2001–2010: Ten Years of Exact String Matching Algorithms

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joint work with S. Faro

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Outline

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Exact String Matching

Definition

Find all the occurrences of a pattern x of length m in a text y of length n.
$x, y \in \Sigma^*$

2 instances

- x is given first
- y is given first

Exact String Matching

Interests

- basic components of many softwares
- theoretical problems

Exact String Matching

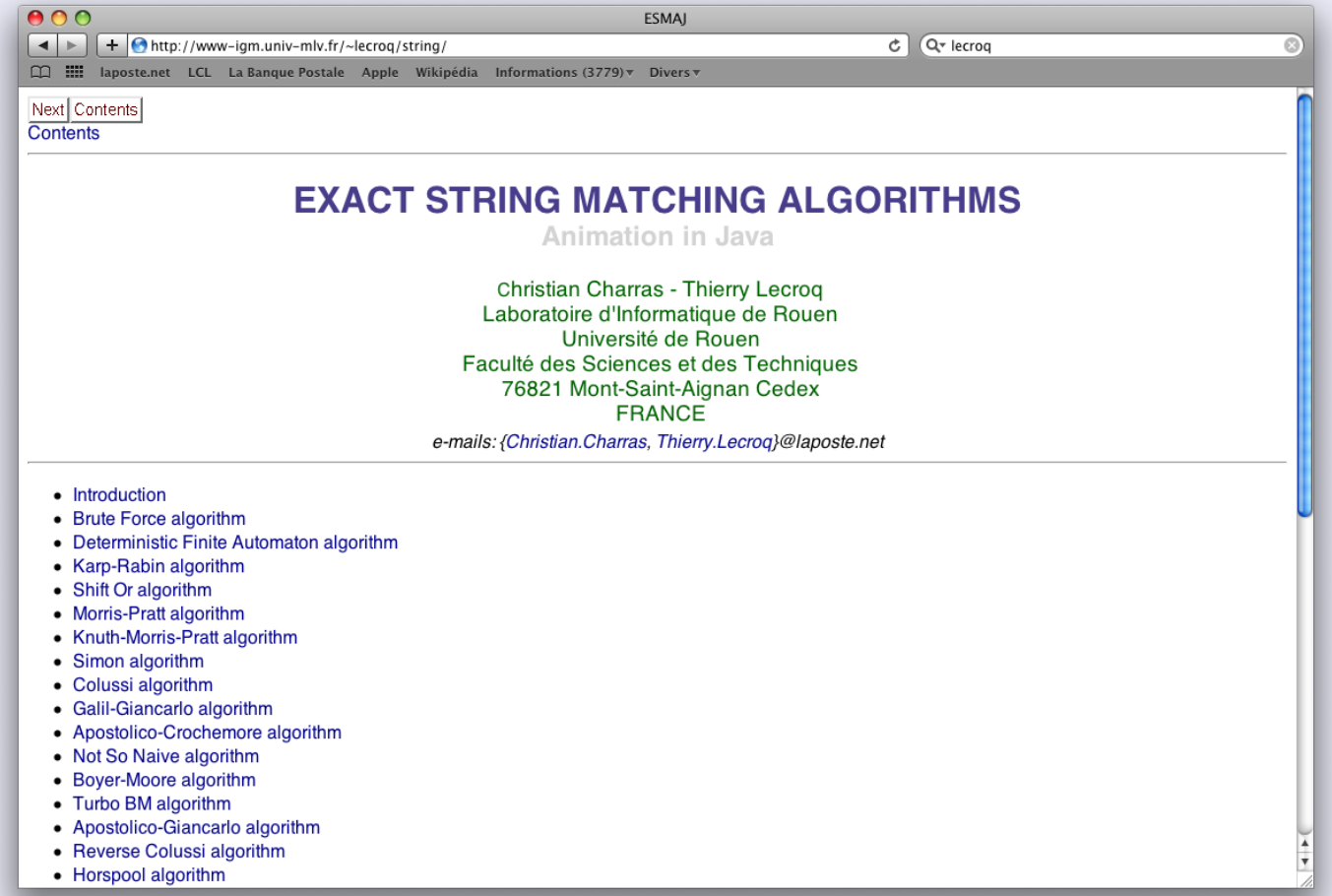
Theory

- linear time since Morris and Pratt 1970
- linear time and constant space
- $O((n \log m)/m)$ in average [Yao 1979]

Exact String Matching

Solutions

Many!! see `http://monge.univ-mlv.fr/~lecroq/string`

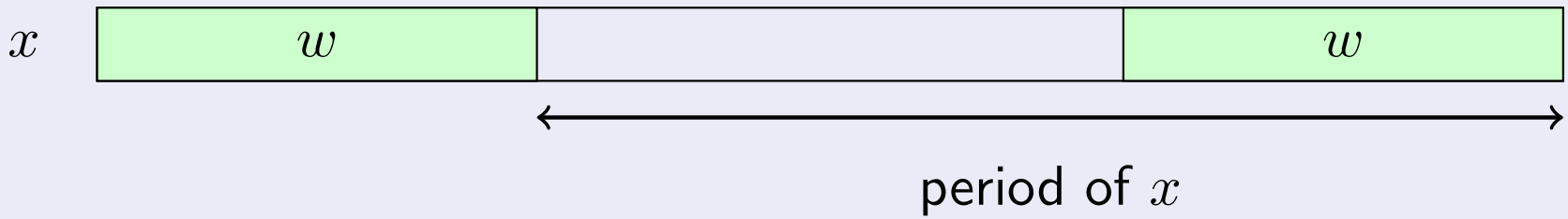


Outline

Definitions

Periods and borders

- w is a border of x if it is both a prefix and a suffix of x
- $|x| - |w|$ is a period of x

