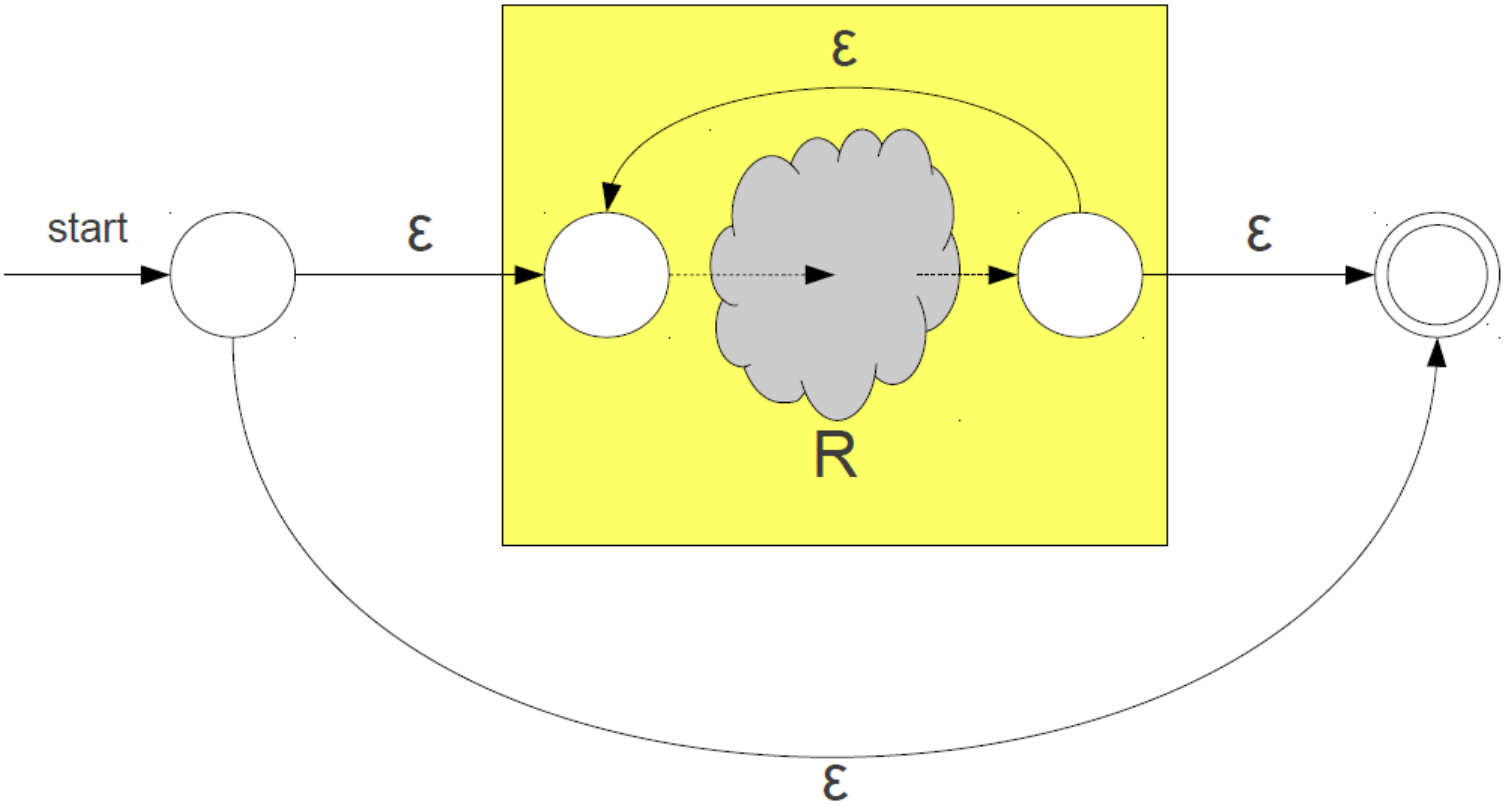
Construction for R_1 | R_2



Construction for R*



Construction for R*



Continue …

Overall Result

McNaughton–Yamada–Thompson Algorithm

- 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?

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

```
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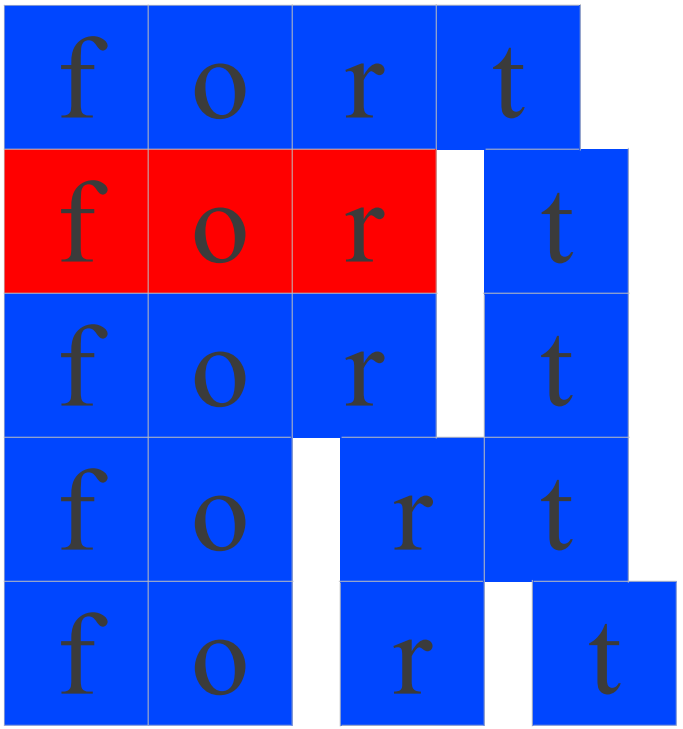

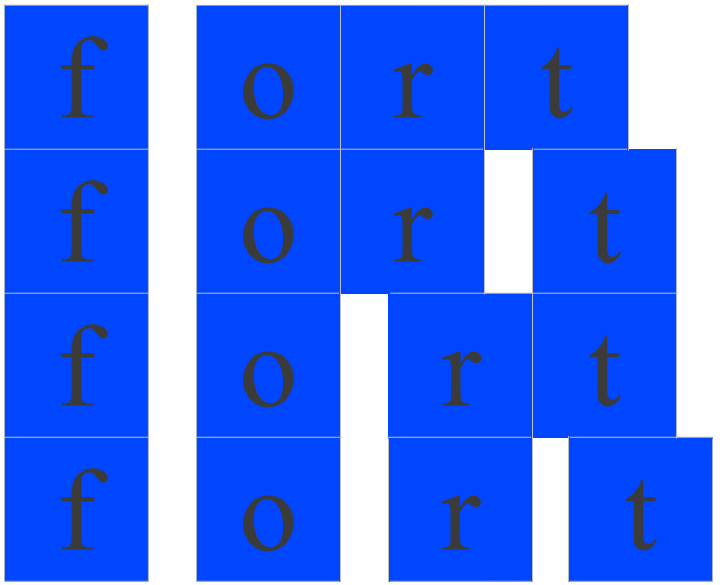

Conflict Resolution

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

Lexing Ambiguities

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```

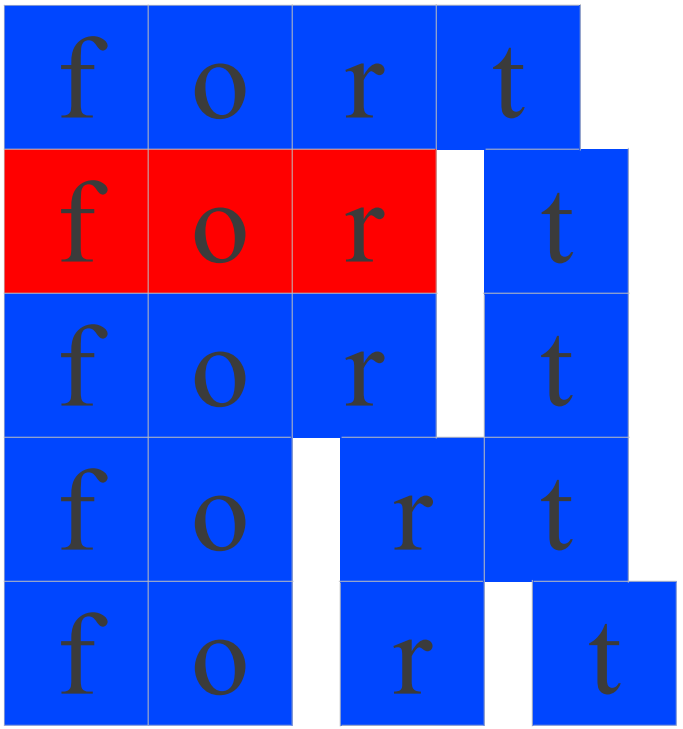

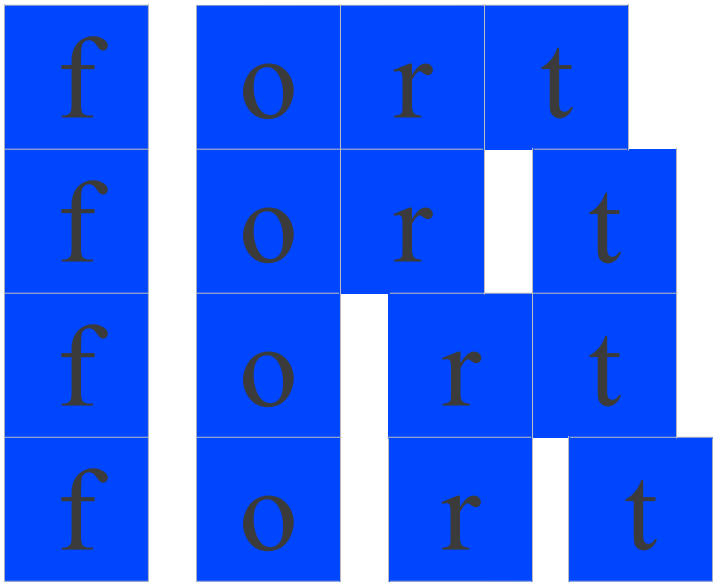

Lexing Ambiguities

```
T_For          for
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```

Implementing Maximal Munch

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

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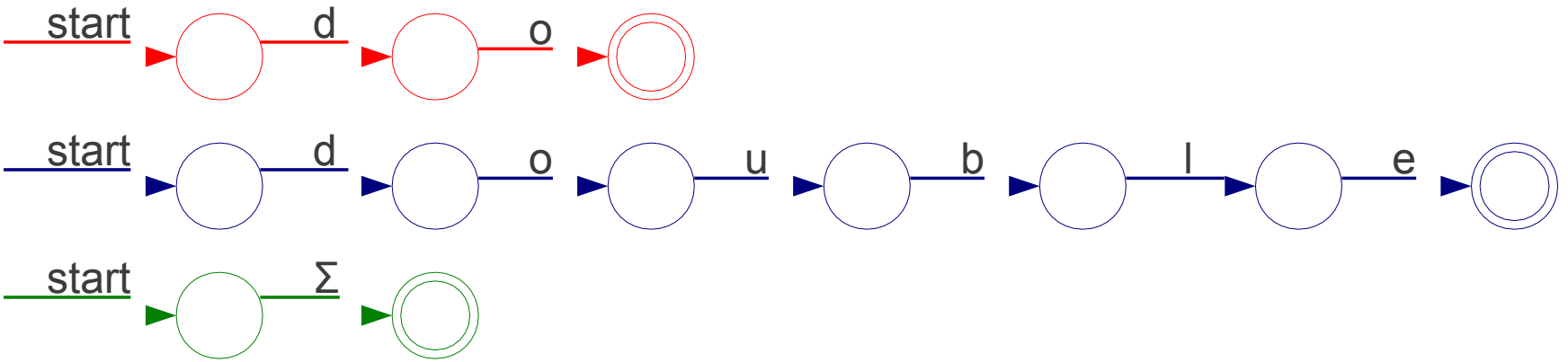

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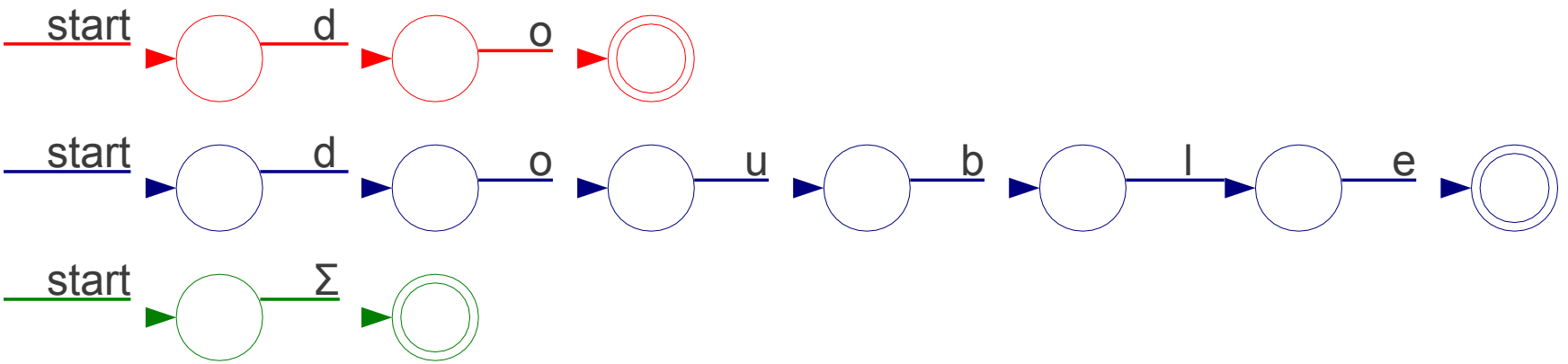

