기본 알고리즘
제8장

2017-Fall

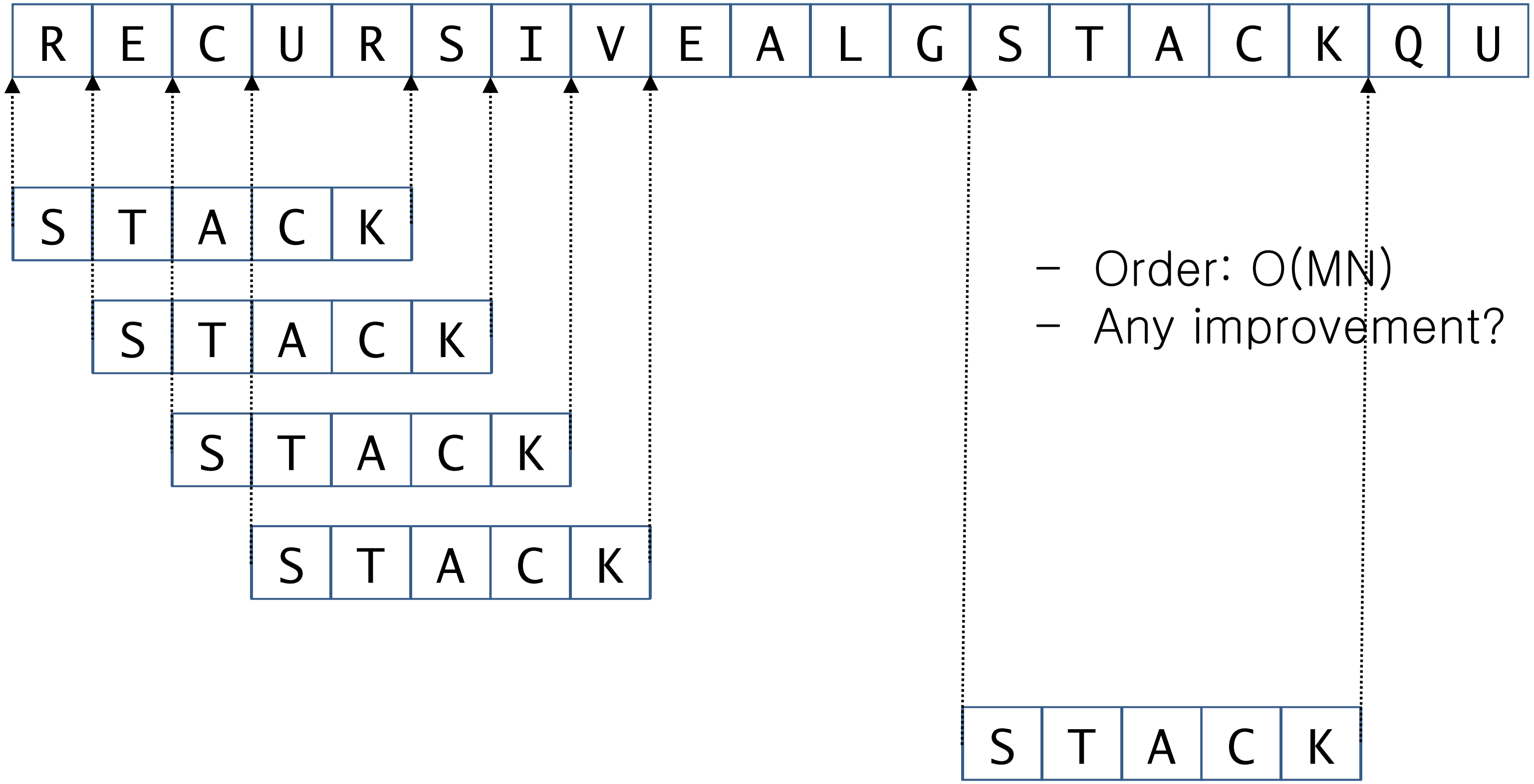
국민대학교 컴퓨터공학부 최준수

String Matching

- Substring search
  - Find pattern of length M in a text of length N. (typically $N \gg M$)

Brute-Force Substring Search

- Naïve Algorithm 1
  - Check for pattern starting at each text position



R E C U R S I V E A L G S T A C K Q U

S T A C K

S T A C K

S T A C K

S T A C K

S T A C K

- Order: O(MN)
- Any improvement?

Brute-Force Substring Search

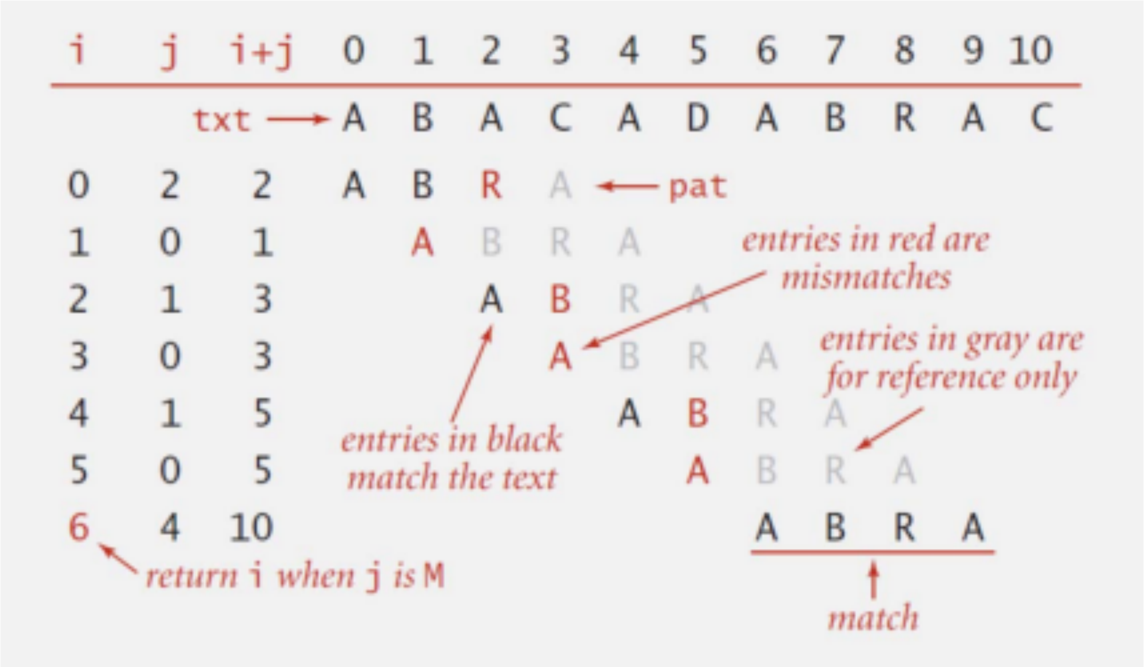
- Naïve Algorithm 2
  - Check for pattern starting at each text position

```
int naiveStringMatch(char text[], char pattern[])
{
    int patLength, txtLength;

    patLength = strlen(pattern);
    txtLength = strlen(text);

    for(int i=0; i <= txtLength – patLength; i++)
    {
        for(int j=0; j < patLength; j++)
            if(text[i+j] != pattern[j])
                break;
        if(j == patLength)
            return i;
    }
    return -1;
}
```

Find just only one sample of pattern.
Modify the code to find all samples of the pattern.

Brute-Force Substring Search

- Naïve Algorithm 2
  - Check for pattern starting at each text position



i	j	i+j	0	1	2	3	4	5	6	7	8	9	10
		txt →	A	B	A	C	A	D	A	B	R	A	C
0	2	2	A	B	R	A							
1	0	1		A	B	R	A						
2	1	3			A	B	R	A					
3	0	3				A	B	R	A				
4	1	5					A	B	R	A			
5	0	5						A	B	R	A		
6	4	10							A	B	R	A	

← pat

entries in red are mismatches

entries in gray are for reference only

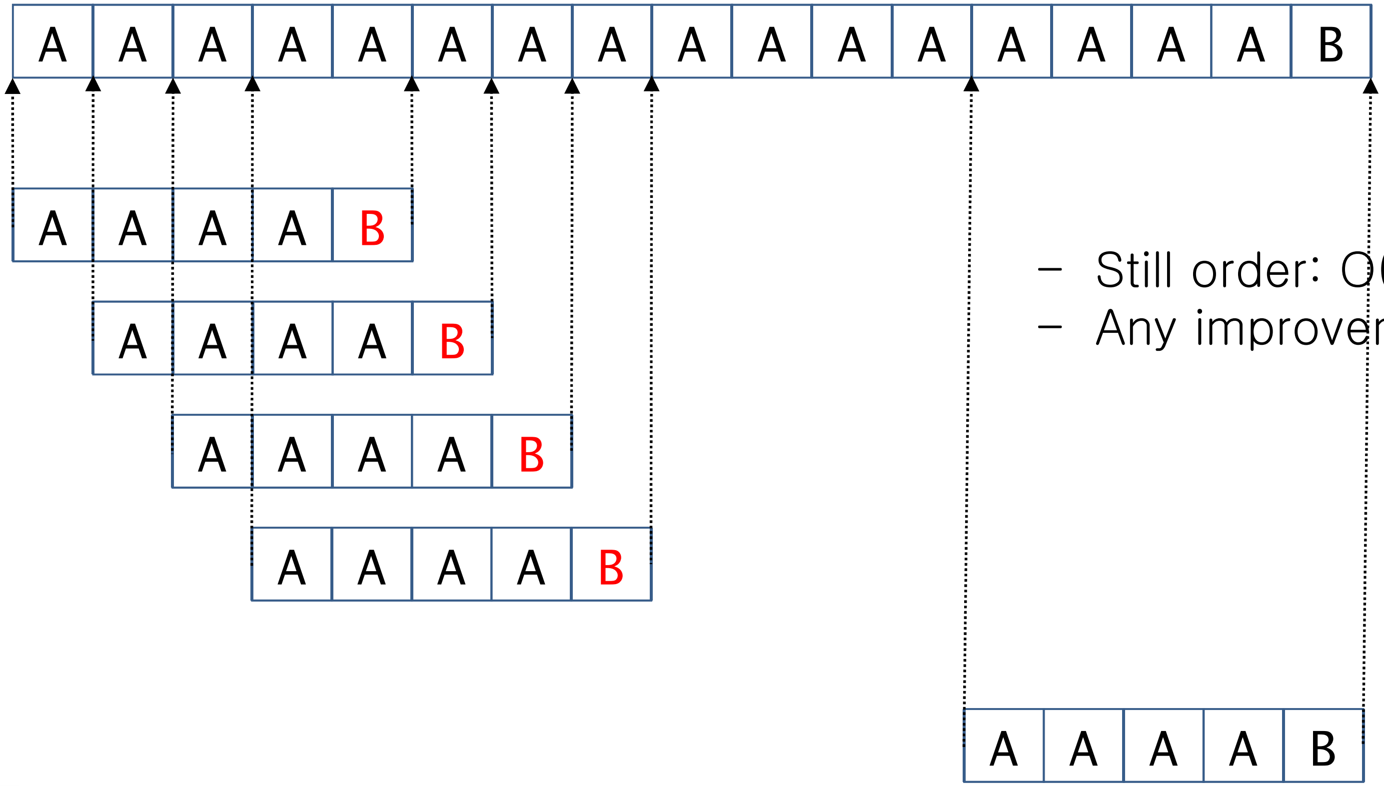
entries in black match the text

return i *when* j *is* M

match

Brute-Force Substring Search

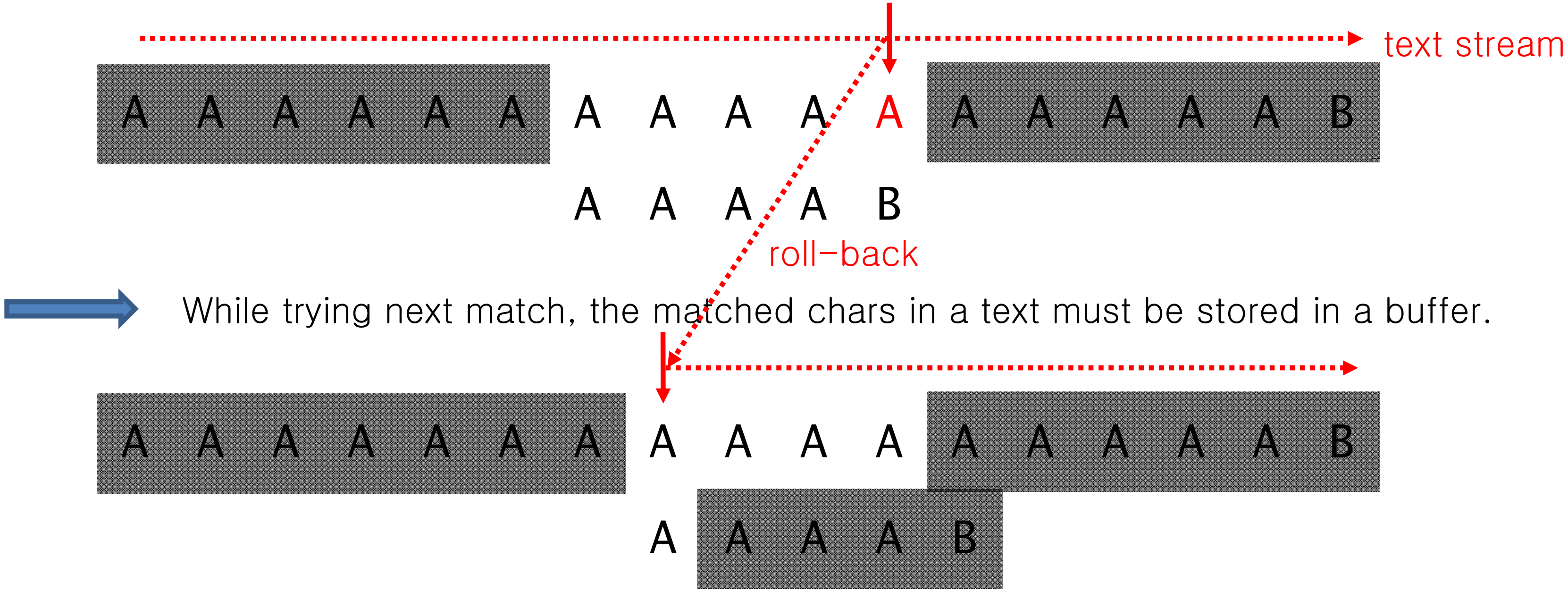
- Naïve Algorithm 2
  - Naïve algorithm can be slow if text and pattern are repetitive



- Still order: O(MN)
- Any improvement?

Brute-Force Substring Search

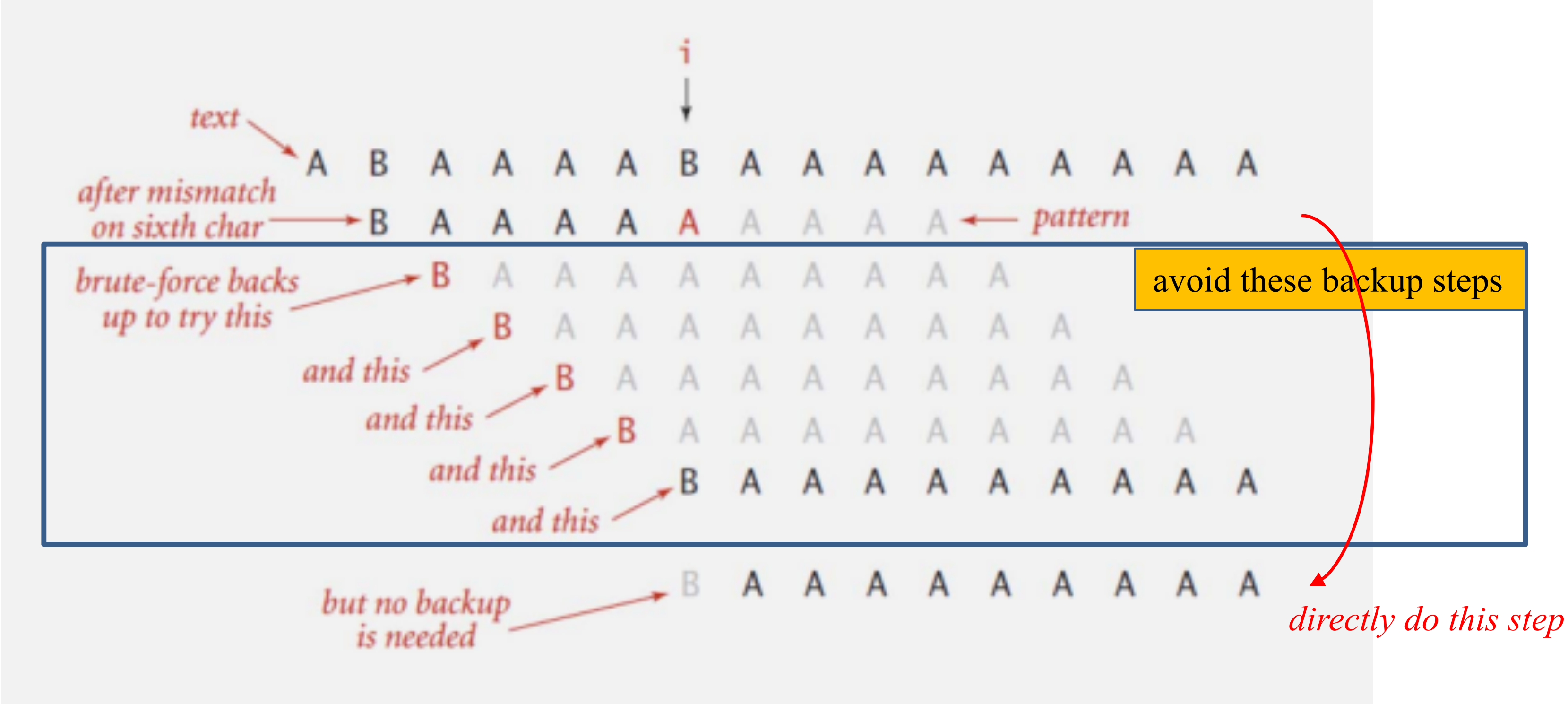
- Improvement
  - Develop a linear time algorithm
  - Avoid backup
    - Naïve algorithm needs backup for every mismatch
    - Thus naïve algorithm cannot be used when input text is a stream.



While trying next match, the matched chars in a text must be stored in a buffer.

Knuth-Morris-Pratt(KMP) Algorithm

- KMP algorithm
  - Clever method to always avoid backup problem.



