Mansoura University
Faculty of Computers and Information
Department of Computer Science
First Semester: 2020-2021

[MED121] Bioinformatics: Boyer Moore Algorithm

Grade: Third Year (Medical Informatics Program)

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AGENDA

- Boyer Moore Algorithm (Bad Character Rule)
- Boyer Moore Algorithm (Good Suffix Rule)
- Boyer Moore Algorithm (Strong Good Suffix Rule)
- Boyer Moore Algorithm (All Together)
- Boyer Moore Algorithm (Algorithm Code and Trace)

BOYER MOORE ALGORITHM

- Boyer Moore is a combination of two approaches:
  - Bad Character Rule
  - Good Suffix Rule

- Naïve algorithm slides the pattern P over the text T one by one.

- Boyer Moore does preprocessing over the pattern so that the pattern can be shifted by more than one.

BOYER MOORE ALGORITHM (BAD CHARACTER RULE)

- The character of the text which doesn't match with the current character of pattern is called the Bad Character.

```
0  1  2  3  4  5  6  7  8  9  10 11 12 13 14 15
G  C  A  A  T  G  C  C  T  A  T  G  T  G  A  C
T  A  T  G  T  G
```

BOYER MOORE ALGORITHM (BAD CHARACTER RULE)

- The character of the text which doesn't match with the current character of pattern is called the Bad Character.

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
G	C	A	A	T	G	C	C	T	A	T	G	T	G	A	C
T	A	T	G	T	G										

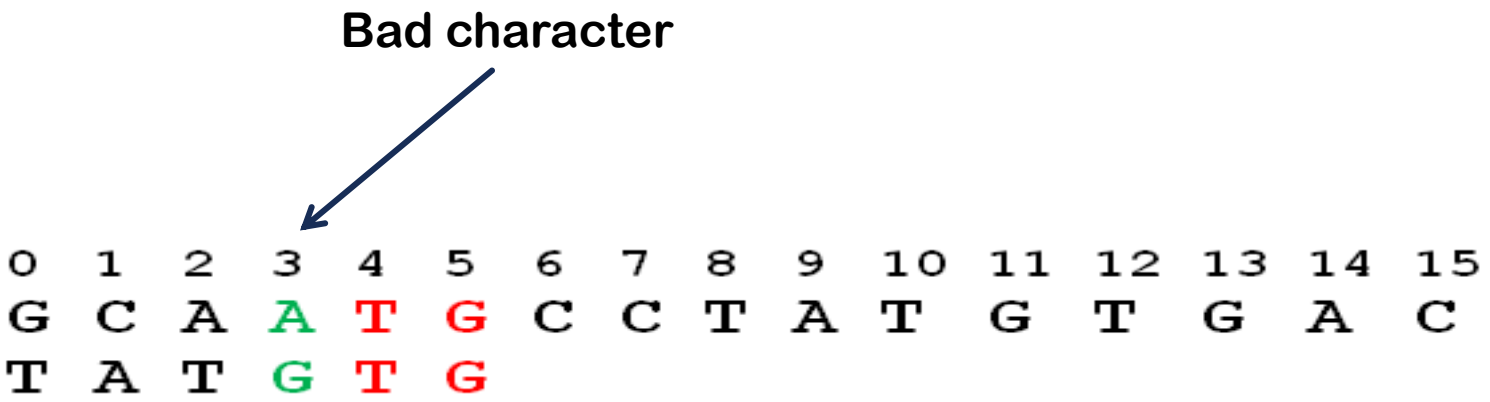
BOYER MOORE ALGORITHM (BAD CHARACTER RULE)

- The character of the text which doesn't match with the current character of pattern is called the Bad Character.

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
G	C	A	A	T	G	C	C	T	A	T	G	T	G	A	C
T	A	T	G	T	G										

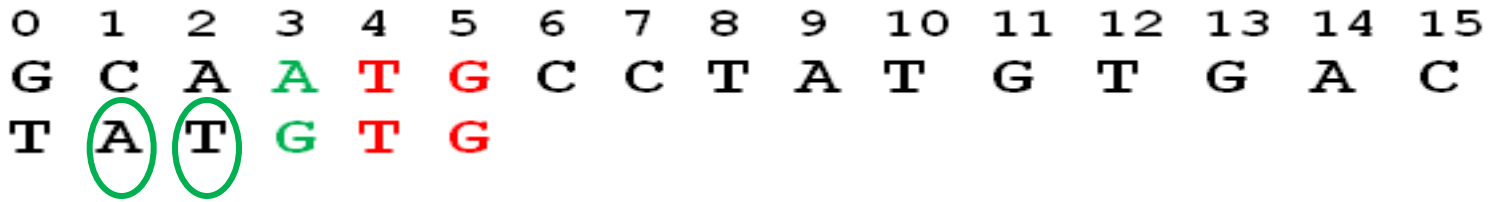
BOYER MOORE ALGORITHM (BAD CHARACTER RULE)

- The character of the text which doesn't match with the current character of pattern is called the Bad Character.