D	O	U	B	D	O	U	B	L	E

Implementing Maximal Munch

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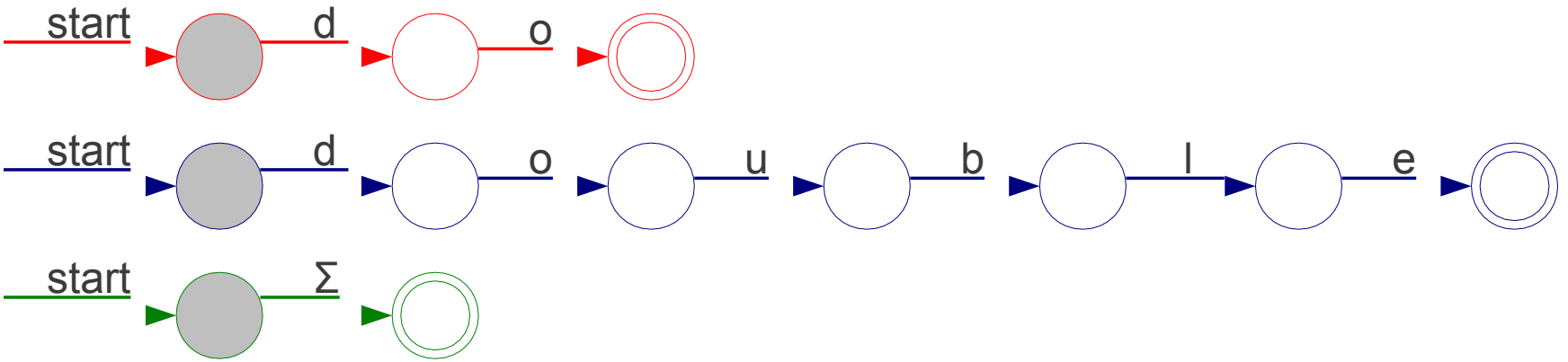
```



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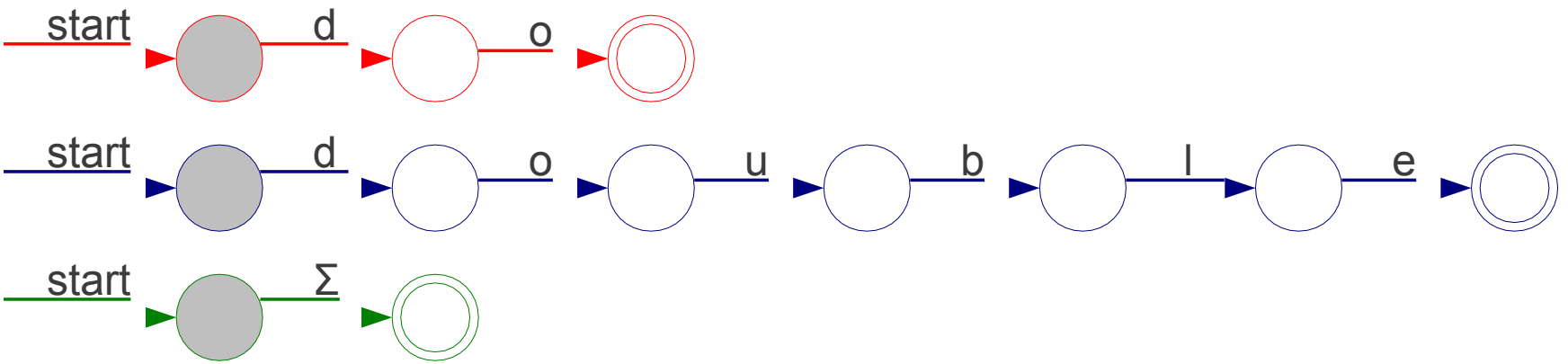

D	O	U	B	D	O	U	B	L	E

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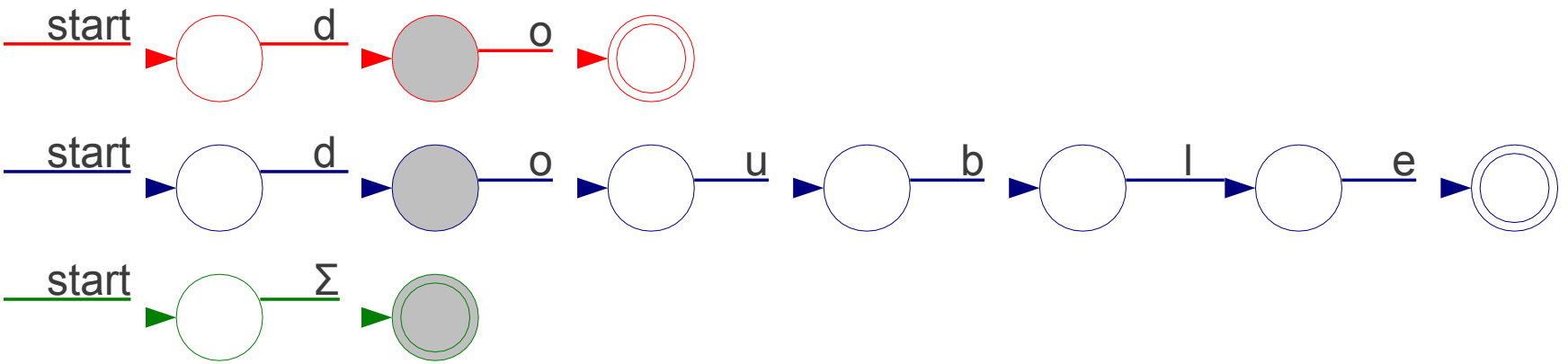

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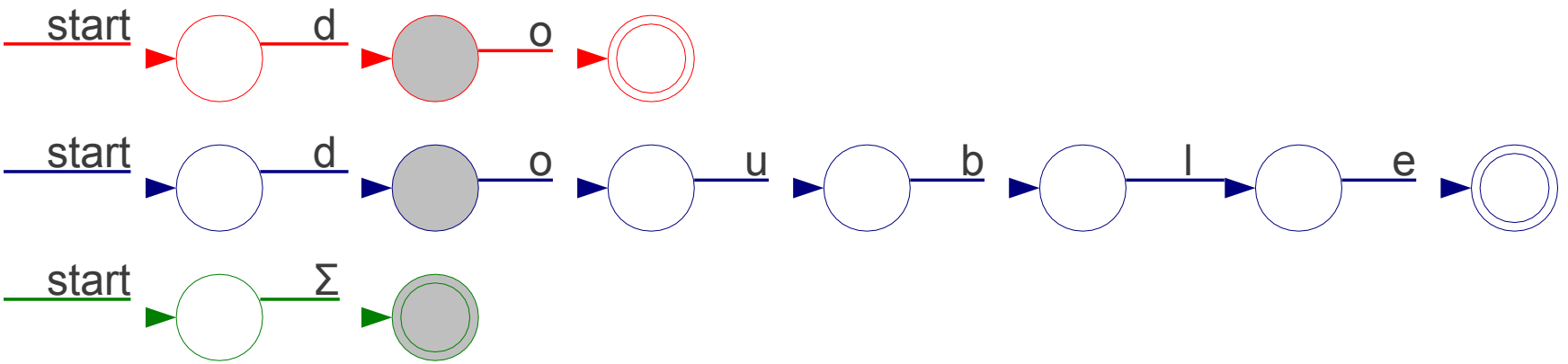

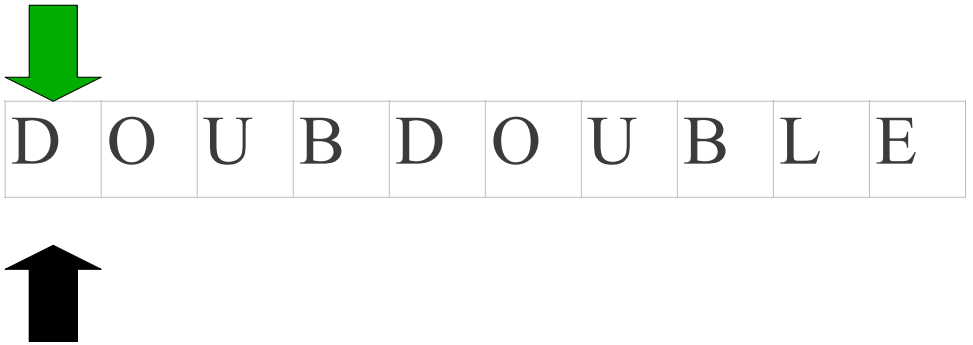

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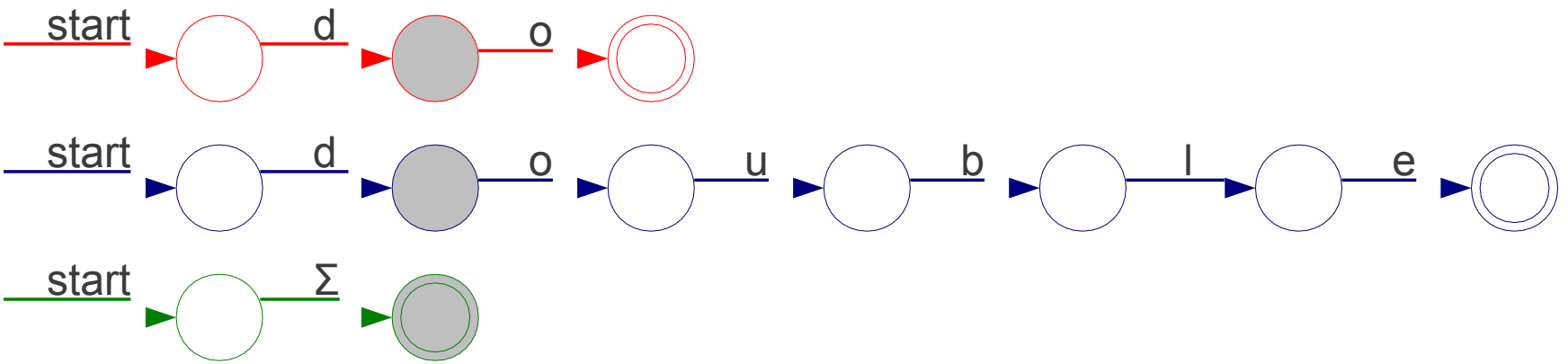

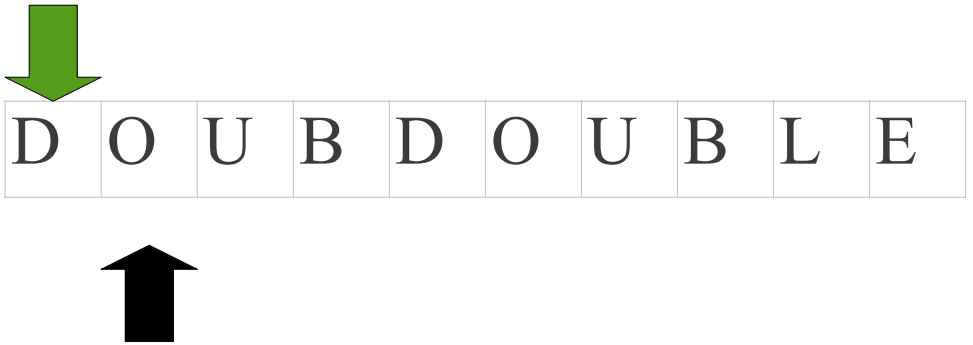

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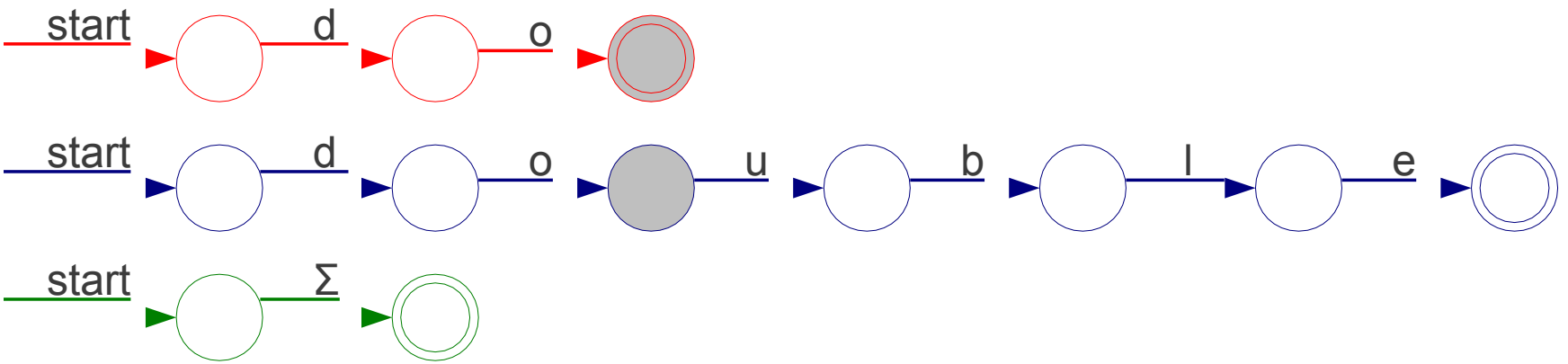

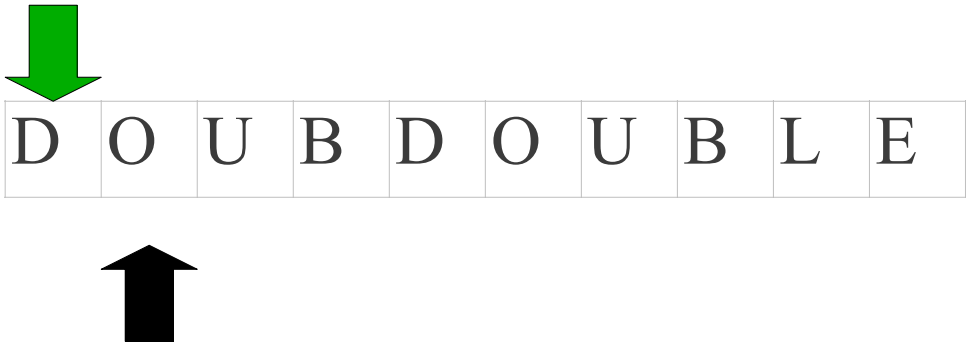

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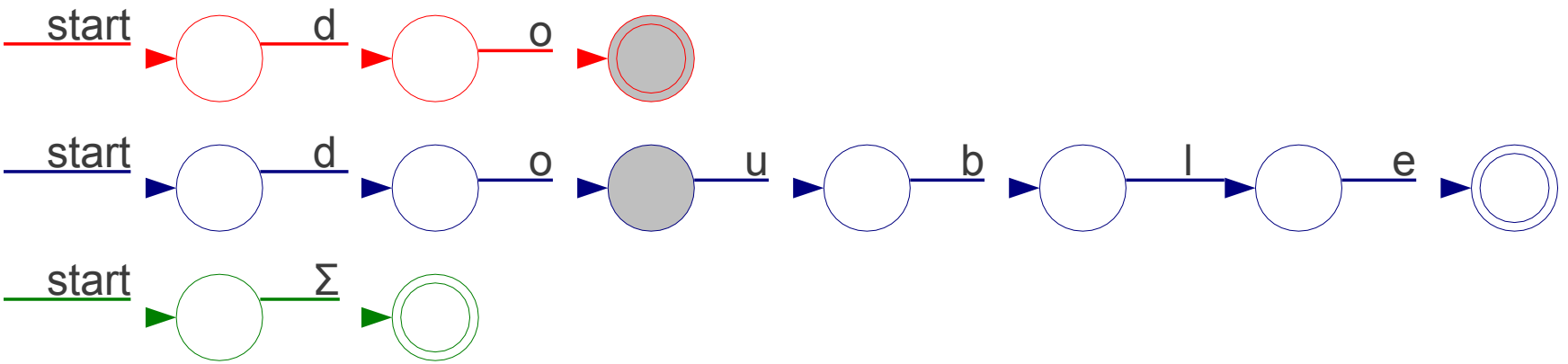

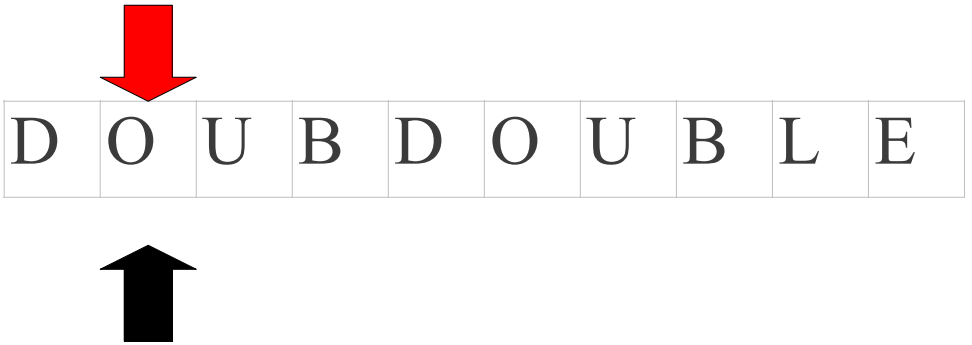

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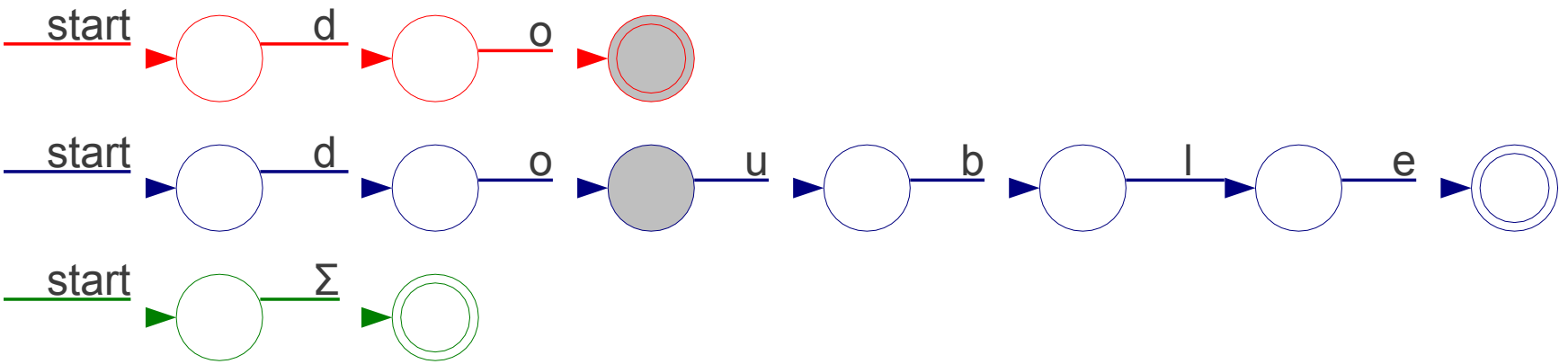

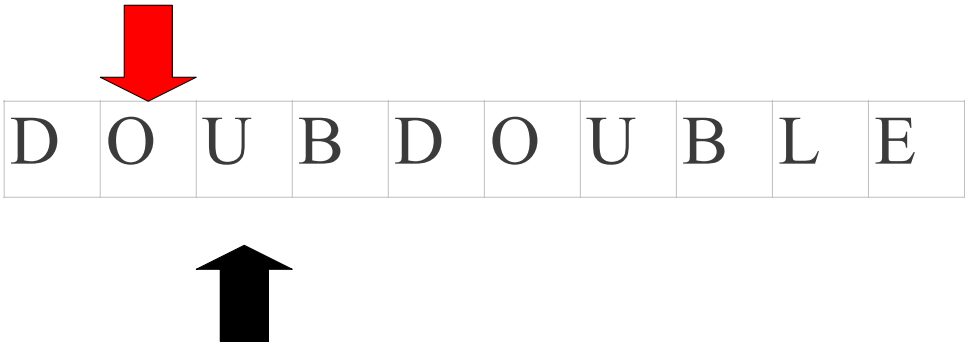

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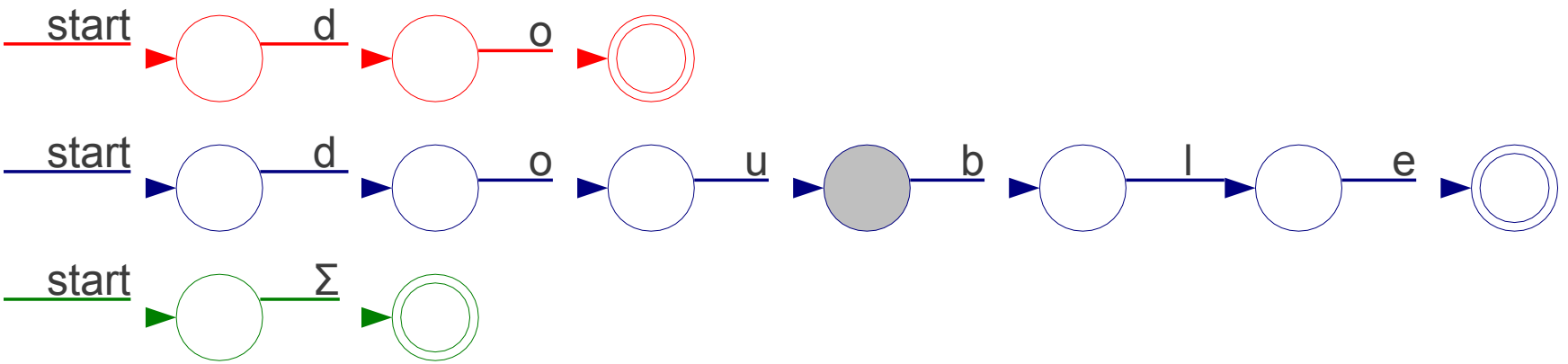

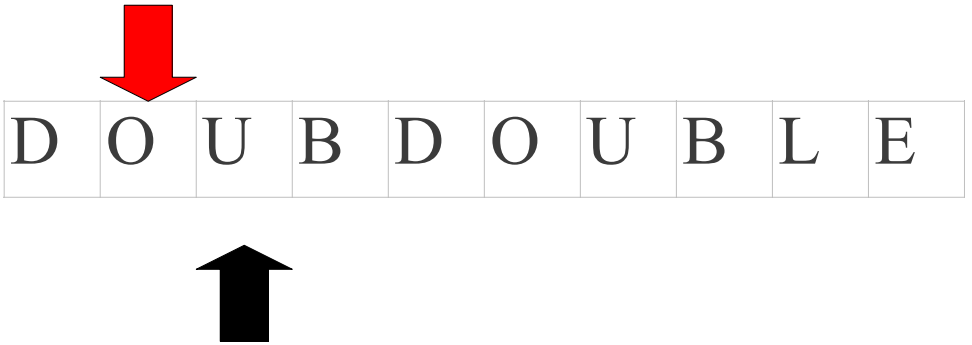

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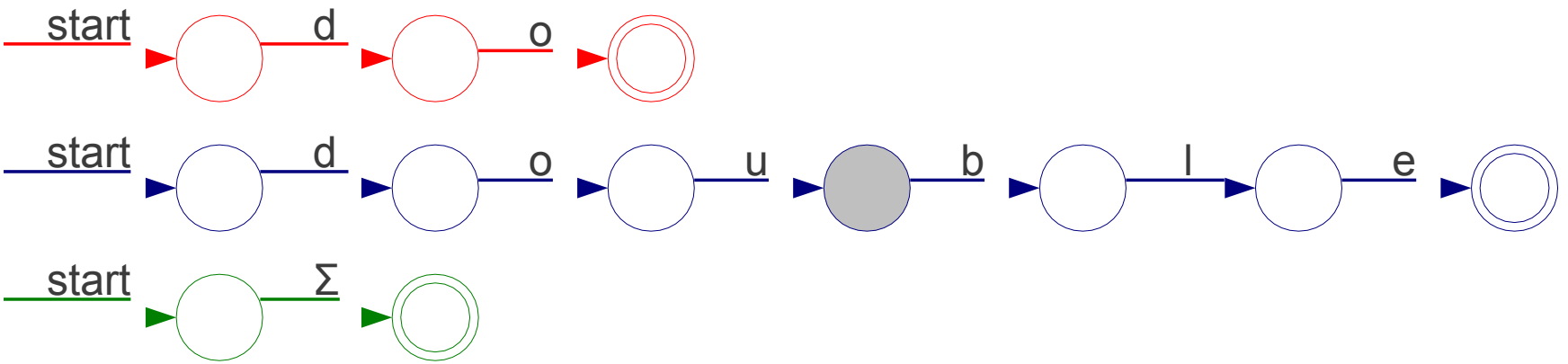

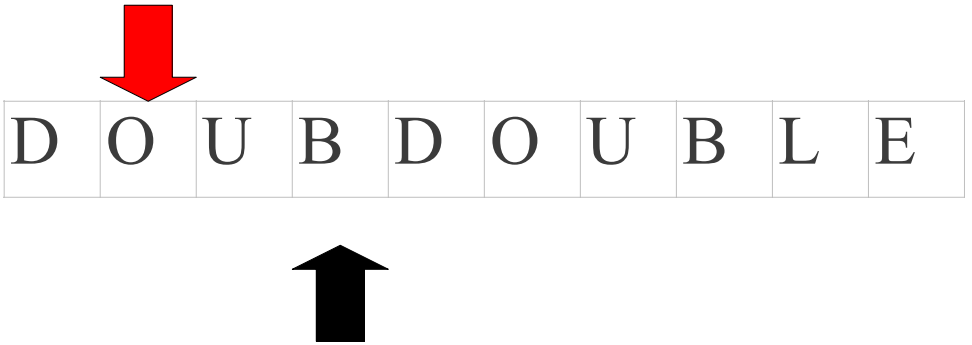

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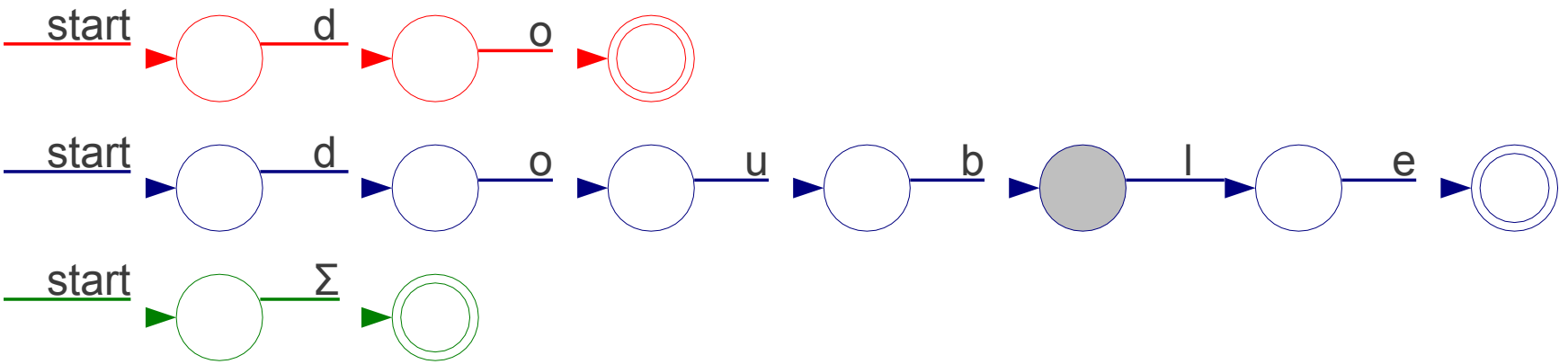

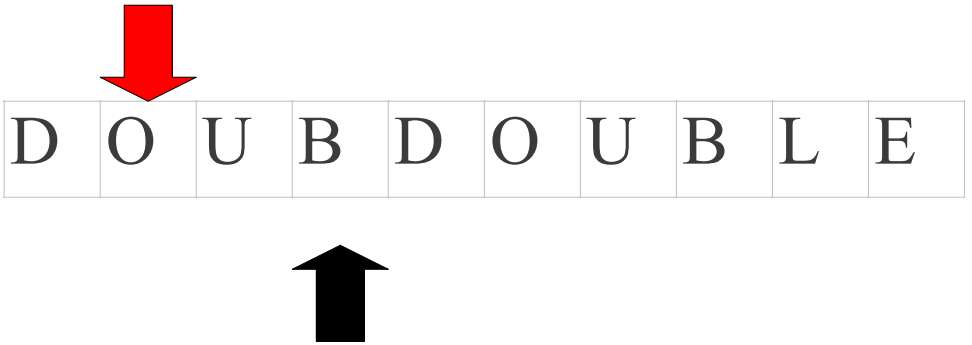

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```
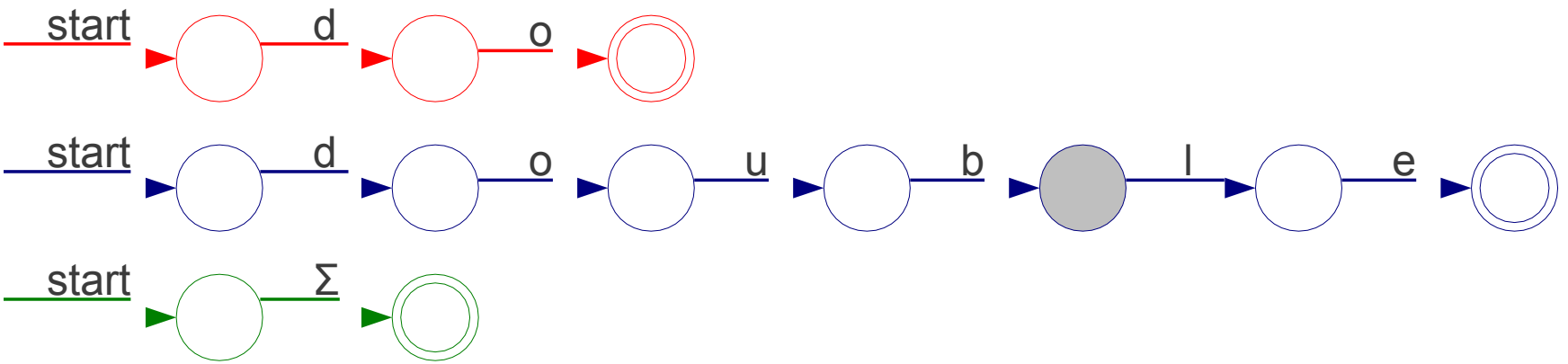
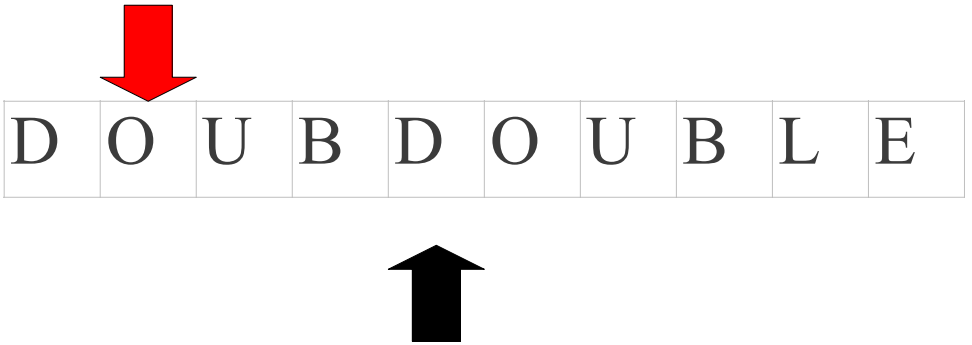
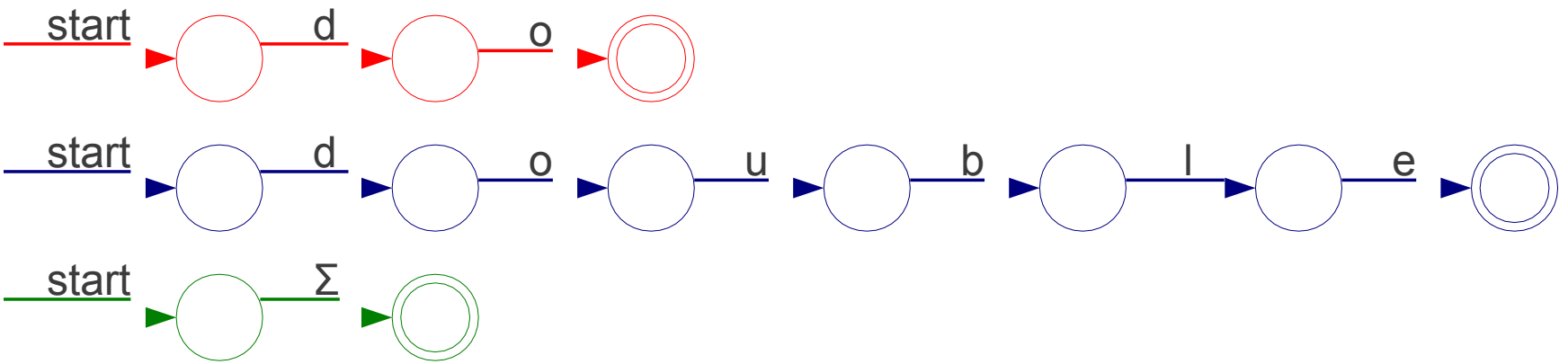
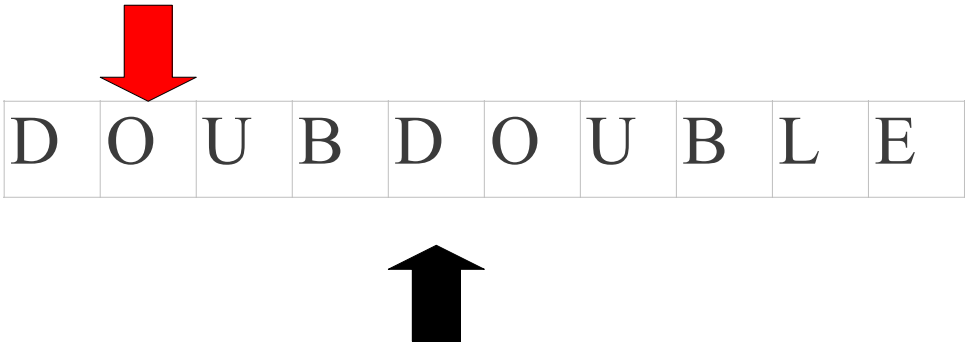





Implementing Maximal Munch

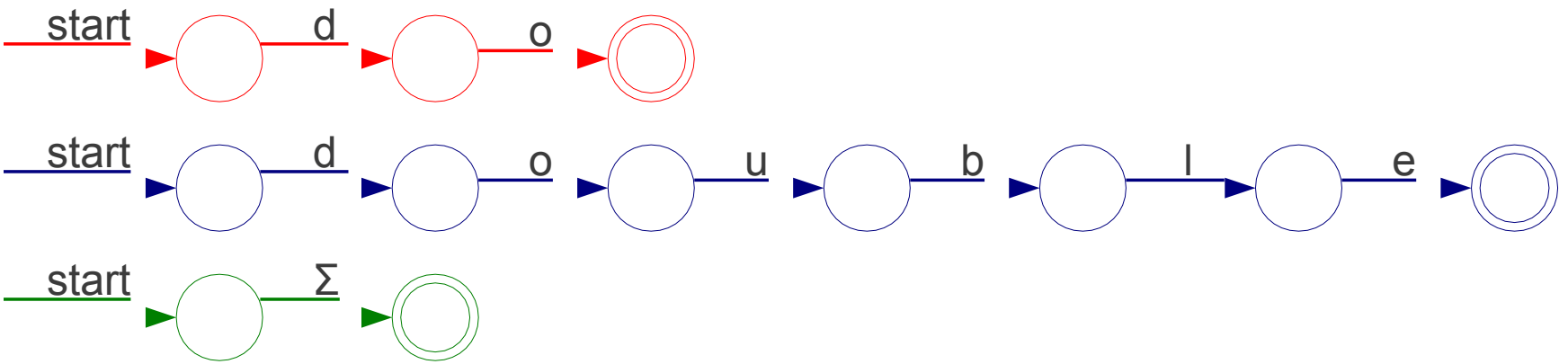
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```