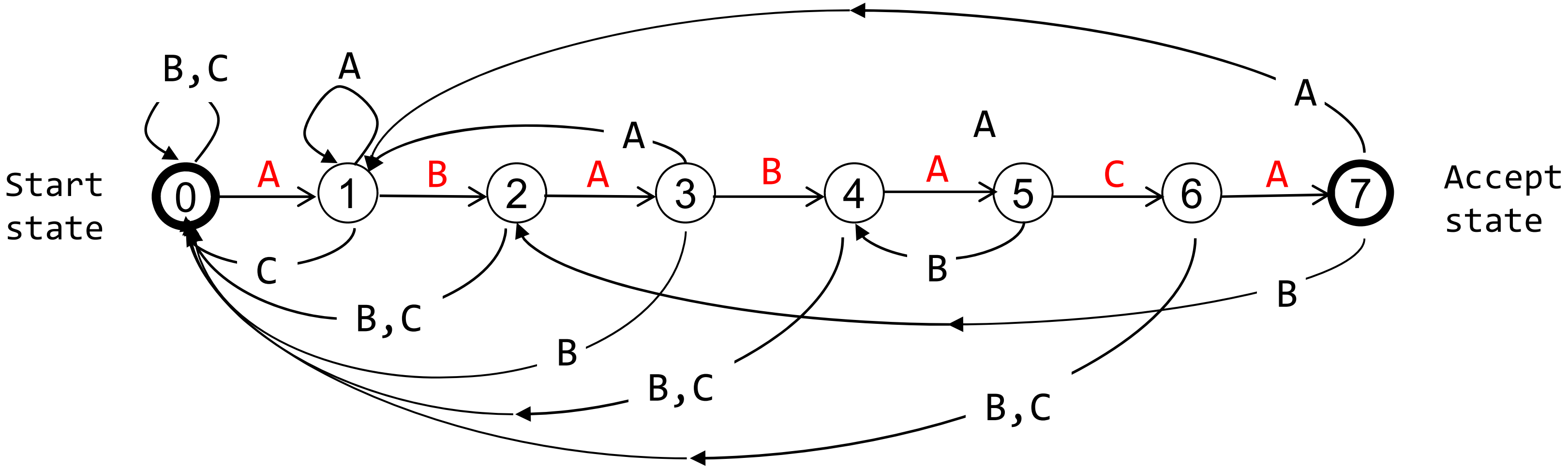
avoid these backup steps

directly do this step

Deterministic Finite Automaton

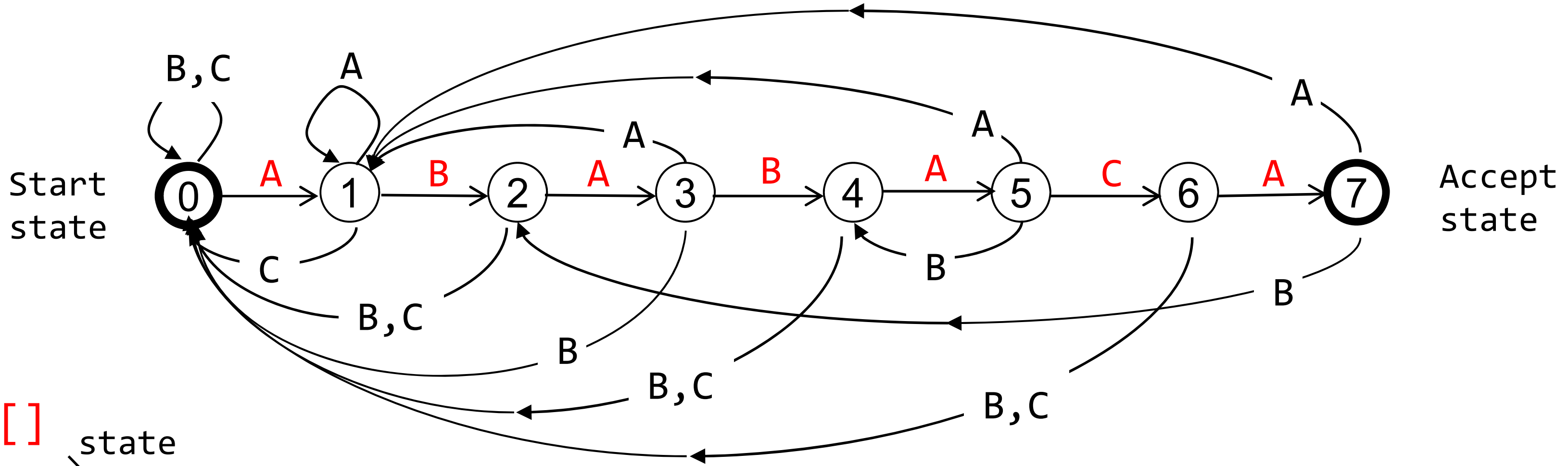
- DFA(Deterministic Finite State Automaton)
  - Finite number of states (including start and accept states)
  - Exactly one transition for each char
  - Accept if sequence of transitions leads to accept state

DFA for pattern ABABACA



DFA

DFA for pattern ABABACA



DFA[][]

char \ state	0	1	2	3	4	5	6	7
A	1	1	3	1	5	1	7	1
B	0	2	0	4	0	4	0	2
C	0	0	0	0	0	6	0	0
others	0	0	0	0	0	0	0	0

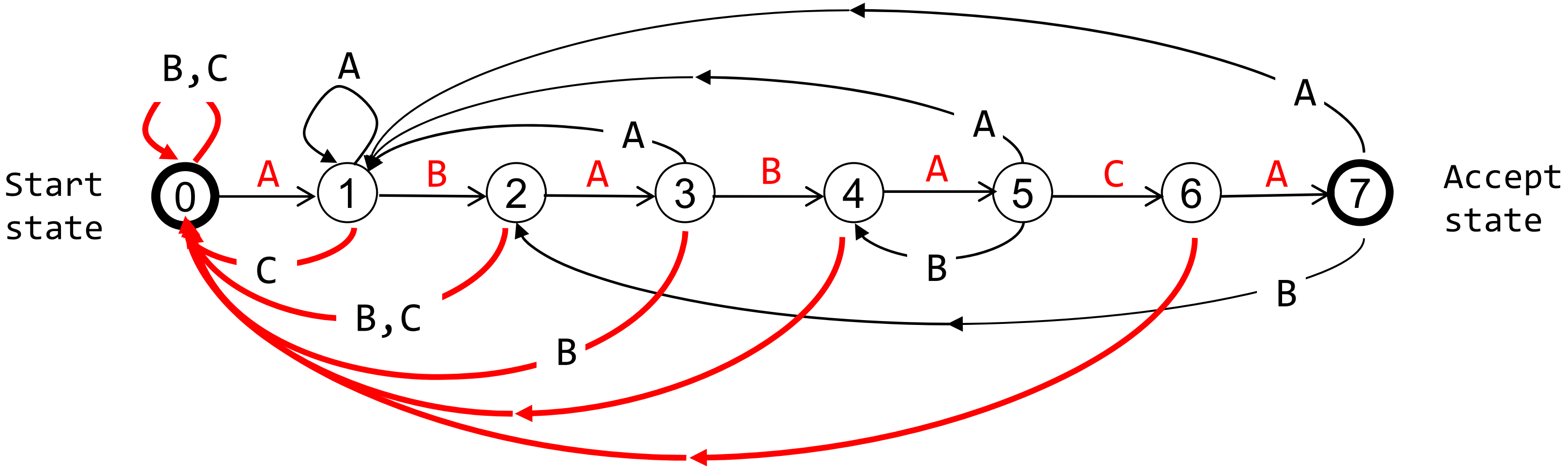
```
if in state j reading char c:
    if j is 7, halt and accept
    else move to state DFA[c][j]
```

Example:

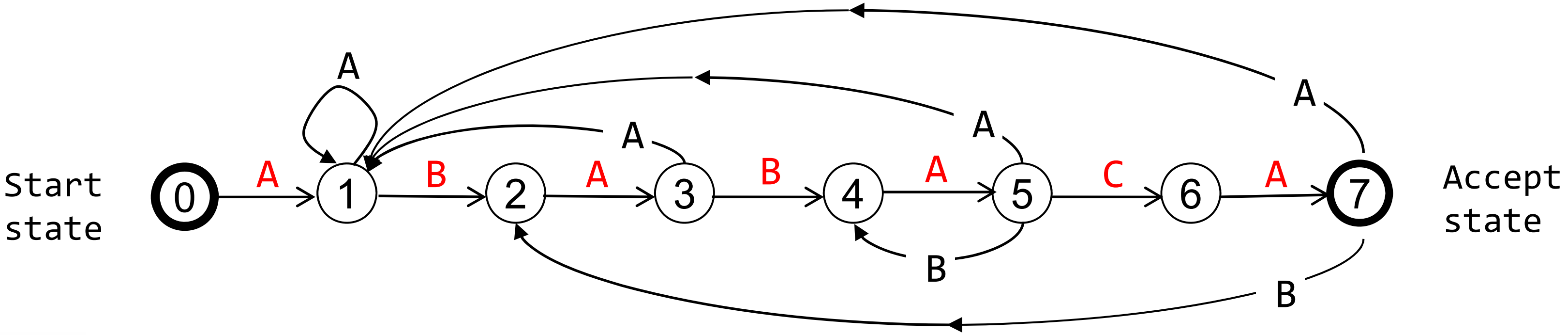
```
    text:  ABCABAABABABACACA
    state:012012312345456
```

DFA

DFA for pattern ABABACA



Simplified Diagram: remove transitions to state 0



Algorithm with DFA

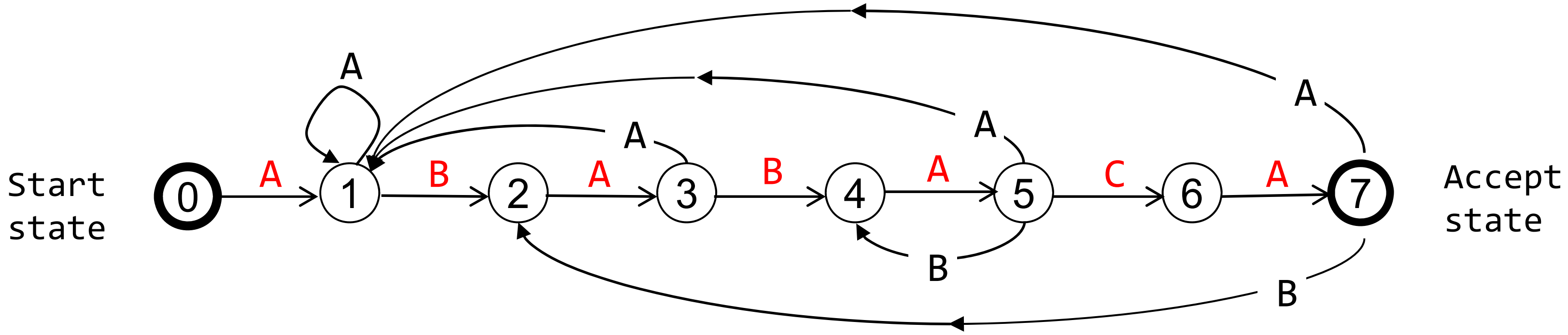
- Difference from naïve algorithm
  - Precomputation of DFA[][] from pattern
  - Text pointer `i` never decrements (no backup)

```
// patLength = strlen(pattern);
int KMP(char text[])
{
    int i, j, txtLength;

    txtLength = strlen(text);

    for(i=0, j=0; i <= txtLength && j < patLength; i++)
        j = DFA[text[i]][j];  // text[i] to be modified

    if(j == patLength)
        return i - patLength;
    else
        return -1;
}
```

- Order: O(N)
  simulation of DFA on text with no backup
- How to build DFA efficiently?

Algorithm with DFA

DFA for pattern ABABACA



Start state

Accept state

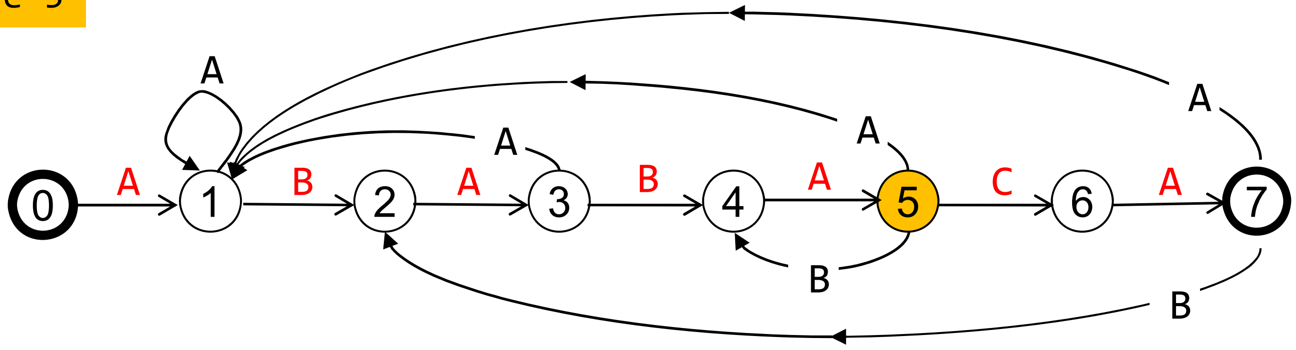
state	0	1	2	0	1	2	3	1	2	3	4	5	4	5	6	7		
text		A	B	C	A	B	A	A	B	A	B	A	B	A	C	A	C	A

return 8

Interpretation of DFA

- The state of DFA represents
  - the number of characters in pattern that have been matched

State 5



text → B C B A A B A B A A B A

Suffix of text[8]

pattern → A B A B A C A

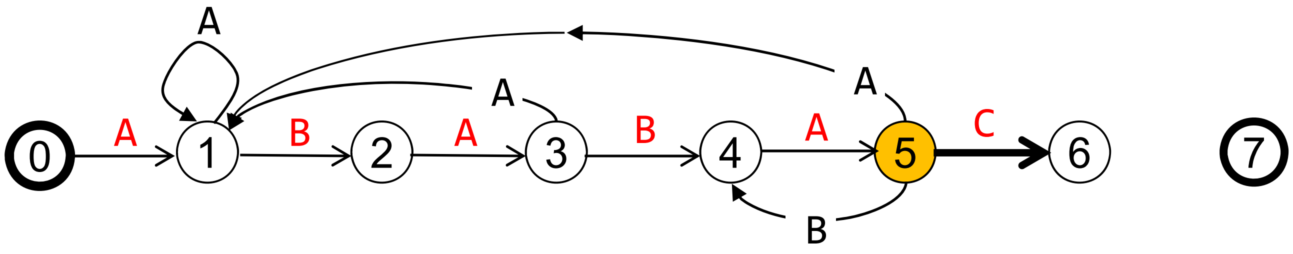
Prefix of pattern[]

DFA Construction

- DFA Construction:
  - Suppose that all transitions from state `0` to state `j-1` are already computed
  - Match transition:
    - If in state `j` and next char `c == pattern[j]`, then transit to state `j+1`.

Pattern: ABABACA

State 5

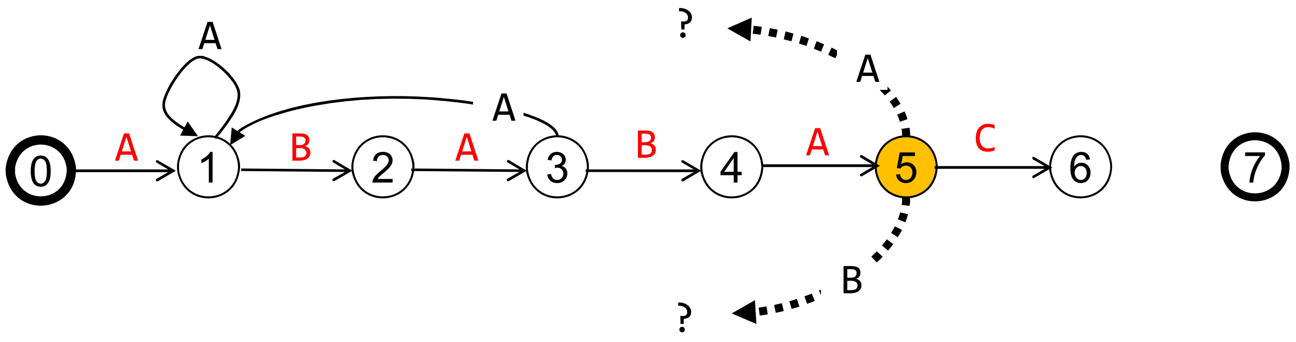


DFA Construction

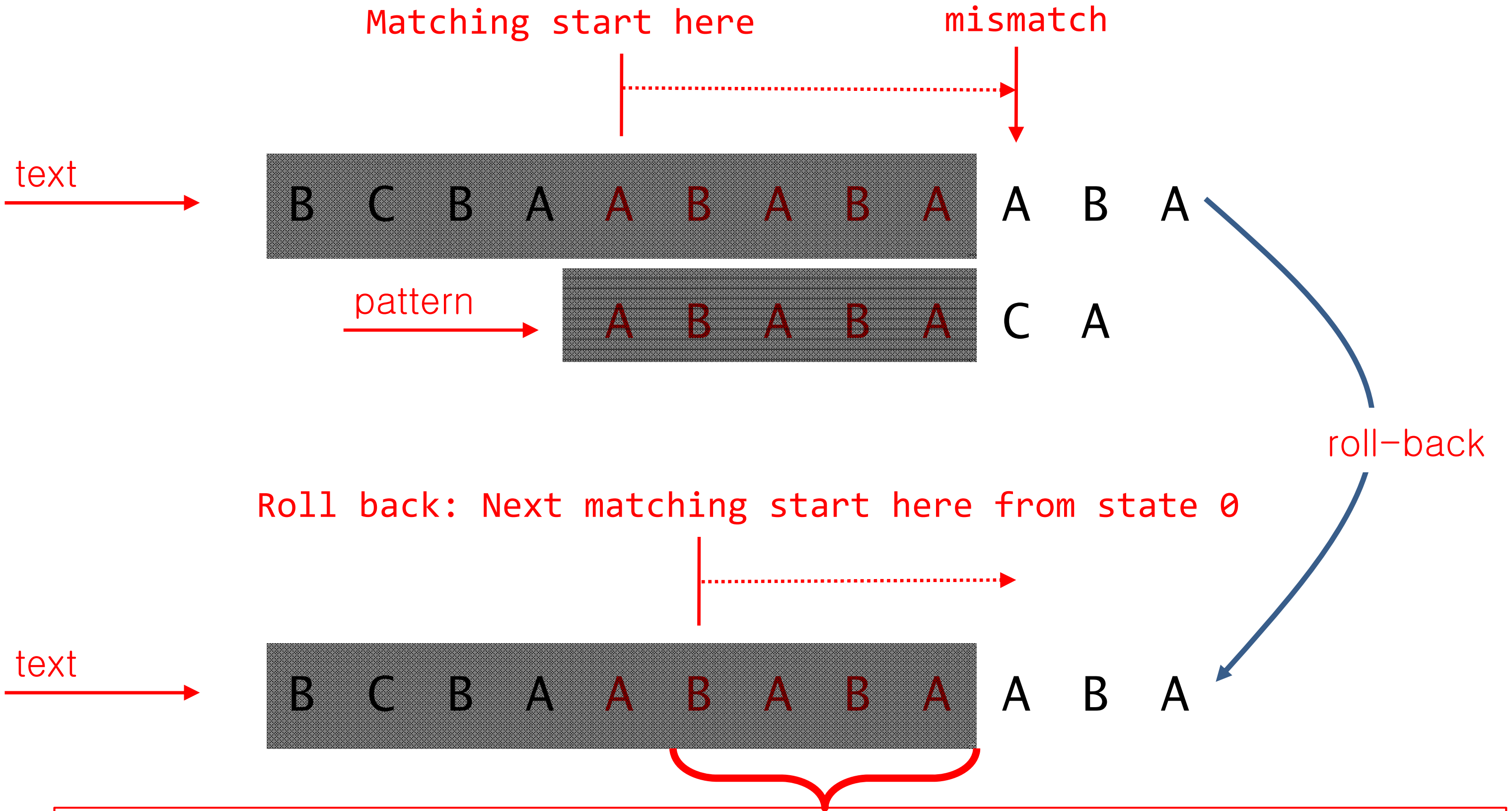
- DFA Construction:
  - Mismatch transition:
    - If in state `j` and next char `c != pattern[j]`, then which state to transit?