BOYER MOORE ALGORITHM (BAD CHARACTER RULE)

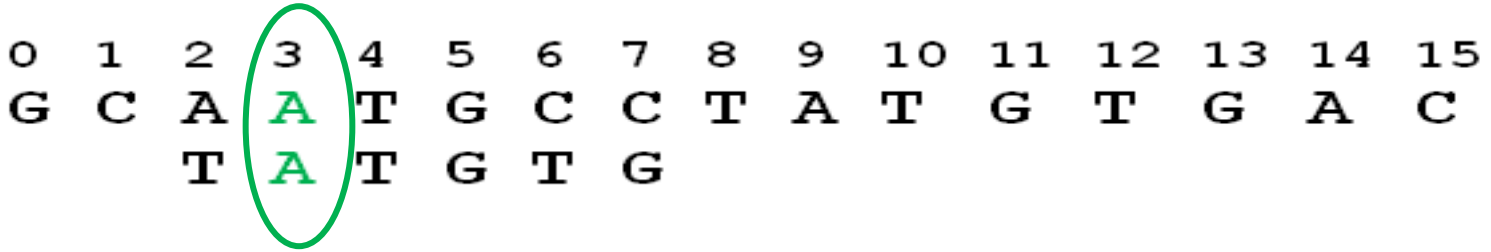
- Upon mismatch we shift the pattern until:
  - The mismatch become a match.



✓ The pattern is shifted by 2 positions (n).
✓ We skip 1 alignment (n-1).

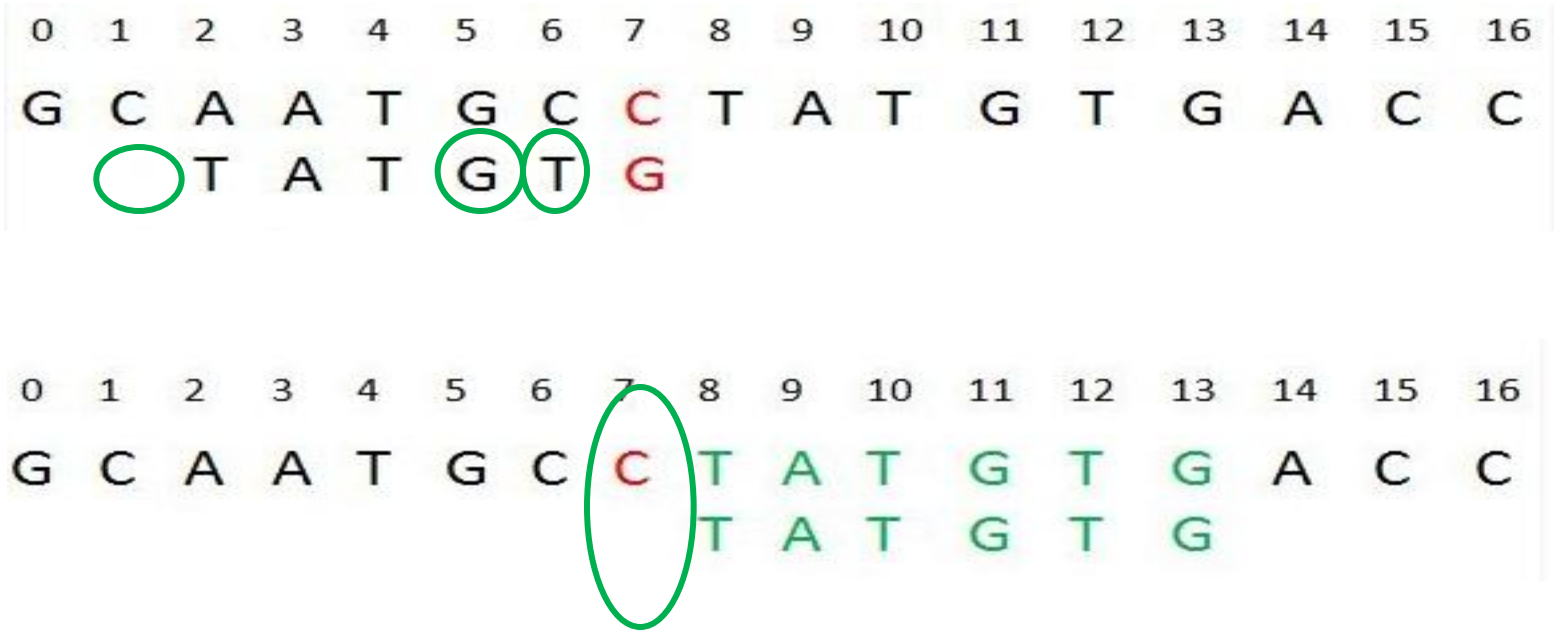
BOYER MOORE ALGORITHM (BAD CHARACTER RULE)

- Upon mismatch we shift the pattern until:
  - The mismatch become a match.