Implementing Maximal Munch

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

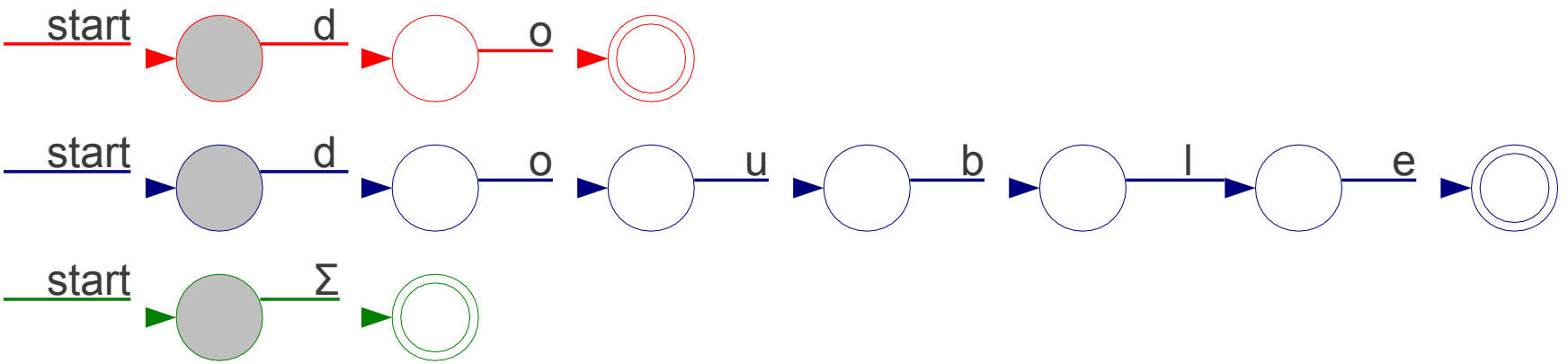


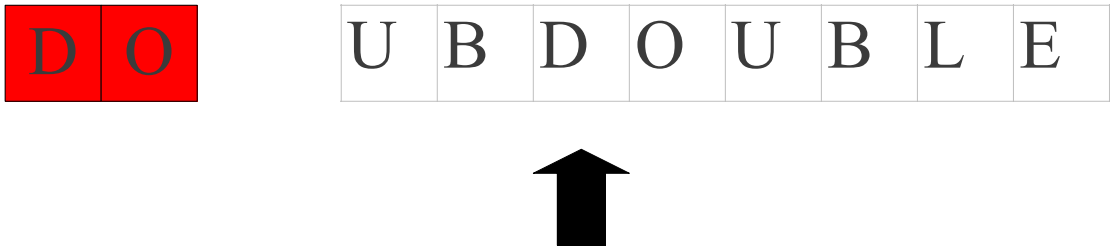
D	O

U	B	D	O	U	B	L	E

Implementing Maximal Munch

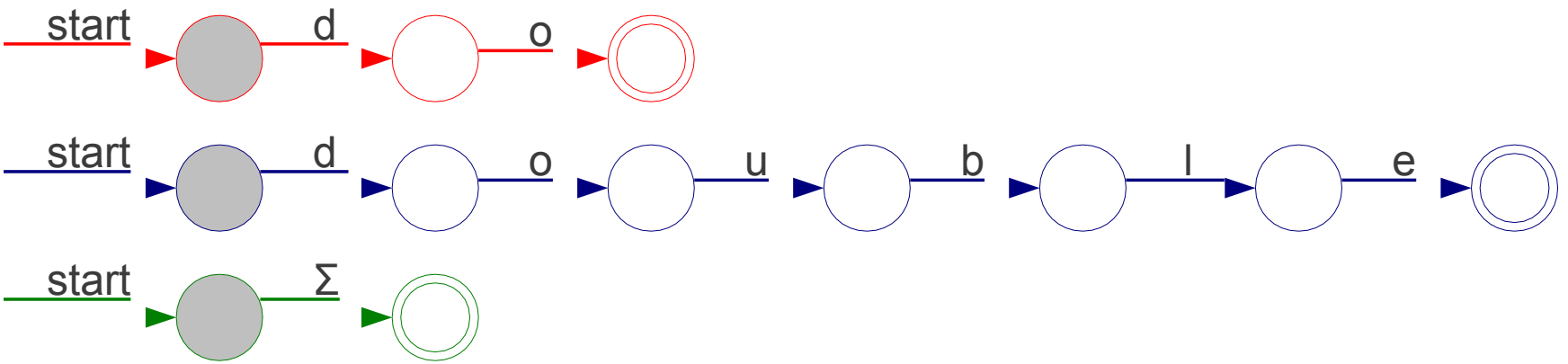
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

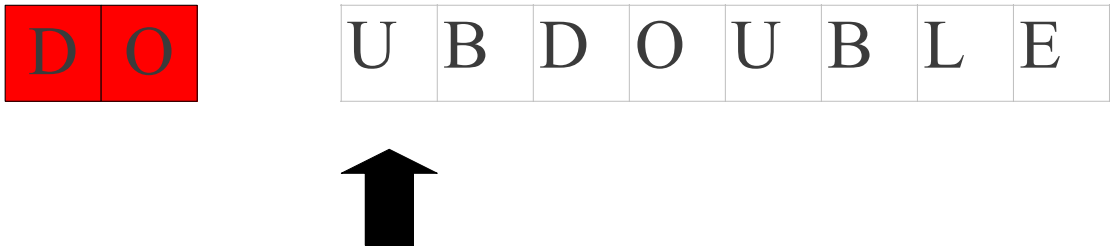




Implementing Maximal Munch

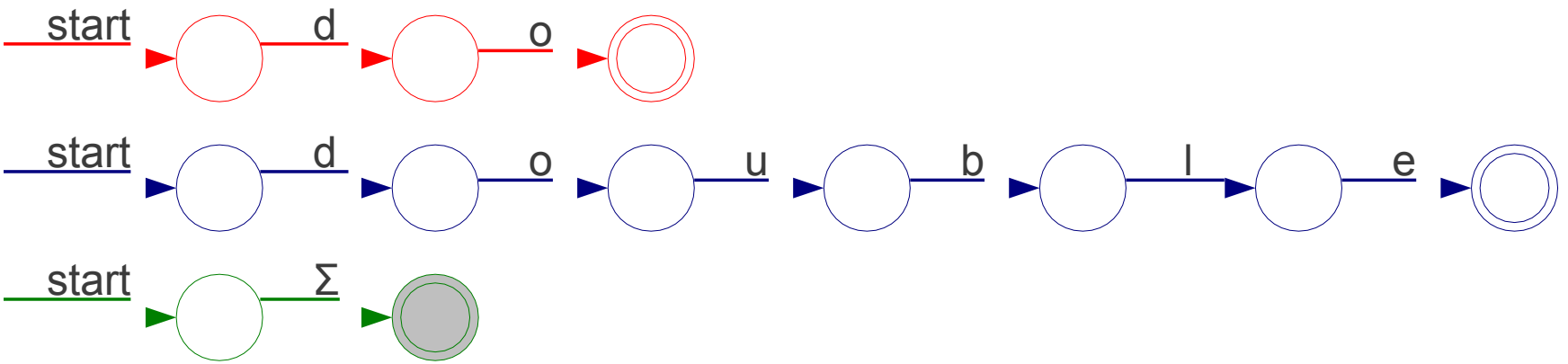
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

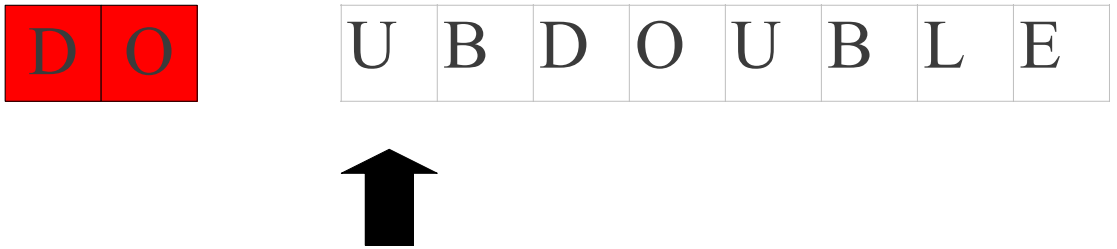




Implementing Maximal Munch

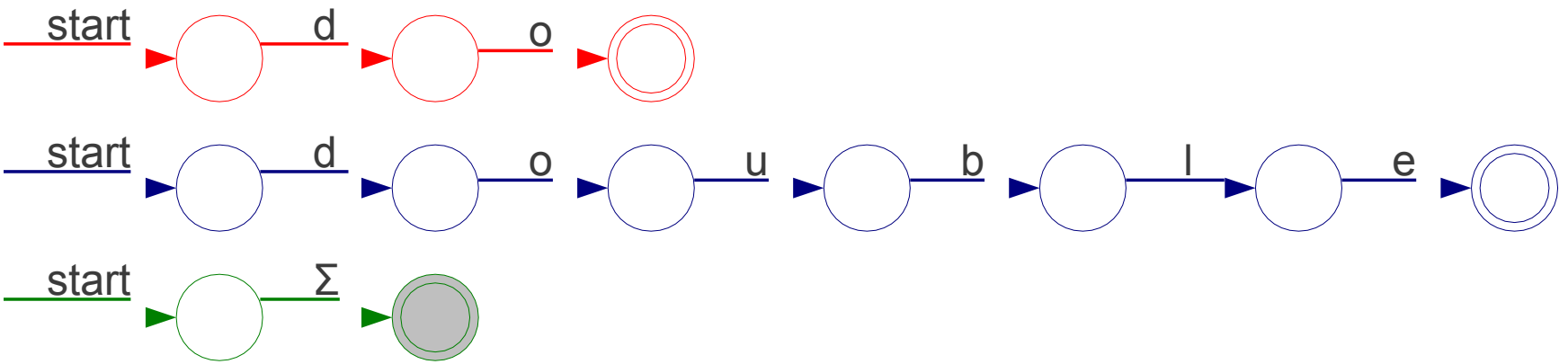
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

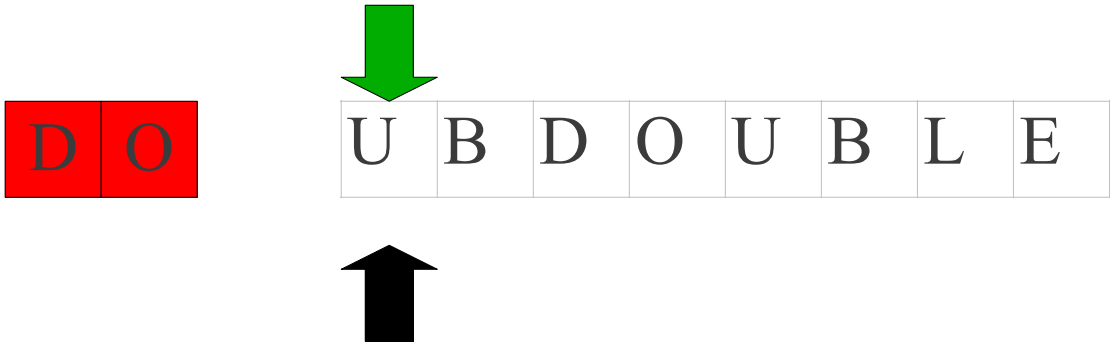




Implementing Maximal Munch

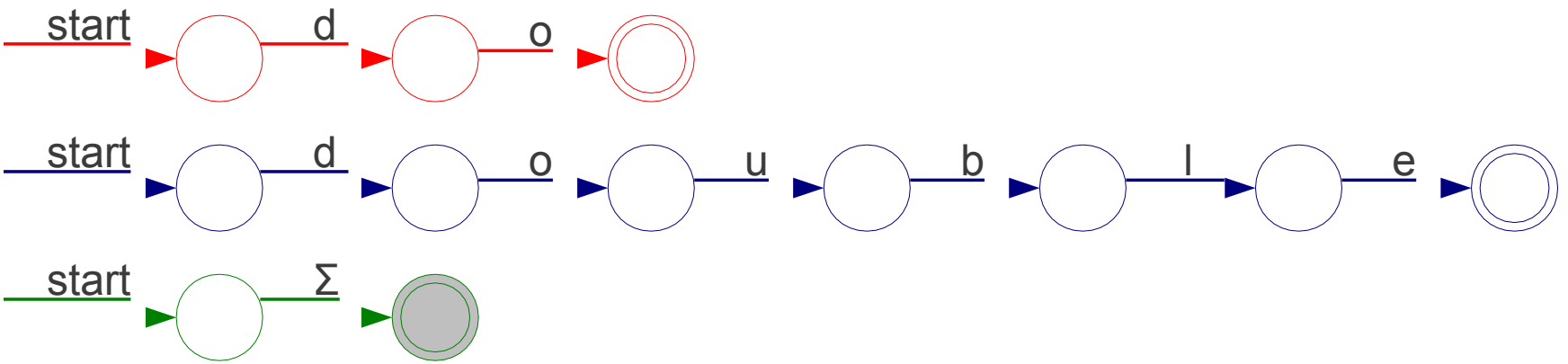
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

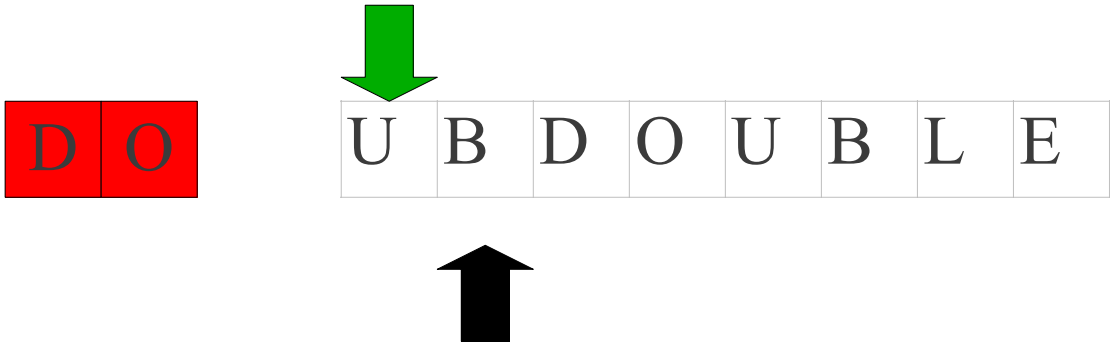




Implementing Maximal Munch

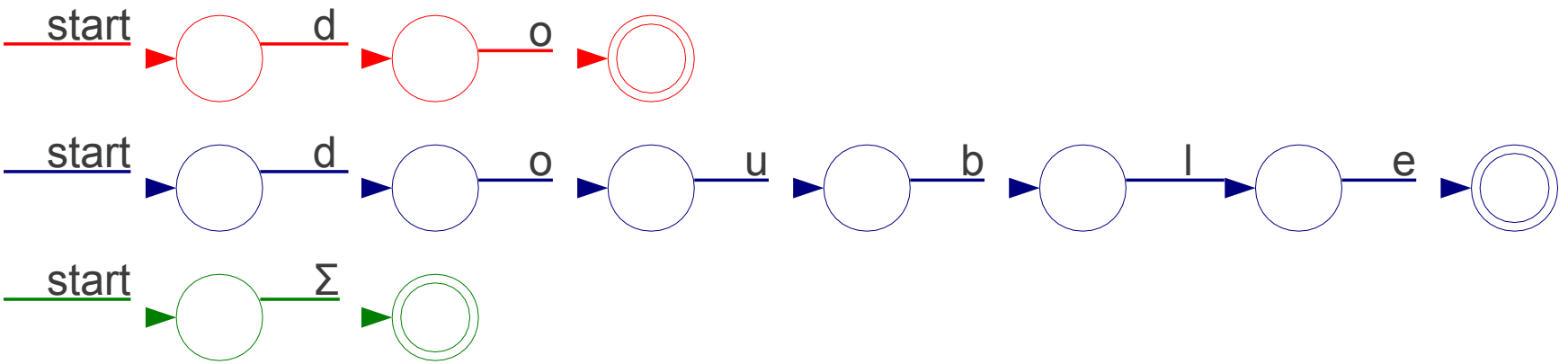
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

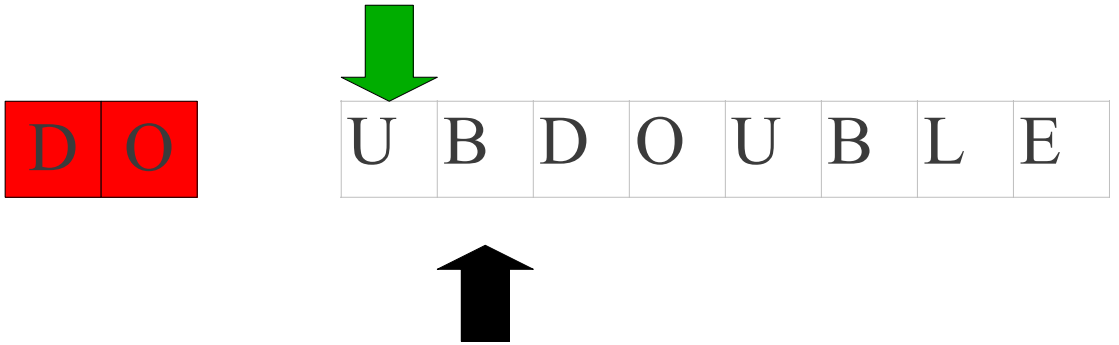




Implementing Maximal Munch

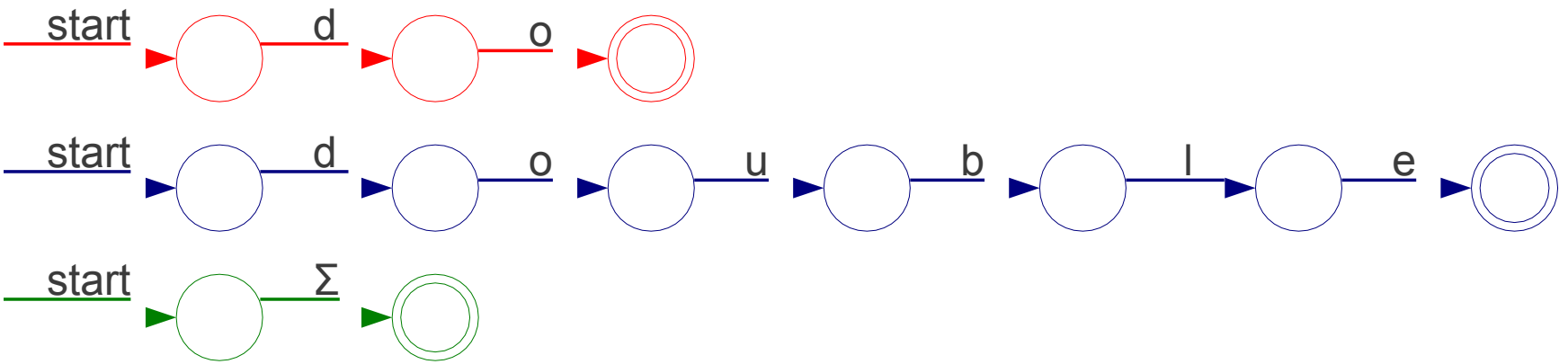
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

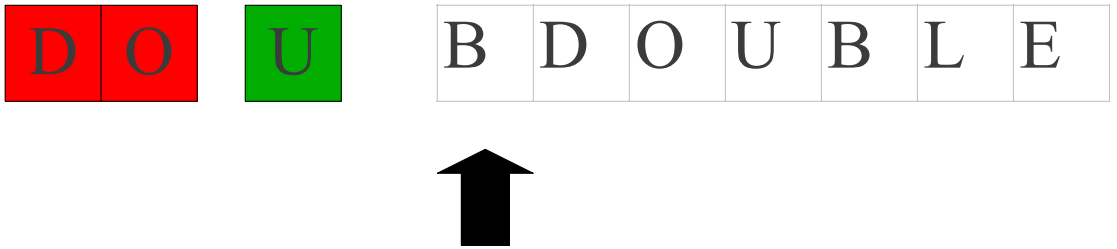




Implementing Maximal Munch

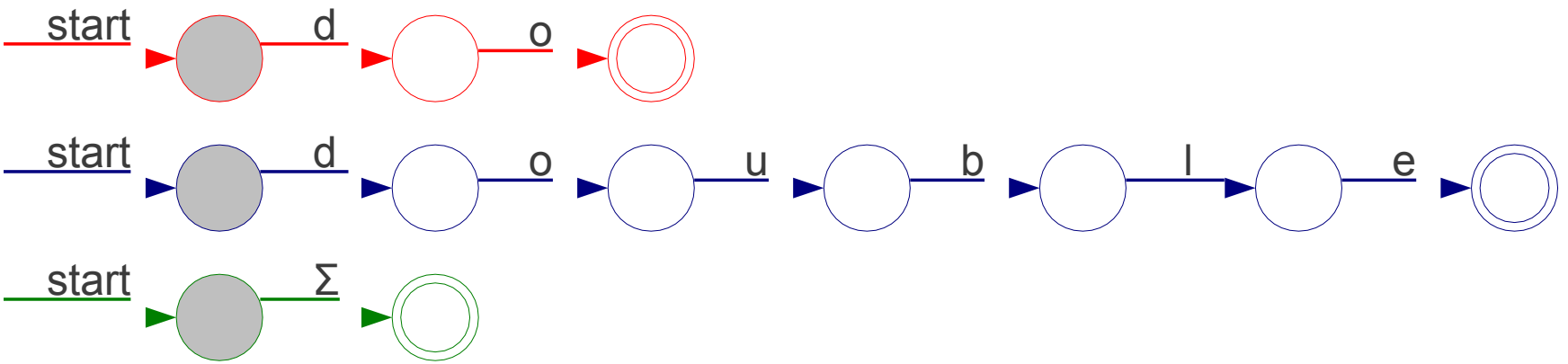
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

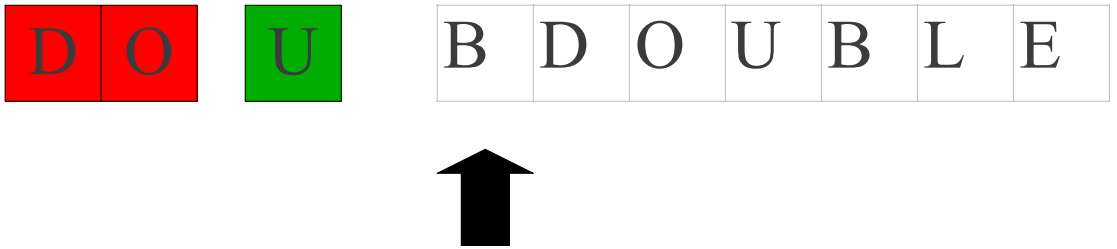




Implementing Maximal Munch

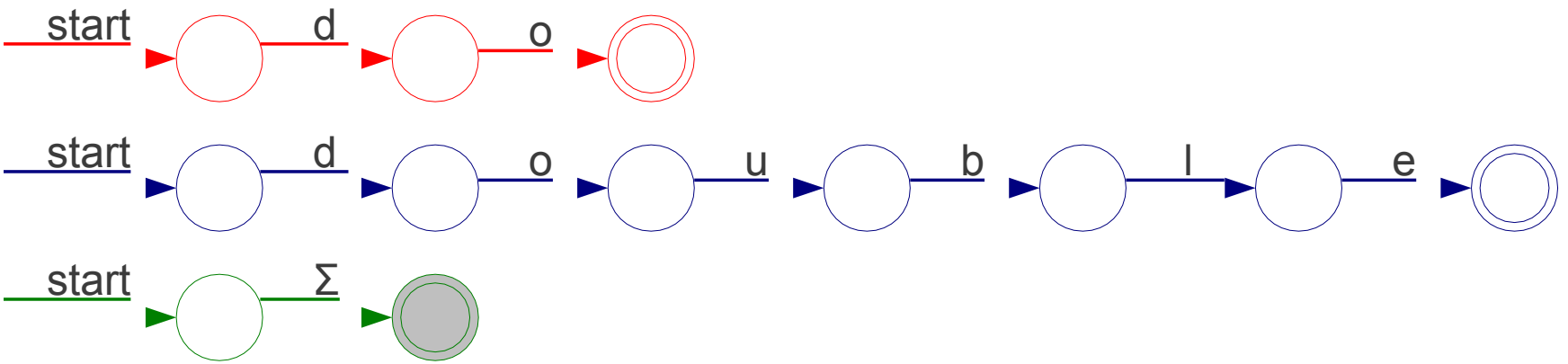
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

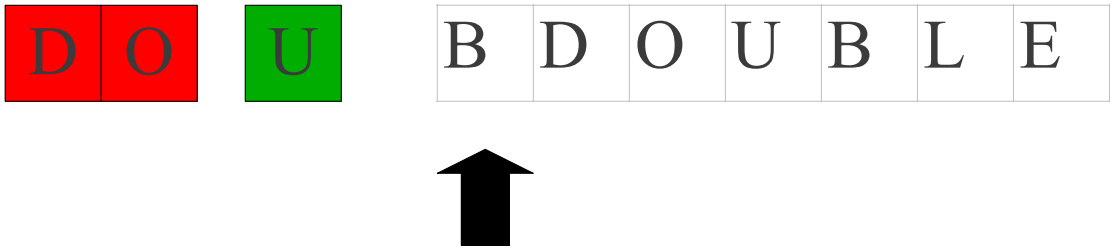




Implementing Maximal Munch

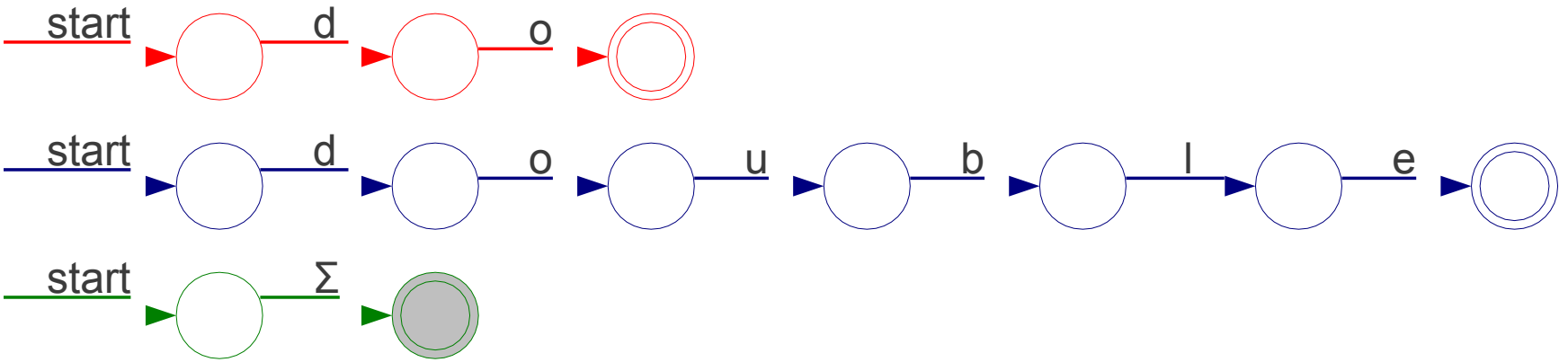
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

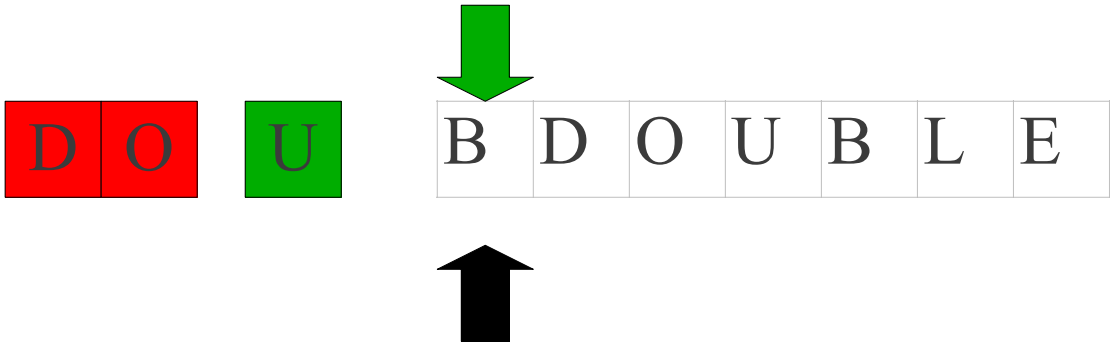




Implementing Maximal Munch

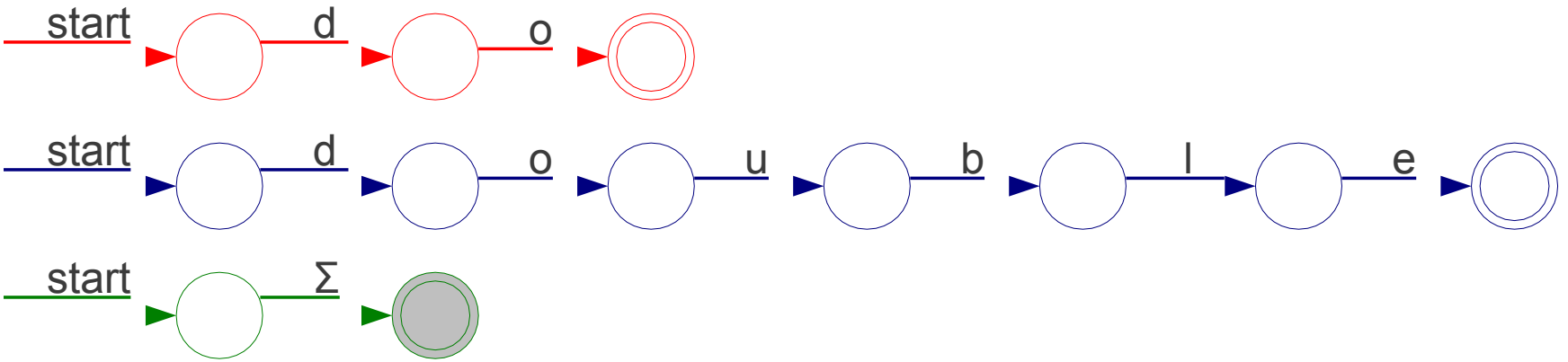
```
T_Do          do
T_Double      double