Pattern: ABABACA

State 5



DFA Construction



- *The same as* `pattern[1] ~ pattern[j-1]`
- Roll-back and transit to some state X by matching
  `pattern[1] ~ pattern[j-1]` from state 0 on DFA.
- Transit to the next state `DFA['A'][X]` for the mismatched char `'A'`.

DFA Construction

- DFA Construction:
  - Mismatch transition:
    - If in state `j` and next char `c != pattern[j]`, then the last `j-1` characters of input text are `pattern[1]` ~ `pattern[j-1]`, followed by `c`.
  - Compute `DFA[c][j]`:
    - Simulate `pattern[1]` ~ `pattern[j-1]` on DFA from state 0 and let `X` be the current state
    - Then `DFA[c][j] = DFA[c][X]`

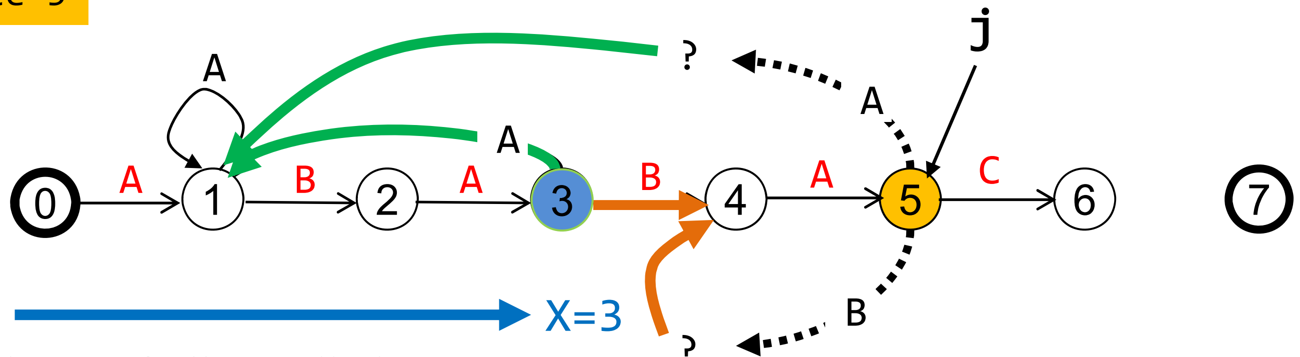
DFA Construction

- DFA Construction:
  - Mismatch transition:
    - `DFA[c][j] = DFA[c][X]`

```
DFA['A'][5] = DFA['A'][3] =  1
DFA['B'][5] = DFA['B'][3] =  4
```

Pattern: ABABACA

State 5



Simulation of “BABA” in ABABACA

DFA Construction

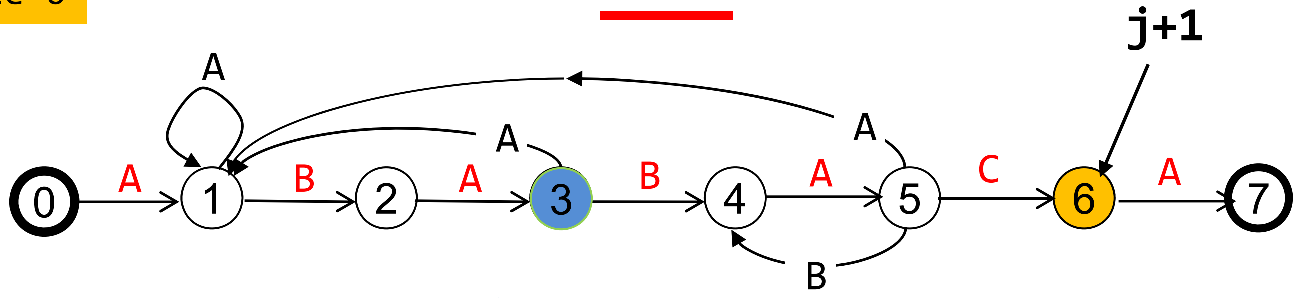
- DFA Construction:
  - Mismatch transition:
    - If in state `j` and next char `c != pattern[j]`, then the last `j-1` characters of input text are `pattern[1]` ~ `pattern[j-1]`, followed by `c`.
  - To compute `DFA[c][j]`:
    - Simulate `pattern[1]` ~ `pattern[j-1]` on DFA (*still under construction*) and let the current state `X`.
    - take a transition `c` from state `X`.
    - Running time : require `j` steps.
    - But, if we maintain state `X`, it takes only constant time!

DFA Construction

- DFA Construction:
  - Maintaining state X:
    - Finished computing transitions from state `j`.
    - Now, now move to next state `j+1`.
    - Then what the new state(X’) of X be?

State 6

Pattern: ABABACA



X=3

Simulation of “BABA” in ABABACA

X’ = ?

Simulation of “BABAC” in ABABACA

- Simulation requires j+1 steps
- But, X’ = DFA[’C’][X]

X’ = DFA[’C’][3] = 0

DFA Construction

- DFA Construction: A Linear Time Algorithm
  - For each state `j`:
    - Match case: set `DFA[pattern[j]][j]=j+1`
    - Mismatch case: Copy `DFA[][X]` to `DFA[][j]`
    - Update `X`

```
int DFA[MAX_SIZE][MAX_SIZE];  /* initially all elements are 0 */
// int R;            /* text character set size */

void constructDFA(char pattern[])
{

    int patLength = strlen(pattern);

    DFA[pattern[0]][0] = 1;

    for(int X=0, j=1; j<patLength; j++)
    {
        for(int c=0; c<R; c++)                  // copy mismatch cases
            DFA[c][j] = DFA[c][X];

        DFA[pattern[j]][j] = j+1;               // copy match case
        X = DFA[pattern[j]][X];                 // update X
    }
}
```

DFA Construction

- DFA Construction: Example

DFA[][]

0123456
Pattern: ABABACA

state char	0	1	2	3	4	5	6	7
A								
B								
C								
others								

DFA Construction

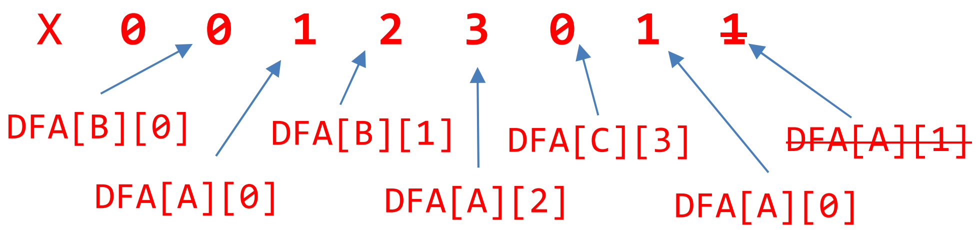
- DFA Construction: Example

DFA[][]

j start from 1

0123456
Pattern: ABABACA

char \ state	0	1	2	3	4	5	6	7
A	**1**	1	**3**	1	**5**	1	**7**	1
B	0	**2**	0	**4**	0	4	0	2
C	0	0	0	0	0	**6**	0	0
others	0	0	0	0	0	0	0	0



X 0 0 1 2 3 0 1 ~~1~~

DFA[B][0]
DFA[A][0]
DFA[B][1]
DFA[A][2]
DFA[C][3]
DFA[A][0]
~~DFA[A][1]~~

Algorithm with DFA

- String matching algorithm with DFA accesses no more than $M+N$ chars to search for a pattern of length M in a text of length N.

- DFA[][] can be constructed in time and space of order O(RM), where R is the number of characters used in a text.

Algorithm with DFA

- Questions:
  - Text에 나타나는 모든 pattern 을 찾을 수 있는가?
    - Text: AAAAAAAAA
    - Pattern: AAAAA
    - 해답: 0, 1, 2, 3, 4, 5

Prefix/Suffix

- Prefix / Suffix of a Text

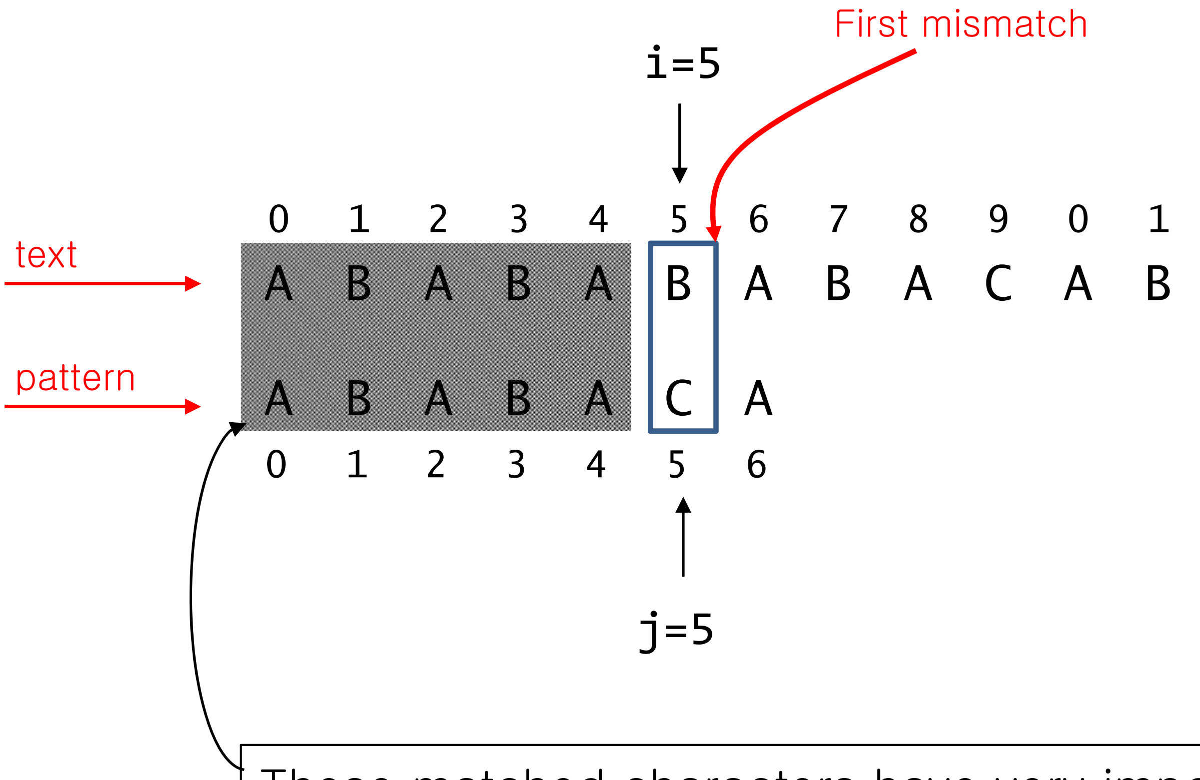
bananada

NULL string

Prefix	Suffix
bananada	bananada
bananada	bananada
bananada	bananada
bananada	bananada
bananada	bananada
bananada	bananada
bananada	bananada
bananada	bananada
bananada	bananada

KMP Algorithm

- Naïve algorithm again:



First mismatch

i=5

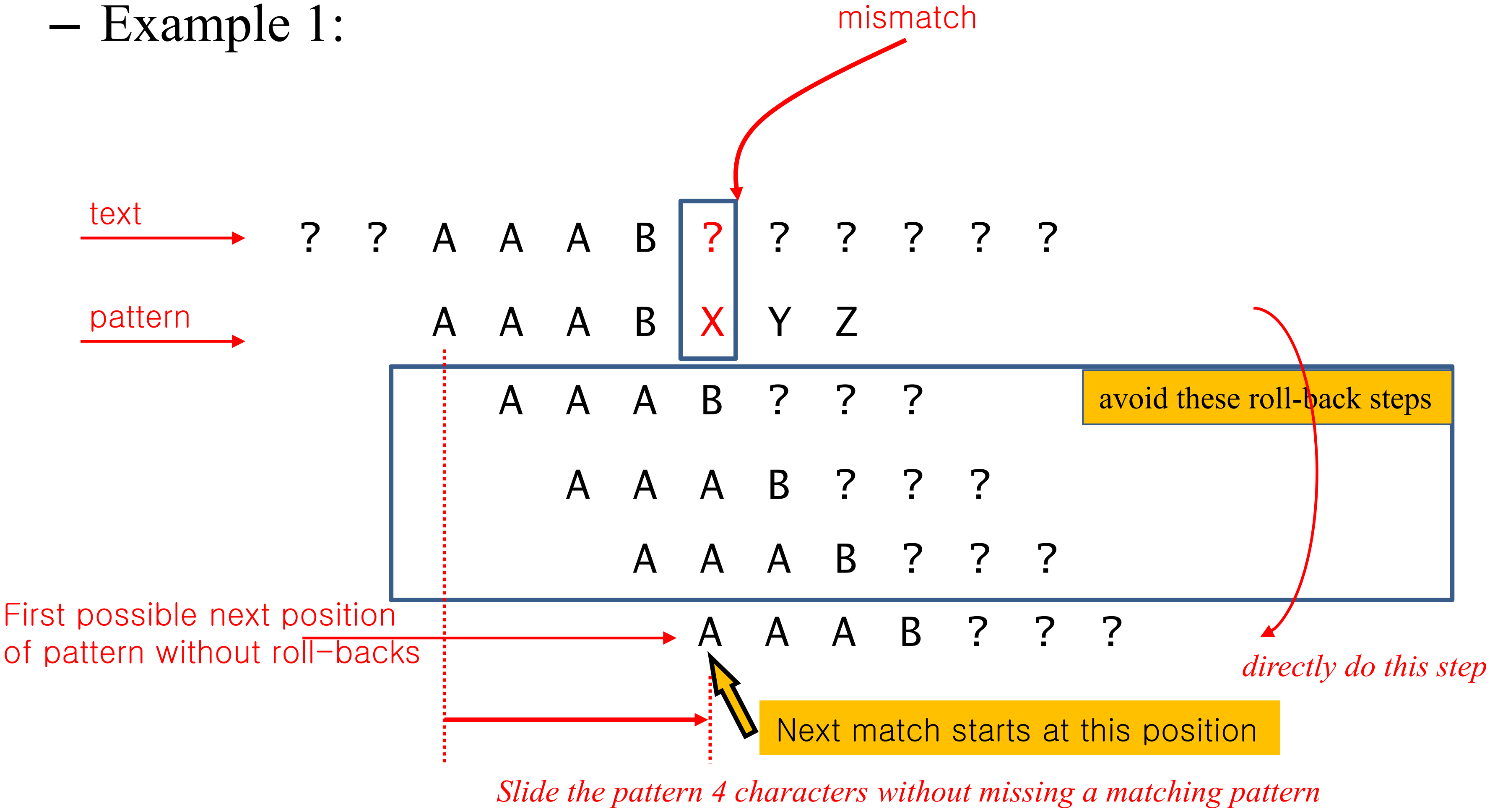
	0	1	2	3	4	5	6	7	8	9	0	1
text	A	B	A	B	A	B	A	B	A	C	A	B
pattern	A	B	A	B	A	C	A					
	0	1	2	3	4	5	6					

j=5

These matched characters have very important information.
Do not waste this information!!!

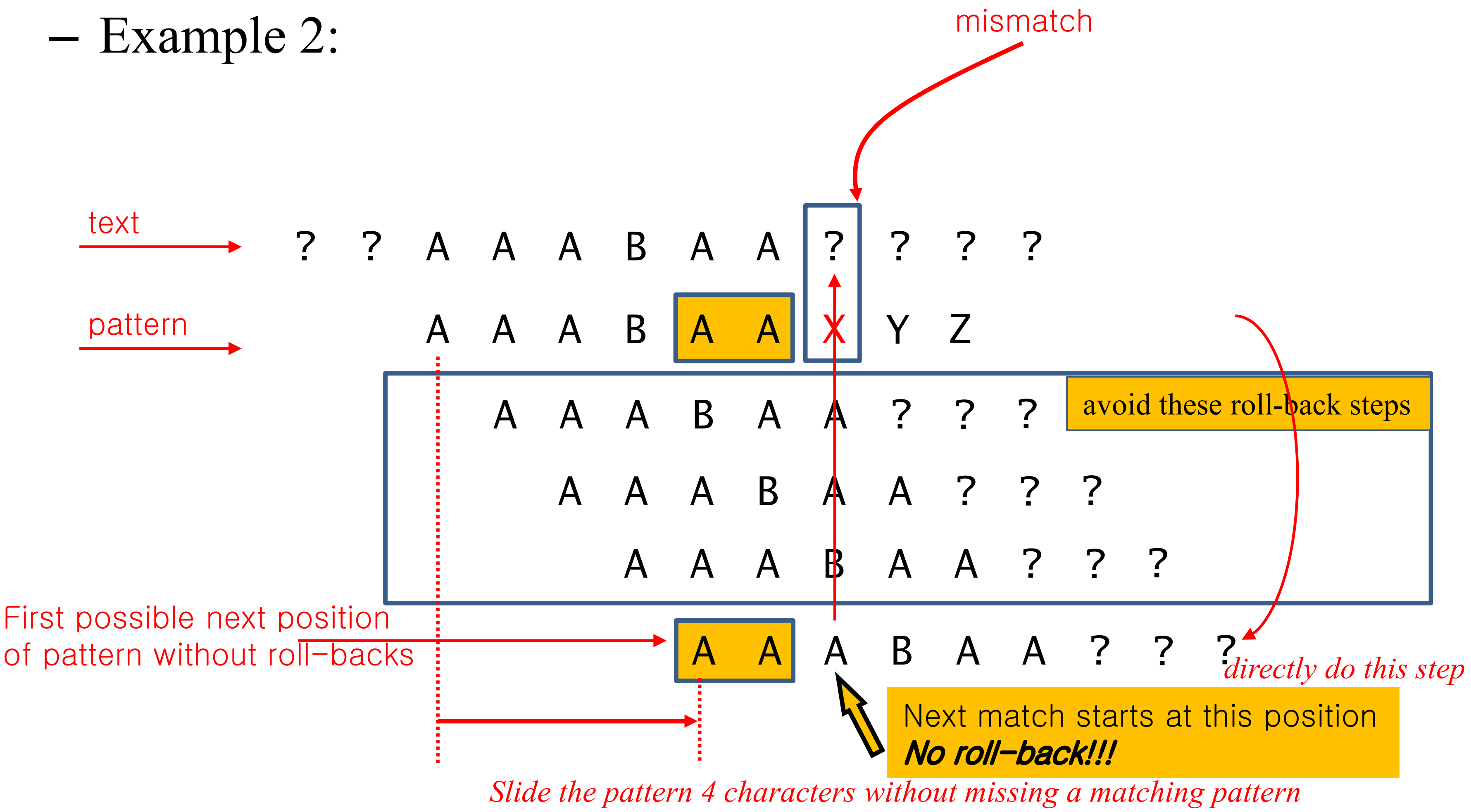
KMP Algorithm

- Avoid roll-backs in naïve algorithm:
  - Example 1:



KMP Algorithm

- Avoid roll-backs in naïve algorithm:
  - Example 2:



mismatch

text

? ? A A A B A A ? ? ? ?

pattern

A A A B A A X Y Z

A A A B A A ? ? ?