BOYER MOORE ALGORITHM (BAD CHARACTER RULE)

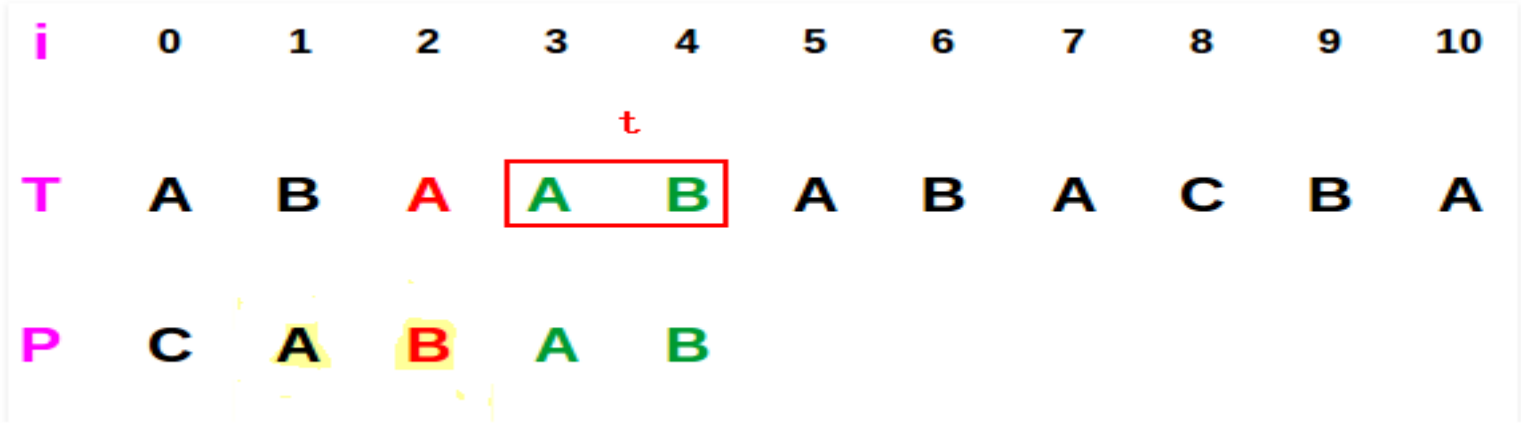
- Upon mismatch we shift the pattern until:
  - Pattern P moves past the mismatched character.



✓ The pattern is shifted by 6 positions (n).
✓ We skip 5 alignment (n-1).

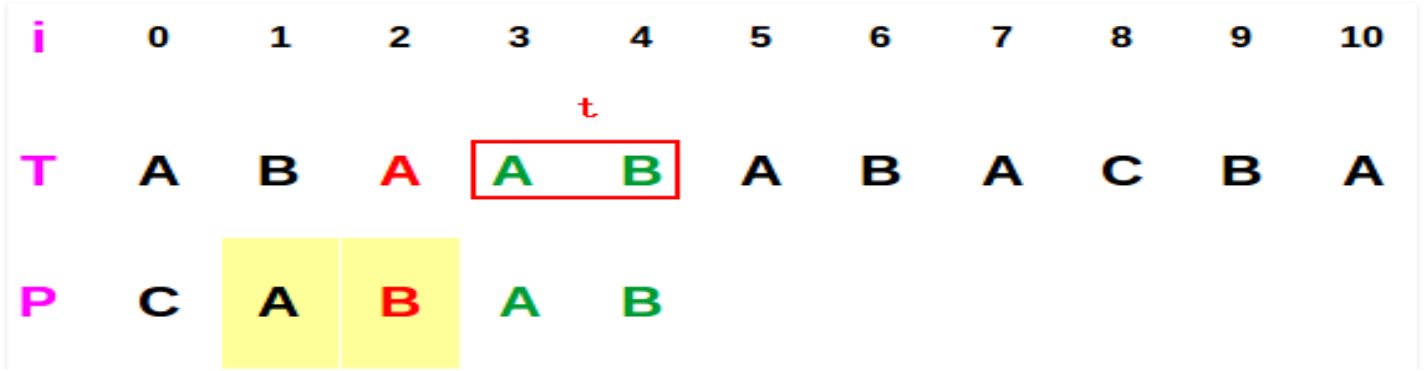
BOYER MOORE ALGORITHM (GOOD SUFFIX RULE)

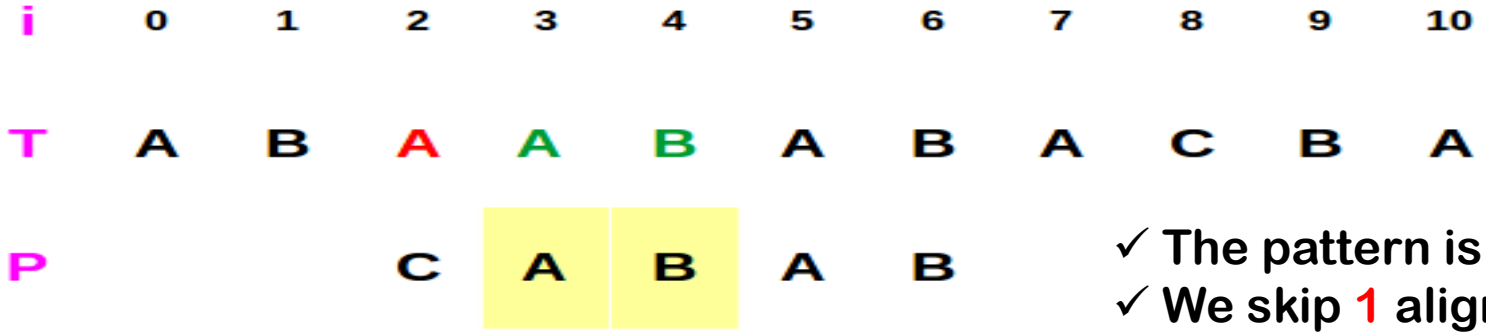
- Let t be substring of text T which is matched with substring of pattern P.