T_Mystery     [A-Za-z]
```

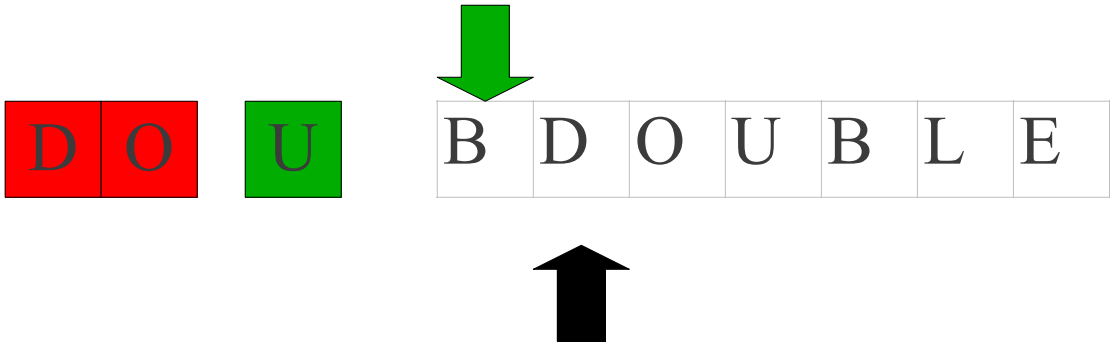




Implementing Maximal Munch

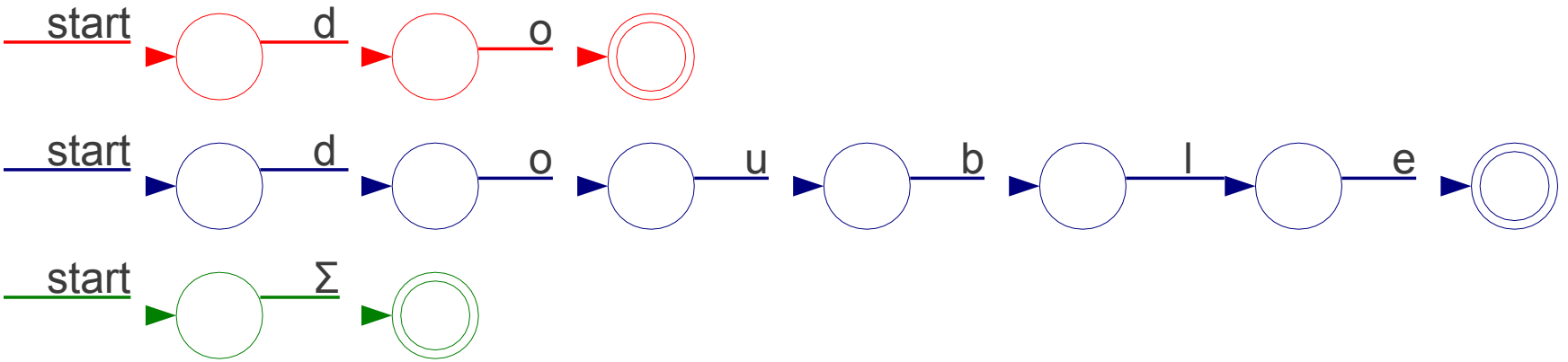
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

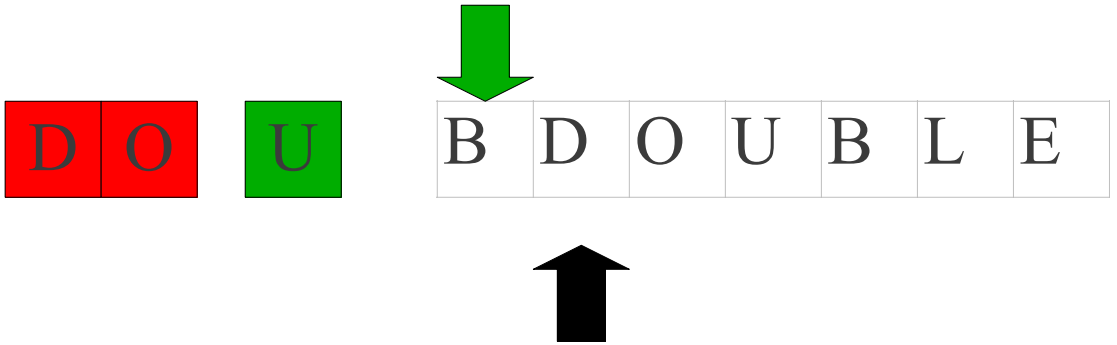




Implementing Maximal Munch

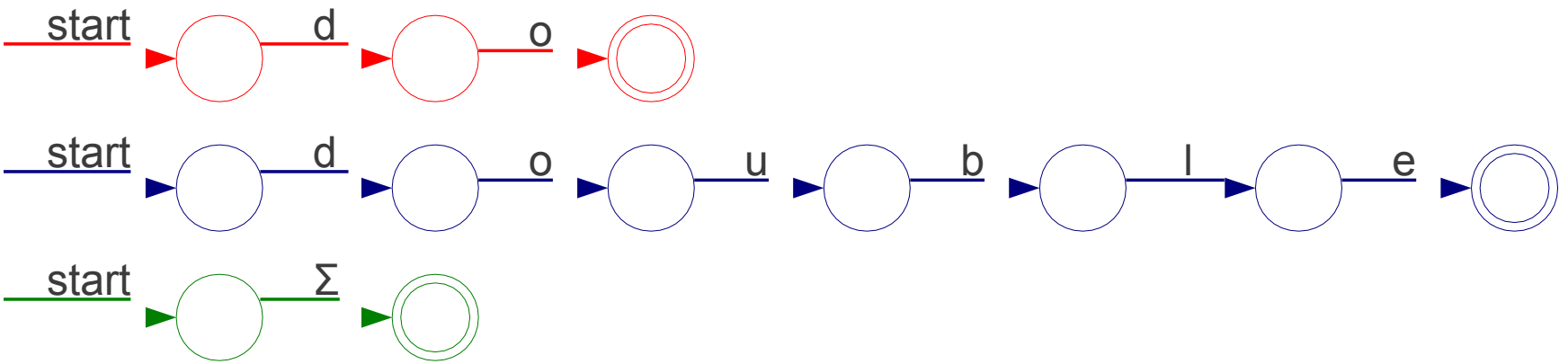
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

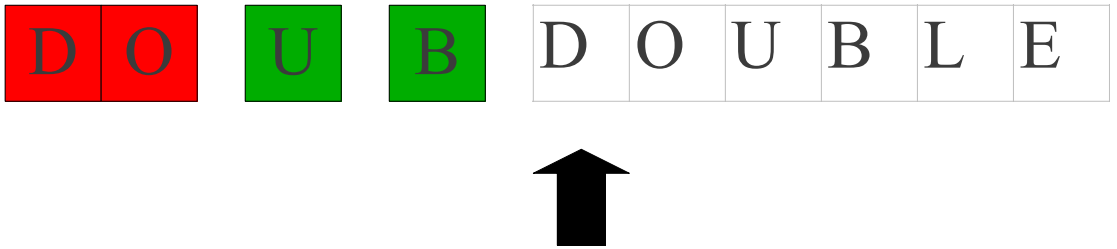




Implementing Maximal Munch

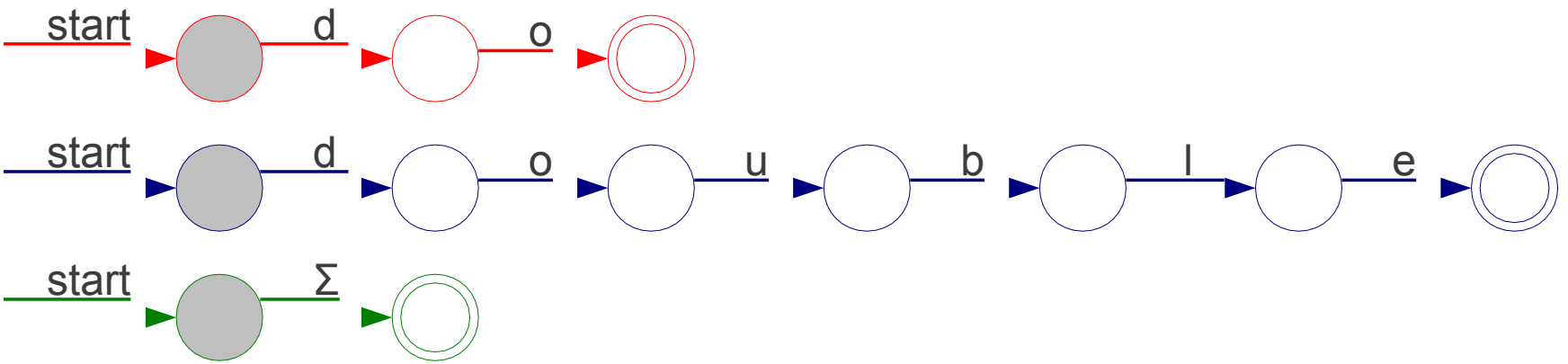
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

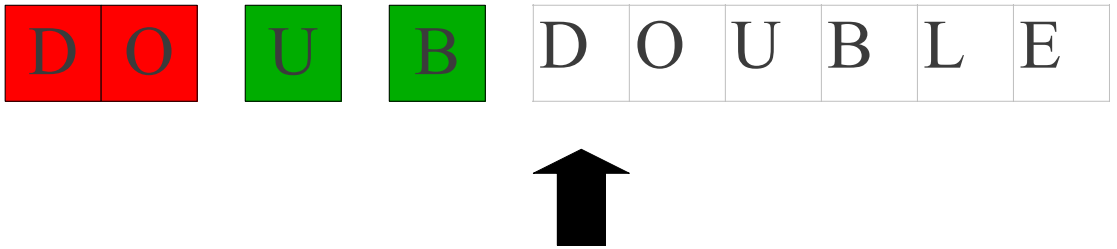




Implementing Maximal Munch

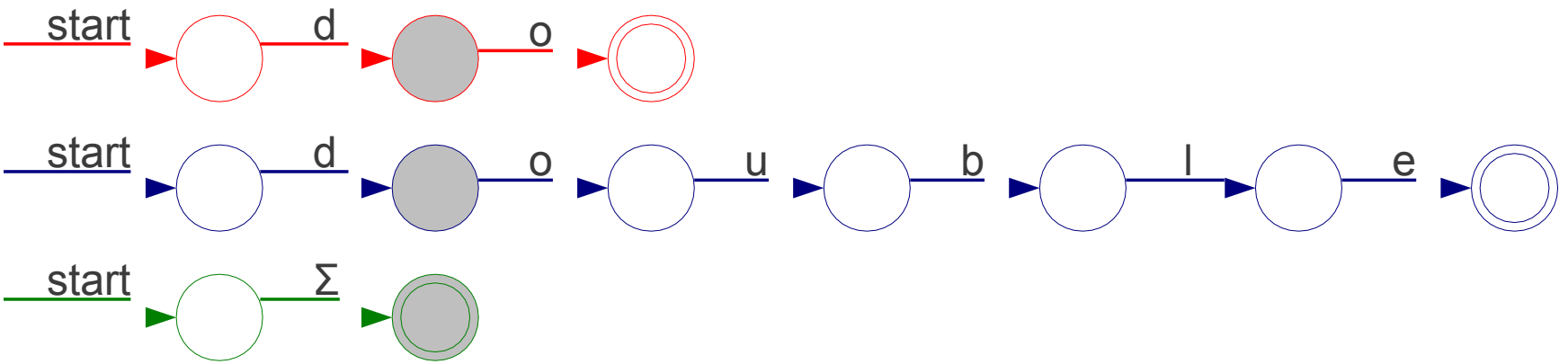
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

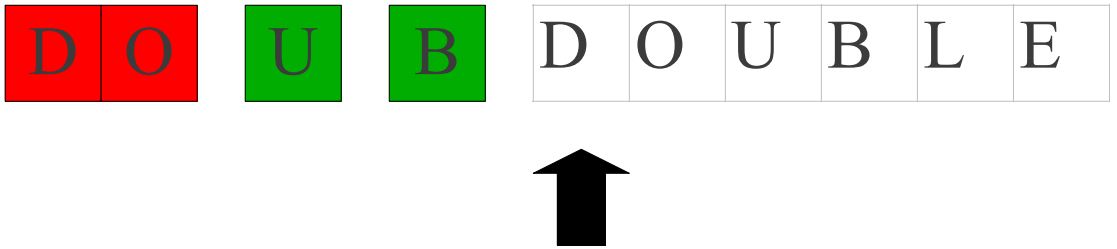




Implementing Maximal Munch

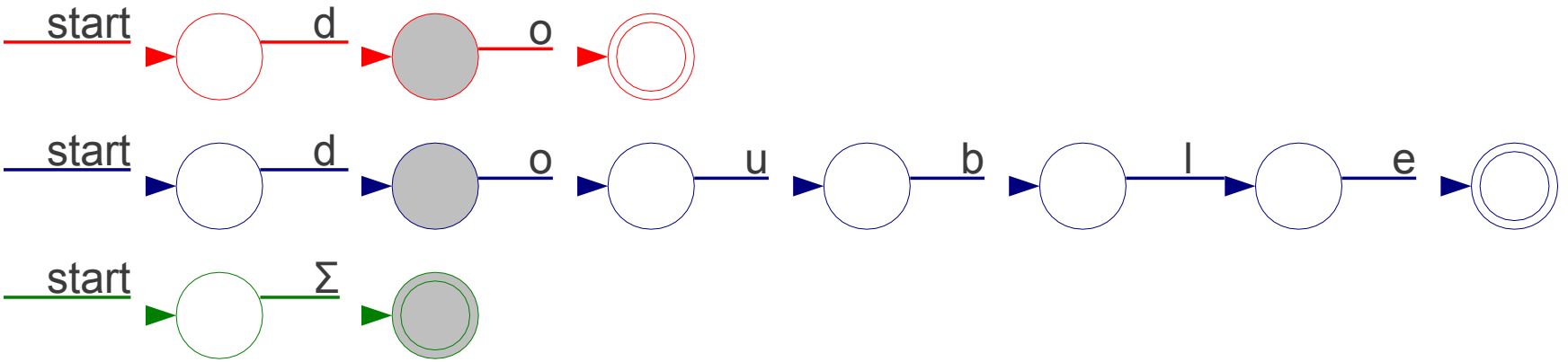
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

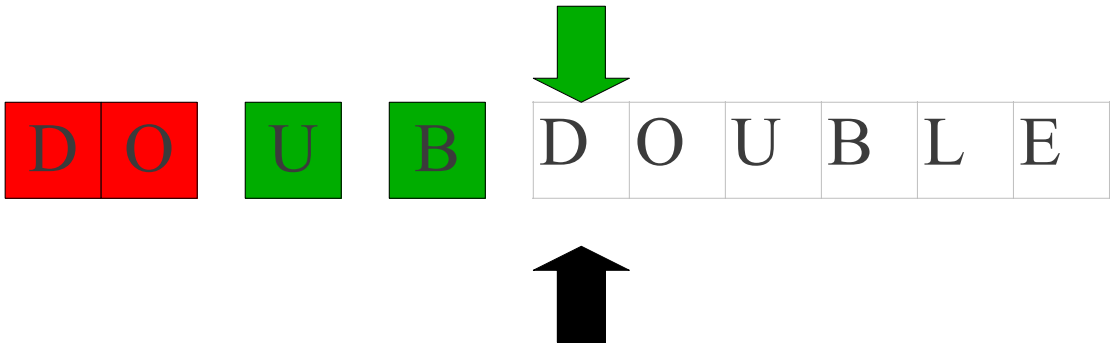




Implementing Maximal Munch

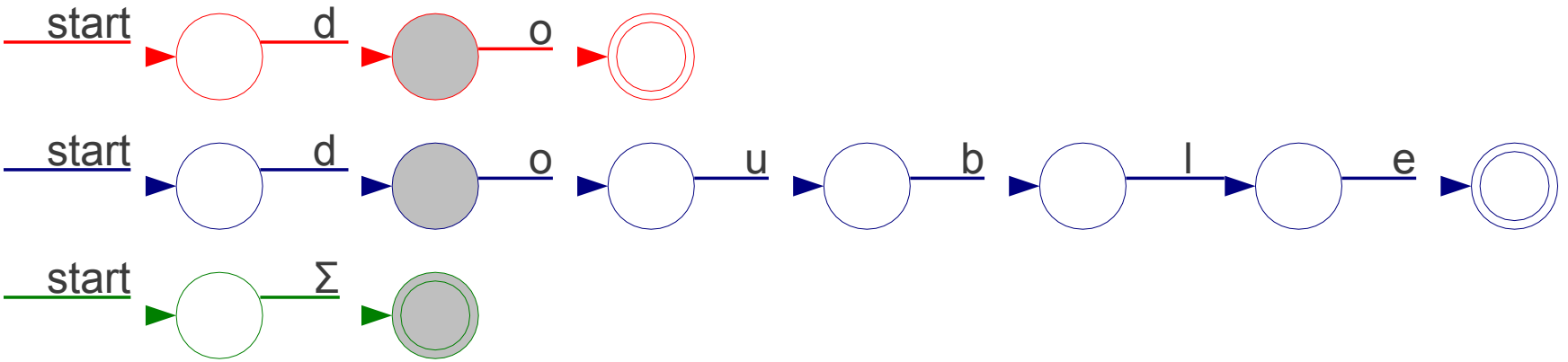
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

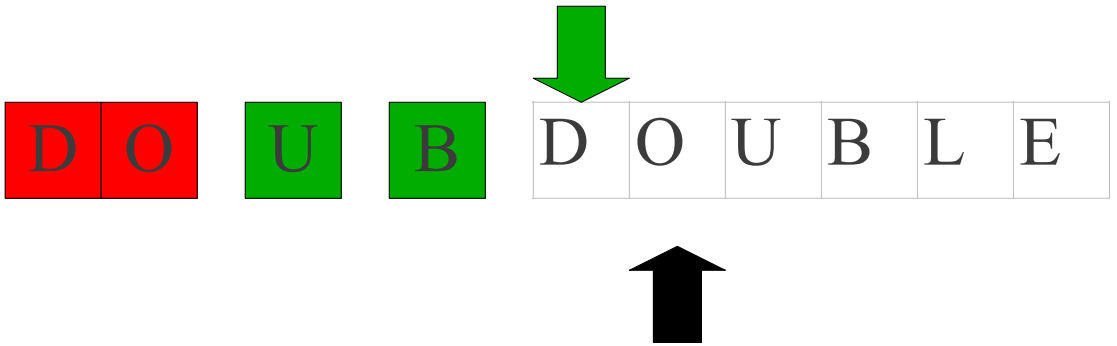




Implementing Maximal Munch

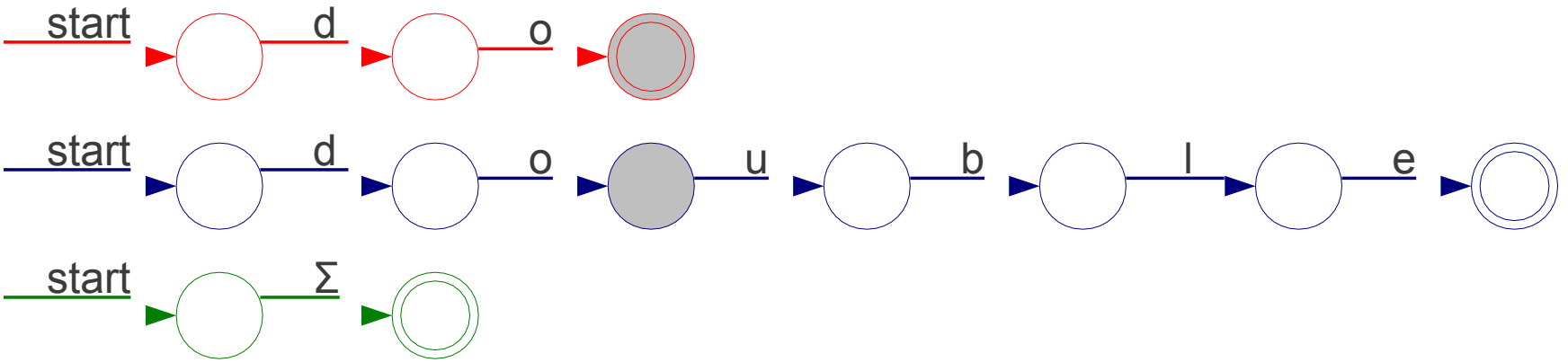
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

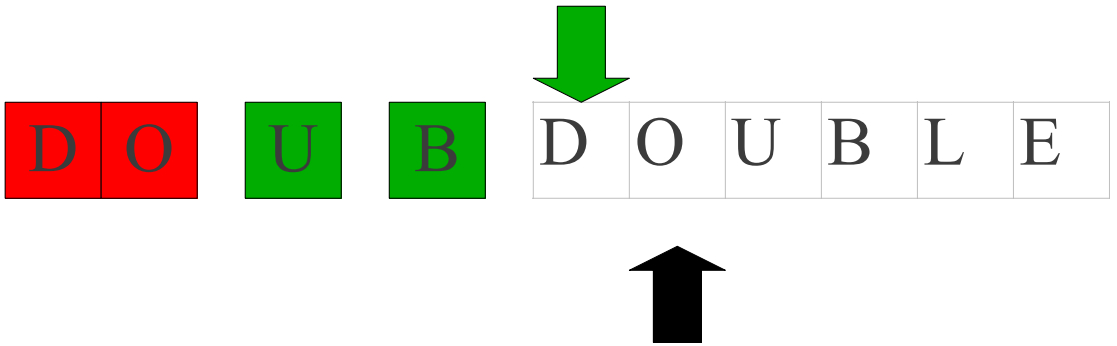




Implementing Maximal Munch

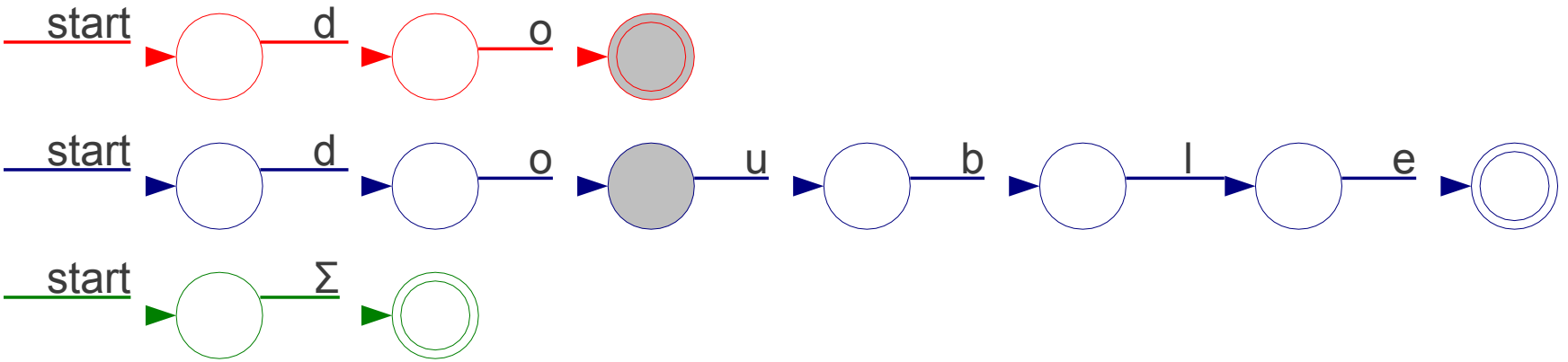
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

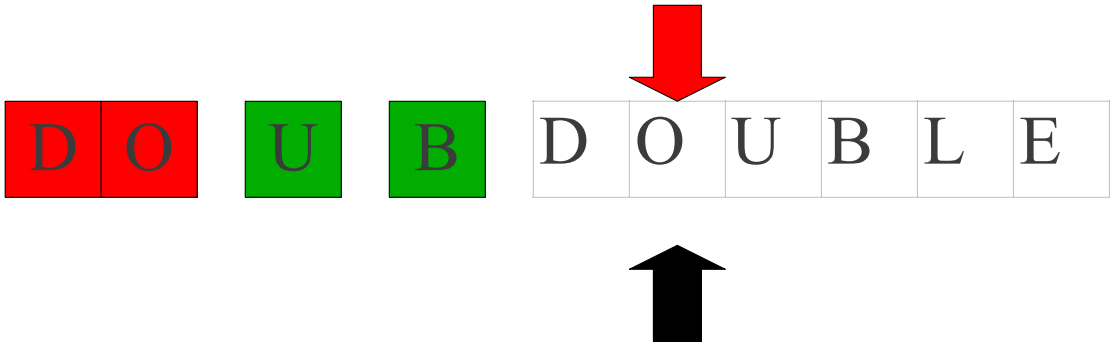




Implementing Maximal Munch

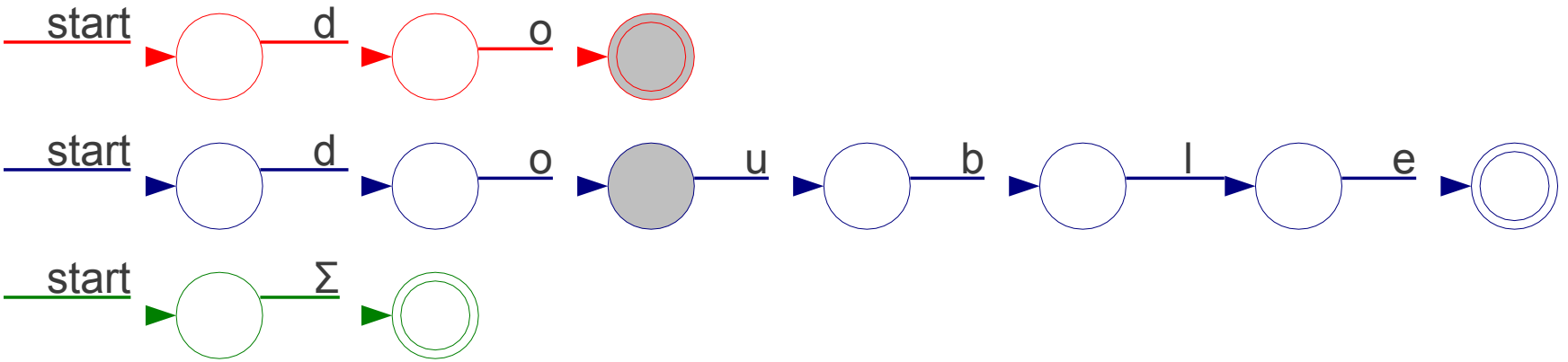
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

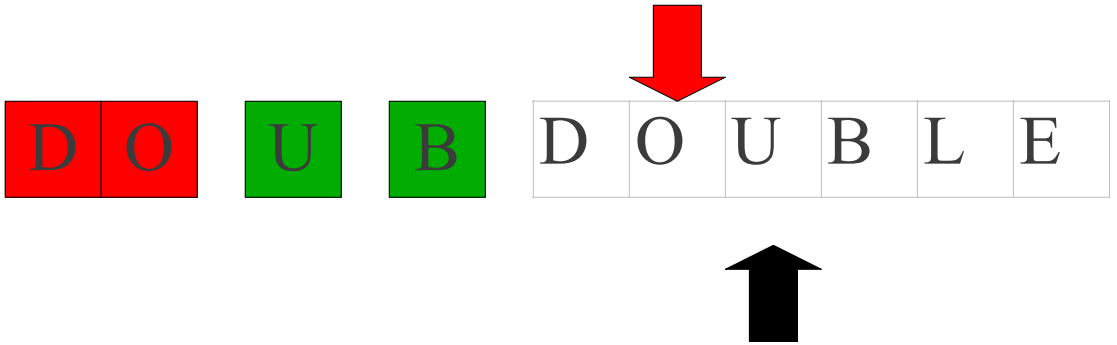




Implementing Maximal Munch

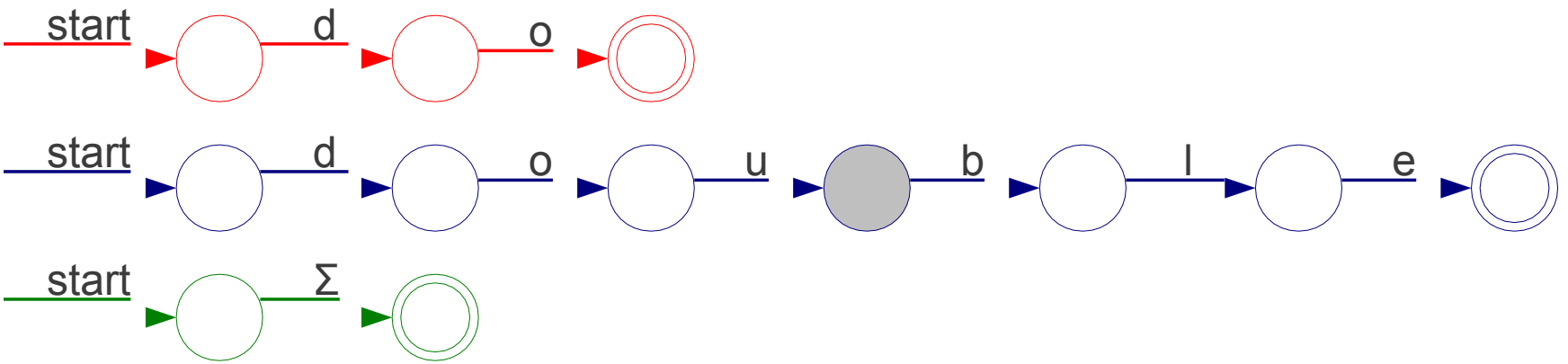
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

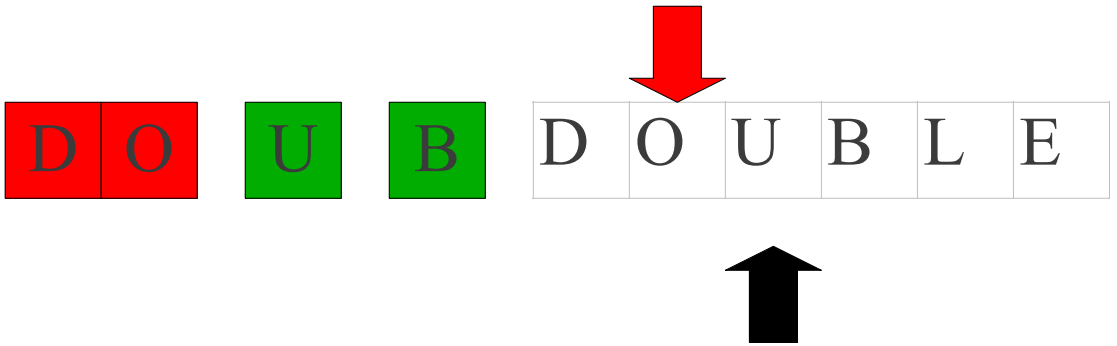




Implementing Maximal Munch

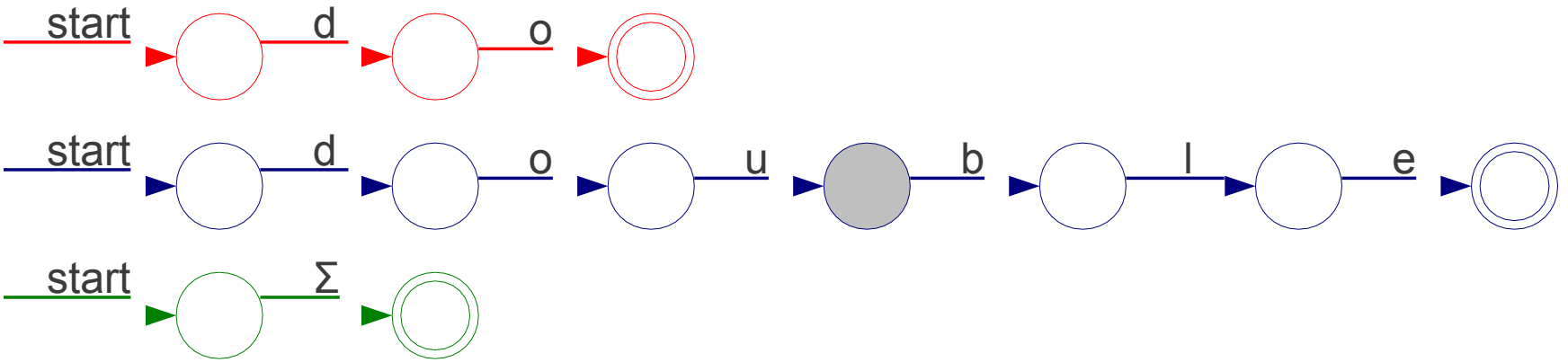