A A A B A A ? ? ?

A A A B A A ? ? ?

avoid these roll-back steps

First possible next position of pattern without roll-backs

A A A B A A ? ? ?

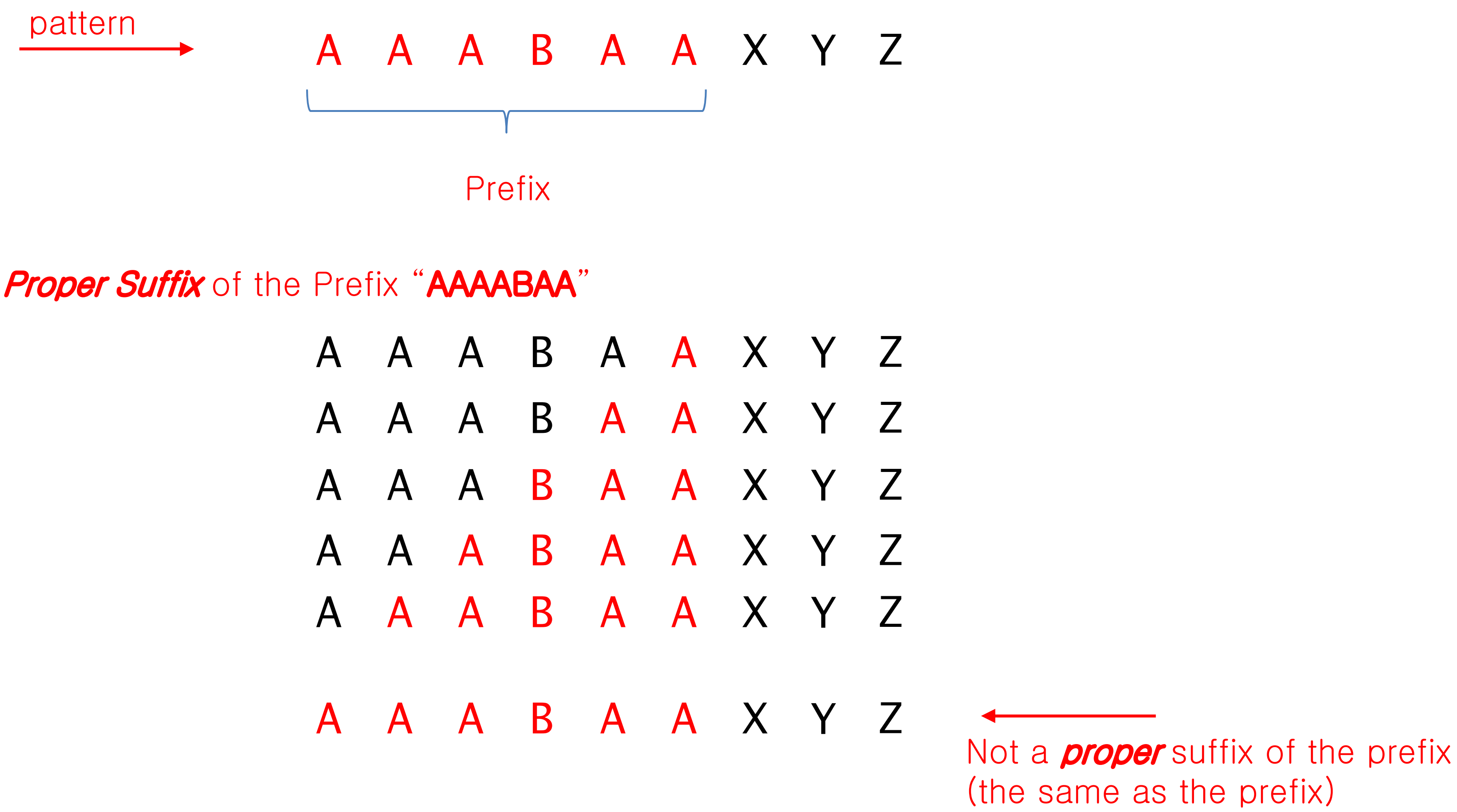
directly do this step

Next match starts at this position
No roll-back!!!

Slide the pattern 4 characters without missing a matching pattern

KMP Algorithm

- Prefix and Proper Suffix of the Prefix


pattern

A A A B A A X Y Z

Prefix

Proper Suffix of the Prefix "**AAAABAA**"

A A A B A A X Y Z

A A A B A A X Y Z

A A A B A A X Y Z

A A A B A A X Y Z

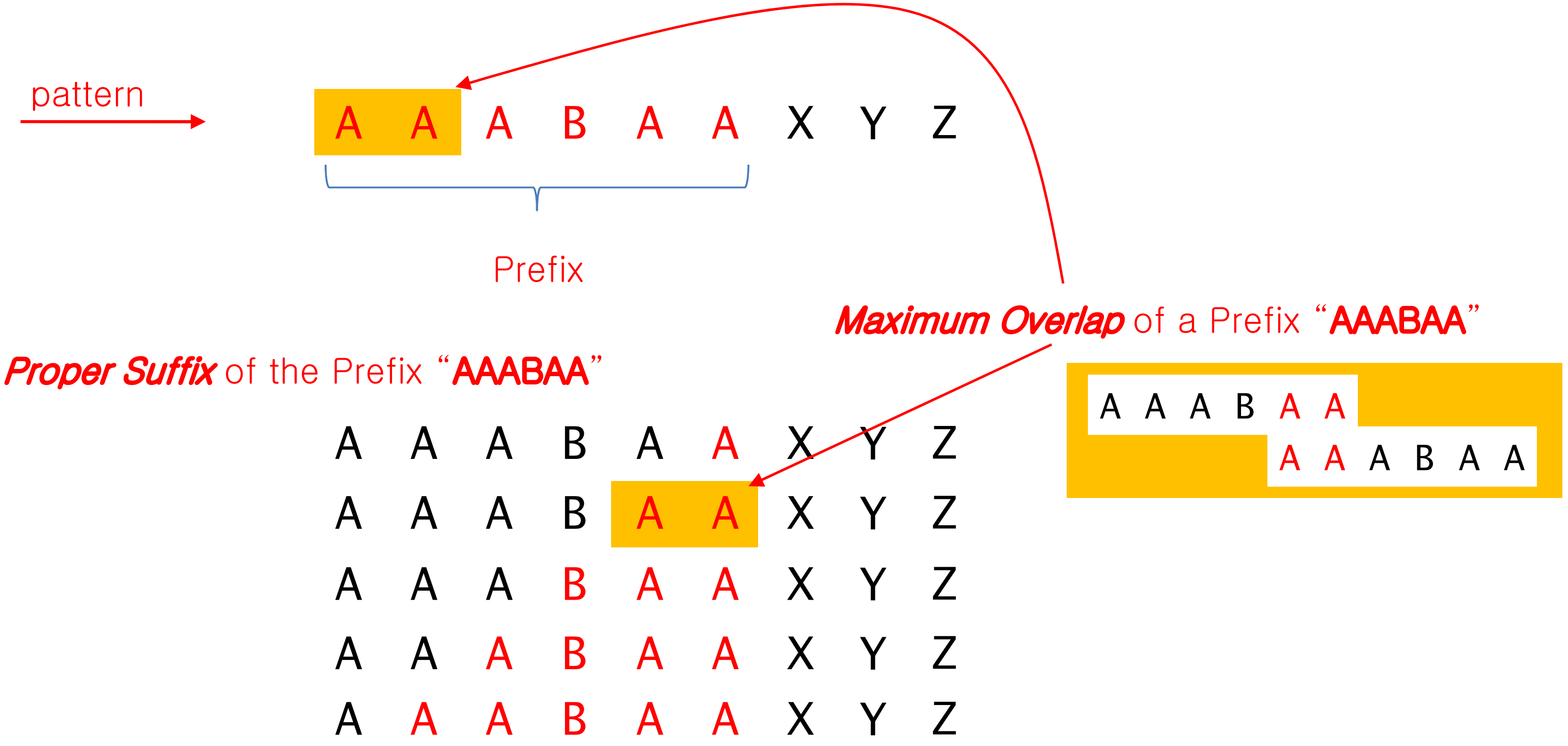
A A A B A A X Y Z

A A A B A A X Y Z

Not a *proper* suffix of the prefix
(the same as the prefix)

KMP Algorithm

- Maximum Overlap of a Prefix
  - the longest proper suffix that is equal to prefix of the prefix



KMP Algorithm

- Maximum Overlap of a Prefix
  - the longest proper suffix that is equal to prefix of the prefix

- Example:

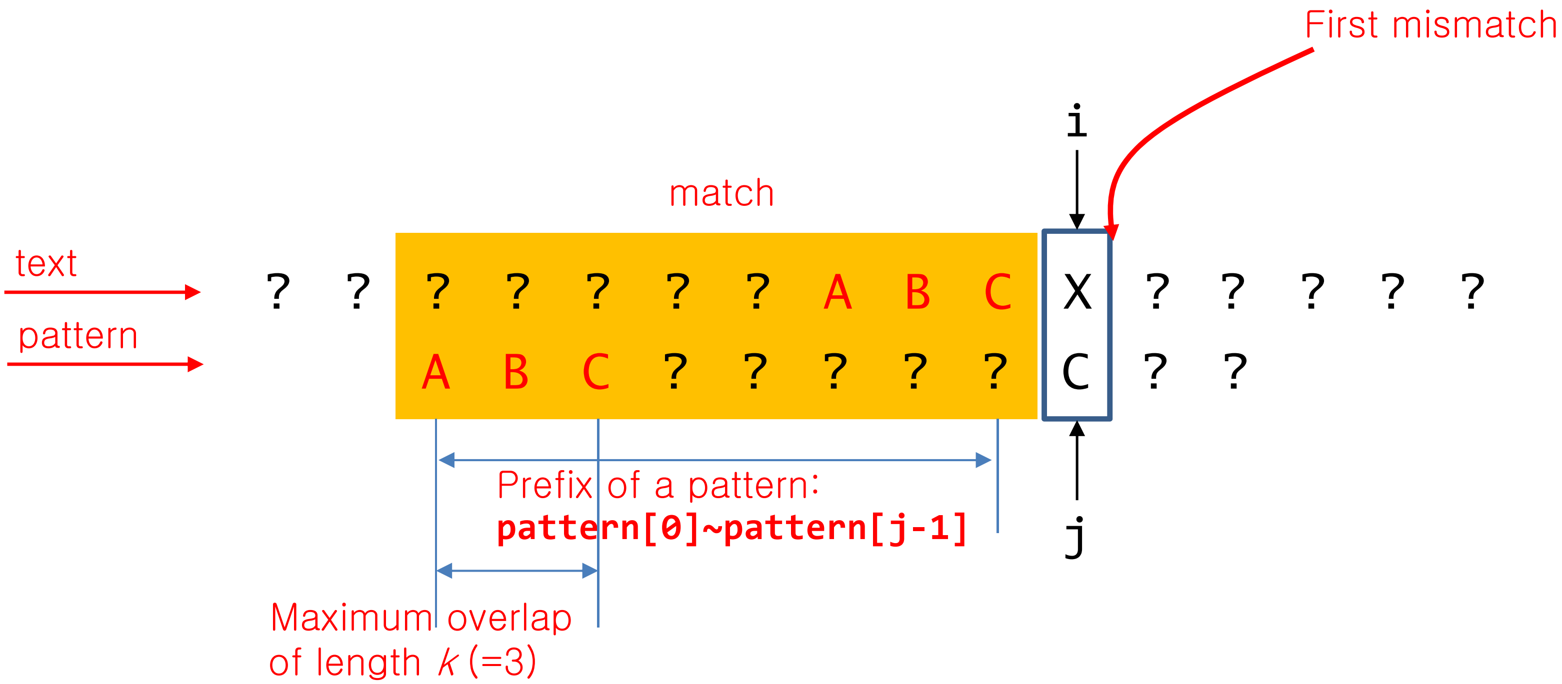
Prefix	Maximum Overlap
AAAAA	AAAA
AABA	A
AAAB	
ABABABAB	ABABAB

← not **AAAAA**

← NULL String

KMP Algorithm

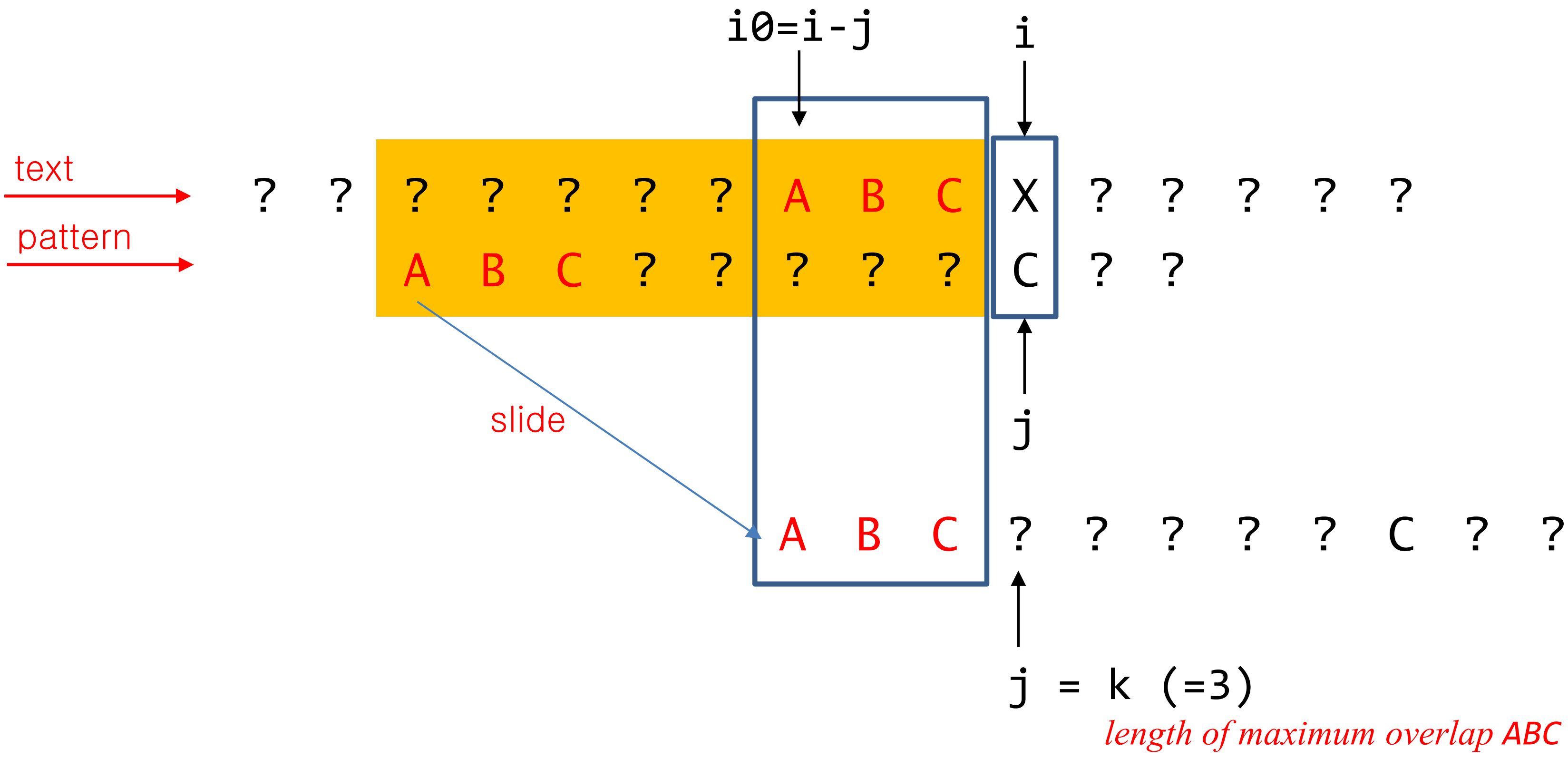
- Reuse of prefix information when there is a mismatch
  - Mismatch at `text[i]` and `pattern[j]`



Note that if the mismatched *location* is `pattern[j]`, then *prefix* is: `pattern[0]~pattern[j-1]`

KMP Algorithm

– Then we can slide the pattern so that the *suffix and prefix aligns without missing out on a match*:



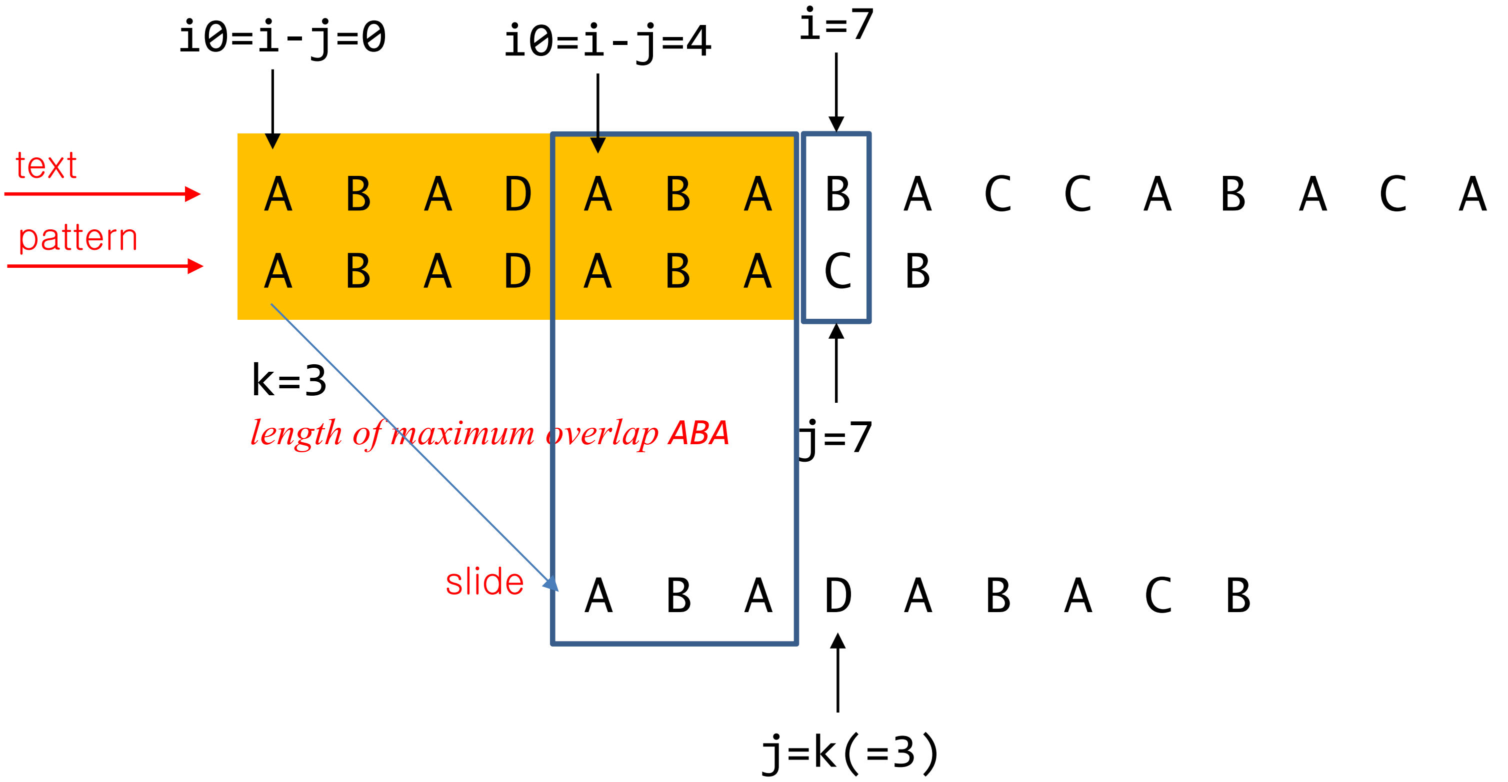
KMP Algorithm

- Fast sliding algorithm:
  - Psuedo program:

```
// mismatch found at text[i], pattern[j]

prefix = pattern[0] ~ pattern[j-1];

k = Length of maximum overlap of prefix;

j = k;
// i is unchanged !

// Matched position i0 in text starts from (i - j);
i0 = i – j;
```

KMP Algorithm

- Fast sliding algorithm:
  - Example:



i0=i-j=0

i0=i-j=4

i=7

text

pattern

A	B	A	D	A	B	A	B	A	C	C	A	B	A	C	A
A	B	A	D	A	B	A	C	B							

k=3

length of maximum overlap ABA

j=7

slide

A	B	A	D	A	B	A	C	B

j=k(=3)

KMP Algorithm

- Failure function:
  - M : the length of a pattern
  - For $0 < k < M$, the failure function $fail(k)$ is the length of maximum overlap of a prefix `pattern[0]` ~ `pattern[k]`
    - Note that $fail(0) = 0$

banabana

k	prefix	$fail(k)$
0	b	0
1	ba	0
2	ban	0
3	bana	0
4	banab	1
5	banaba	2
6	banaban	0
7	banabana	4

KMU 국민대학교 KOOKMIN UNIVERSITY

Algorithmic Engineering Laboratory

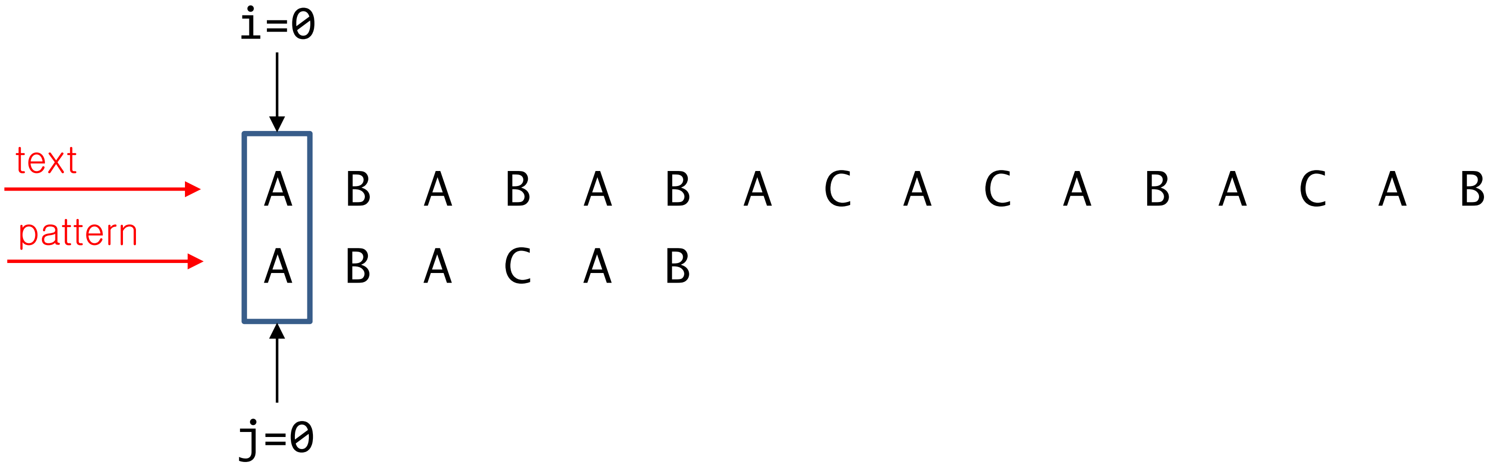
KMP Algorithm

- Knuth-Morris-Pratt(KMP) Algorithm

```
vector<int> kmp(string text, string pattern)
{
    vector<int> ans;
    fail = getFail(pattern);        // failure function
    int n = (int) text.size(), m = (int) pattern.size();
    int j =0;                       // j : index of pattern

    for(int i = 0 ; i < n ; i++)    // i : index of text
    {
        while(j>0 && text[i] != pattern[j])
            j = fail[j-1];
        if(text[i] == pattern[j])
            if(j==m-1)              // pattern matching is found
            {
                ans.push_back(i-j); // save the matched position
                j = fail[j];
            }
            else
                j++;
    }
    return ans;
}
```

KMP Algorithm

– Example:



i=0

text → A B A B A B A C A C A B A C A B

pattern → A B A C A B

j=0

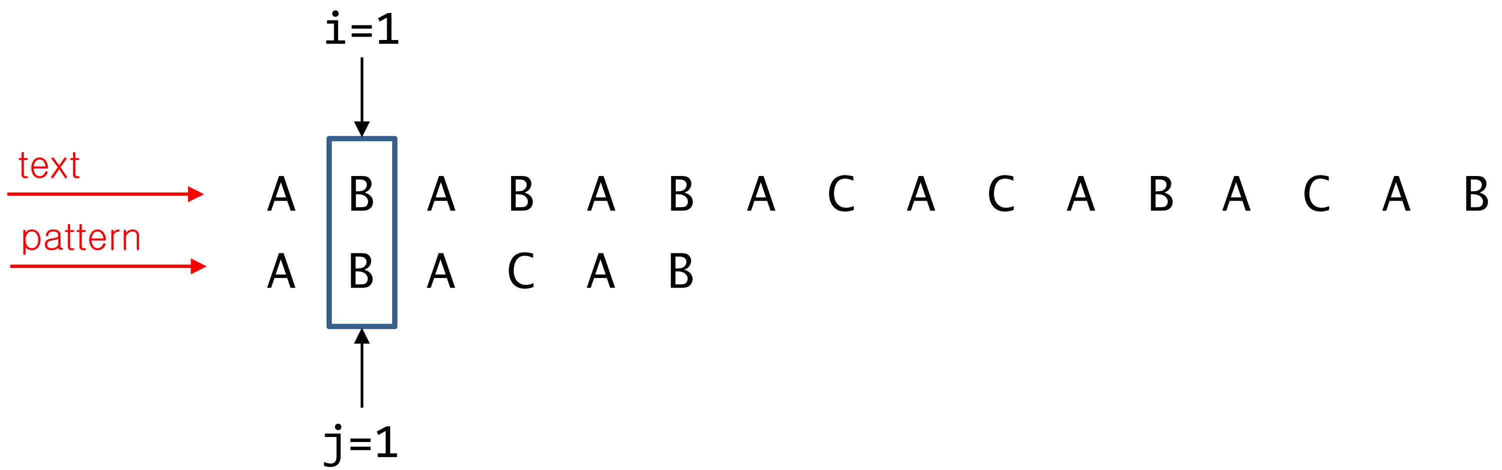
`text[i] == pattern[j]`

➔ `i++, j++`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



i=1

text

A B A B A B A C A C A B A C A B

pattern

A B A C A B

j=1

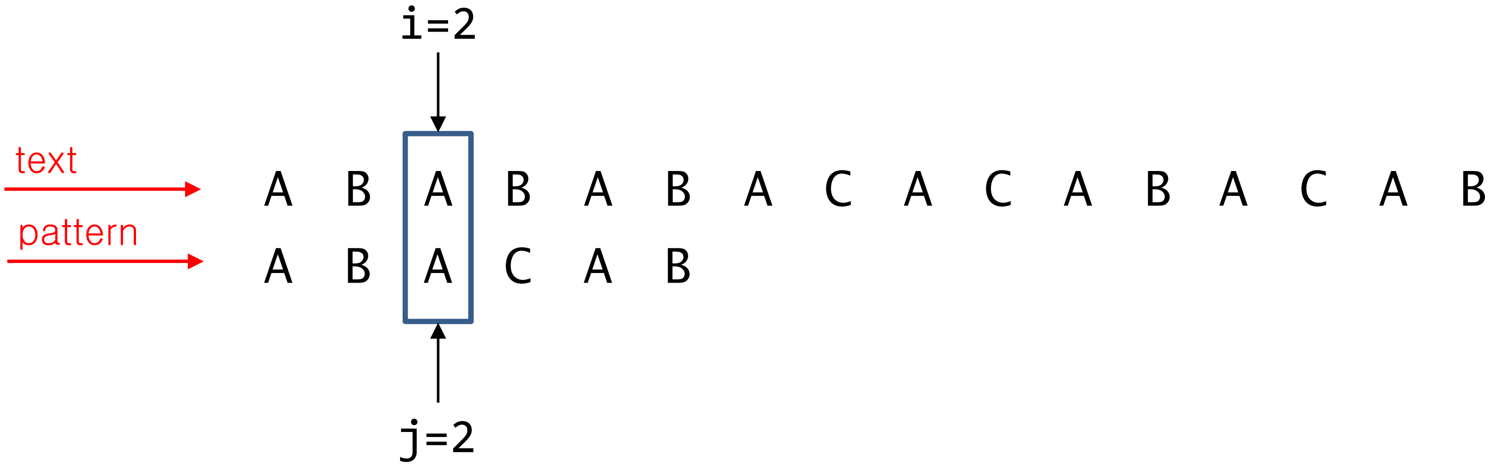
`text[i] == pattern[j]`

➔ `i++, j++`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



i=2

text

A B A B A B A C A C A B A C A B

pattern

A B A C A B

j=2

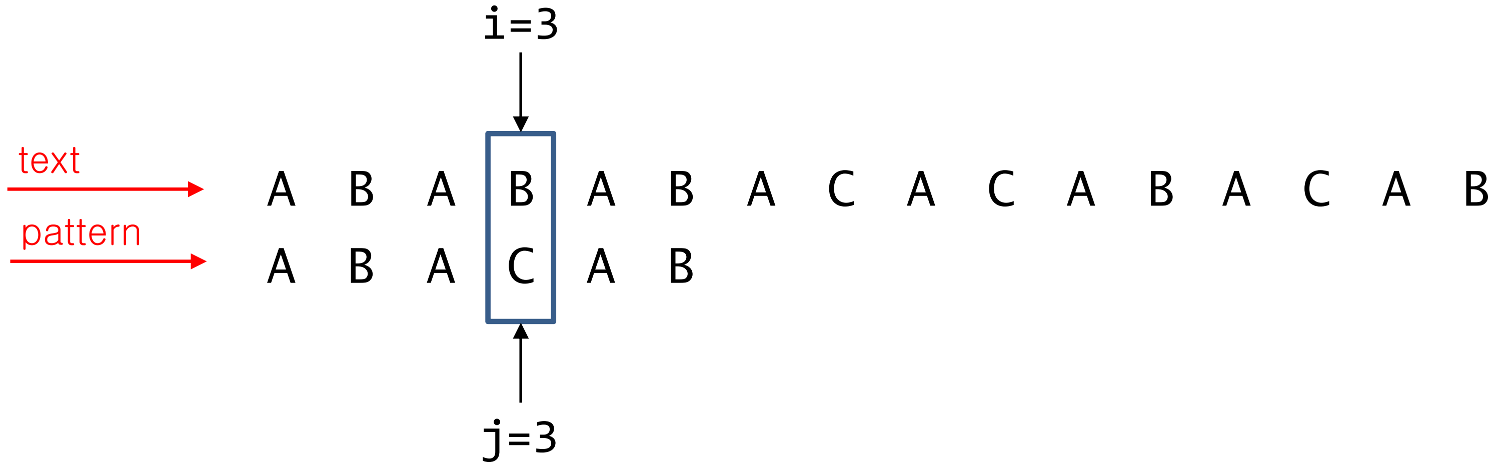
`text[i] == pattern[j]`

➔ `i++, j++`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



i=3

text A B A B A B A C A C A B A C A B

pattern A B A C A B

j=3

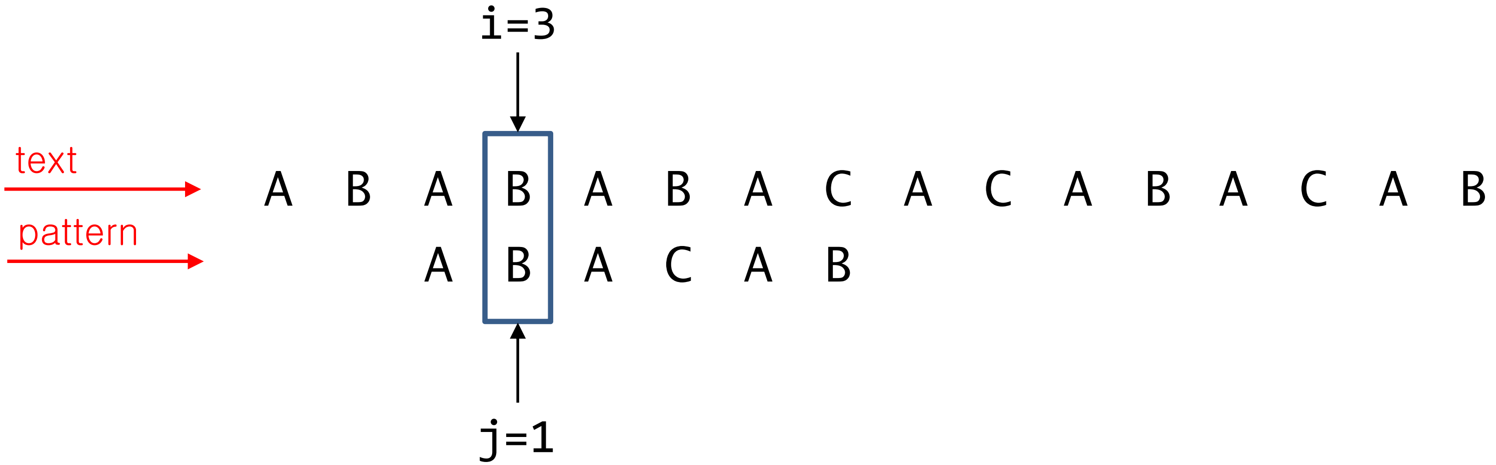
`text[i] != pattern[j]`

➔ `j = fail[j-1]`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:

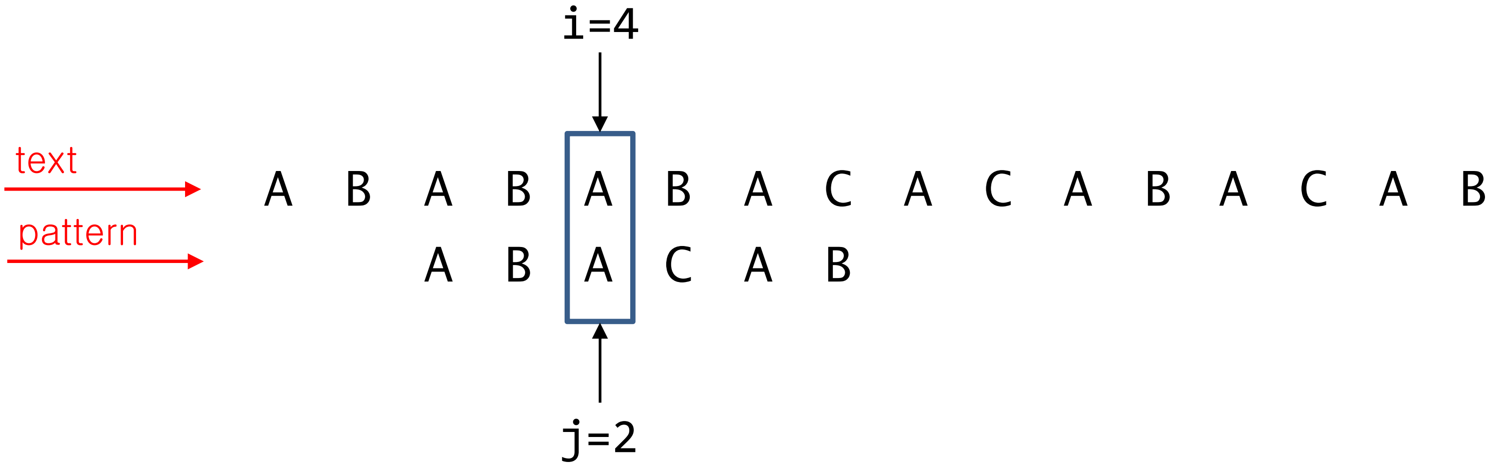


```
text[i] == pattern[j]

➔ i++, j++
```