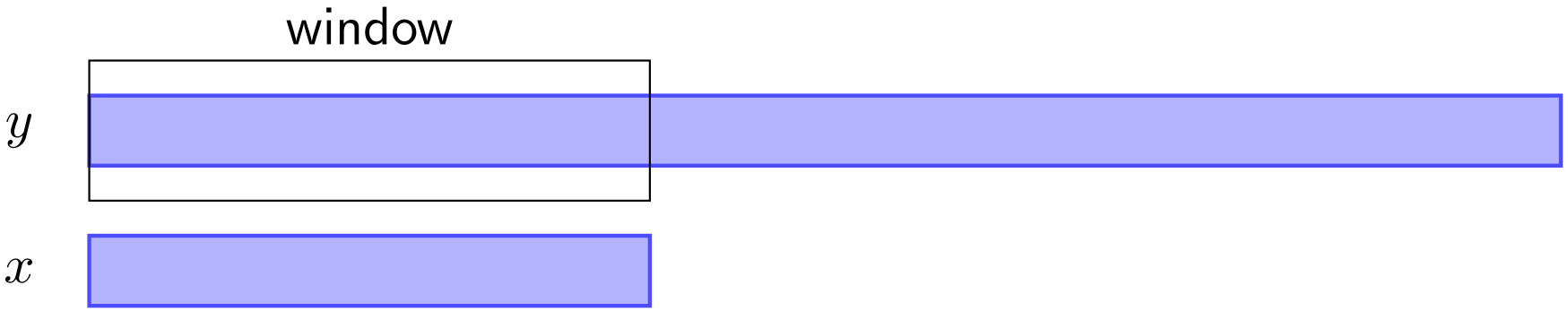


Exact String Matching

Classical solutions

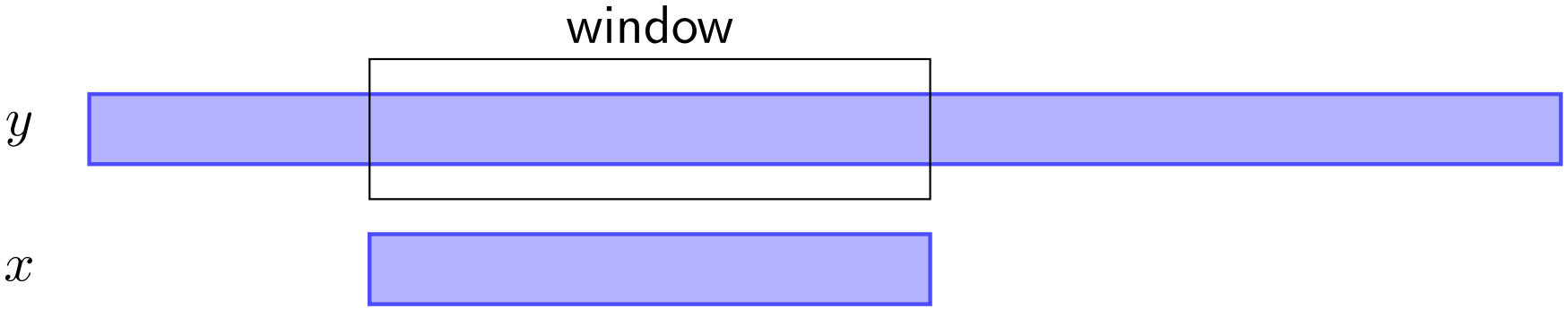
- comparisons
  - Knuth-Morris-Pratt
  - Boyer-Moore
- automata
  - Backward DAWG Matching (with suffix automaton or oracle)
- bit-parallelism
  - Shift Or
  - Backward Nondeterministic DAWG Matching
- filtering
  - Karp-Rabin