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

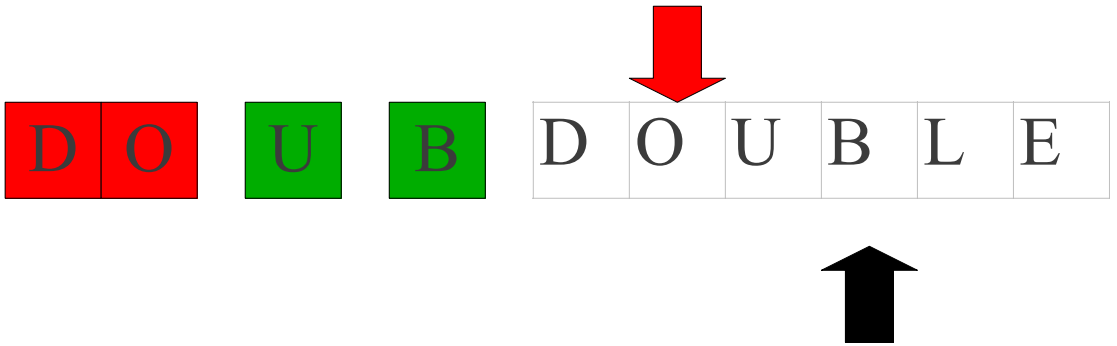




Implementing Maximal Munch

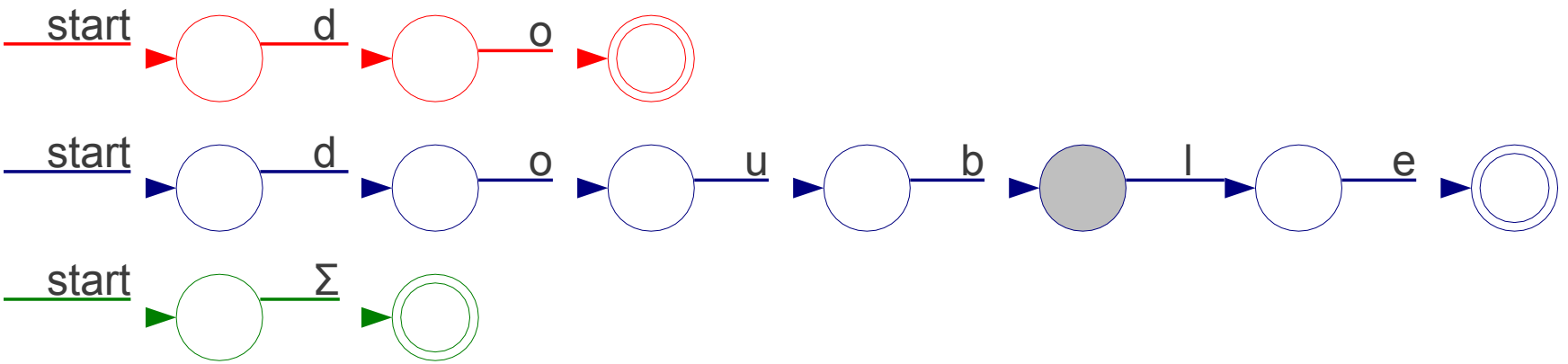
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

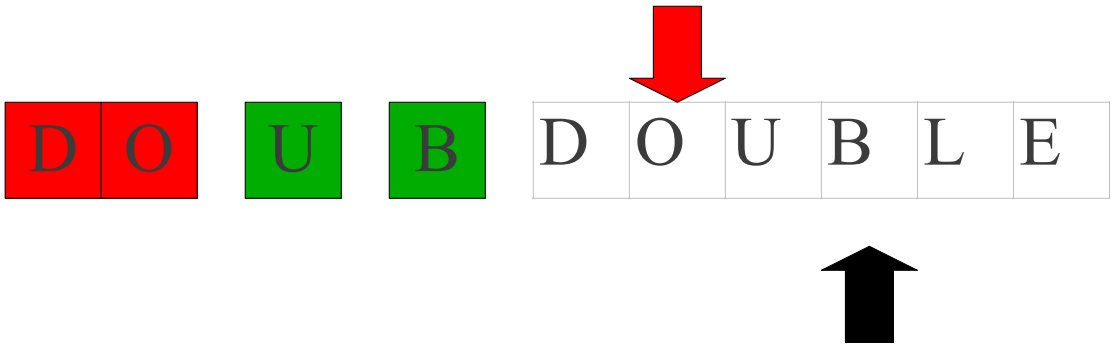




Implementing Maximal Munch

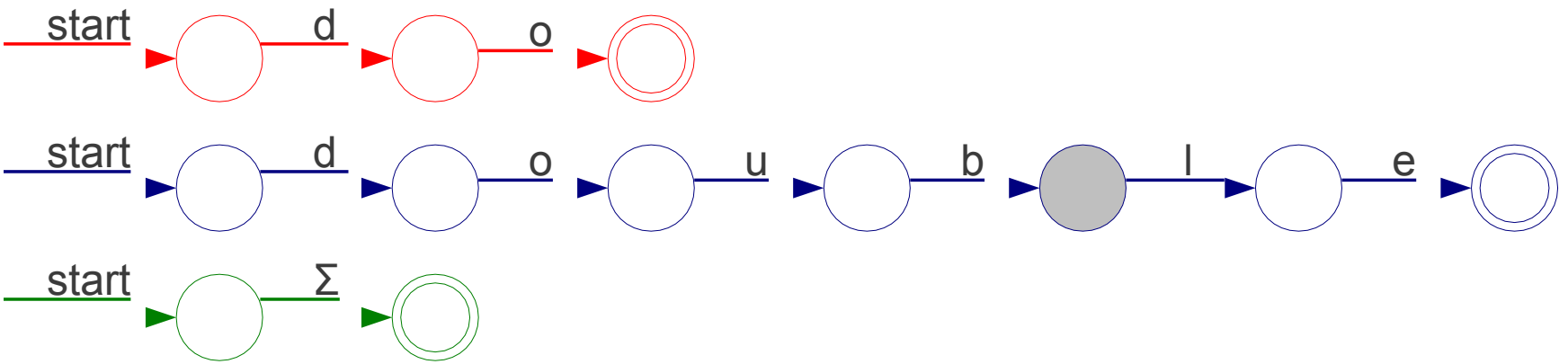
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

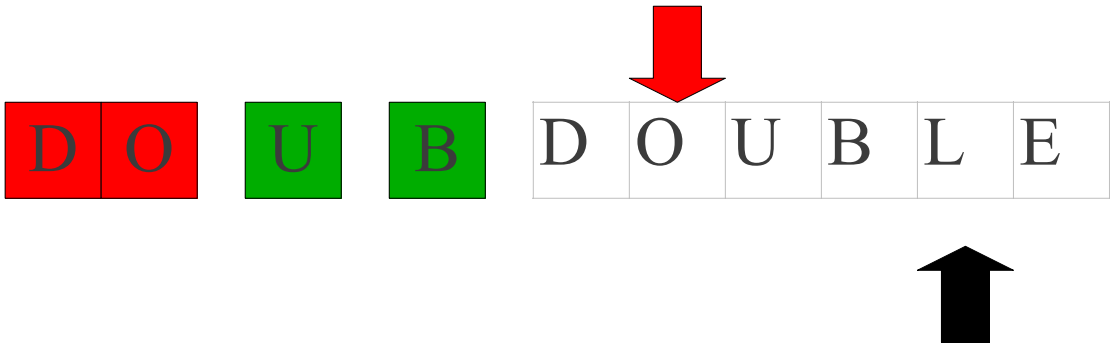




Implementing Maximal Munch

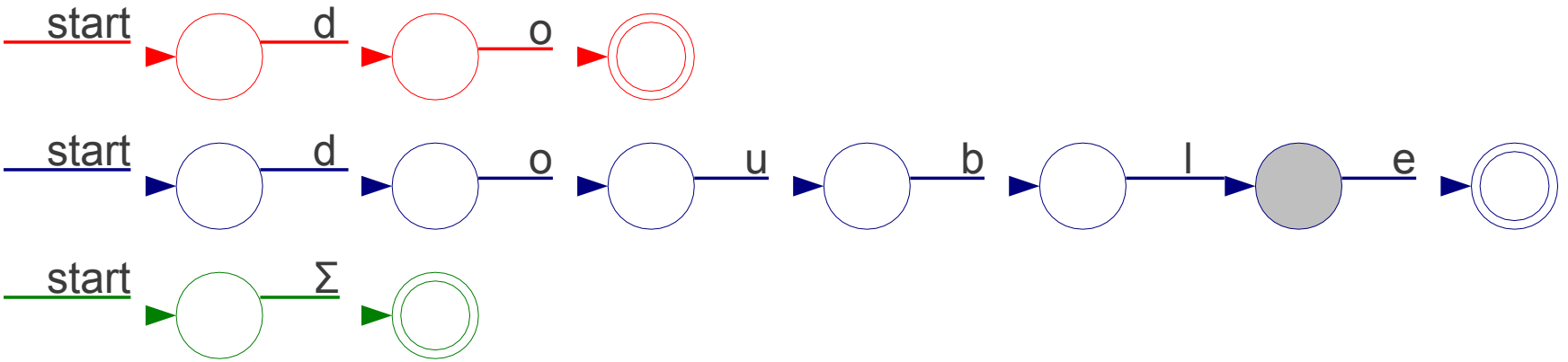
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

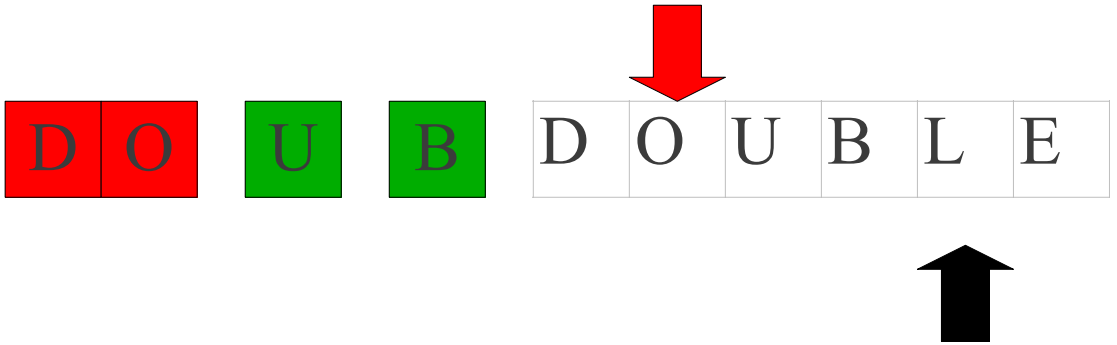




Implementing Maximal Munch

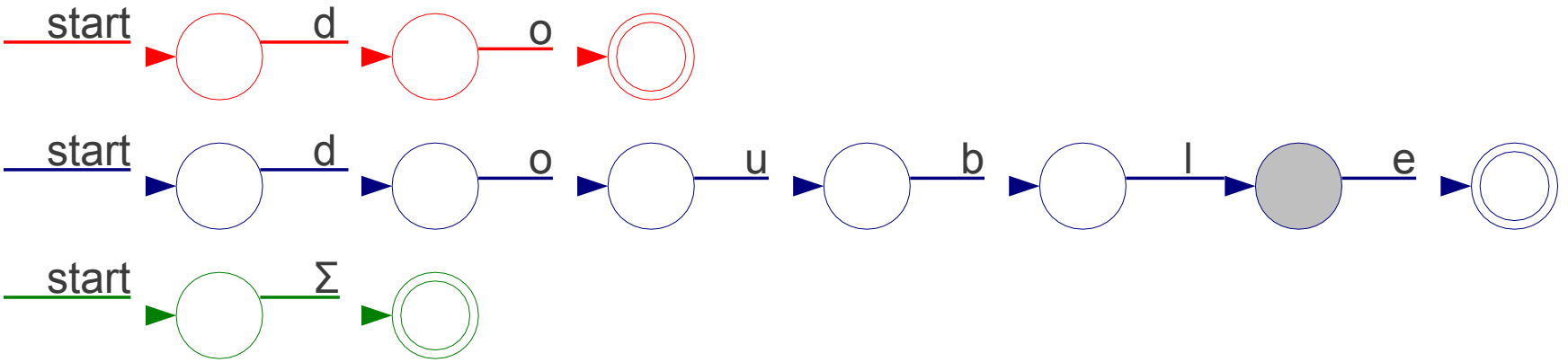
```
T_Do            do
T_Double        double
T_Mystery       [A-Za-z]
```

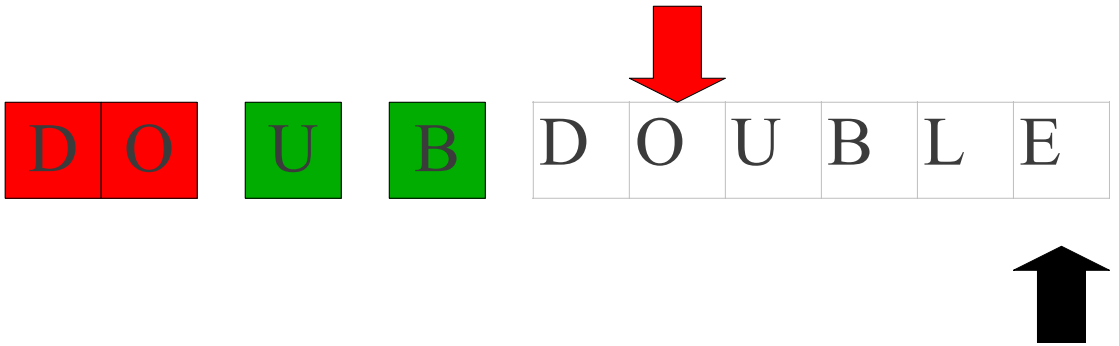




Implementing Maximal Munch

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





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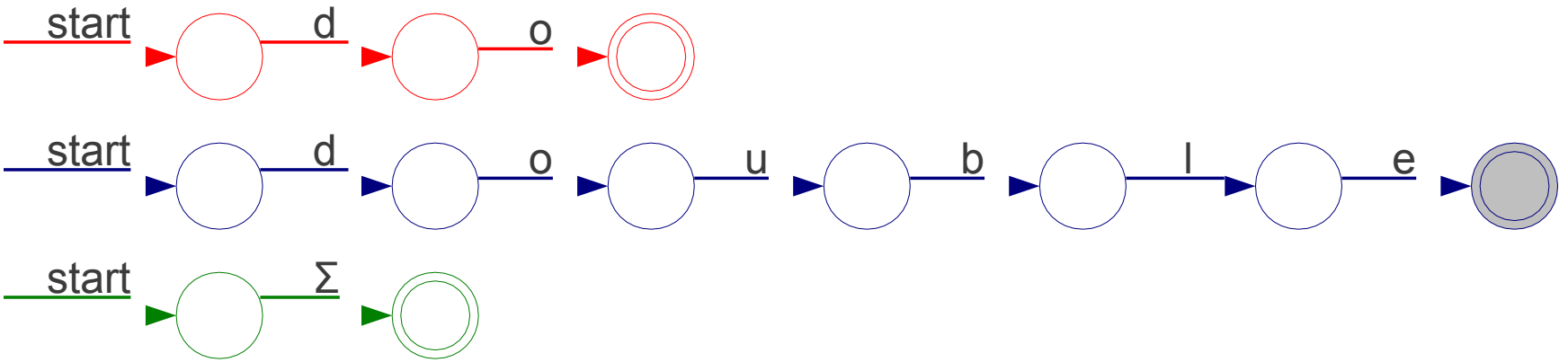

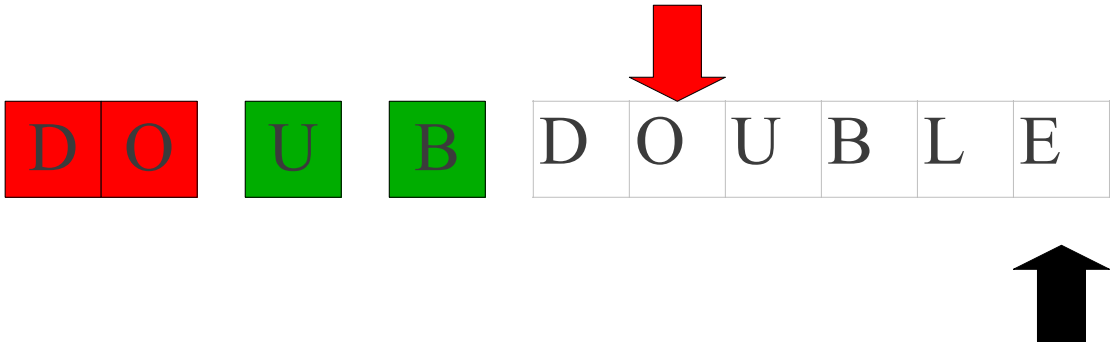

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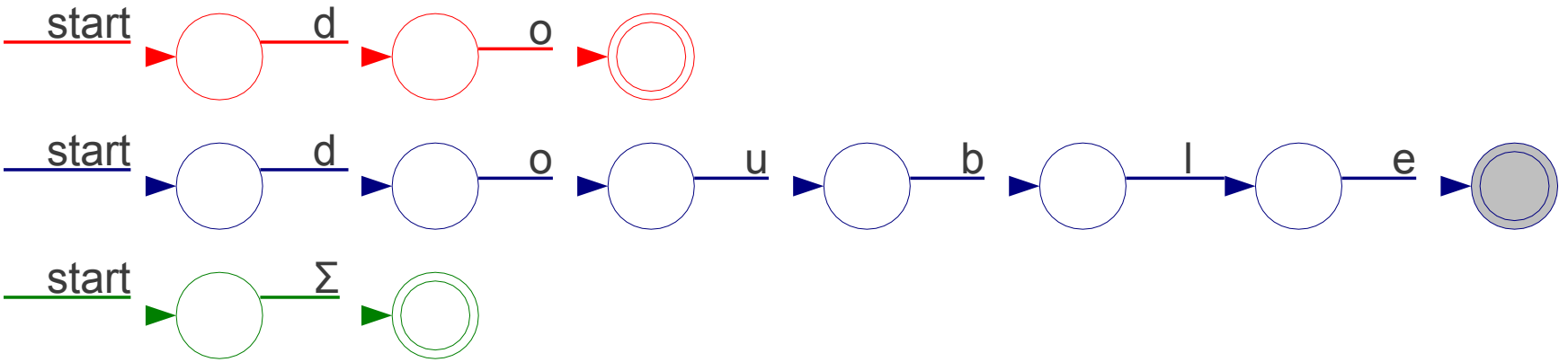

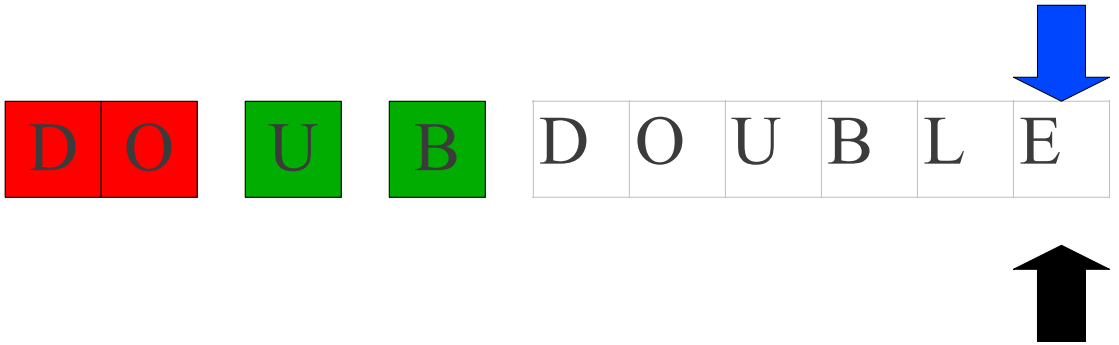

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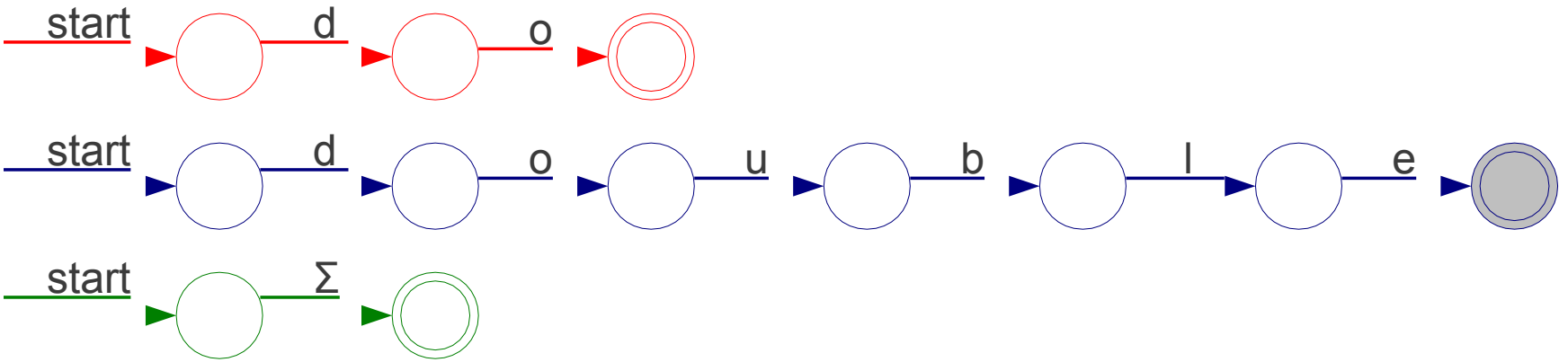

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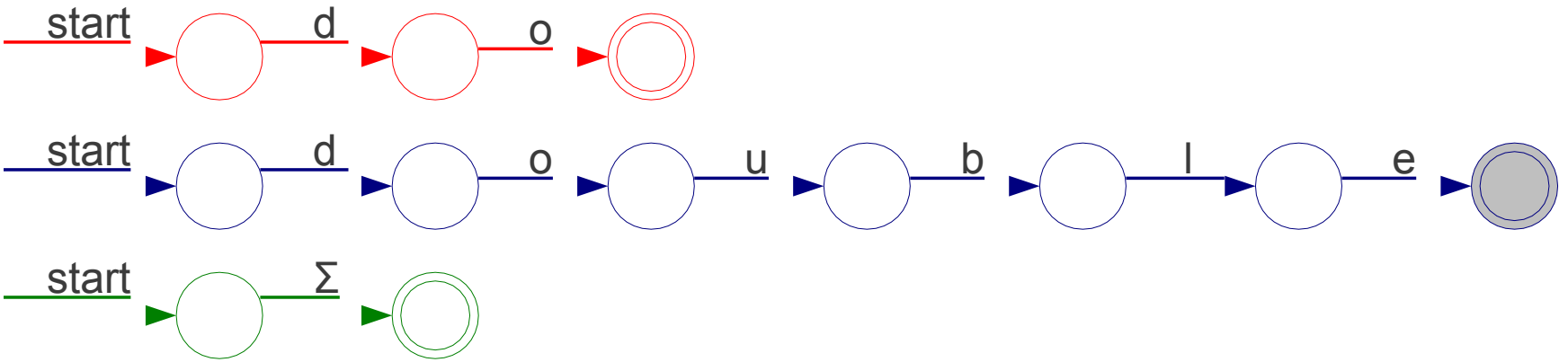

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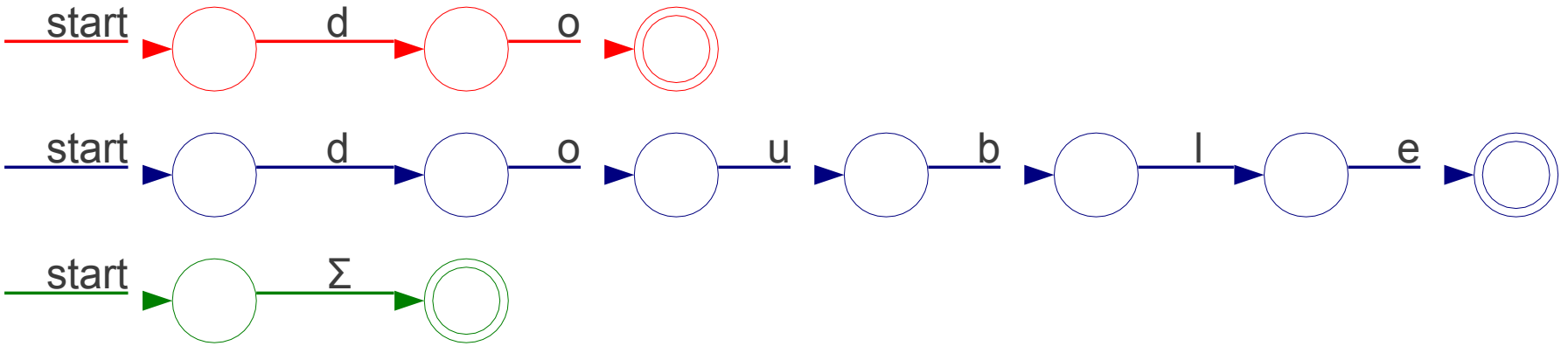

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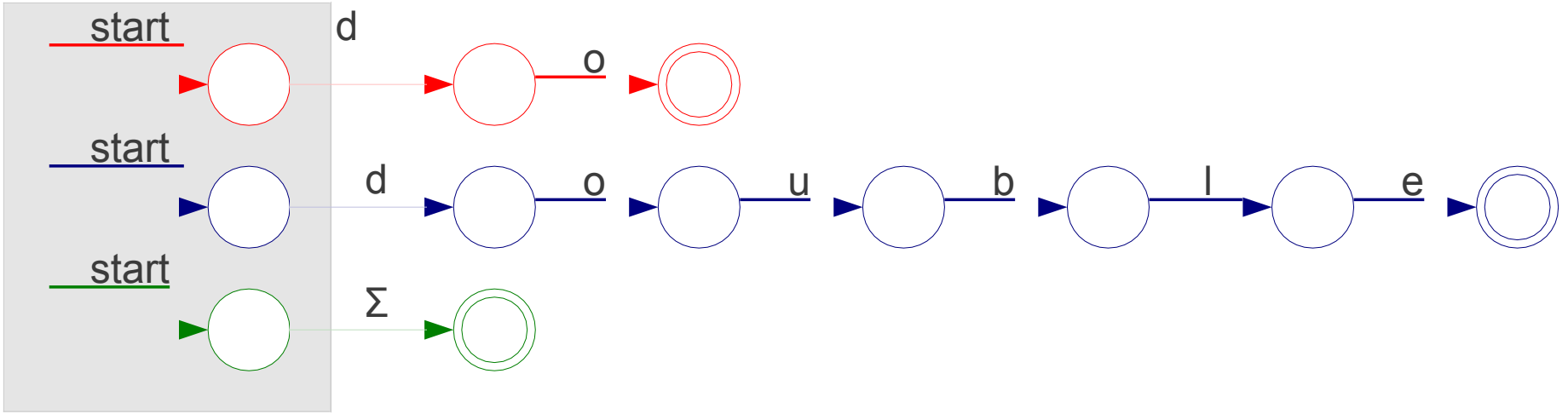

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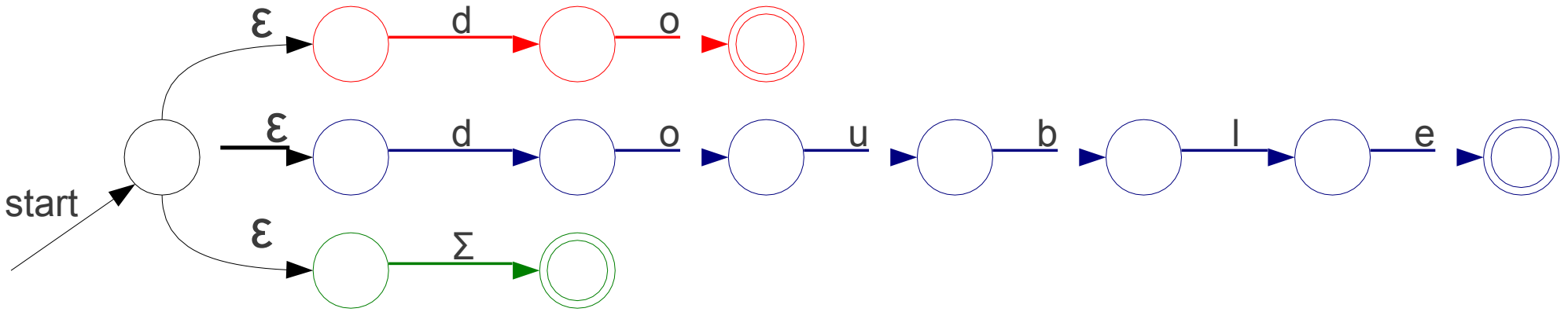
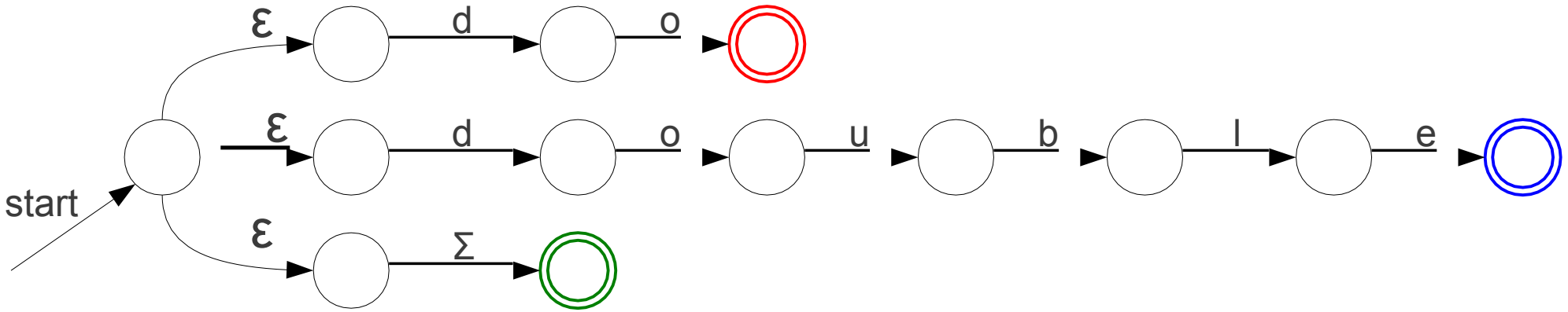


Build a single automaton that runs all the matching automata in parallel.

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_]*
```