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



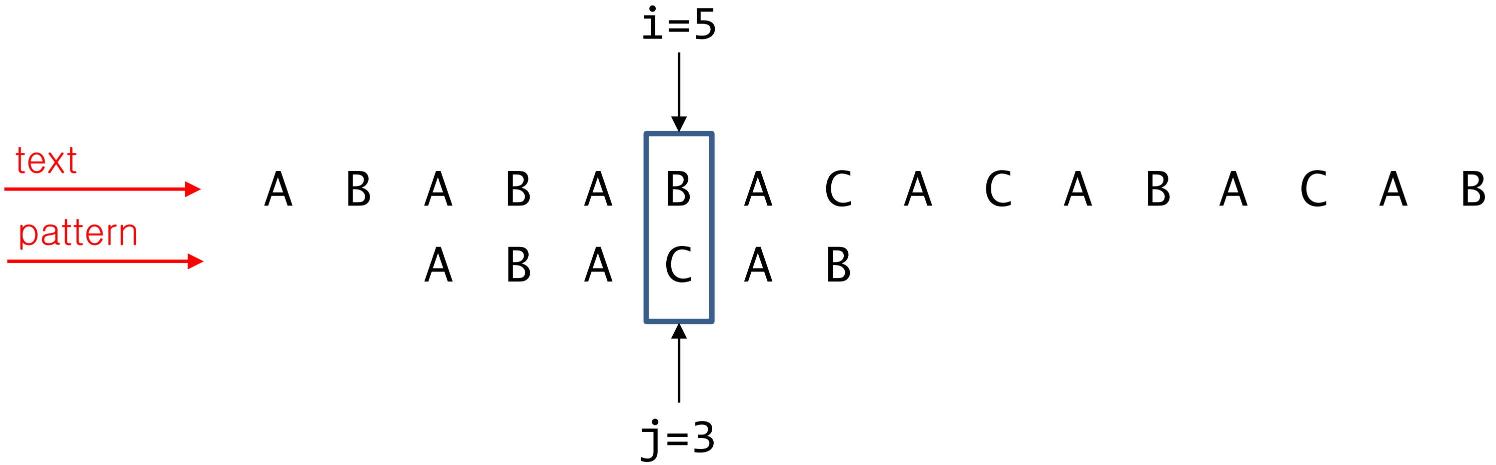
`text[i] == pattern[j]`

➔ `i++, j++`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



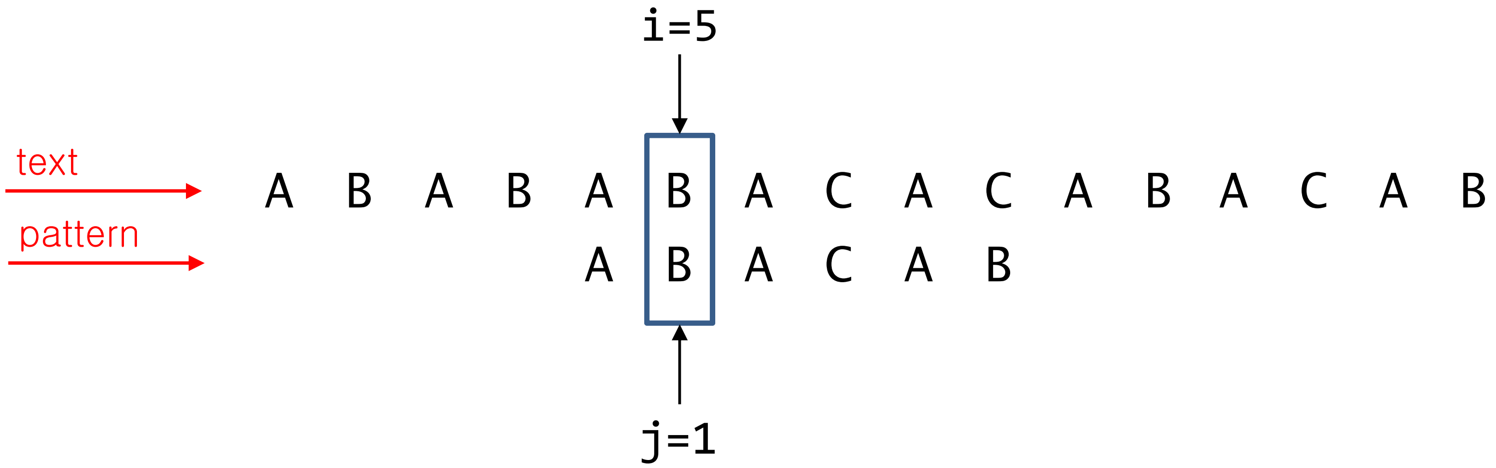
`text[i] != pattern[j]`

➔ `j = fail[j-1]`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



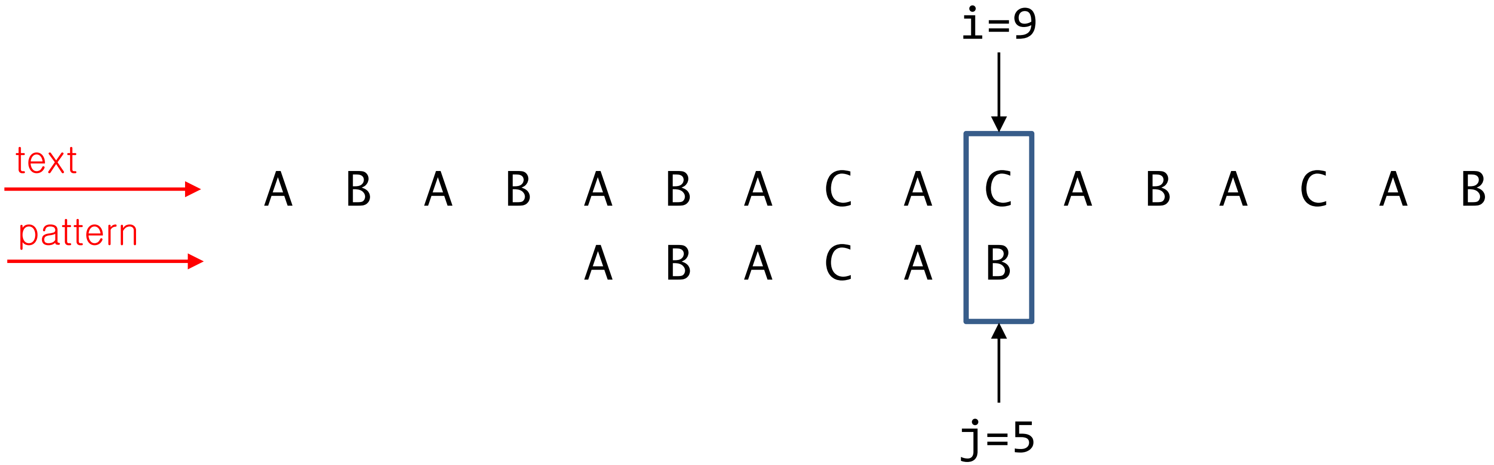
`text[i] == pattern[j]`

➔ `i++, j++`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



i=9

text

A B A B A B A C A C A B A C A B

pattern

A B A C A B

j=5

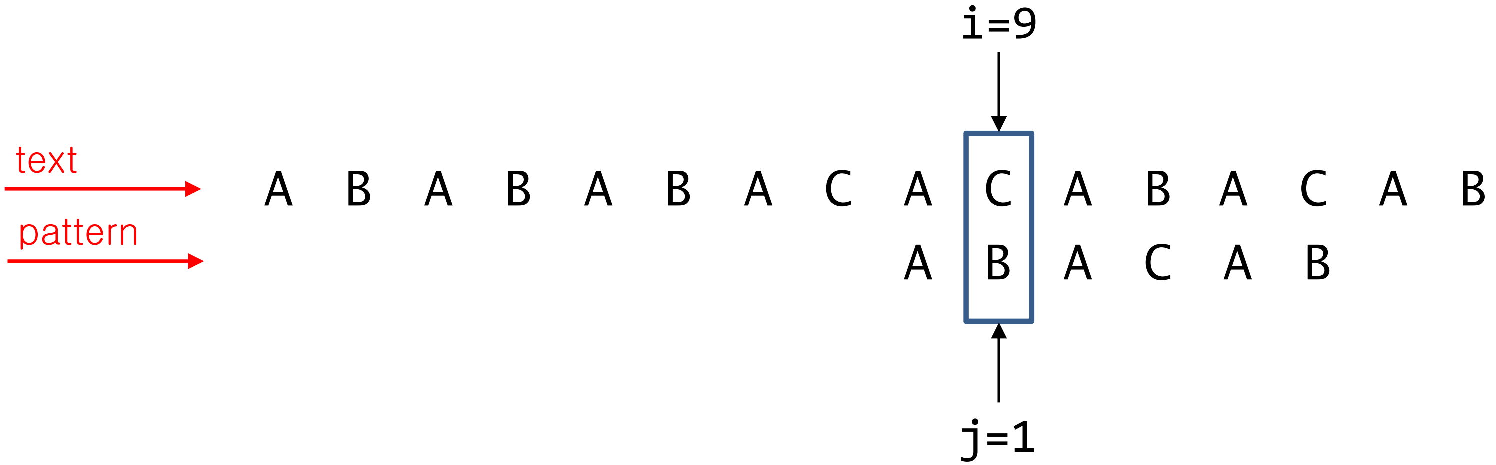
`text[i] != pattern[j]`

➔ `j = fail[j-1]`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

- Example:



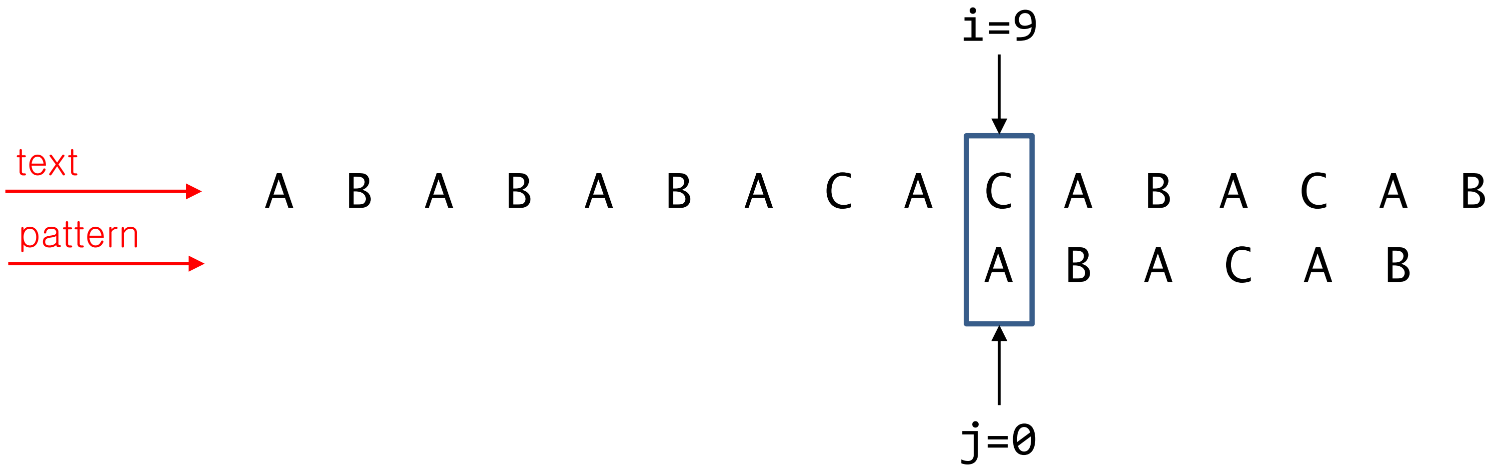
`text[i] != pattern[j]`

➔ `j = fail[j-1]`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



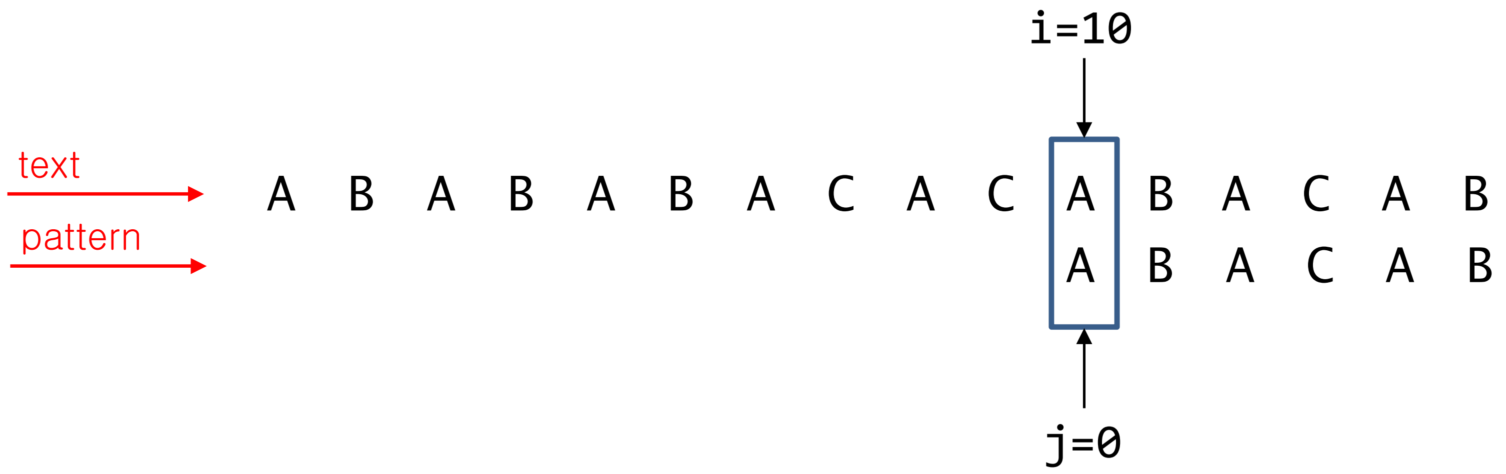
`j==0 && text[i] != pattern[j]`

➔ `i++`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



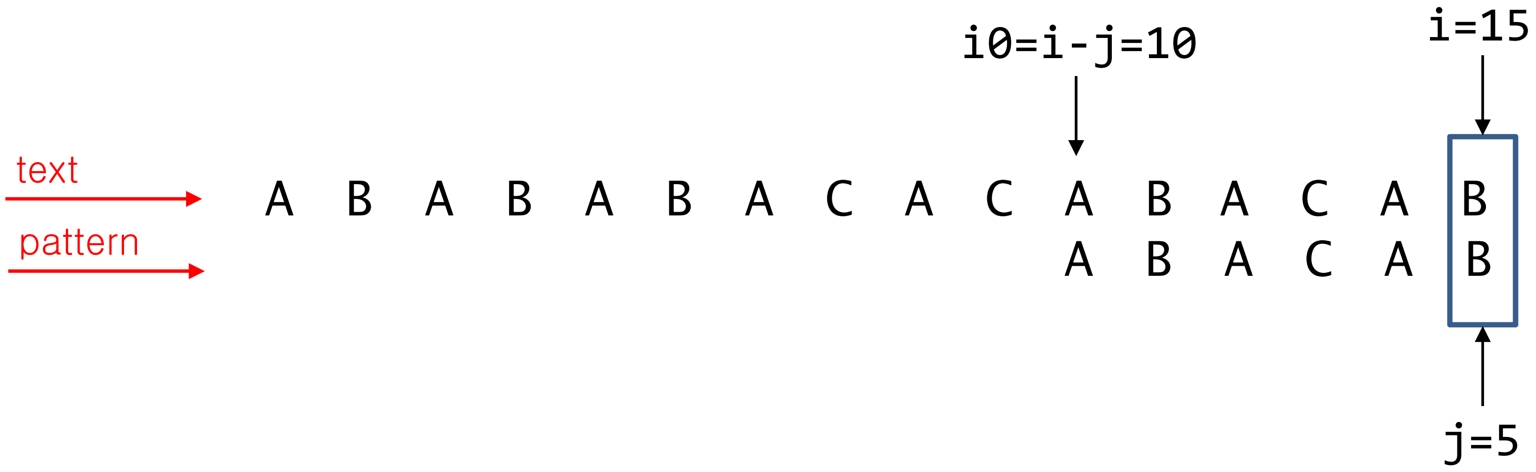
`text[i] == pattern[j]`

➔ `i++, j++`

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

– Example:



i0=i-j=10

i=15

text

pattern

A B A B A B A C A C A B A C A B

A B A C A B

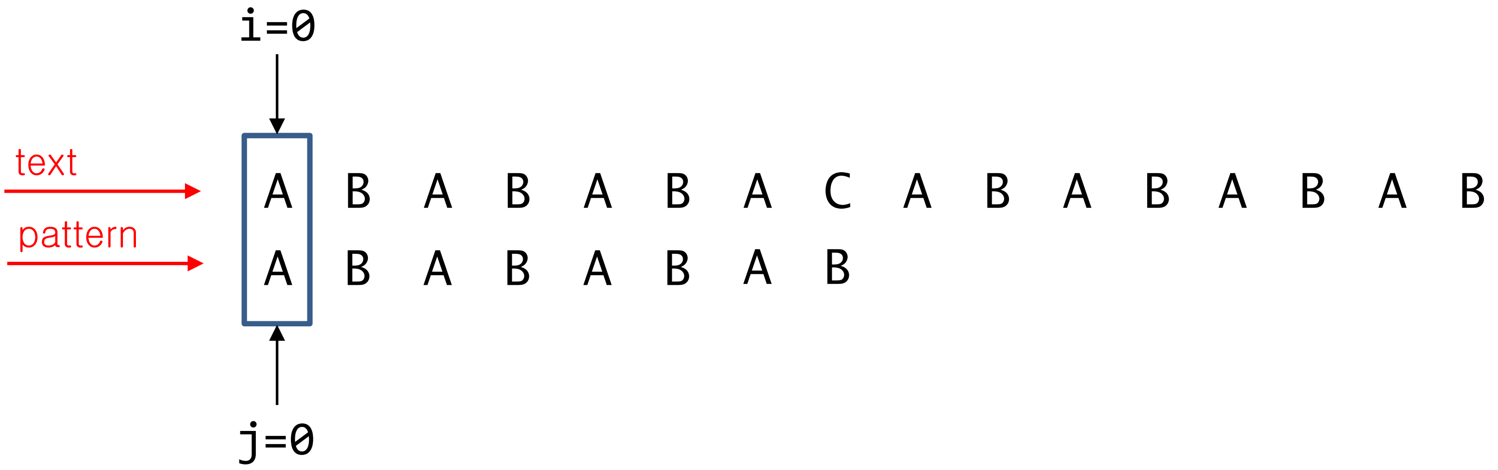
j=5

i	0	1	2	3	4	5
fail(i)	0	0	1	0	1	2

KMP Algorithm

- Knuth-Morris-Pratt(KMP) Algorithm
  - Why?

```
while(j>0 && text[i] != pattern[j])
        j = fail[j-1];
```



i=0

text A B A B A B A C A B A B A B A B

pattern A B A B A B A B

j=0

text[i] == pattern[j]