Sliding Window



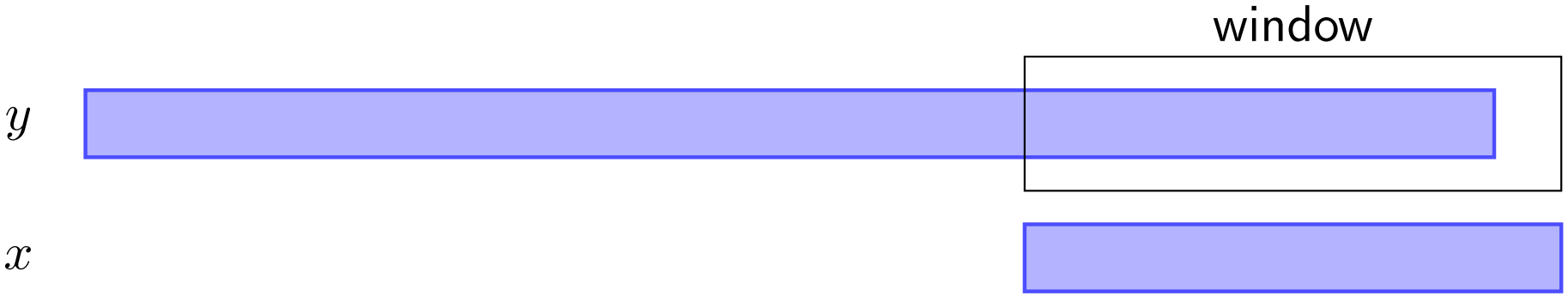
beginning

Sliding Window



middle

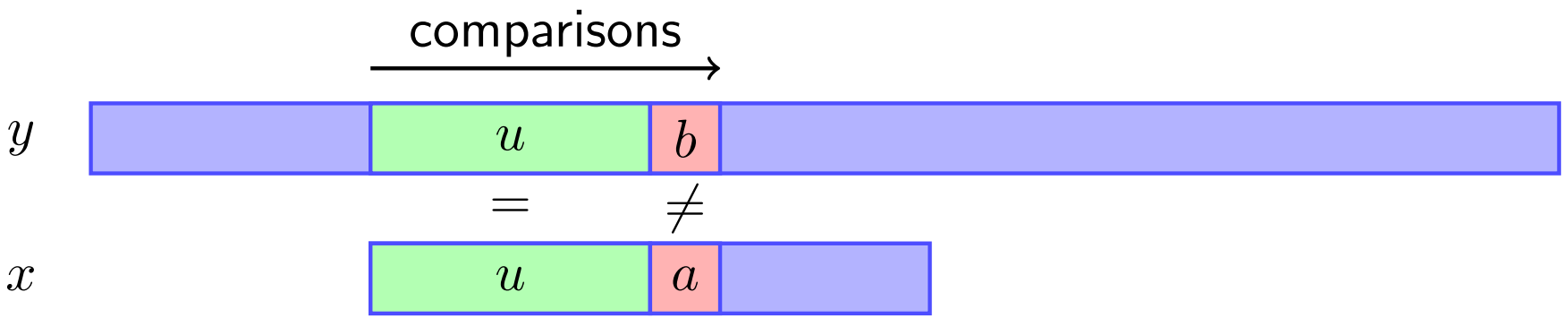
Sliding Window



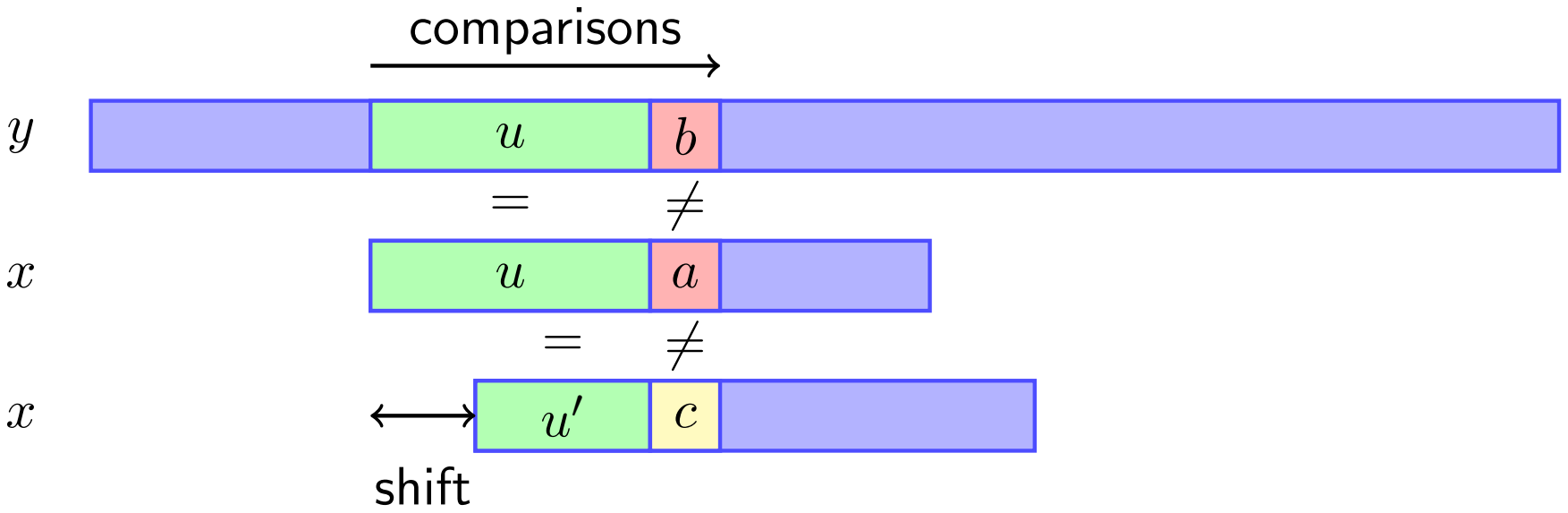
end

Knuth-Morris-Pratt (1977)

Knuth-Morris-Pratt (1977)



Knuth-Morris-Pratt (1977)



u' is the longest border of u followed by a letter $\neq a$

Boyer-Moore (1977)

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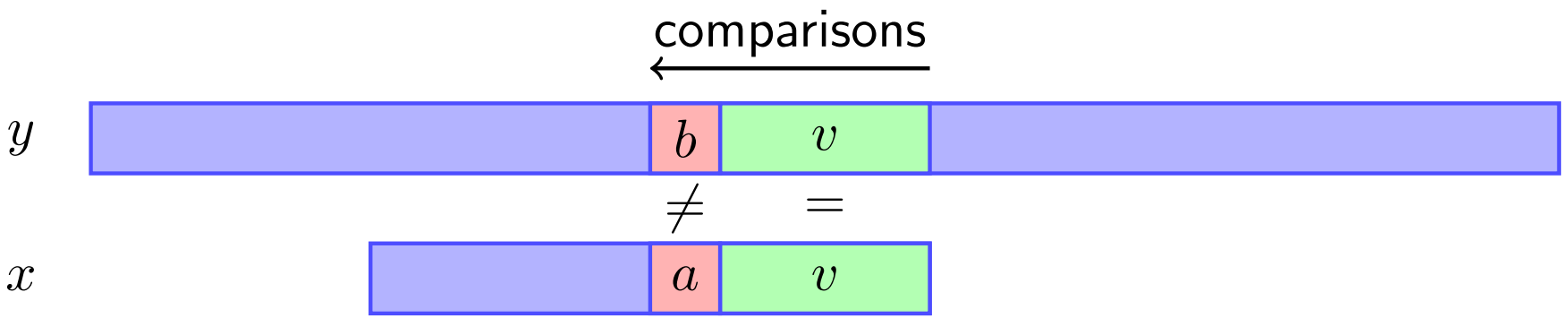