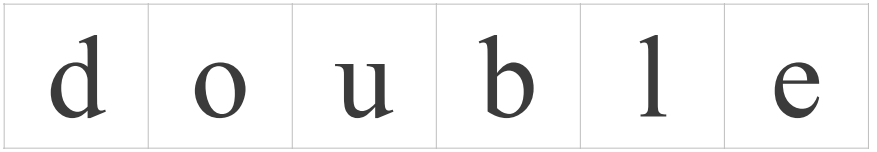
Other Conflicts

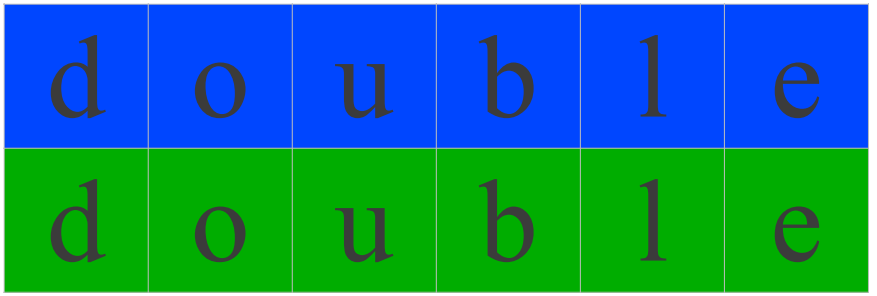
```
T_Do           do
T_Double       double
T_Identifier [A-Za-z_][A-Za-z0-9_]*
```

d	o	u	b	l	e

Other Conflicts

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



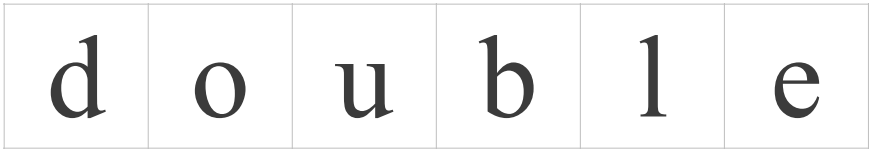


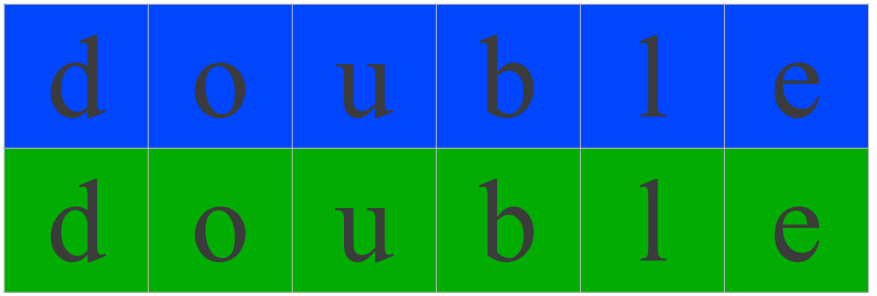
More Tiebreaking

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

Other Conflicts

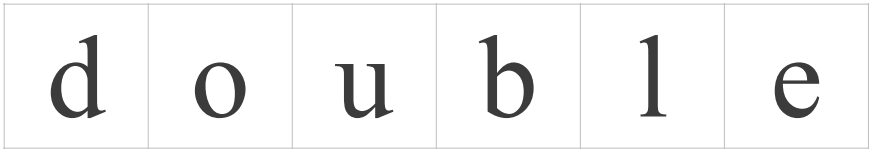
```
T_Do            do
T_Double        double
T_Identifier    [A-Za-z_][A-Za-z0-9_]*
```

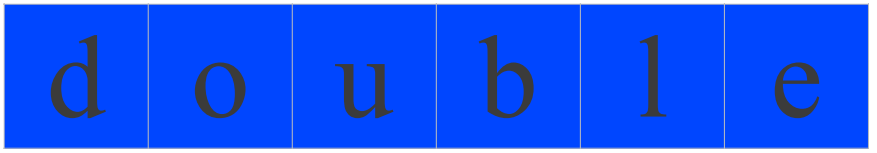




Other Conflicts

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





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

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- 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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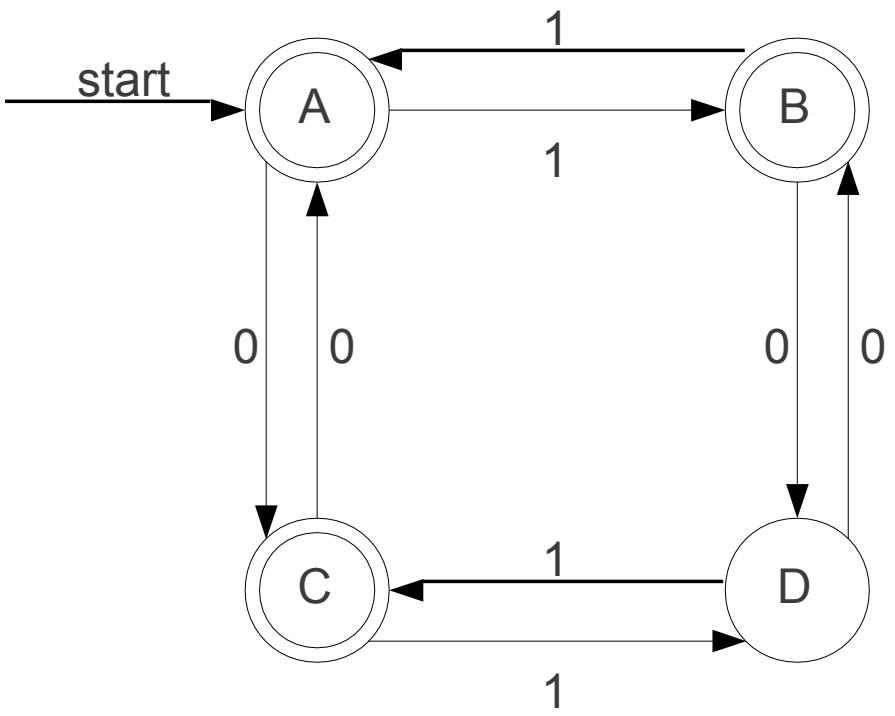
DFAs

- 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



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

Speeding up Matching

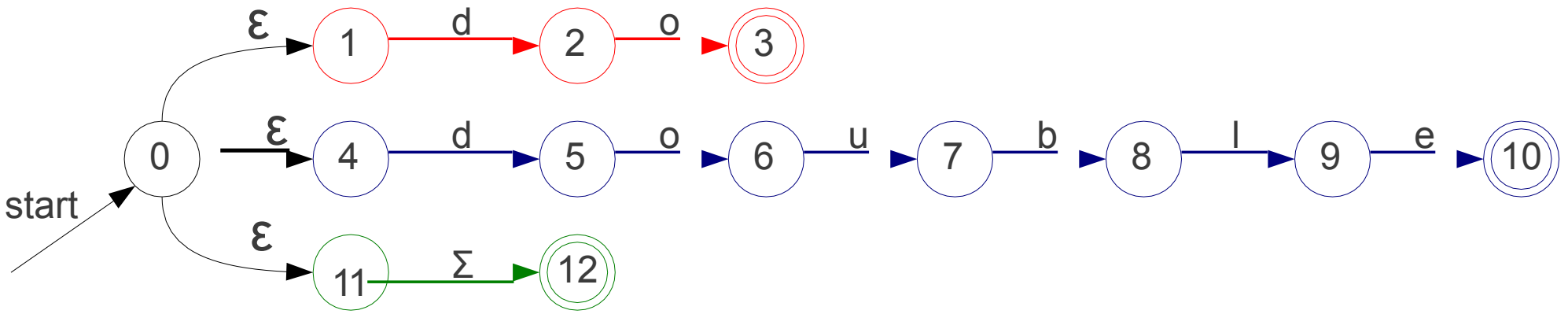
- In the worst-case, an NFA with n states takes time $O(mn^2)$ to match a string of length m.
- DFAs, on the other hand, take only $O(m)$.
- There is another (beautiful!) algorithm to convert NFAs to DFAs.

Subset Construction

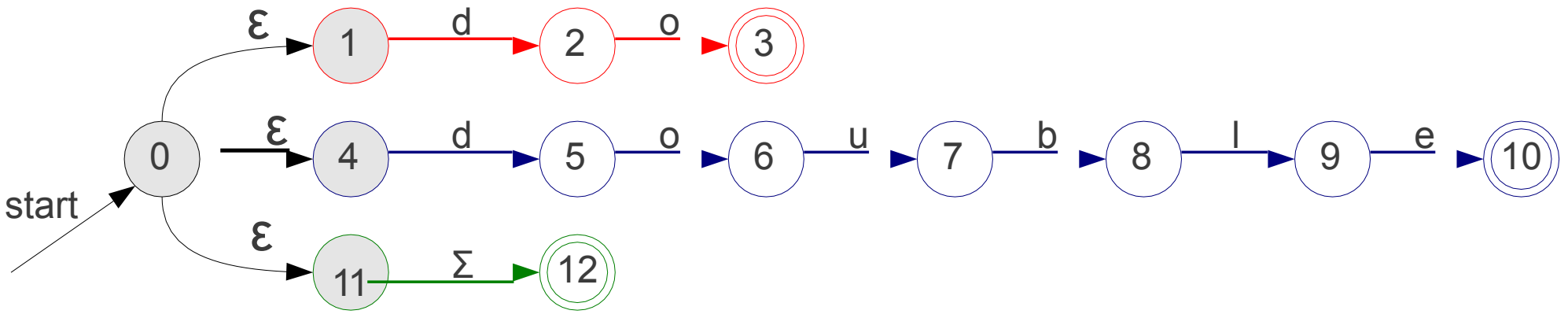
- NFAs can be in many states at once, while DFAs can only be in a single state at a time.
- Key idea: **Make the DFA simulate the NFA**.
- Have the states of the DFA correspond to the *sets of states* of the NFA.
- Transitions between states of DFA correspond to transitions between *sets of states* in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

From NFA to DFA

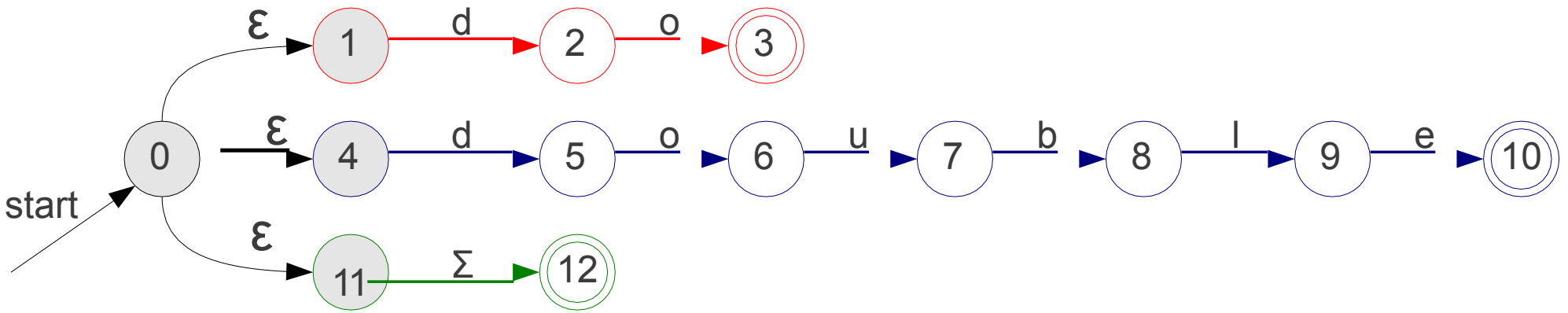
From NFA to DFA

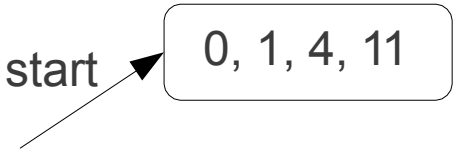


From NFA to DFA



From NFA to DFA





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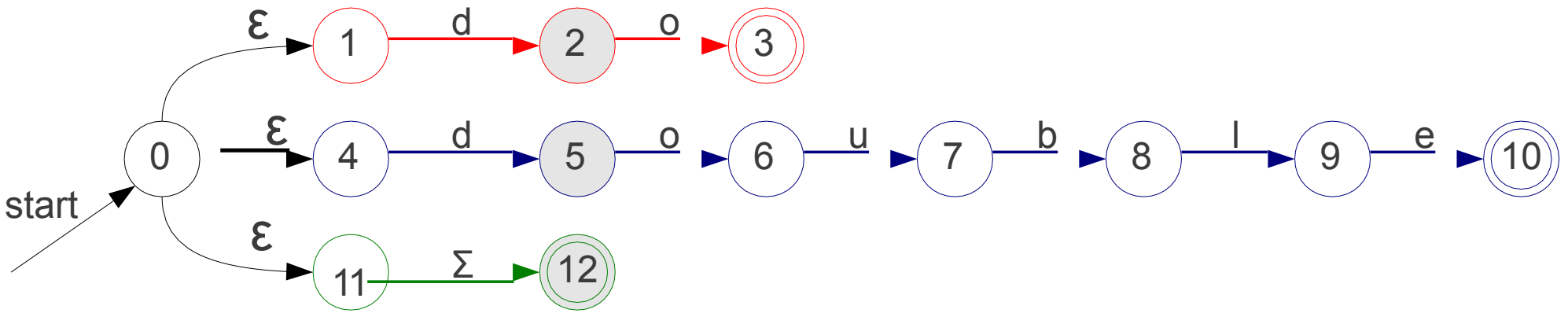

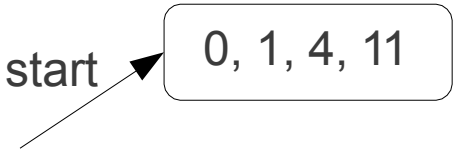

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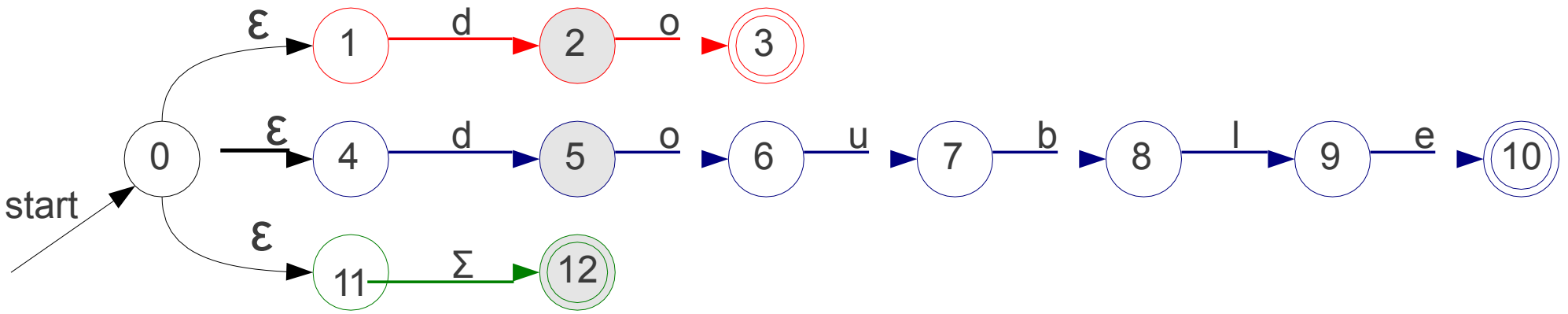

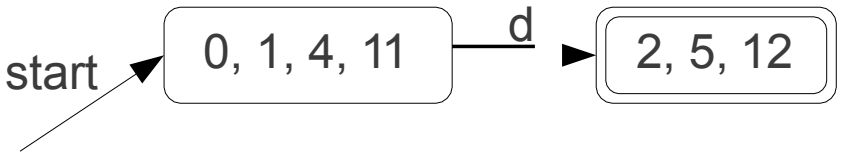

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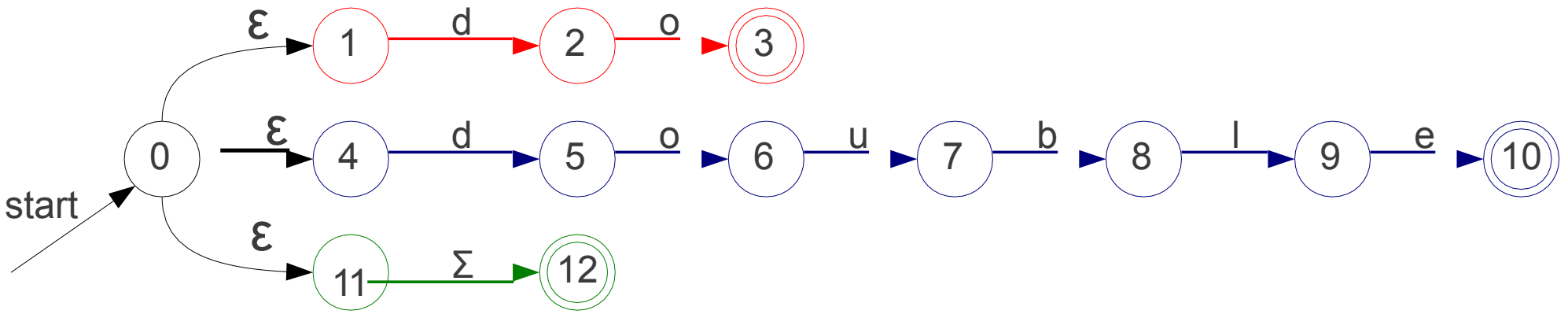

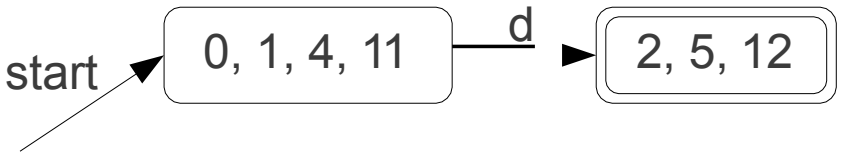

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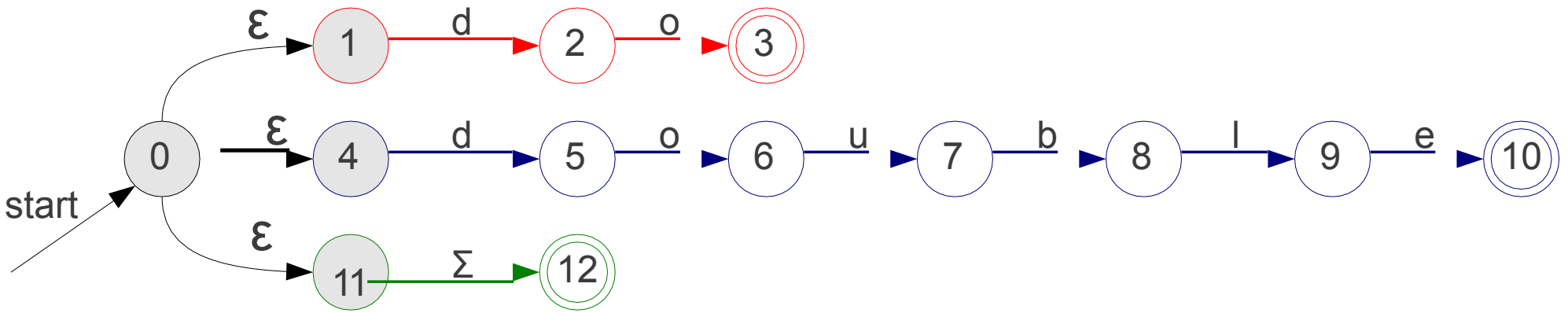

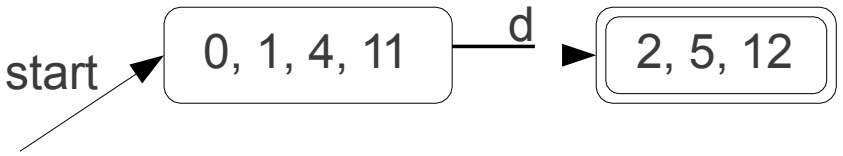

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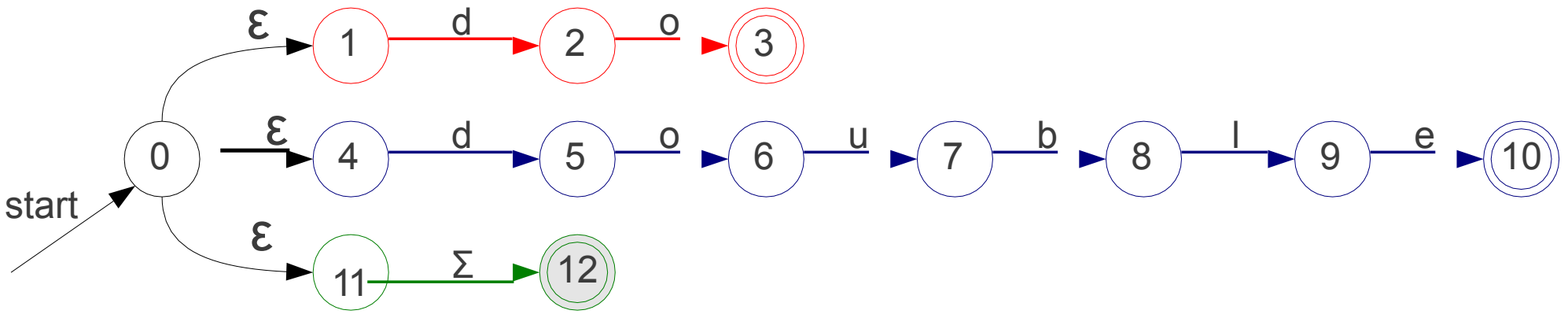

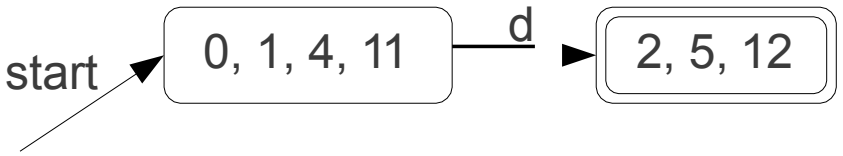

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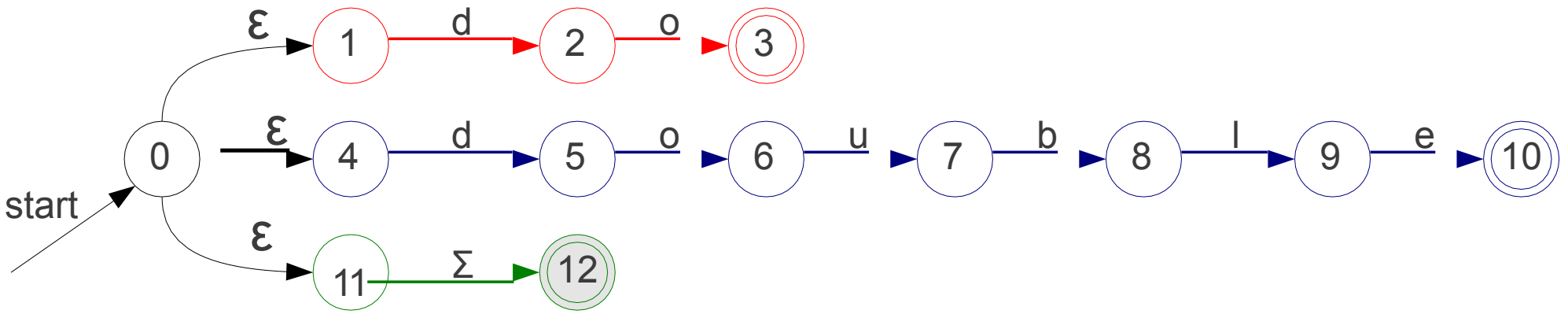