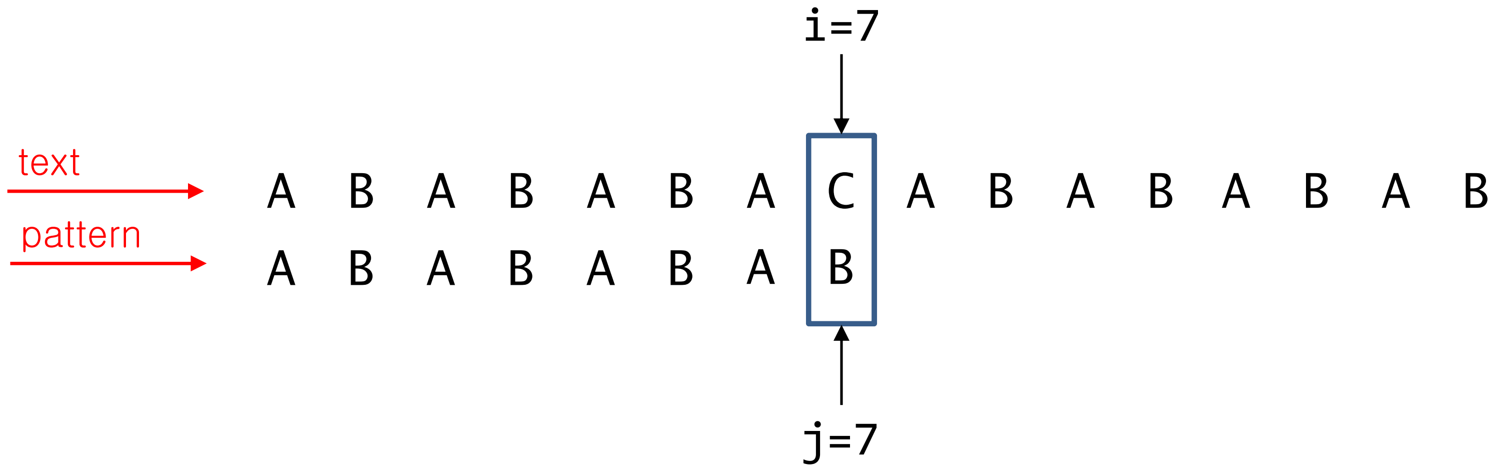
➔ i++, j++

i	0	1	2	3	4	5	6	7
fail(i)	0	0	1	2	3	4	5	0

KMP Algorithm

- Knuth-Morris-Pratt(KMP) Algorithm
  - Why?

```
while(j>0 && text[i] != pattern[j])
        j = fail[j-1];
```



i=7

text → A B A B A B A C A B A B A B A B

pattern → A B A B A B A B

j=7

text[i] != pattern[j]

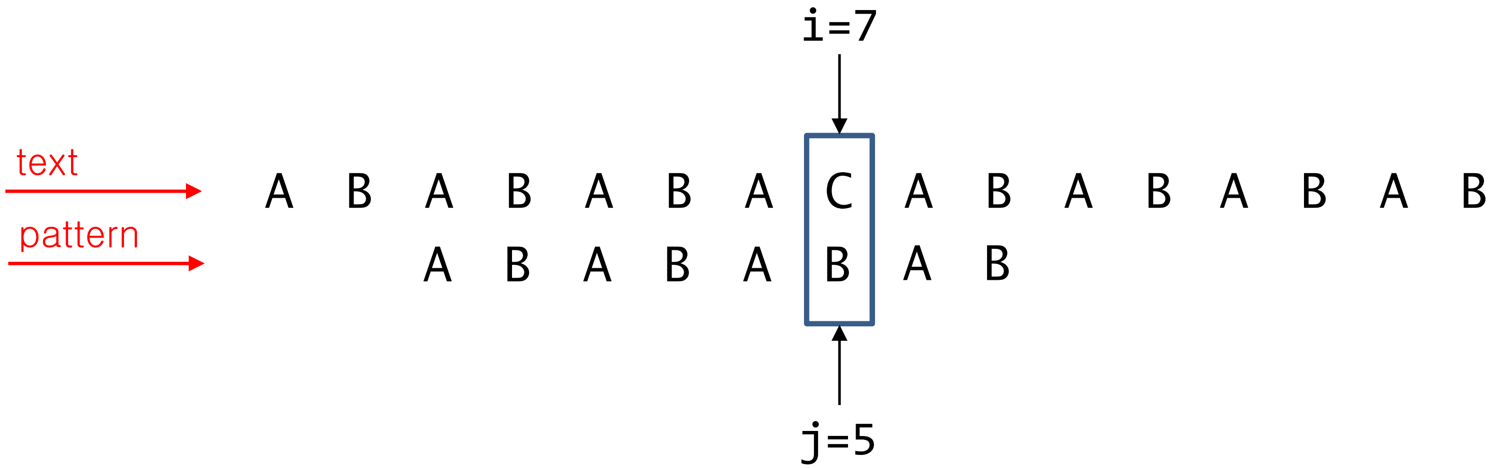
➔ j = fail[j-1]

i	0	1	2	3	4	5	6	7
fail(i)	0	0	1	2	3	4	5	0

KMP Algorithm

- Knuth-Morris-Pratt(KMP) Algorithm
  - Why?

```
while(j>0 && text[i] != pattern[j])
        j = fail[j-1];
```



i=7

text → A B A B A B A C A B A B A B A B

pattern → A B A B A B A B

j=5

text[i] != pattern[j]

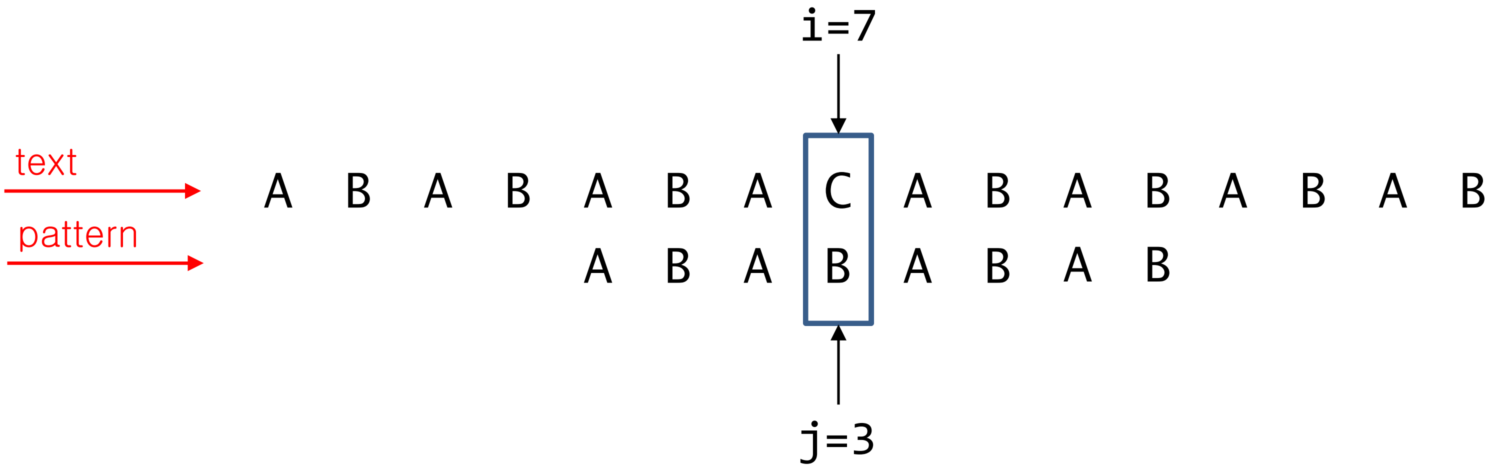
➔ j = fail[j-1]

i	0	1	2	3	4	5	6	7
fail(i)	0	0	1	2	3	4	5	0

KMP Algorithm

- Knuth-Morris-Pratt(KMP) Algorithm
  - Why?

```
while(j>0 && text[i] != pattern[j])
        j = fail[j-1];
```



i=7

text → A B A B A B A C A B A B A B A B

pattern → A B A B A B A B

j=3

`text[i] != pattern[j]`

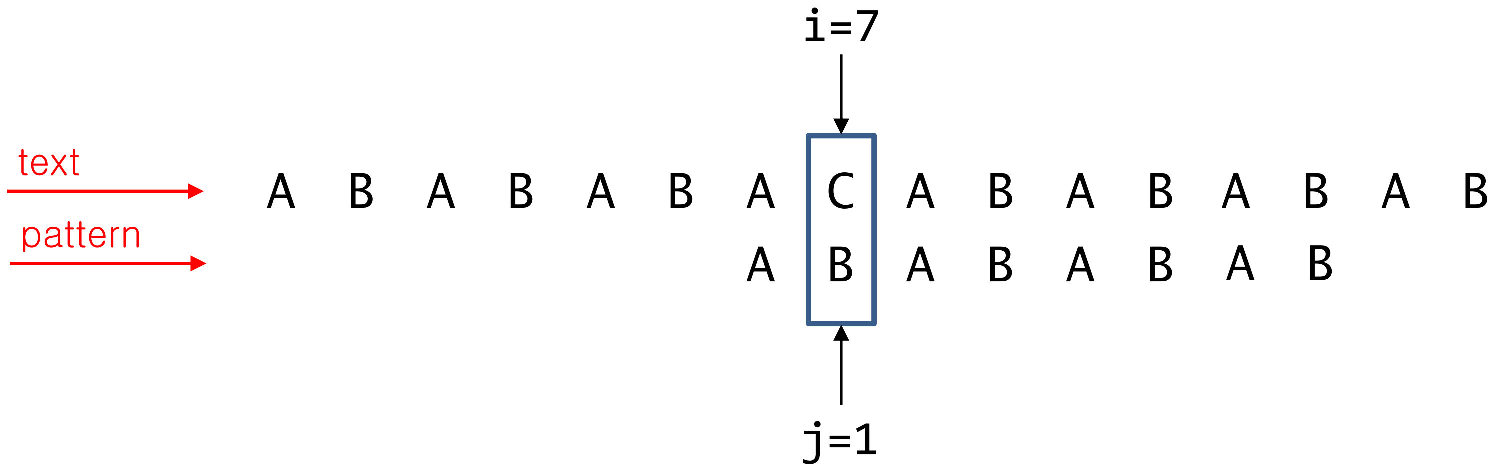
➔ `j = fail[j-1]`

i	0	1	2	3	4	5	6	7
fail(i)	0	0	1	2	3	4	5	0

KMP Algorithm

- Knuth-Morris-Pratt(KMP) Algorithm
  - Why?

```
while(j>0 && text[i] != pattern[j])
        j = fail[j-1];
```



text[i] != pattern[j]

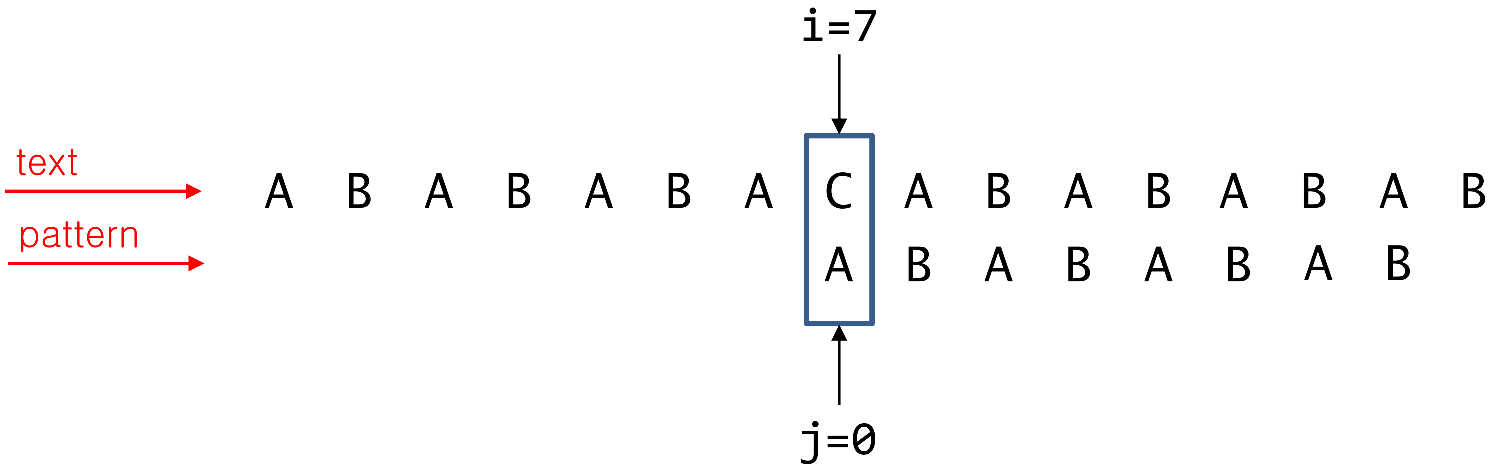
➔ j = fail[j-1]

i	0	1	2	3	4	5	6	7
fail(i)	0	0	1	2	3	4	5	0

KMP Algorithm

- Knuth-Morris-Pratt(KMP) Algorithm
  - Why?

```
while(j>0 && text[i] != pattern[j])
        j = fail[j-1];
```



`text[i] != pattern[j]`

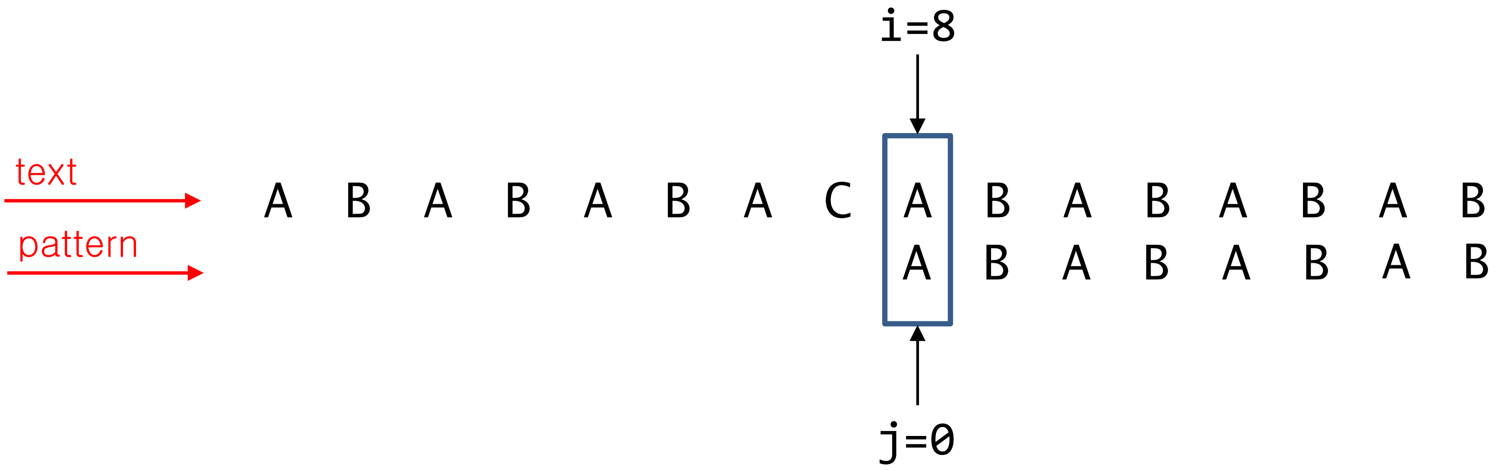
➔ `j = fail[j-1]`

i	0	1	2	3	4	5	6	7
fail(i)	0	0	1	2	3	4	5	0

KMP Algorithm

- Knuth-Morris-Pratt(KMP) Algorithm
  - Why?

```
while(j>0 && text[i] != pattern[j])
        j = fail[j-1];
```



j==0 && text[i] != pattern[j]

➔ i++

i	0	1	2	3	4	5	6	7
fail(i)	0	0	1	2	3	4	5	0

KMP Algorithm

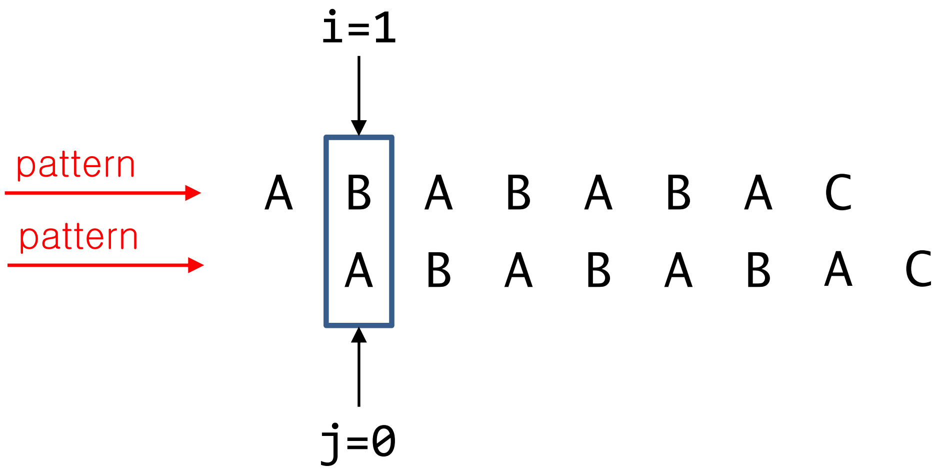
- `getFail()` function
  - Simple `fail[]` computation needs $O(M^3)$ time.
  - $O(M)$ time algorithm: very similar to KMP algorithm itself

```
vector<int> getFail(string pattern)
{
    int m = (int) pattern.size();
    int j=0;
    vector<int> fail(m, 0);

    for(int i = 1; i< m ; i++)
    {
        while(j > 0 && pattern[i] != pattern[j])
            j = fail[j-1];
        if(pattern[i] == pattern[j])
            fail[i] = ++j;
    }
    return fail;
}
```