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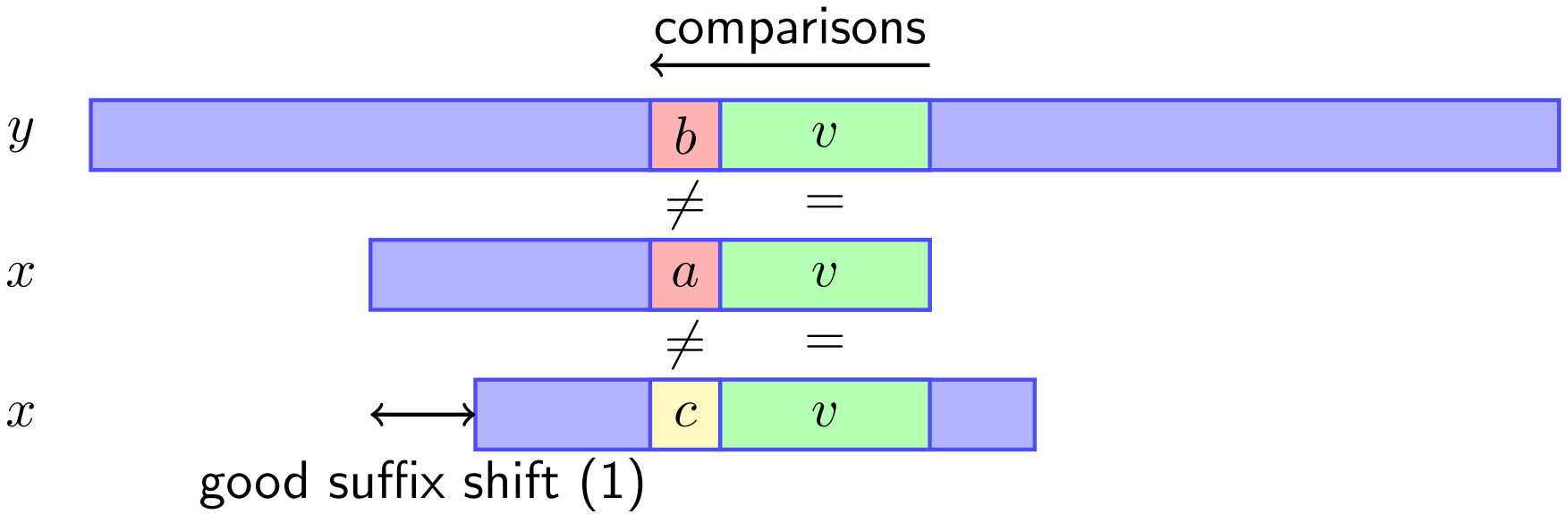
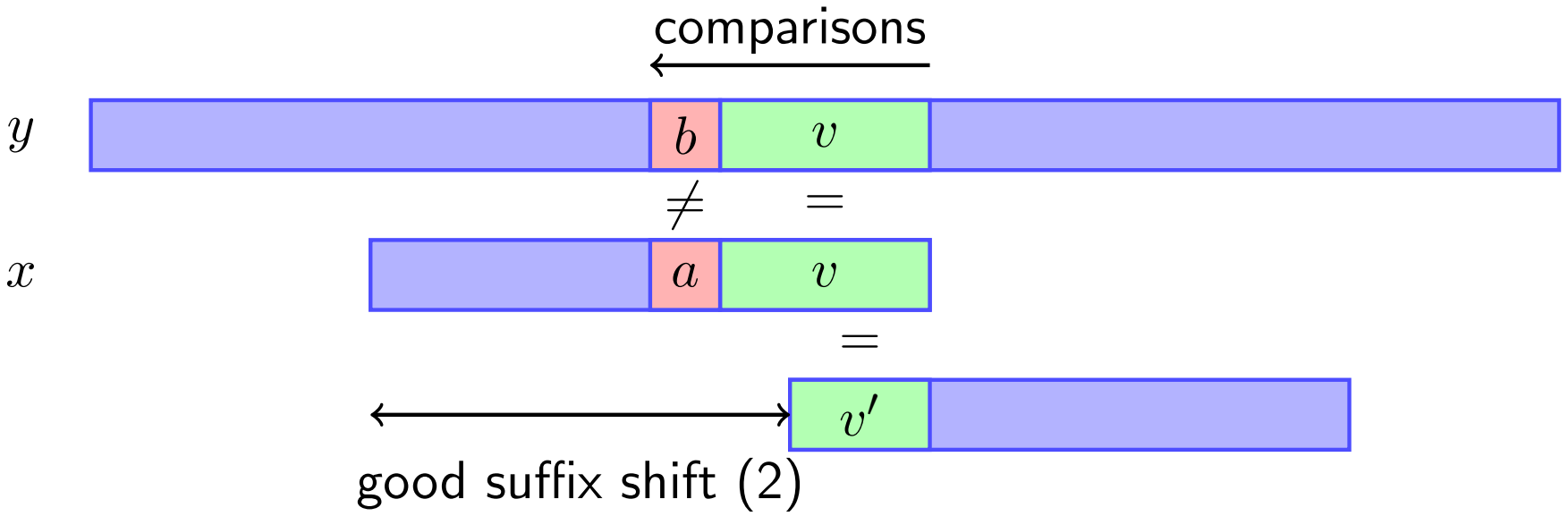


good suffix shift (1)

Boyer-Moore (1977)



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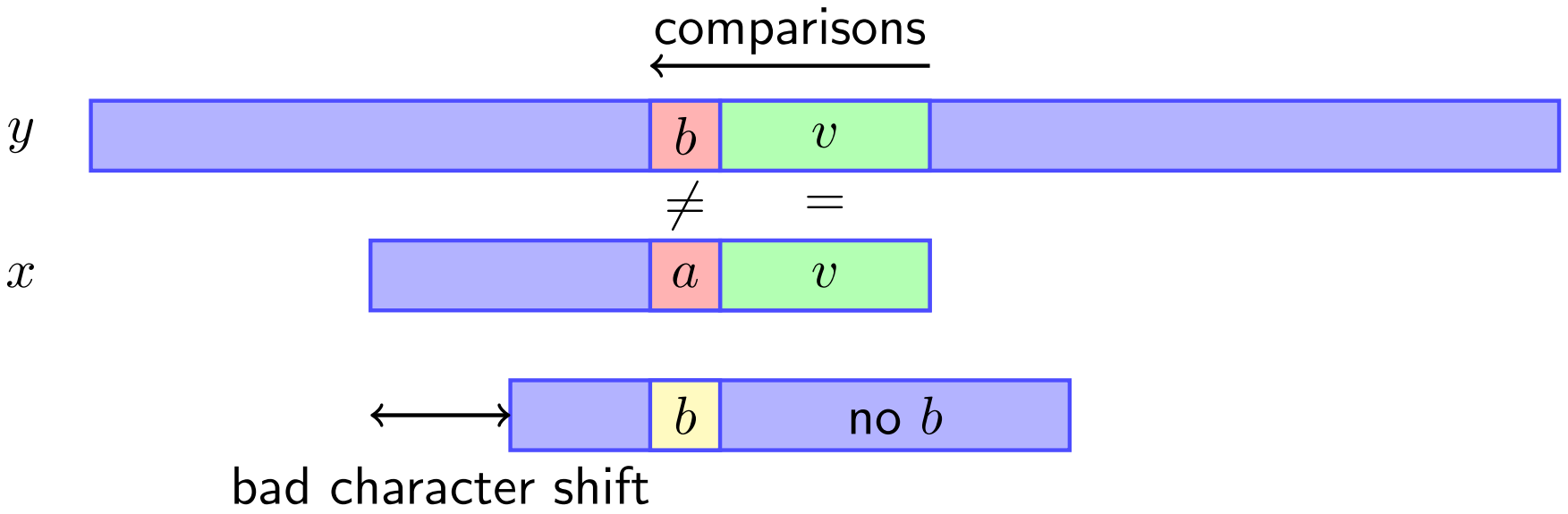

Horspool (1981)