BOYER MOORE ALGORITHM (GOOD SUFFIX RULE)

- Now we shift pattern until :
  - Another occurrence of t in P matched with t in T.

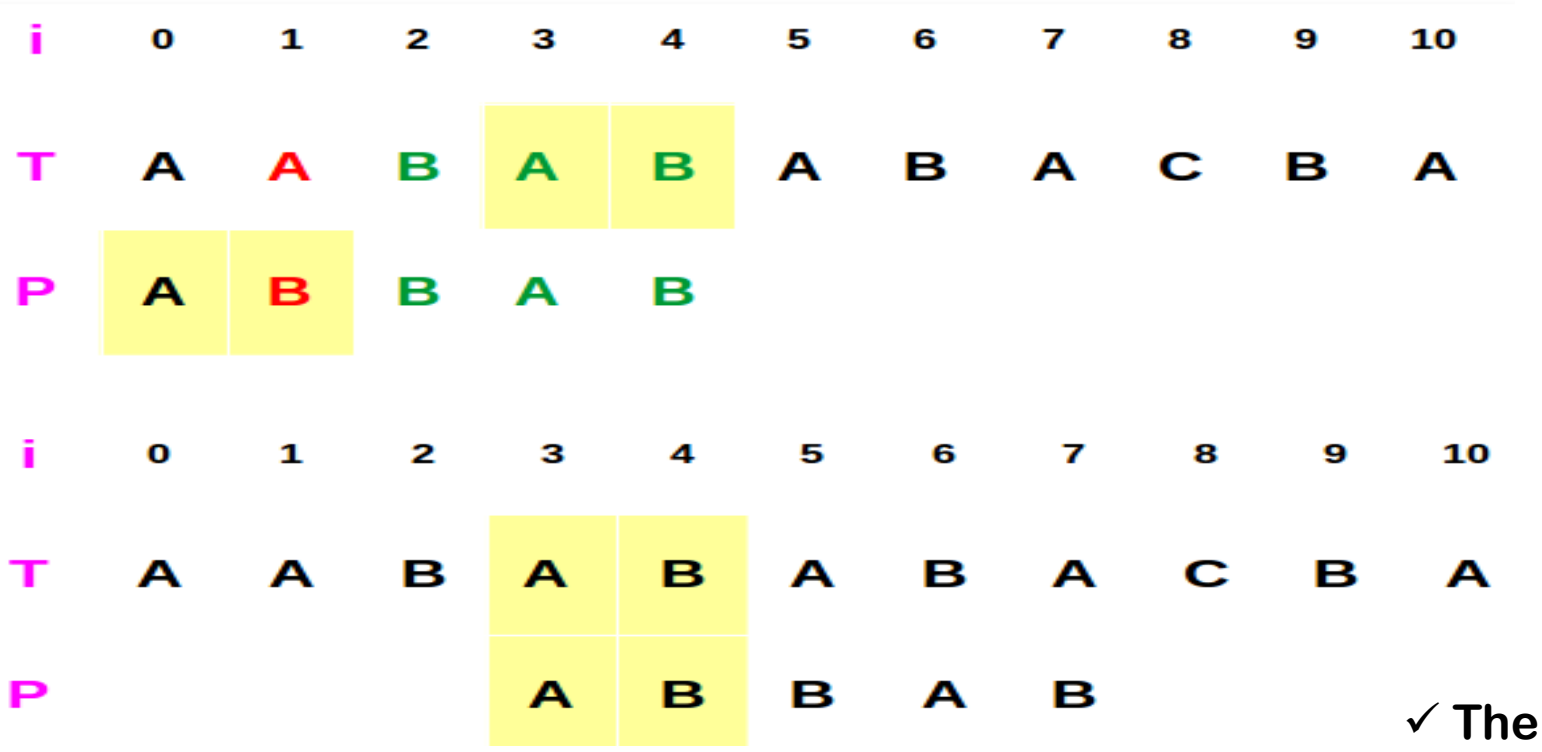




✓ The pattern is shifted by 2 positions (n).
✓ We skip 1 alignment (n-1).

BOYER MOORE ALGORITHM (GOOD SUFFIX RULE)

- Now we shift pattern until :
  - A prefix of P, which matches with suffix of t in T



✓ The pattern is shifted by 3 positions (n).
✓ We skip 2 alignment (n-1).