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0						



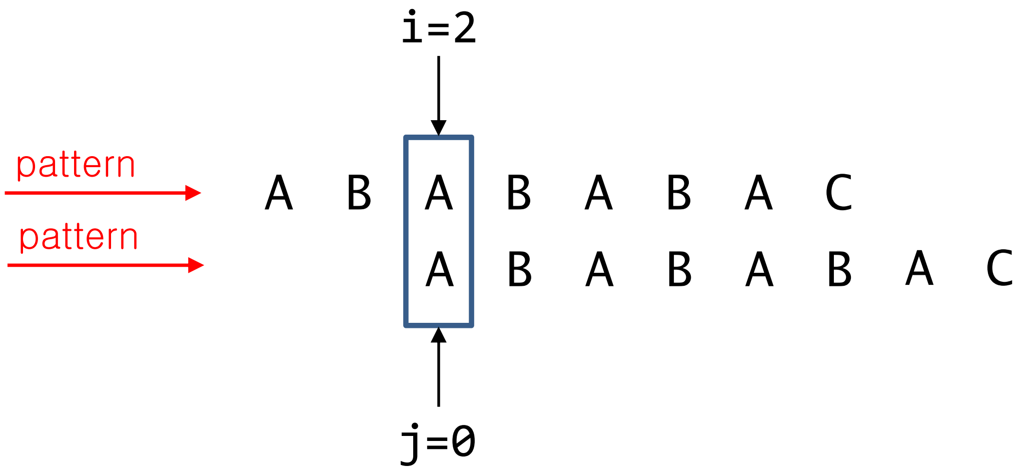
`pattern[i] != pattern[j]`

➔ `fail[i] = 0 // initial value`
`i++`

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1					



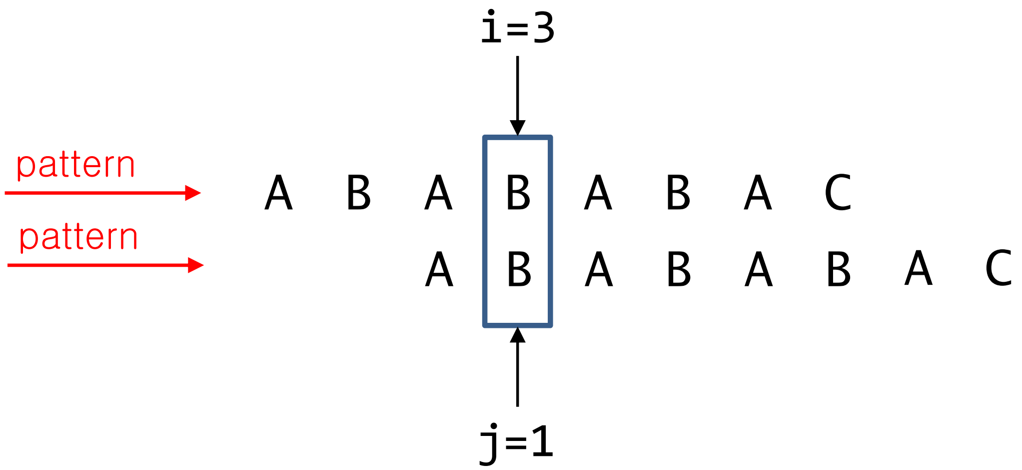
`pattern[i] == pattern[j]`

➔ `fail[i] = ++j`
`i++`

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1	**2**				



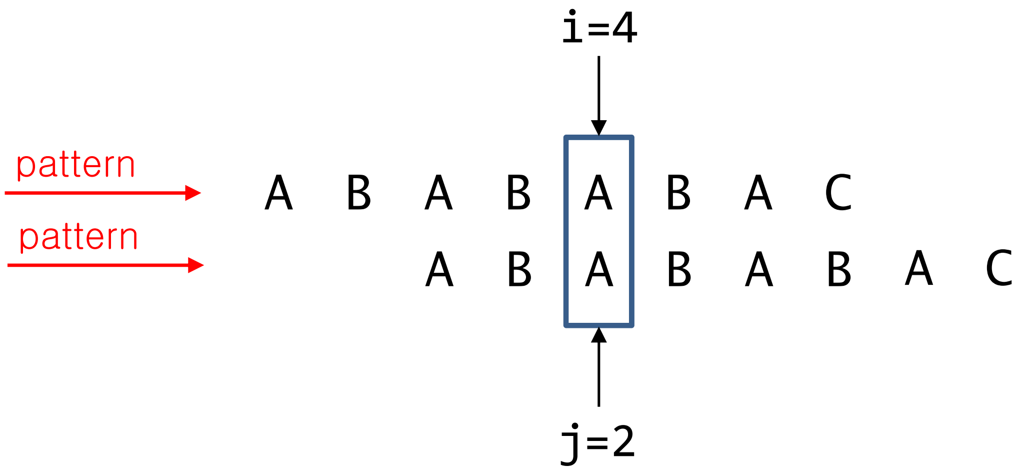
`pattern[i] == pattern[j]`

➔ `fail[i] = ++j`
`i++`

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1	2	3			



i=4

pattern → A B A B A B A C

pattern → A B A B A B A C

j=2

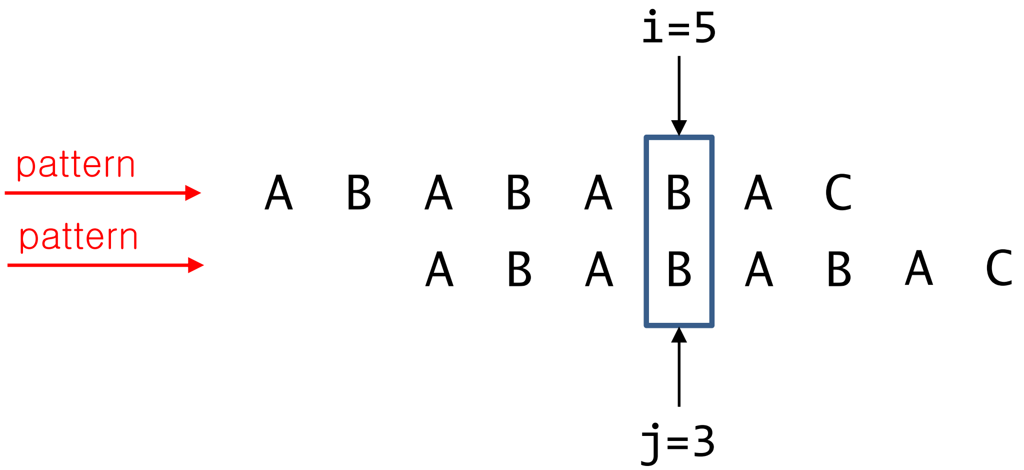
`pattern[i] == pattern[j]`

→ `fail[i] = ++j`
`i++`

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1	2	3	**4**		



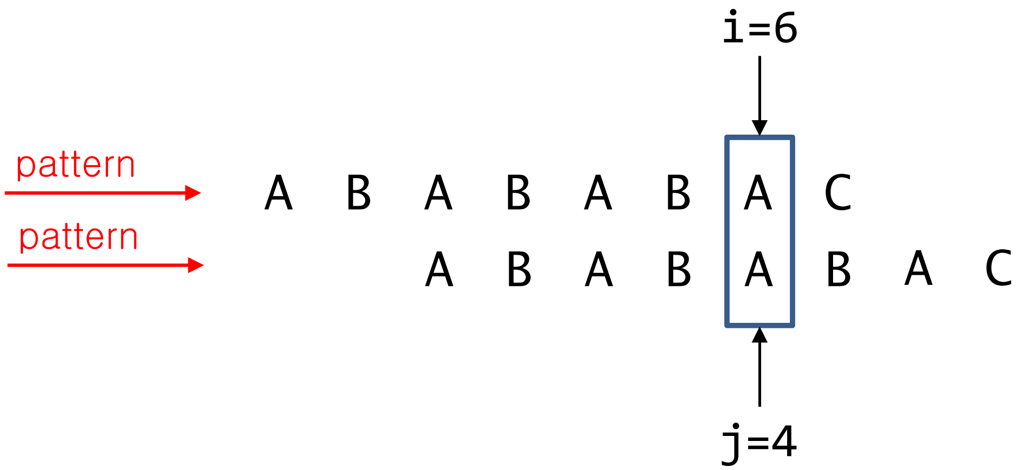
`pattern[i] == pattern[j]`

➔ `fail[i] = ++j`
`i++`

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1	2	3	4	**5**	



i=6

pattern → A B A B A B A C

pattern → A B A B A B A C

j=4

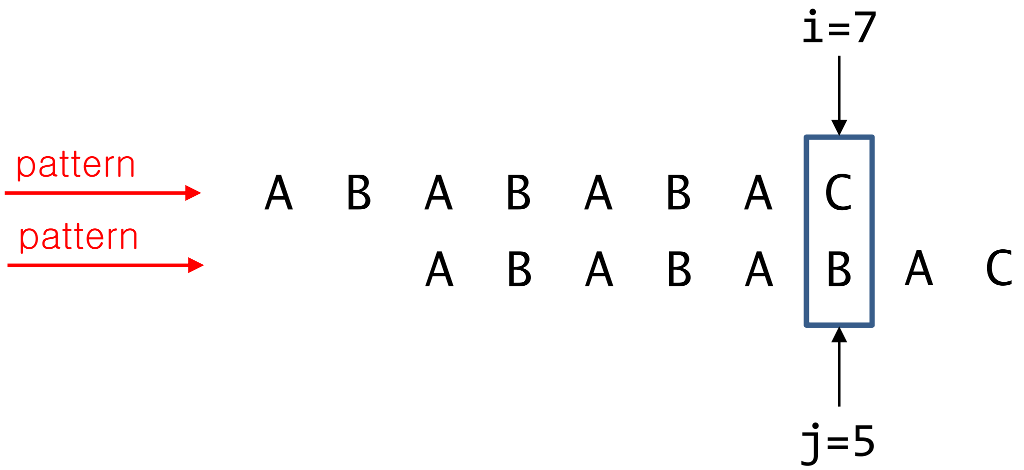
`pattern[i] == pattern[j]`

```
➔ fail[i] = ++j
  i++
```

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1	2	3	4	**5**	



i=7

pattern → A B A B A B A C

pattern → A B A B A B A C

j=5

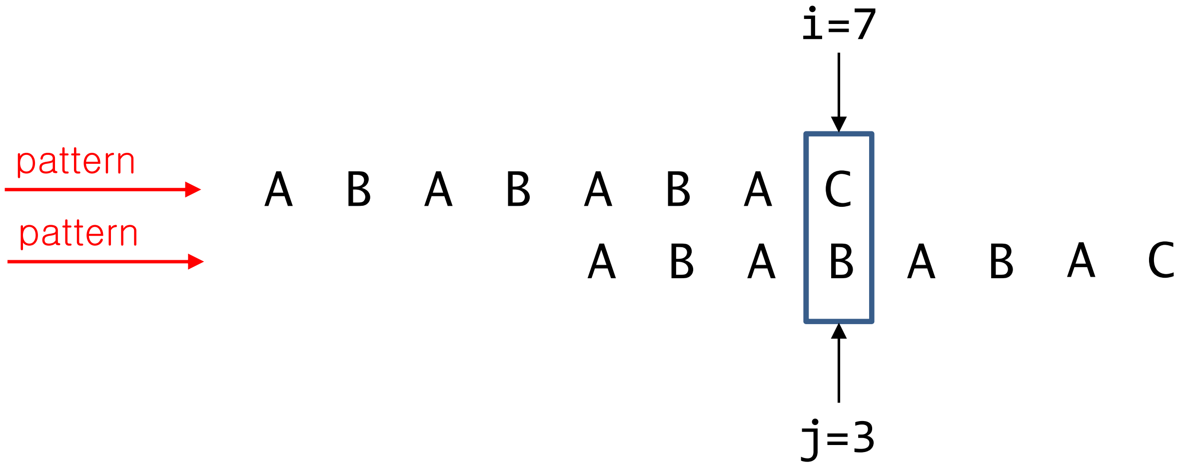
`pattern[i] != pattern[j]`

➔ `j = fail[j-1] (=3)`

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1	2	3	4	**5**	



i=7

pattern → A B A B A B A C

pattern → A B A B A B A C

j=3

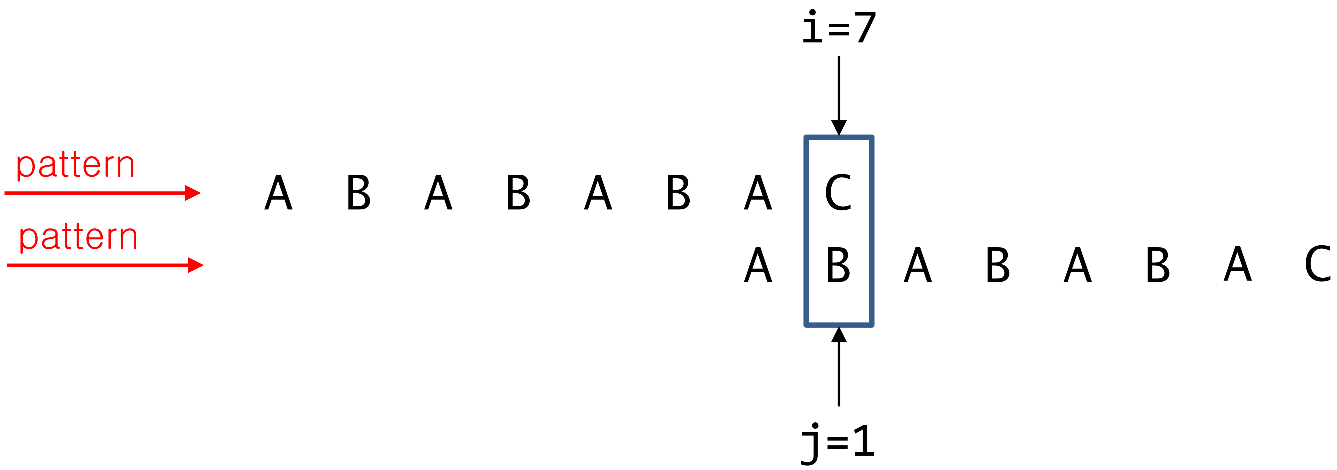
`pattern[i] != pattern[j]`

➔ `j = fail[j-1] (=1)`

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1	2	3	4	**5**	



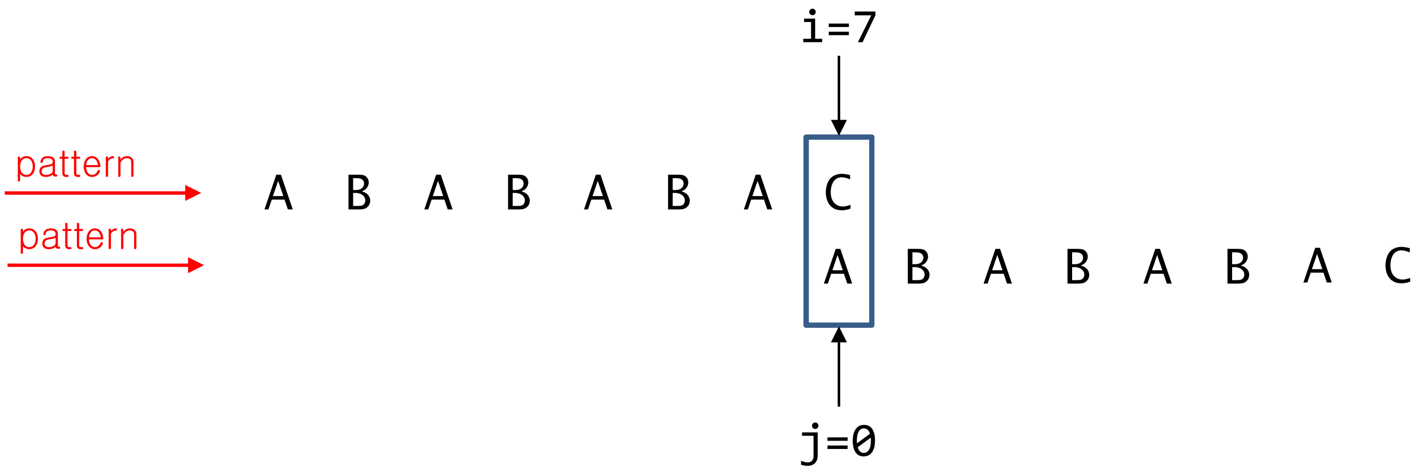
`pattern[i] != pattern[j]`

➔ `j = fail[j-1] (=1)`

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1	2	3	4	5	**0**



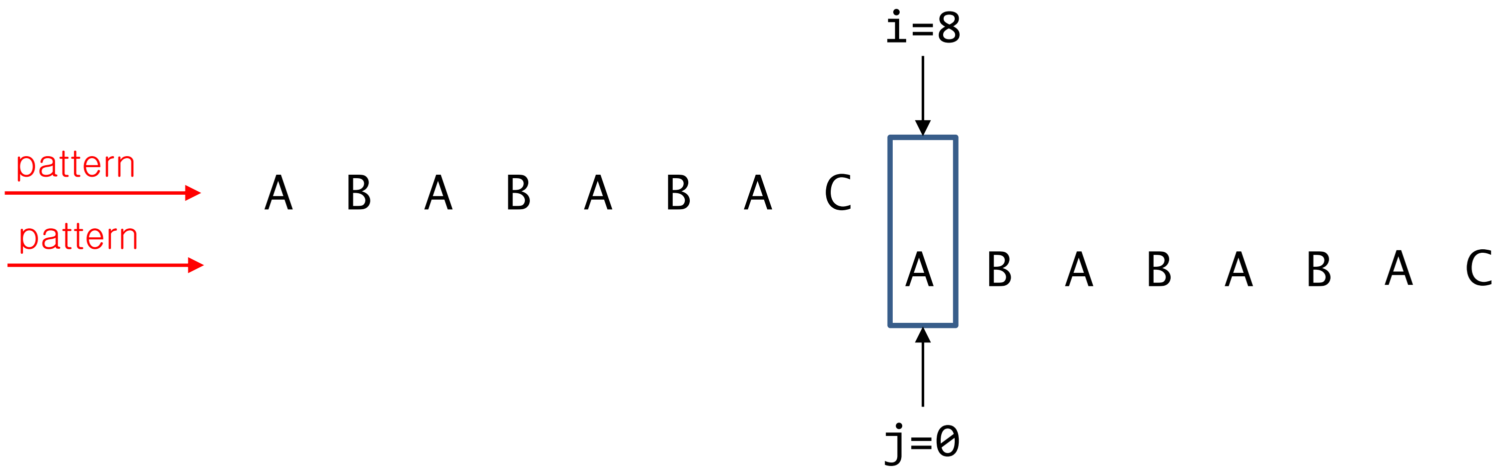
`pattern[i] != pattern[j]`

➔ `j = fail[j-1] (=0)`

KMP Algorithm

- `getFail()` function
  - Example:

i	0	1	2	3	4	5	6	7
fail[i]	0	0	1	2	3	4	5	0



i++

KMP Algorithm

- `getFail()` function
  - Example: `aabaabac`

i	0	1	2	3	4	5	6	7
fail[i]	0	1	0	1	2	3	4	0

페일함수 의미 : 프리픽스와 같은 방식(?))

KMP Algorithm

- `getFail()` function
  - Why $O(M)$?
    - Index `i` increases from 1 to M-1
    - Index `j` *increases* maximally as many as `i` increases
    - Also index `j` *decreases* maximally as many as `j` increases

- KMP algorithm
  - Why $O(N)$ algorithm?
    - Similar logic to get the time complexity of `getFail()` function