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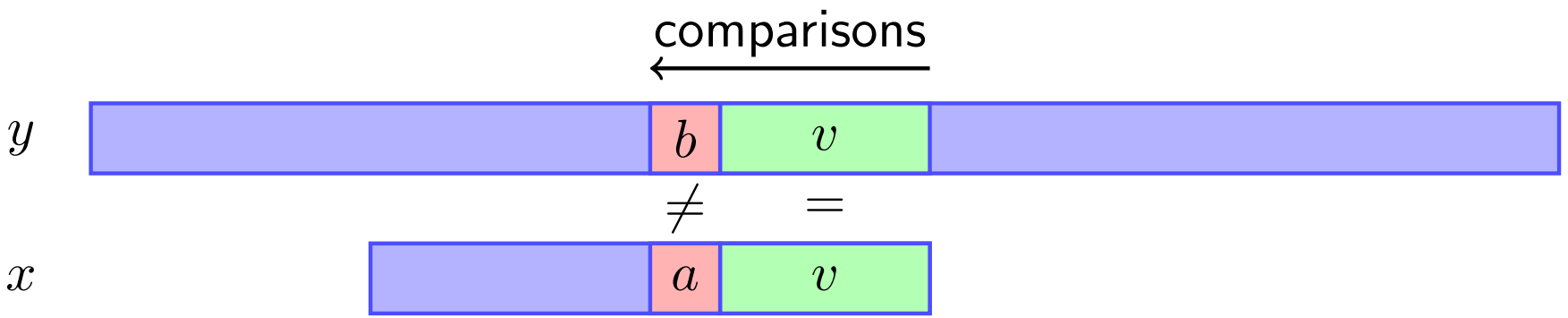

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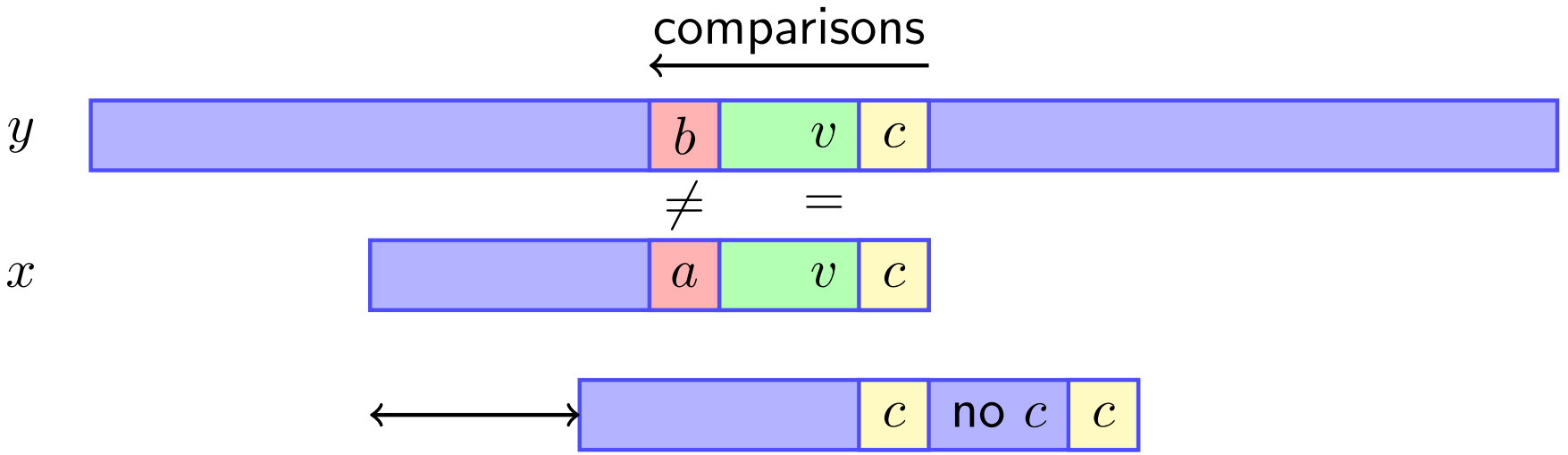

Horspool bad character shift

Zhu-Takaoka (1987)

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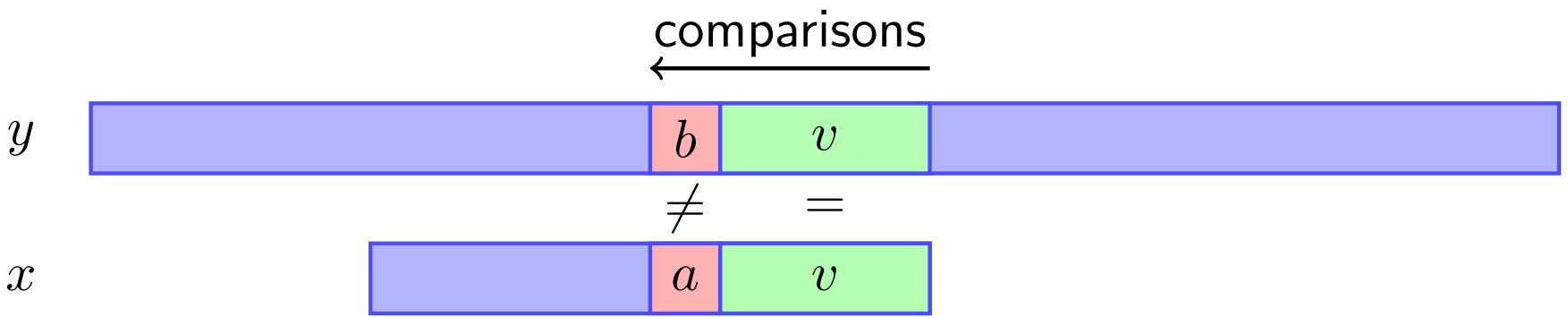