BOYER MOORE ALGORITHM (GOOD SUFFIX RULE)

- Now we shift pattern until :
  - P moves past t

i	0	1	2	3	4	5	6	7	8	9	10
T	A	A	C	A	B	A	B	A	C	B	A
P	C	B	A	A	B						

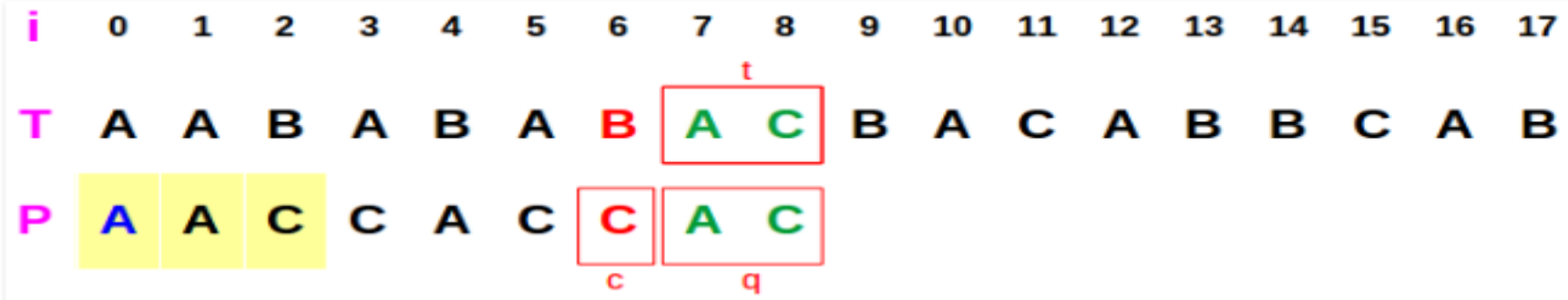
i	0	1	2	3	4	5	6	7	8	9	10
T	A	B	A	A	B	A	B	A	C	B	A
P						C	B	A	A	B	

✓ The pattern is shifted by 5 positions (n).
✓ We skip 4 alignment (n-1).

BOYER MOORE ALGORITHM (STRONG GOOD SUFFIX RULE)

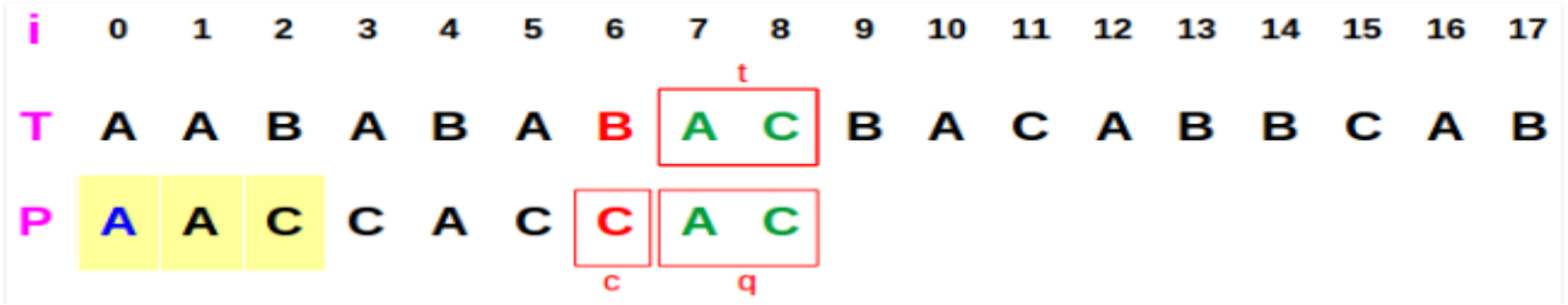
- Suppose substring q = P[i to n] got matched with t in T and c = P[i-1] is the mismatching character.

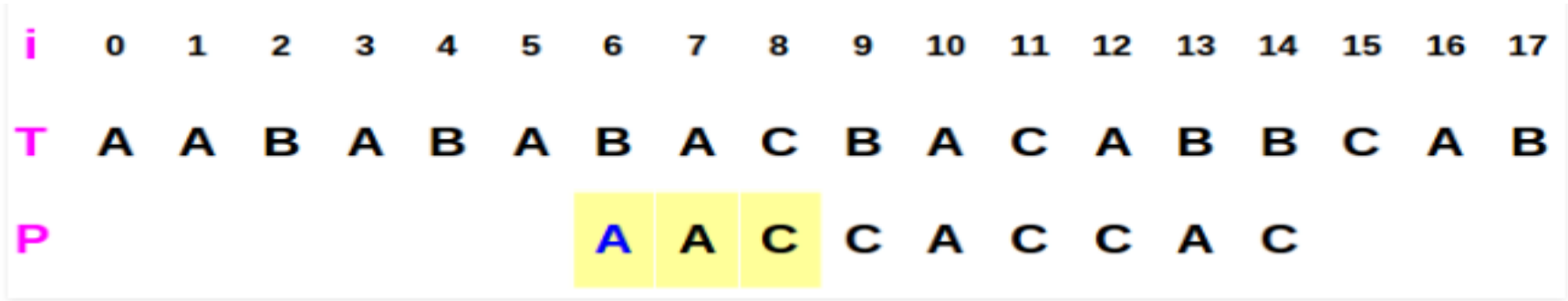
  - Now unlike case 1 we will search for t in P which is not preceded by character c. The closest such occurrence is then aligned with t in T by shifting pattern P.