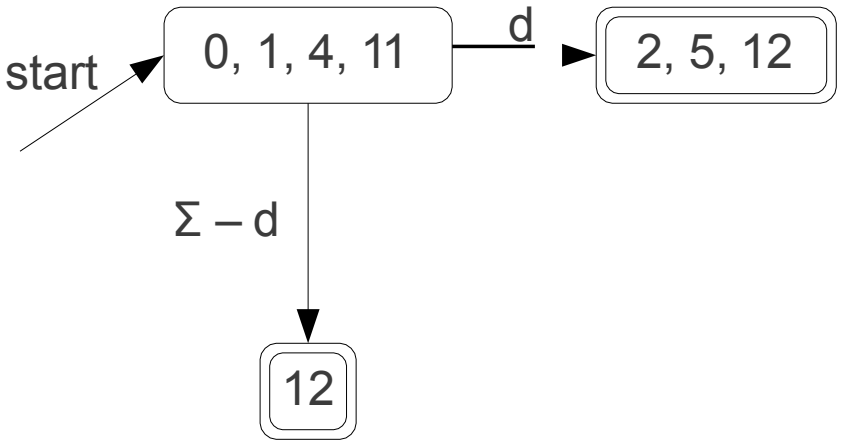

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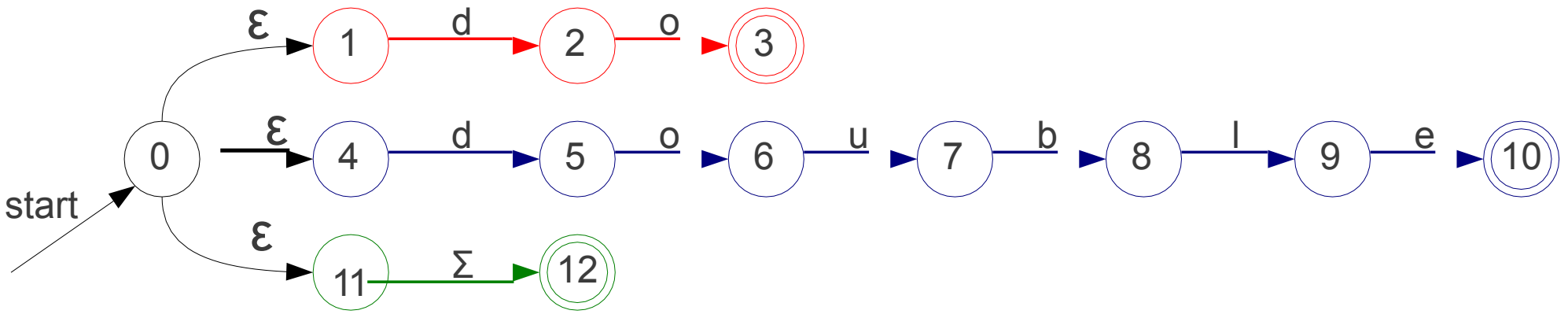

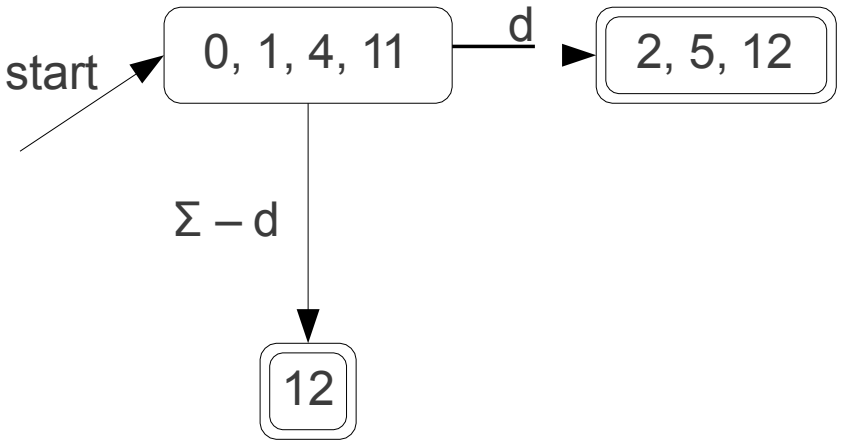

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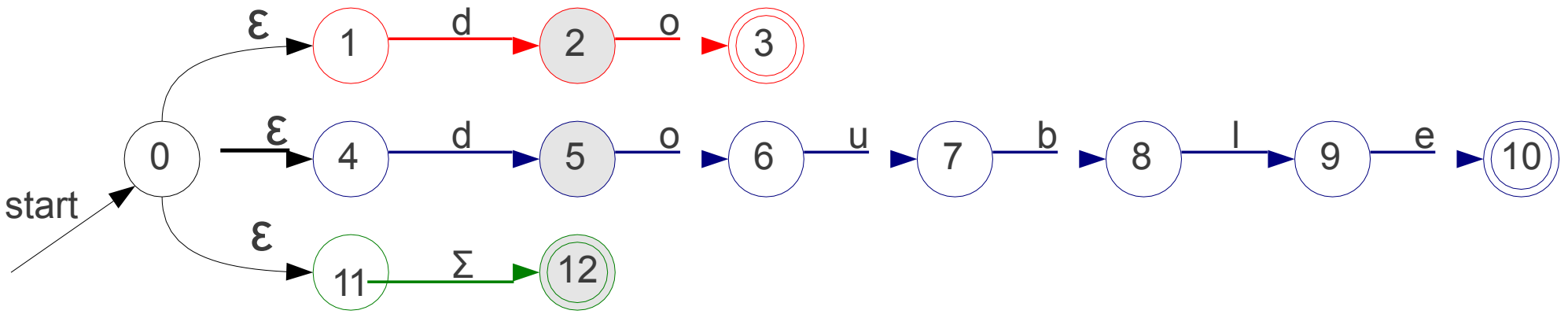

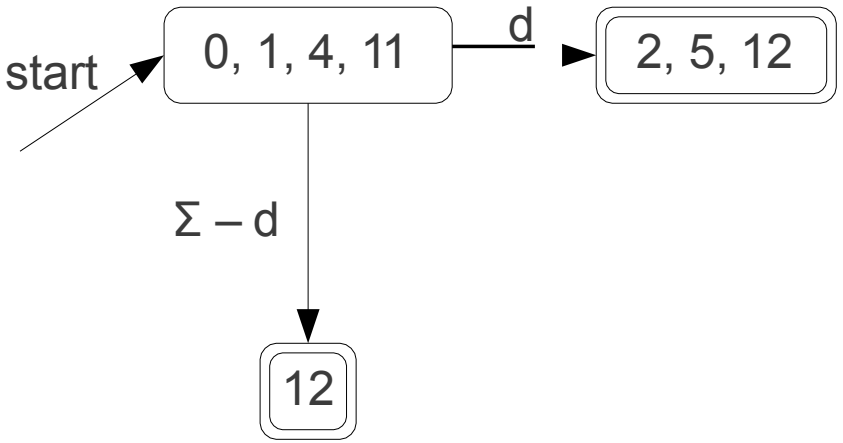

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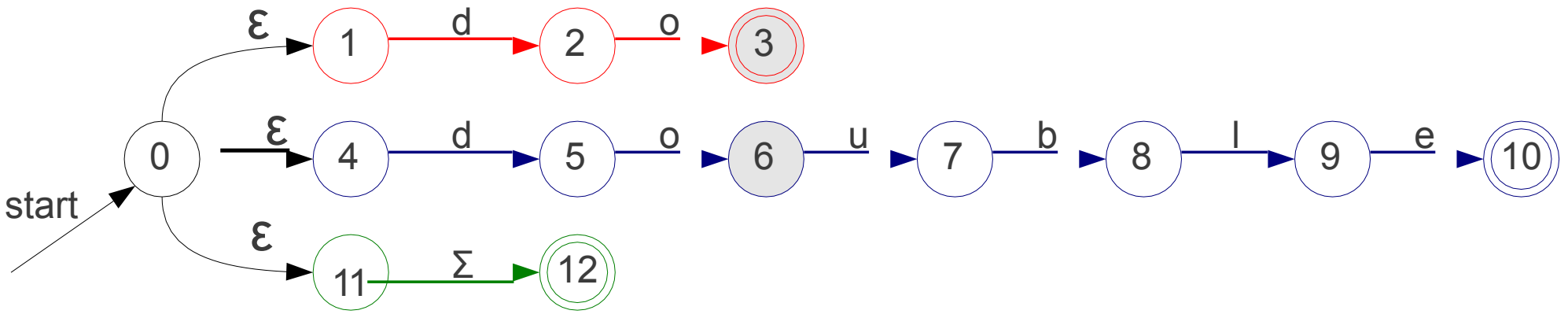

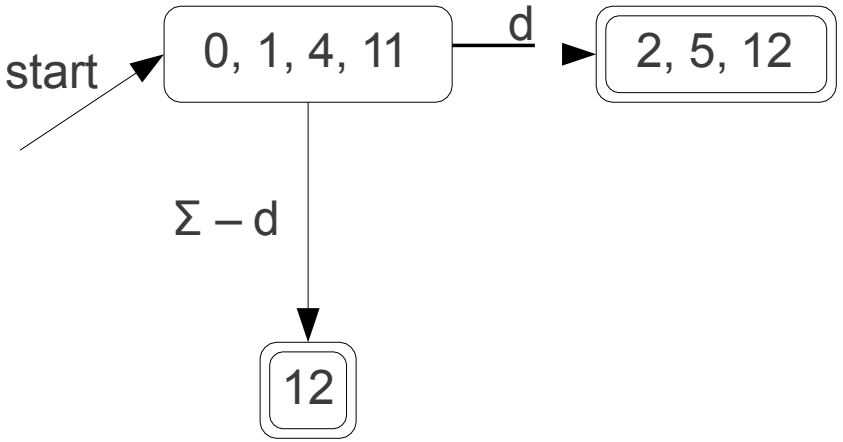

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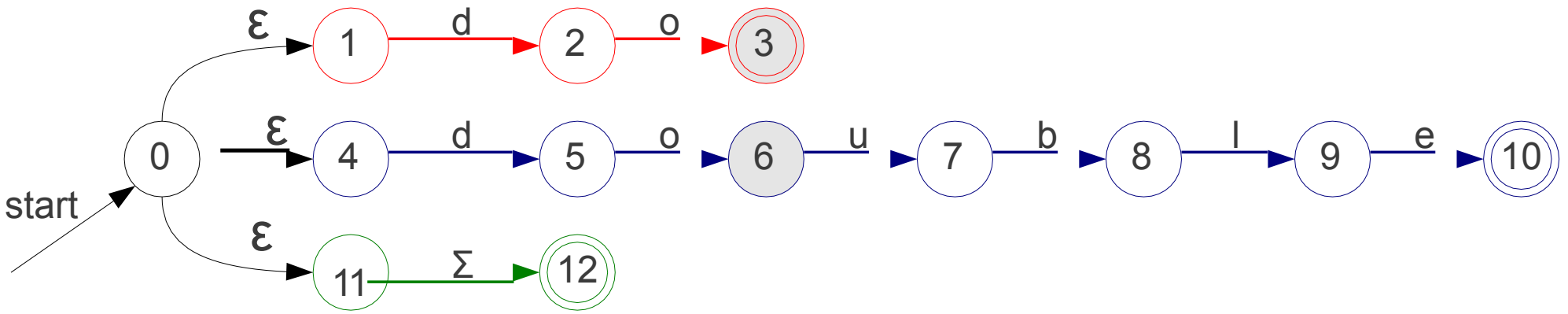

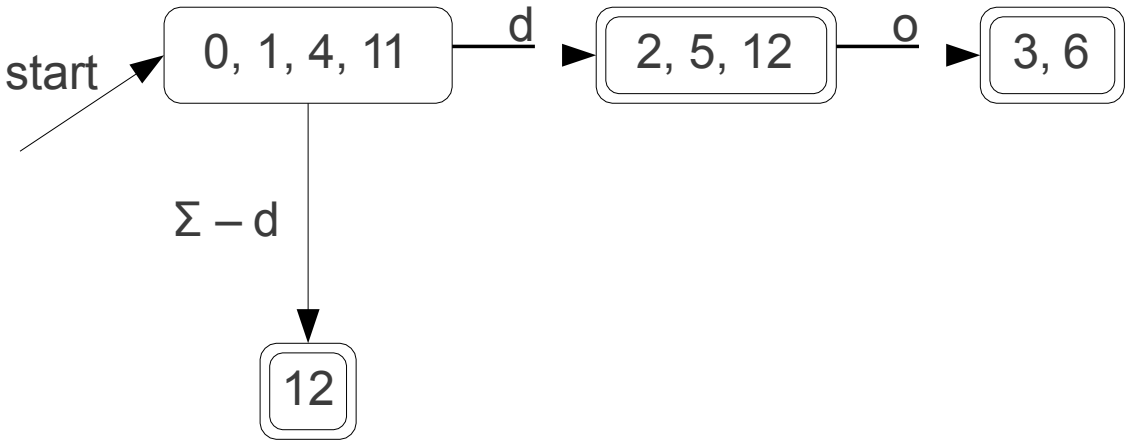

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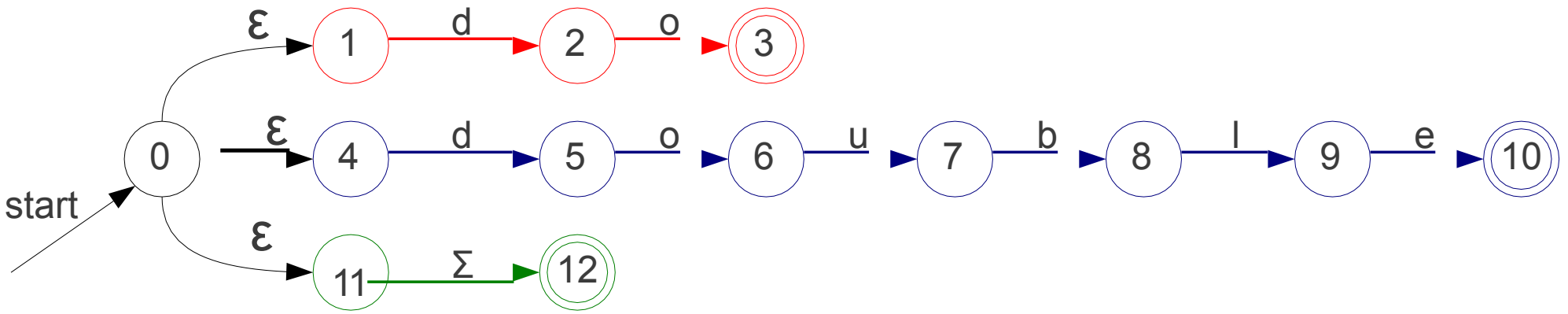

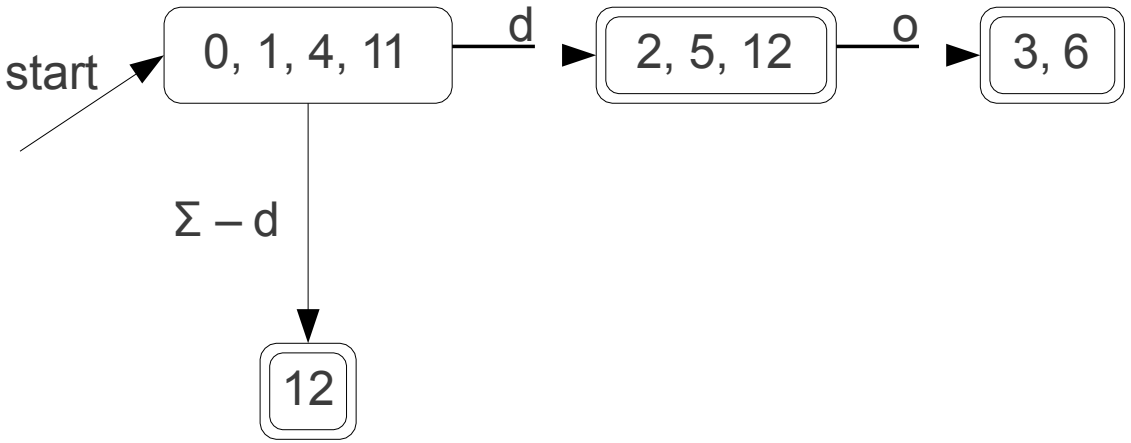

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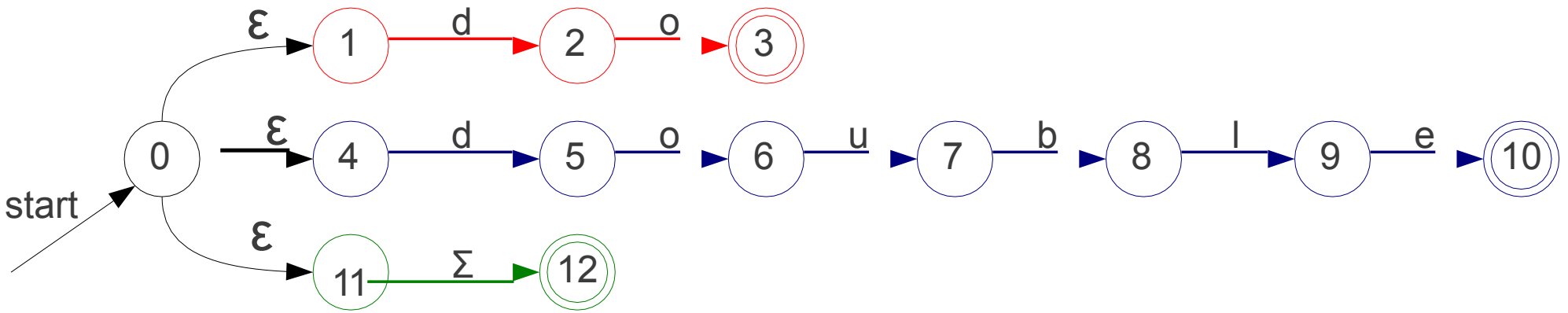

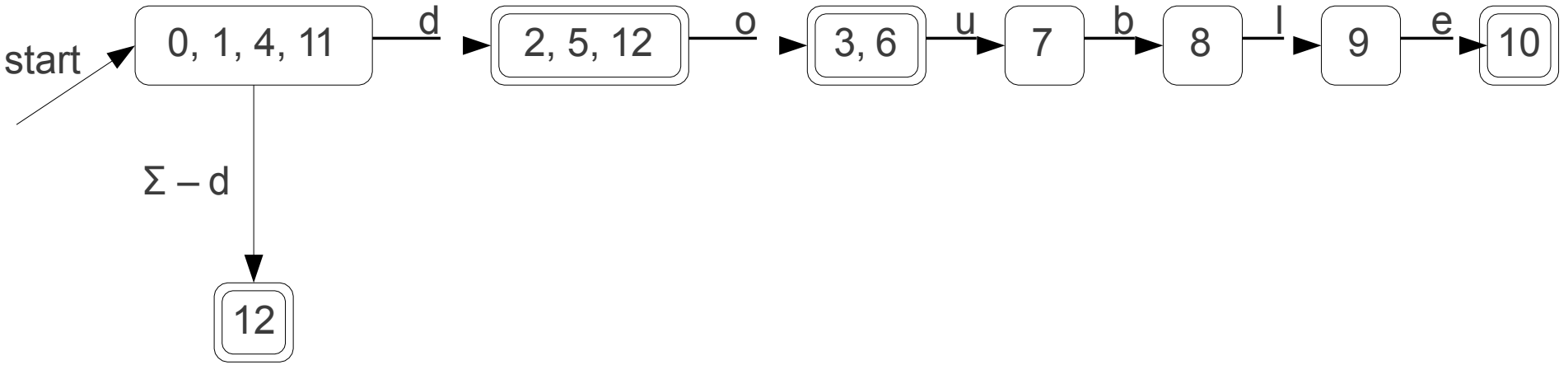

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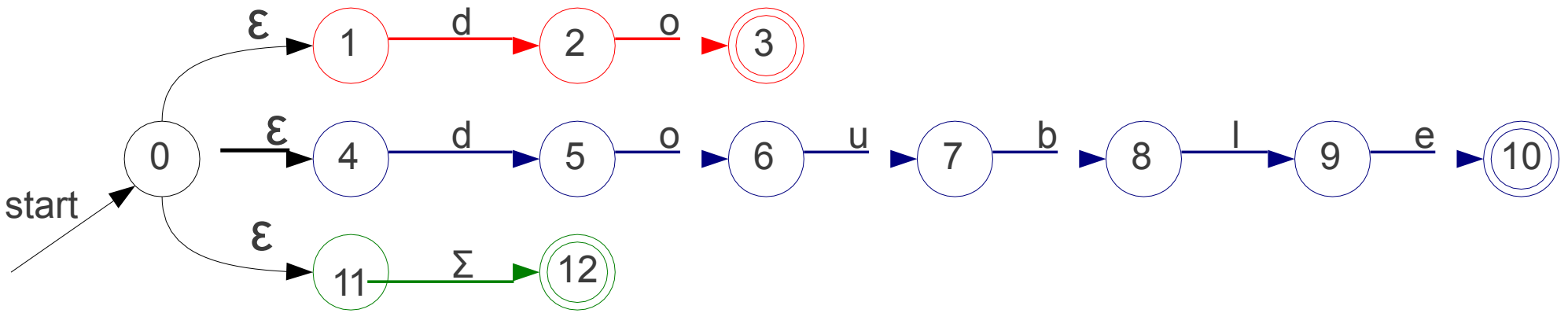
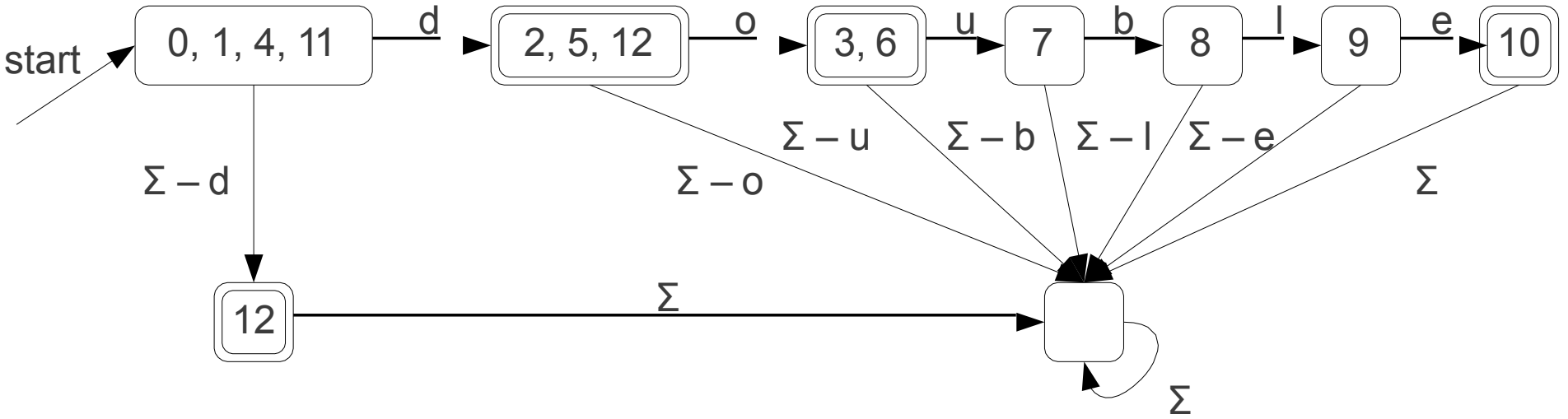
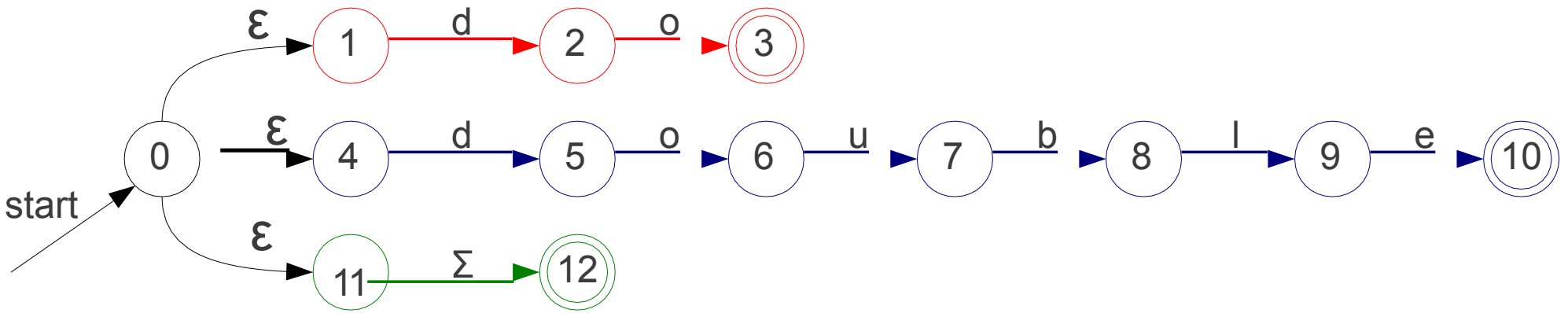
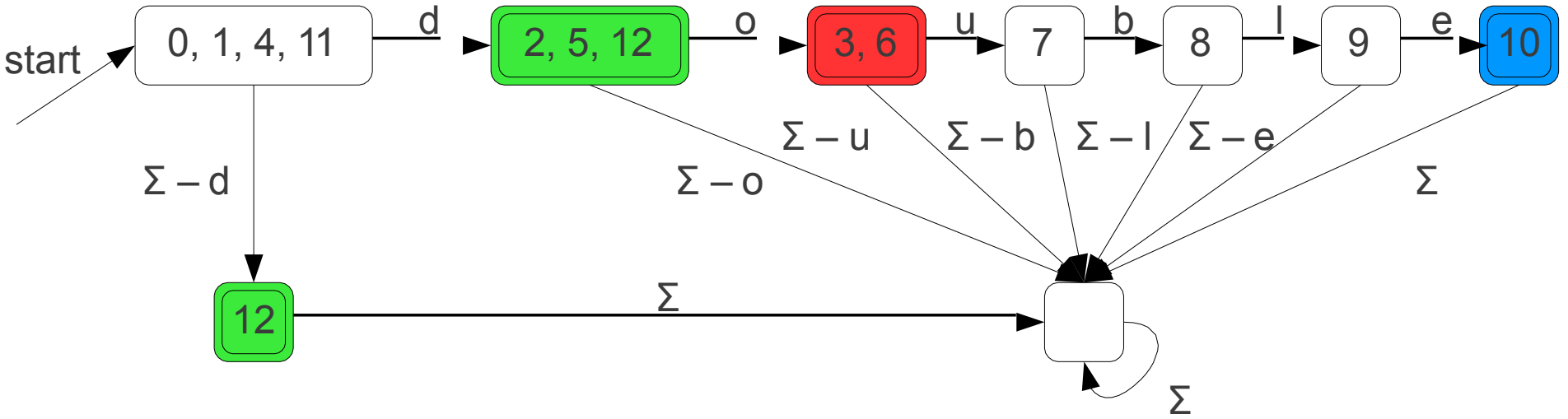