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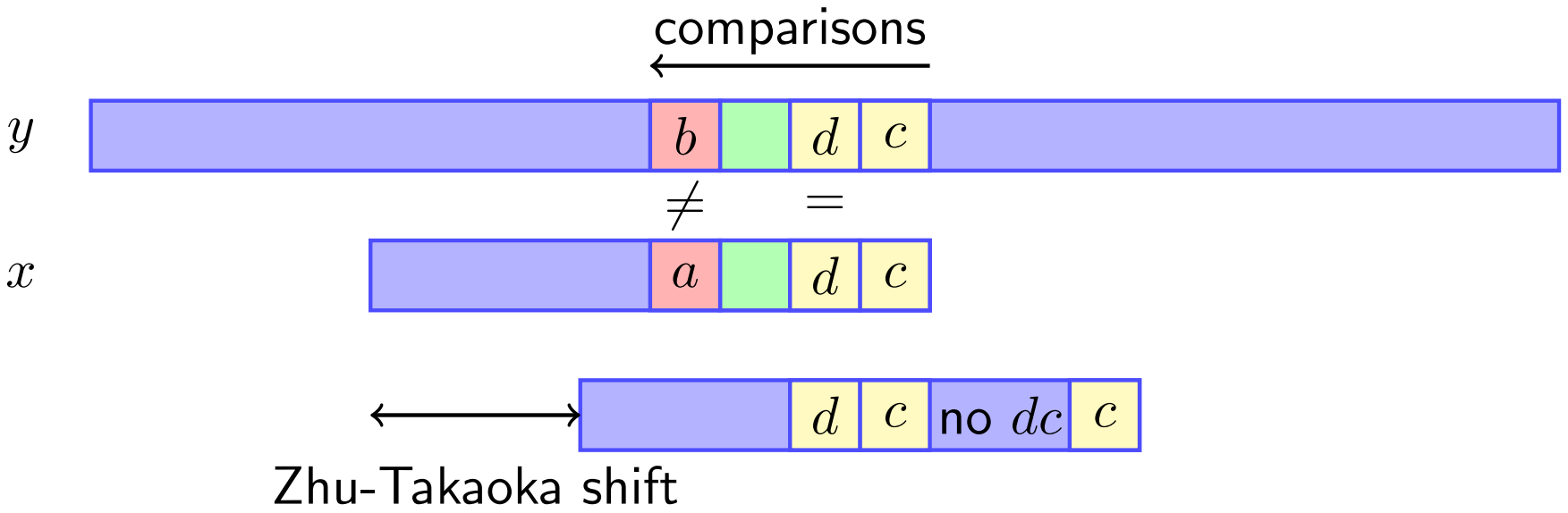

Quick Search (Sunday, 1990)

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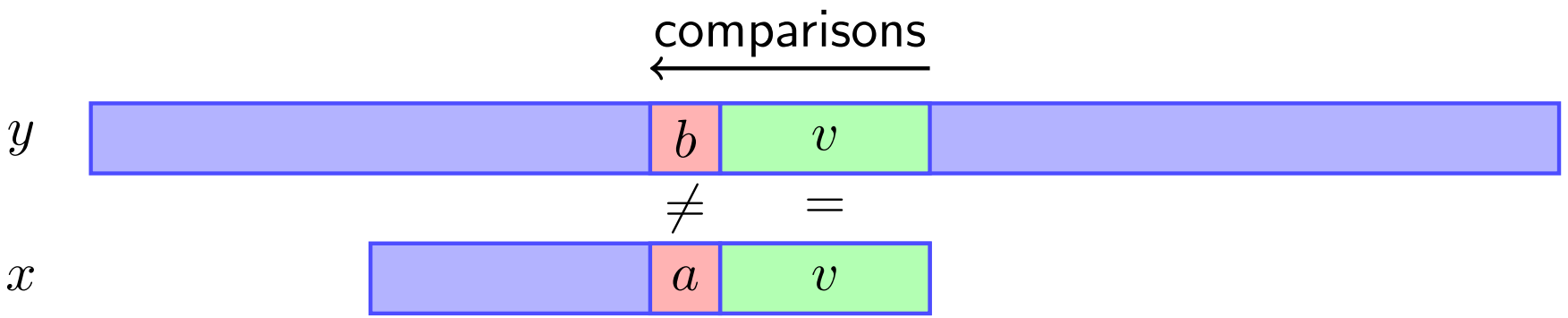

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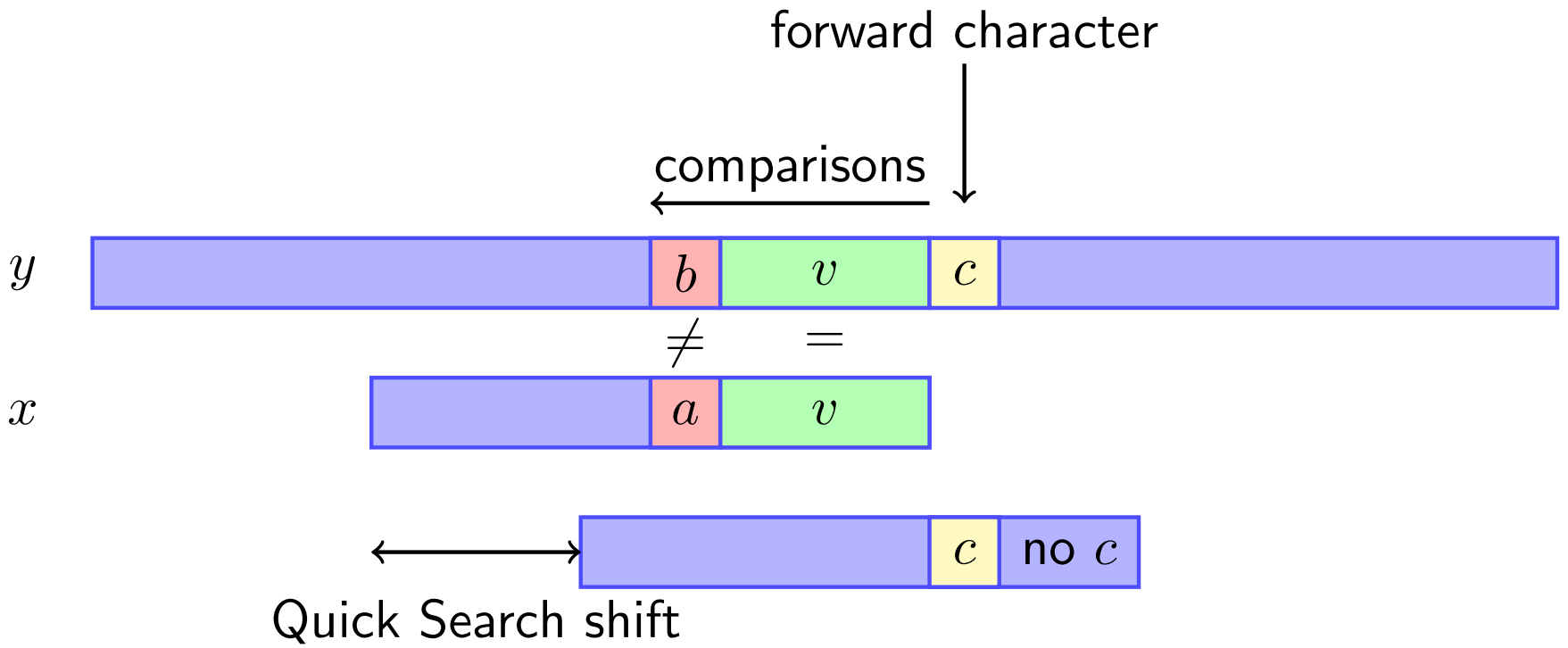