BOYER MOORE ALGORITHM (STRONG GOOD SUFFIX RULE)

- Now unlike case 1 we will search for t in P which is not preceded by character c. The closest such occurrence is then aligned with t in T by shifting pattern P.





✓ The pattern is shifted by 6 positions (n).
✓ We skip 5 alignment (n-1).

BOYER MOORE ALGORITHM (ALL TOGETHER)

Text= GTTATAGCTGATCGCGGCGTAGCGGCGAA
Pattern= GTAGCGGCG

GTTATAGCTGATCGCGGCGTAGCGGCGAA
GTAGCGGCG

BOYER MOORE ALGORITHM (ALL TOGETHER)

GTTATAGCTGATCGCGGCGTAGCGGCGAA
GTAGCGGCG

No matching chars, no good suffix rule is used, bad char rule = 7positions

GTTATAGCTGATCGCGGCGTAGCGGCGAA
GTAGCGGCG

BOYER MOORE ALGORITHM (ALL TOGETHER)

GTTATAGCTGATCGCGGCGTAGCGGCGAA
GTAGCGGCG

GTTATAGCTGATCGCGGCGTAGCGGCGAA
GTAGCGGCG

GTTATAGCTGATCGCGGCGTAGCGGCGAA
GTAGCGGCG

BOYER MOORE ALGORITHM (ALL TOGETHER)

BOYER MOORE ALGORITHM (ALL TOGETHER)

GTTATAGCTGATCGCGGCGTAGCGGCGAA

GTAGCGGCG

GTTATAGCTGATCGCGGCGTAGCGGCGAA

GTAGCGGCG

GTTATAGCTGATCGCGGCGTAGCGGCGAA

GTAGCGGCG

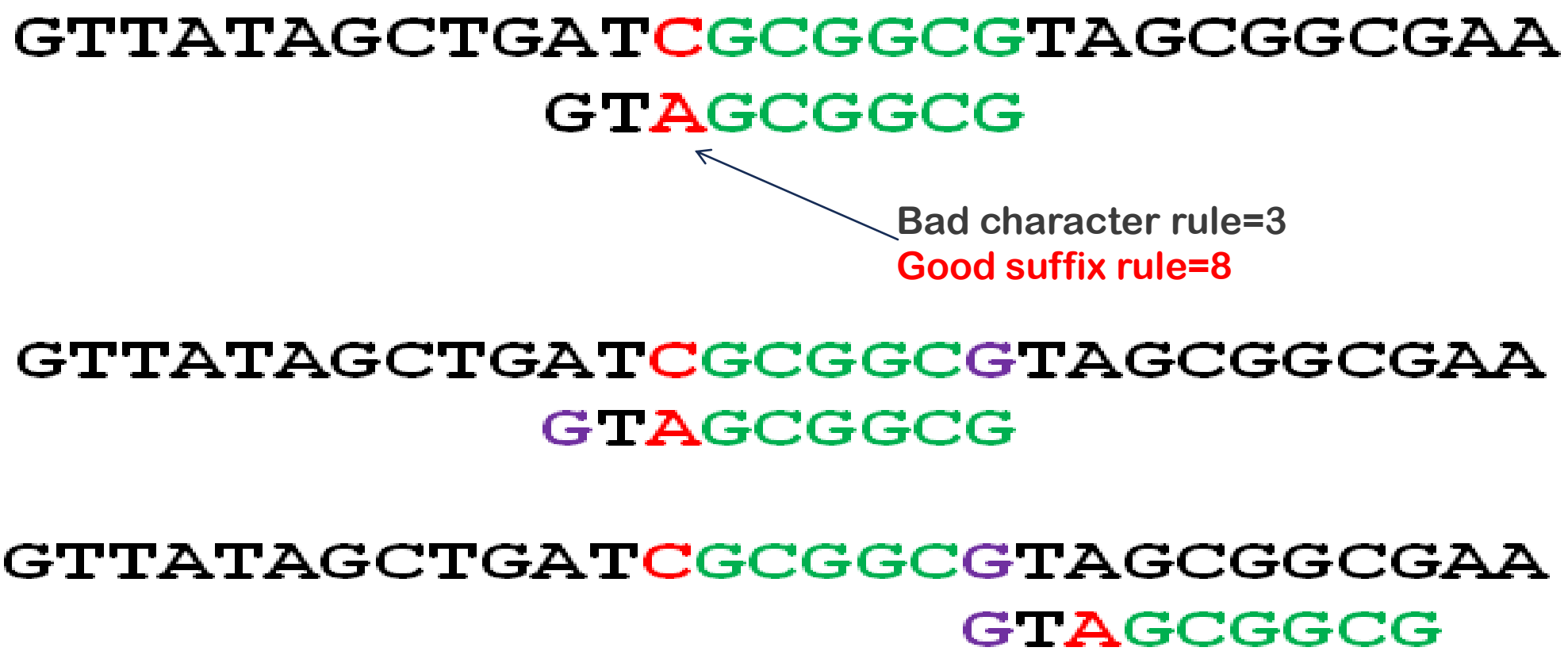
BOYER MOORE ALGORITHM (ALL TOGETHER)