From NFA to DFA

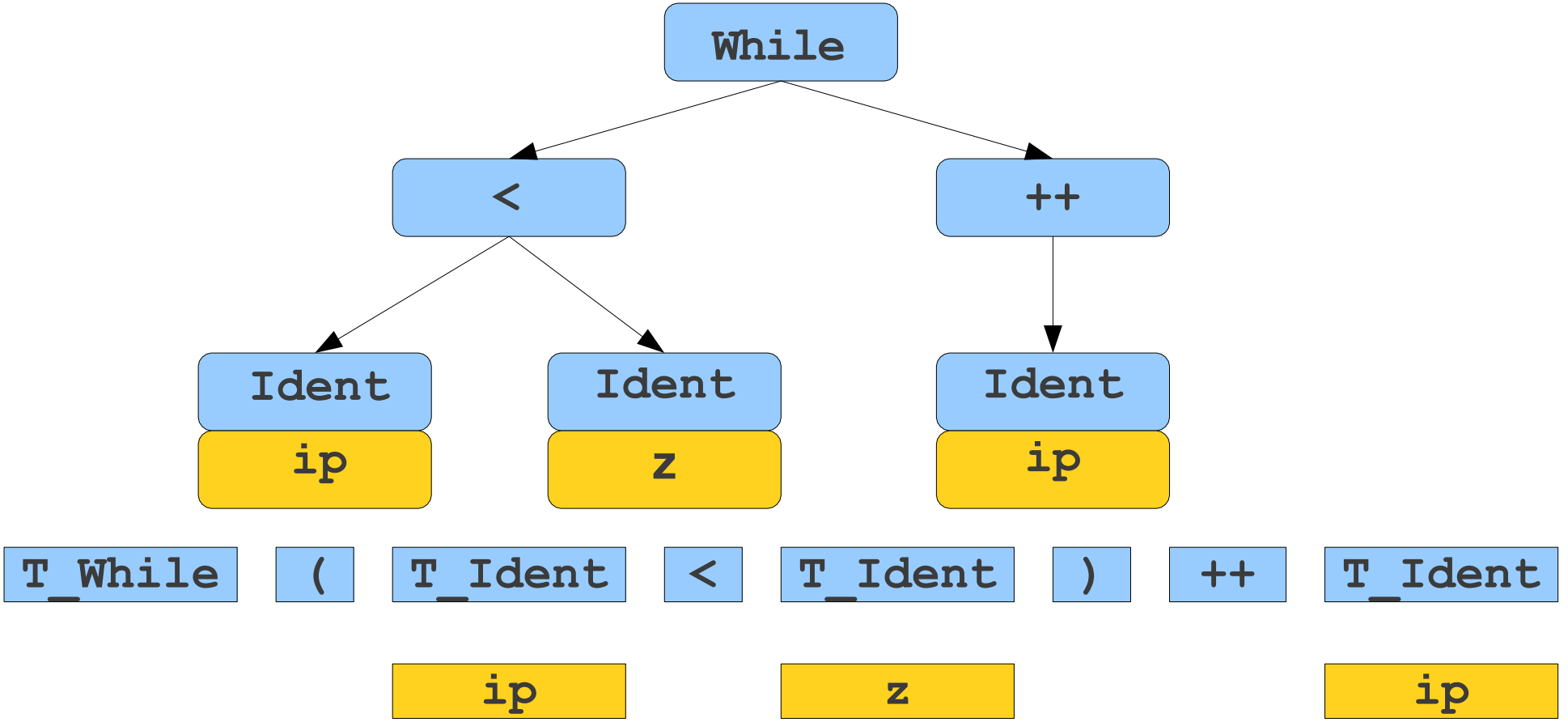




Performance Concerns

- 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
```

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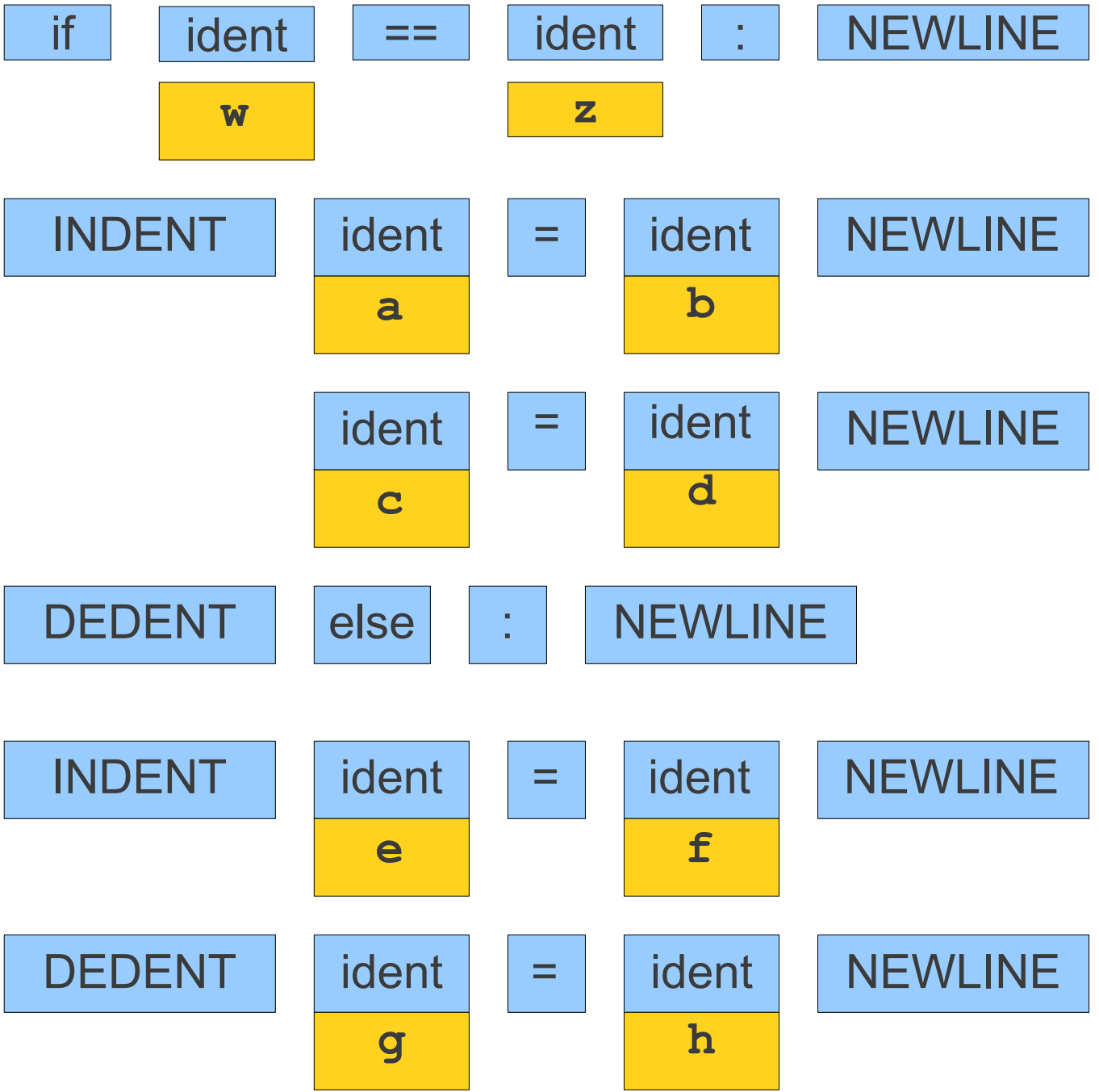
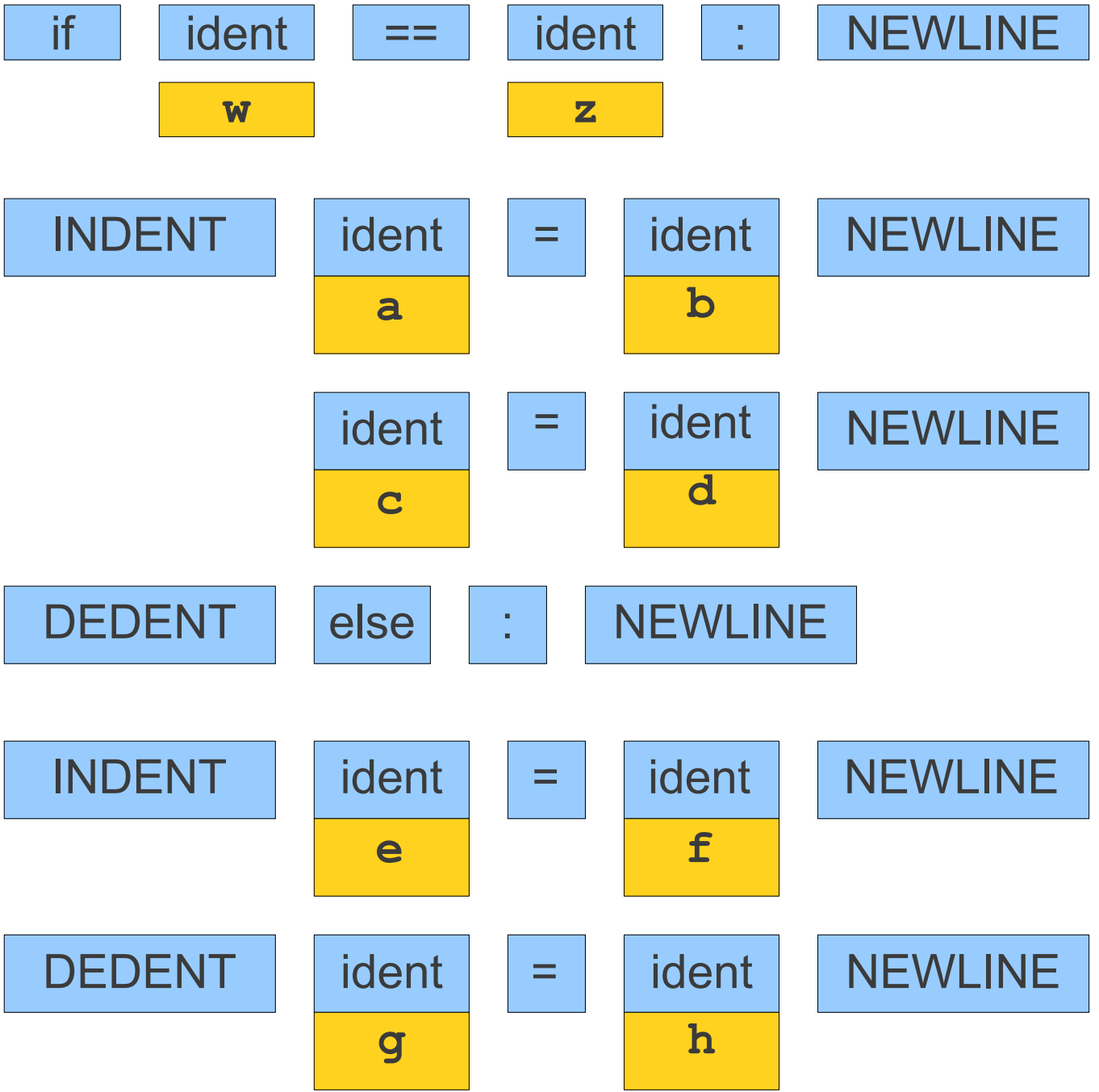


Scanning Python

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



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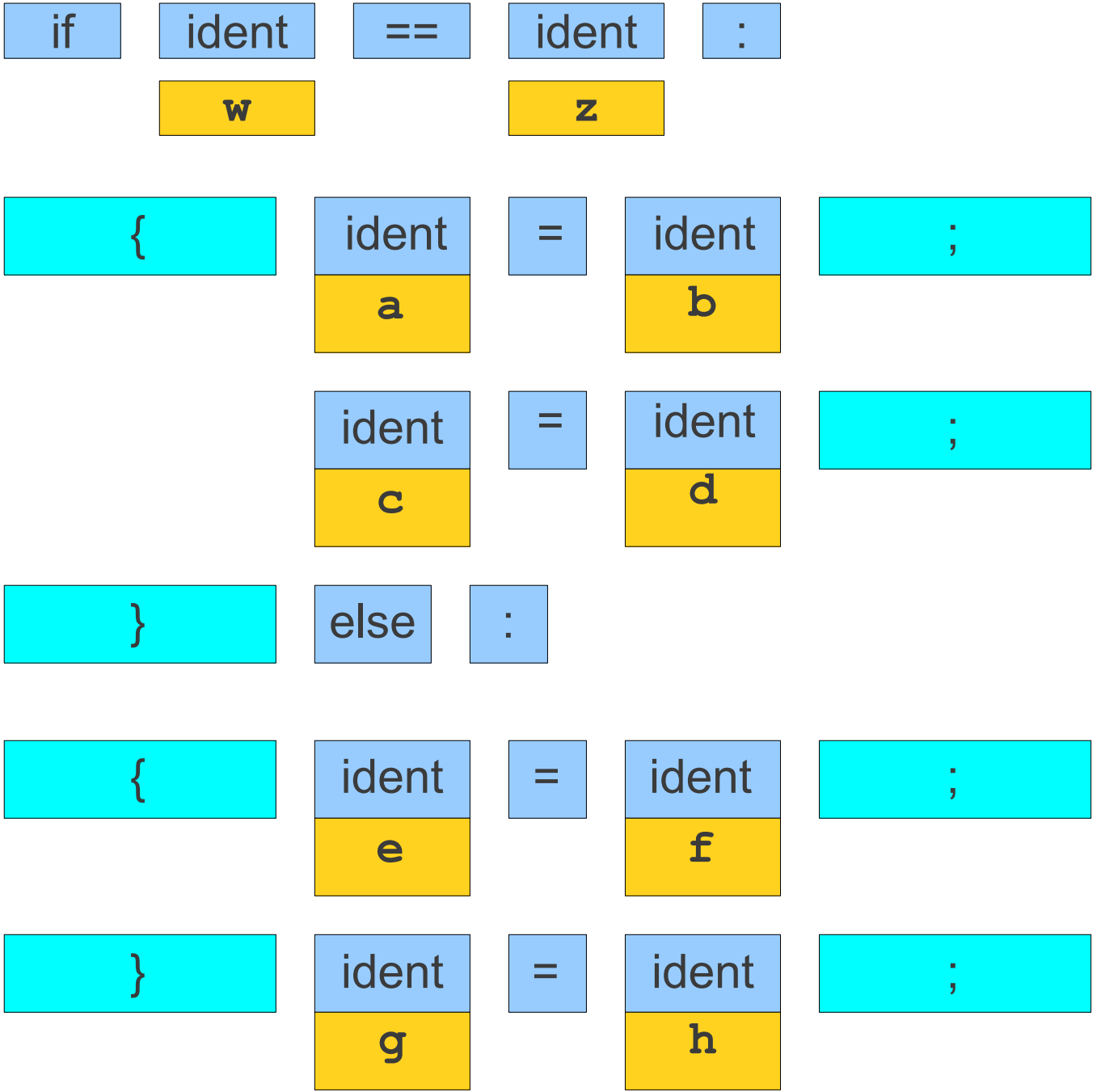

Where to INDENT/DEDENT?

-
-
  -
  -

  Otherwise, while the value is less than the top of the stack:

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

Where to INDENT/DEDENT?

Scanner maintains a stack of line indentations keeping track of all indented contexts so far.

-
-
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Initially, this stack contains 0, since initially the contents of the file aren't indented.

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-
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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:
  -
  -

  Otherwise, while the value is less than the top of the stack:

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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.

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- 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

Summary

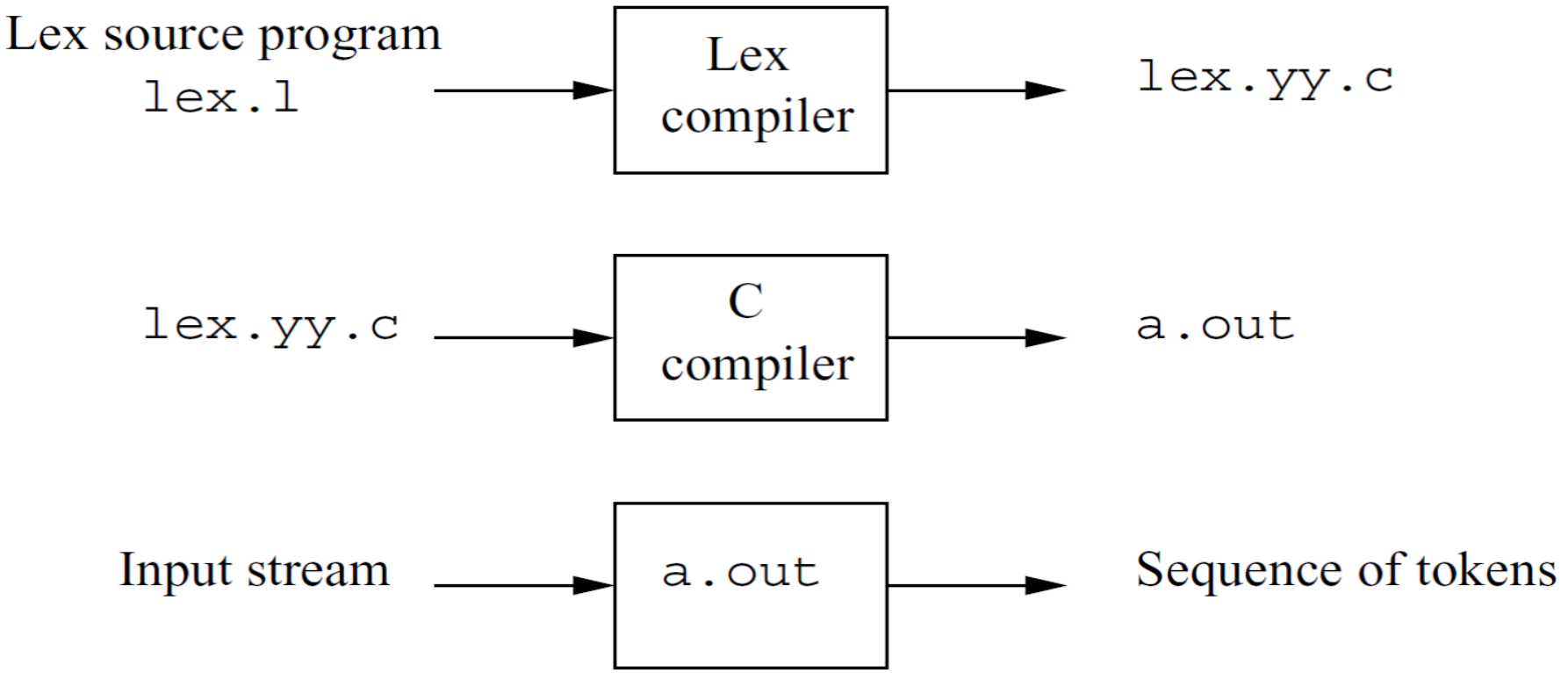
- Lexical analysis splits input text into **tokens** holding a **lexeme** and an **attribute**.
- Lexemes are sets of strings often defined with **regular expressions**.
- Regular expressions can be converted to **NFAs** and from there to **DFAs**.
- **Maximal-munch** using an automaton allows for fast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

Introduction To `flex`

What is flex?

- Automated tool for generating scanners.
- Uses maximal-munch/precedence system.
- Internally, builds a DFA from regular expressions.

(F) `lex` Structure



Structure of flex file

```
declarations
%%
translation rules
%%
auxiliary functions
```

The **declarations** section includes declarations of variables, manifest constants

(identifiers declared to stand for a constant, e.g., the name of a **token**), and regular dentitions.

Structure of flex file

declarations
%%
translation rules
%%
auxiliary functions

The **translation rules** each have the form:

```
Pattern {Action}
```

Each pattern is a regular expression, which may use the regular definitions of the declaration section.

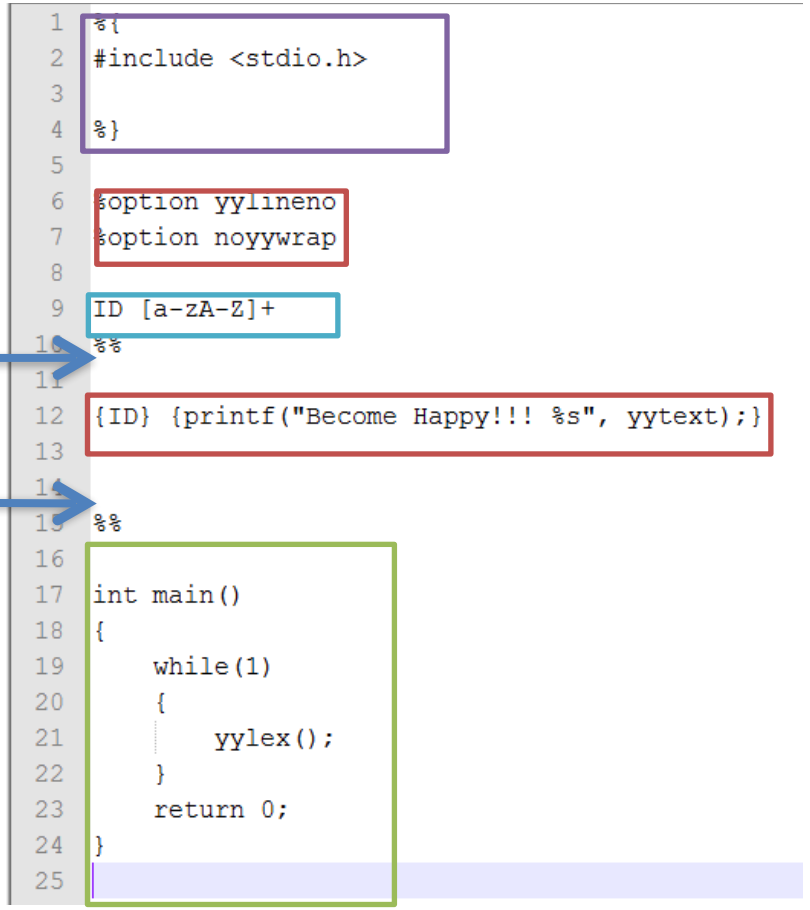
declarations

%%

translation rules

%%

auxiliary functions



```
%{
#include <stdio.h>

%}

%option yylineno
%option noyywrap

ID [a-zA-Z]+
%%

{ID} {printf("Become Happy!!! %s", yytext);}

%%

int main()
{
    while(1)
    {
        yylex();
    }
    return 0;
}
```

Work on an Example

- Imagine we have the following definitions:

LEXEMES	TOKEN NAME	ATTRIBUTE VALUE
Any *ws*	–	–
`if`	**if**	–
`then`	**then**	–
`else`	**else**	–
Any *id*	**id**	Pointer to table entry
Any *number*	**number**	Pointer to table entry
`<`	**relop**	`LT`
`<=`	**relop**	`LE`
`=`	**relop**	`EQ`
`<>`	**relop**	`NE`
`>`	**relop**	`GT`
`>=`	**relop**	`GE`

Example: definition

```
%{
/* definitions of manifest constants
LT, LE, EQ, NE, GT, GE, IF, THEN, ELSE, ID, NUMBER, RELOP *
/
%}
/* regular definitions */
delim       [ \t\n]
ws          {delim}+
letter      [A-Za-z]
digit       [0-9]
id          {letter}({letter}|{digit})*
number      {digit}+(\.{digit}+)?(E[+-]?{digit}+)?
%%
```

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[s] : any one of char in string *s*

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Complete Guide can be found in Book figure 3.8

Example: Transition

```
{ws} {/* no action and no return */}
if     {return(IF);}
then   {return(THEN);}
else   {return(ELSE);}
{id}   {yylval = (int) installID(); return(ID);}
{number} {yylval = (int) installNum(); return(NUMBER);}
"<"  {yylval  = LT; return(RELOP);}
"<=" {yylval  = LE; return(RELOP);}
"="  {yylval  = EQ; return(RELOP);}
"<>" {yylval  = NE; return(RELOP);}
">"  {yylval  = GT; return(RELOP);}
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We can use C++ inside **{}**

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%%
```

We can use C++ inside **{}**

`yytext()` contains lexemes.

Example: auxiliary functions

```
int installID() {/* function to install the lexeme, whose first
character is pointed to by yytext,
and whose length is yyleng, into the
symbol table and return a pointer thereto */}

int installNum() {/
* similar to installID, but puts numerical constants into a separ
ate table */
}
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```
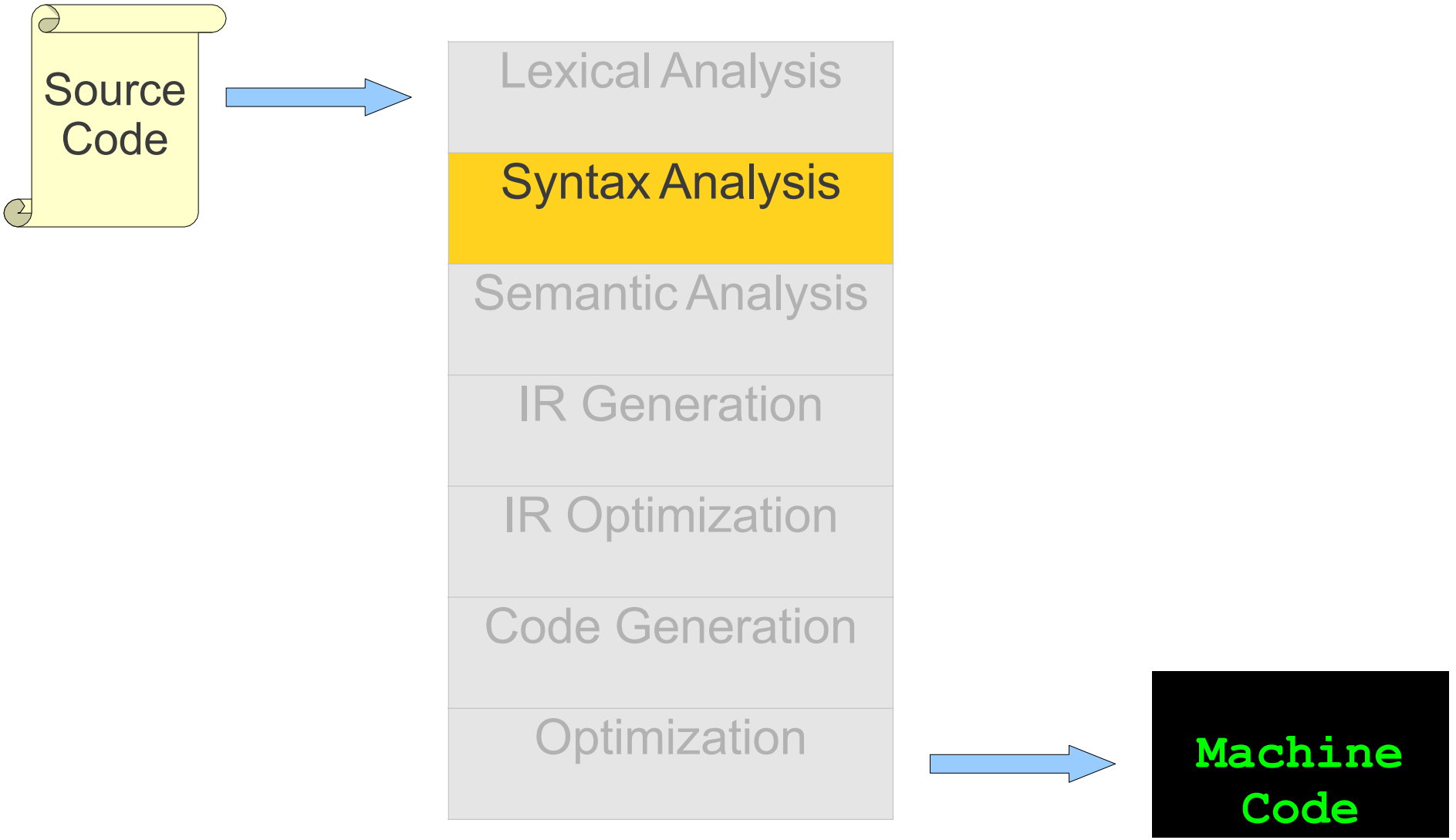

We can use C++ inside **auxiliary function part**

Next Time


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