Berry-Ravindran (1999)

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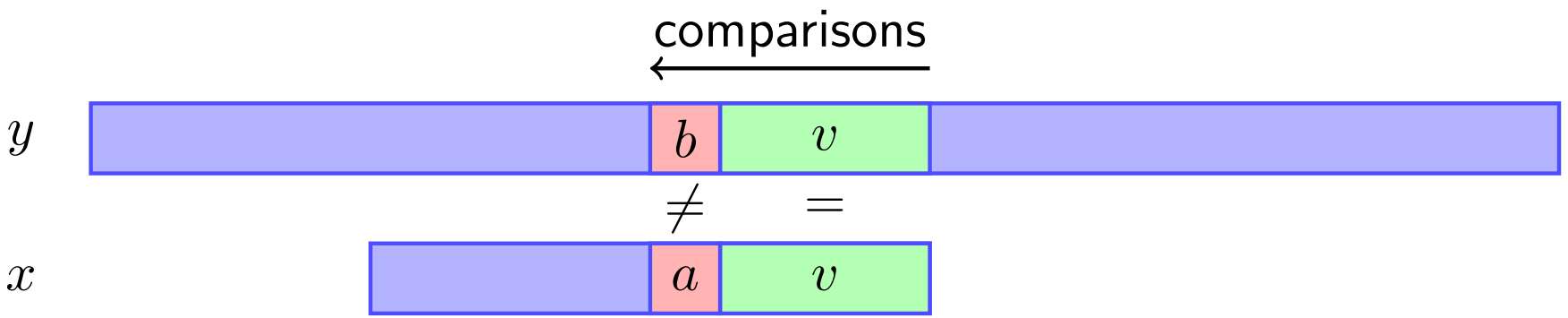

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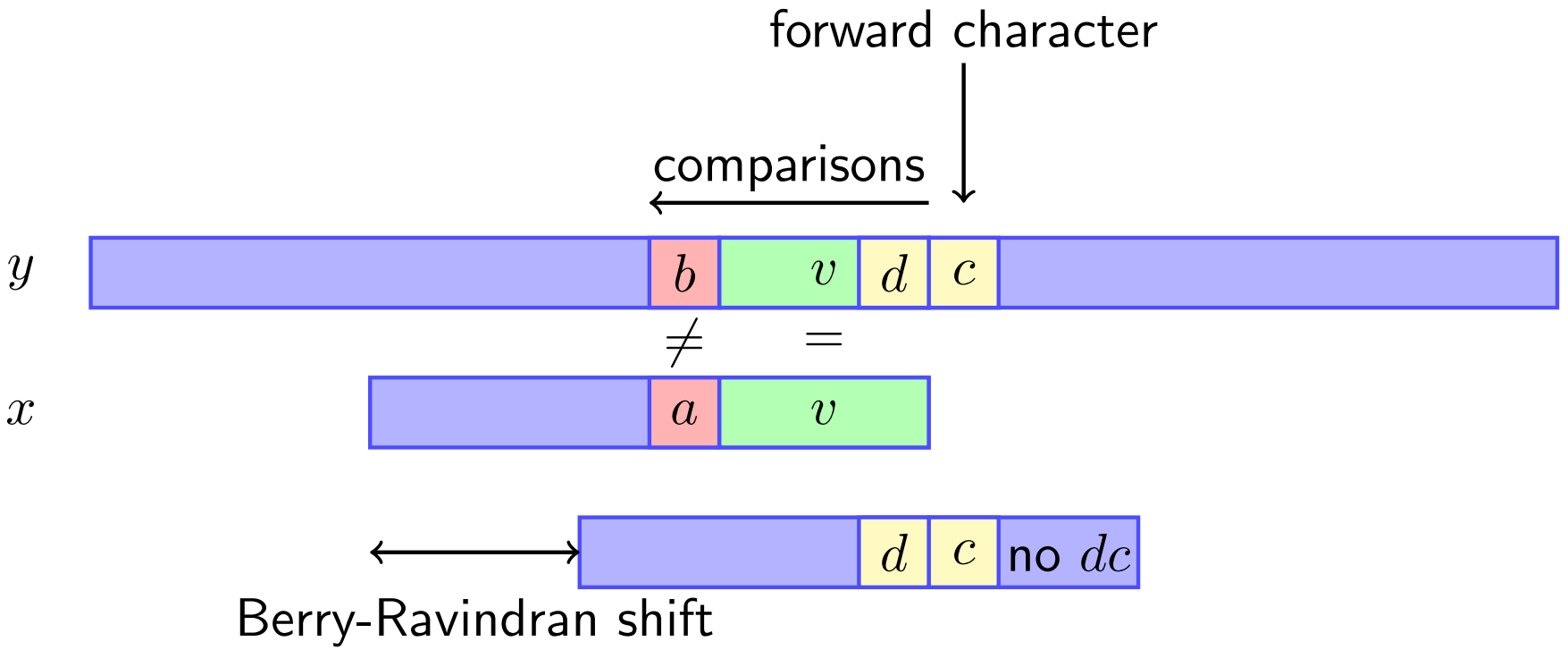

Backward DAWG Matching (Crochemore & Rytter, 1994)