GTTATAGCTGATCGCGGCGTAGCGGCGAA
GTAGCGGCG

GTTATAGCTGATCGCGGCGTAGCGGCGAA
GTAGCGGCG

GTTATAGCTGATCGCGGCGTAGCGGCGAA
GTAGCGGCG

BOYER MOORE ALGORITHM (ALL TOGETHER)



BOYER MOORE ALGORITHM (ALL TOGETHER)

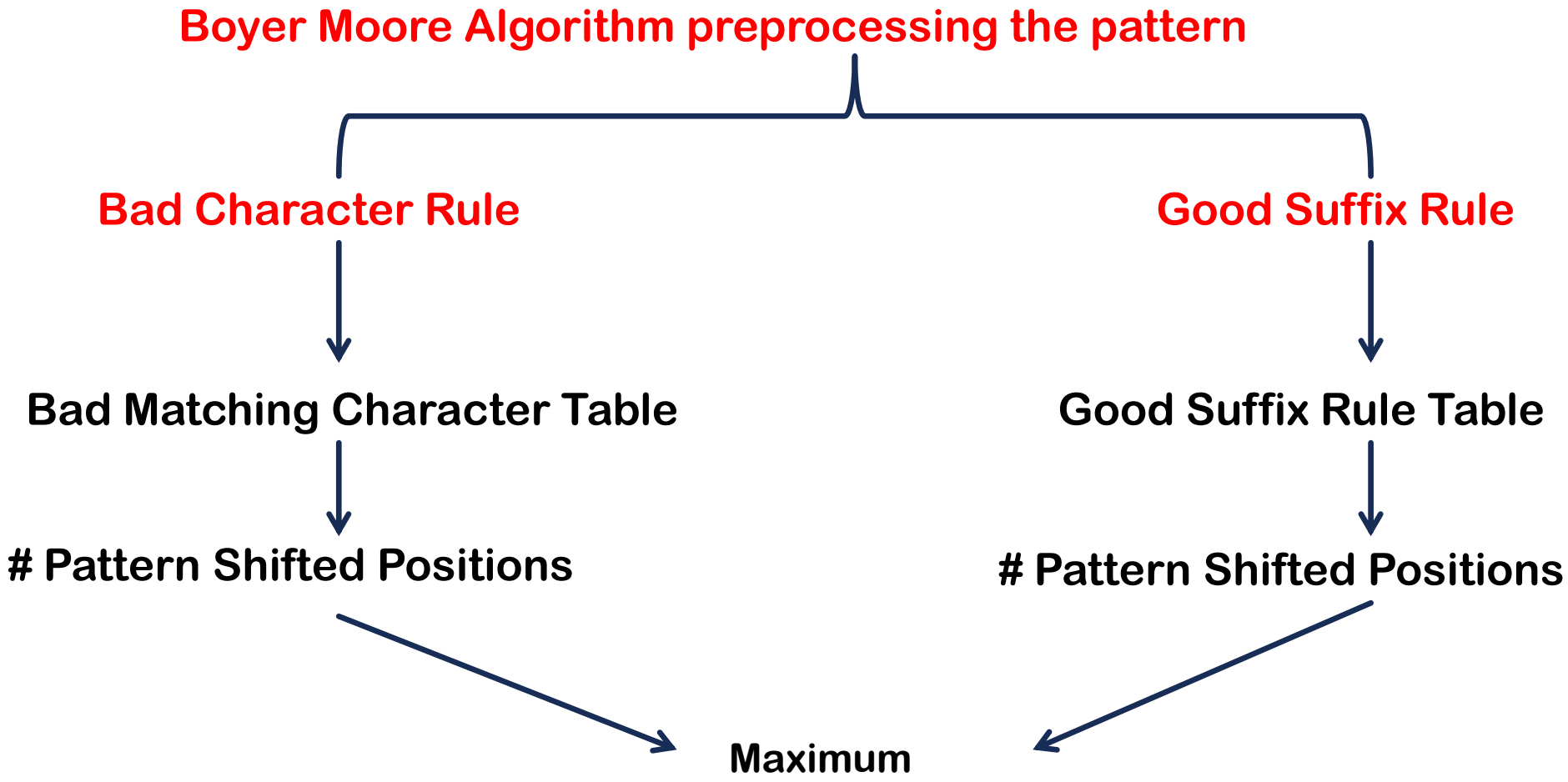
GTTATAGCTGATCGCGGCGTAGCGGCGAA

GTAGCGGCG

GTTATAGCTGATCGCGGCGTAGCGGCGAA

GTAGCGGCG

BOYER MOORE ALGORITHM



BOYER MOORE ALGORITHM

- How to Construct Bad Match Table?
  - The table columns corresponding to $\sum$ in the pattern.
  - Value = last occurrence of this character in the pattern.
- Example 1: for pattern **ACGGA** construct the bad matching character table?

✓Determine $\sum$

$$\sum \{A, C, G\}$$

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

0 1 2 3 4

ACGGA

AACCGACGGAATGTTAACGGA

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
0						

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

j

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
0	4	4	A	G	N	badChar [txt[4]] = badChar[G]=3 s = s + max (1, j -3) s = s + max (1, 4-3) s= 0+ 1=1

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

j

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
1	4	5	A	A	Y	

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

j

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
1	4	5	A	G	Y	
1	3	4	G	G	Y	

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

j

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
1	4	5	A	G	Y	
1	3	4	G	G	Y	
1	2	3	G	C	N	badChar [txt[3]] = badChar[C]=1 s = s + max (1, j -1) s = s + max (1, 2-1) s= 1+ 1=2

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

j

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
2	4	6	A	C	N	badChar [txt[6]] = badChar[C]=1 s = s + max (1, j -1) s = s + max (1, 4-1) s= 2+ 3=5

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

j

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
5	4	9	A	A	Y	

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

j

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
5	4	9	A	A	Y	
5	3	8	G	G	Y	
5	2	7	G	G	Y	
5	1	6	C	C	Y	
5	0	5	A	A	Y	
5	-1	-	-	-	-	Pattern at index s=5 s+n = 5+5 = 10 < 20 badChar[T[s+n]]= badChar[A]=4 s=s+ (n-4) s=5+(5-4)=6

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

j

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
6	4	10	A	A	Y	
6	3	9	G	A	N	badChar [txt[9]] = badChar[A]=4 s = s + max (1, j -4) s = s + max (1, 3-4) s= 6+ 1=7

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

j

n= 5

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
7	4	11	A	T	N	badChar [txt[11]] = badChar[T]= -1 s = s + max (1, j –(-1)) s = s + max (1, 4+1) s= 7+ 5=12

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

n= 5 j

m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
12	4	16	A	C	N	badChar [txt[16]] = badChar[C]= 1 s = s + max (1, j -1)) s = s + max (1, 4-1) s= 12+ 3=15

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

BOYER MOORE ALGORITHM

A	C	G
4	1	3

badCharTable

s+j

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

AACCGACGGAATGTTACGGA

0 1 2 3 4

ACGGA

n= 5 j

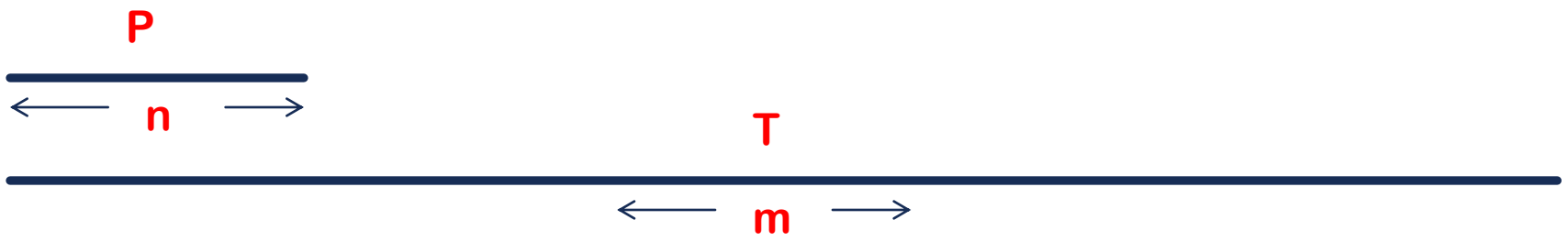
m = 20

s	j	s+j	P[j]	T[s+j]	match	new s
15	4	19	A	A	Y	Pattern at index s=15 s+n = 15+5 = 20 < 20 s=15+(1)=16
						16 < = 15

```
def search(txt, pat):
    n = len(pat)
    m = len(txt)
    badChar = badCharHeuristic(pat, n)
    s = 0
    while(s <= m-n):
        j = n-1
        while j>=0 and pat[j] == txt[s+j]:
            j -= 1

        if j<0:
            print("Pattern occur at index ".format(s))
            s += (n-badChar[ord(txt[s+n])] if s+n<m else 1)
            print(s)
        else:
            s += max(1, j-badChar[ord(txt[s+j])])
            print(s)
```

Q



- What is the worst case running time? Give me example?
- What is the best case running time? Give me example?

BOYER MOORE ALGORITHM ANALYSIS

- What is the worst case running time? Give me example?

1^m Input text, length m

01111 Pattern, length n

O(mn)

- What is the best case running time? Give me example?

1^m Input text, length m

0^n Pattern, length n

$$O\left(\frac{m}{n}\right)$$

Thank you!