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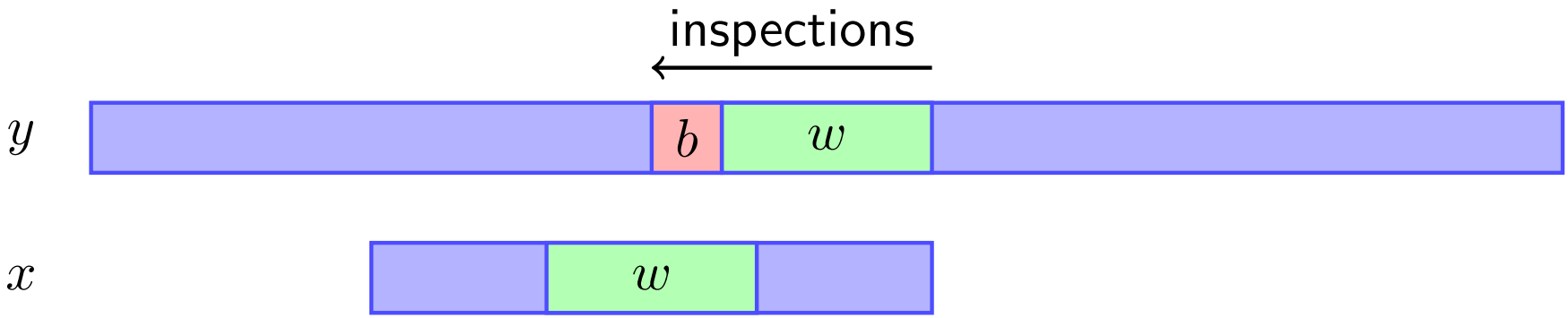

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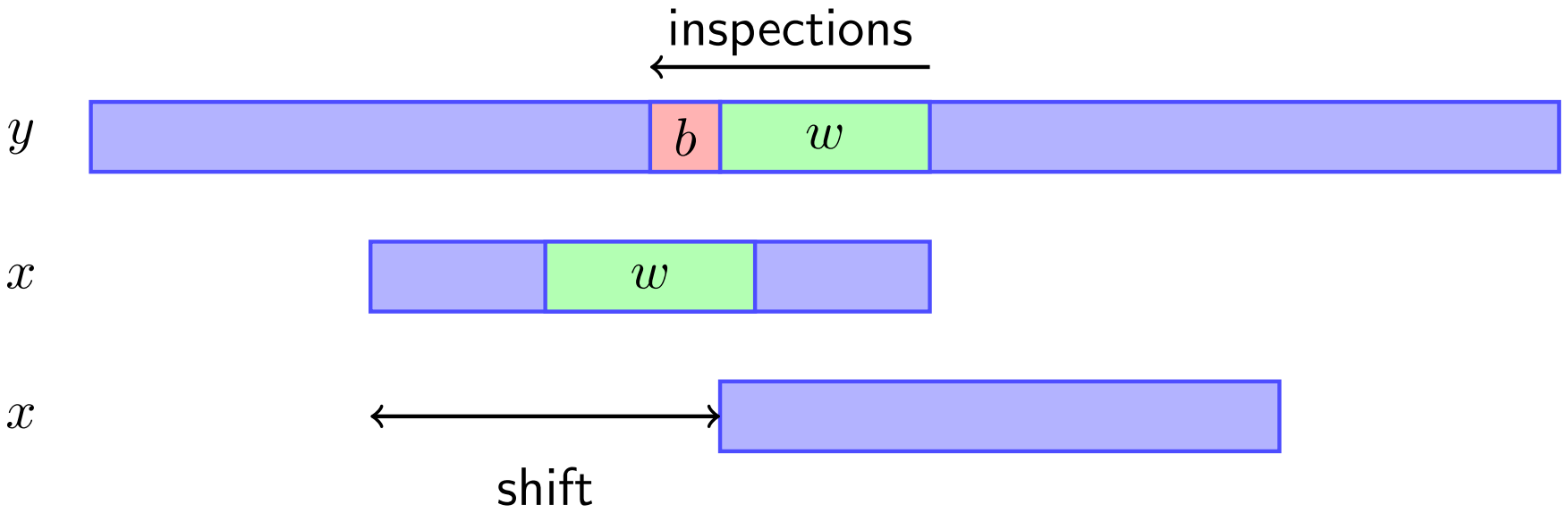

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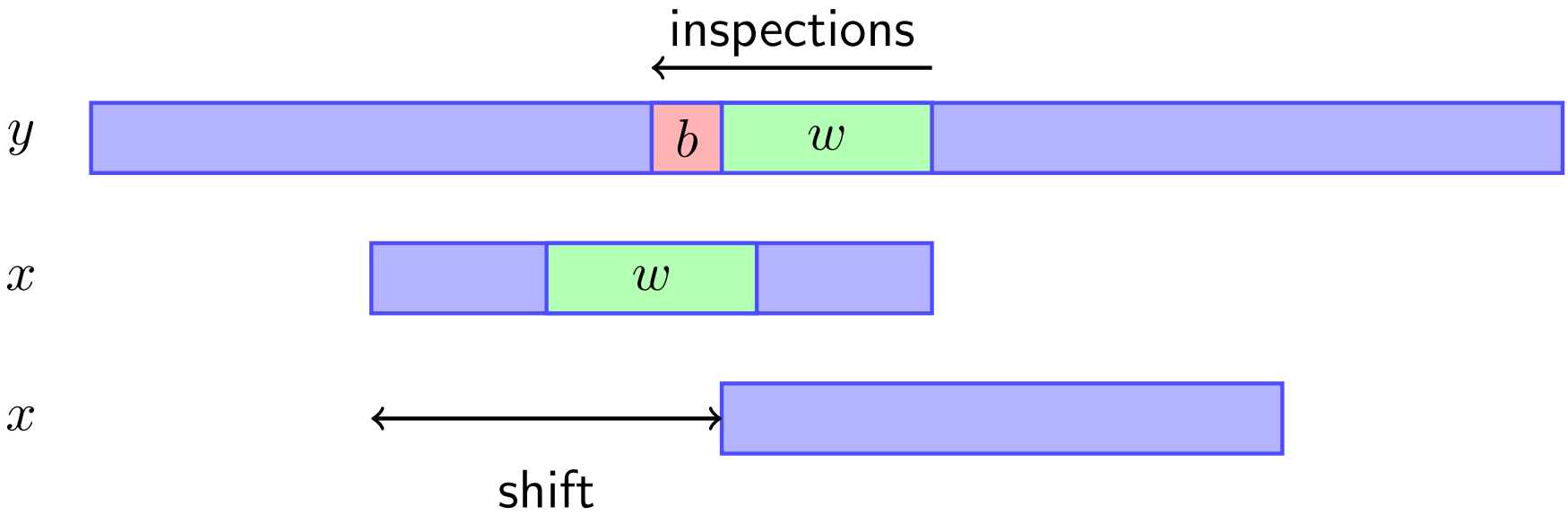

with Factor Oracle: BOM
(Backward Oracle Matching, Allauzen, Crochemore & Raffinot, 1999)

Reverse Factor (Lecroq, 1992)

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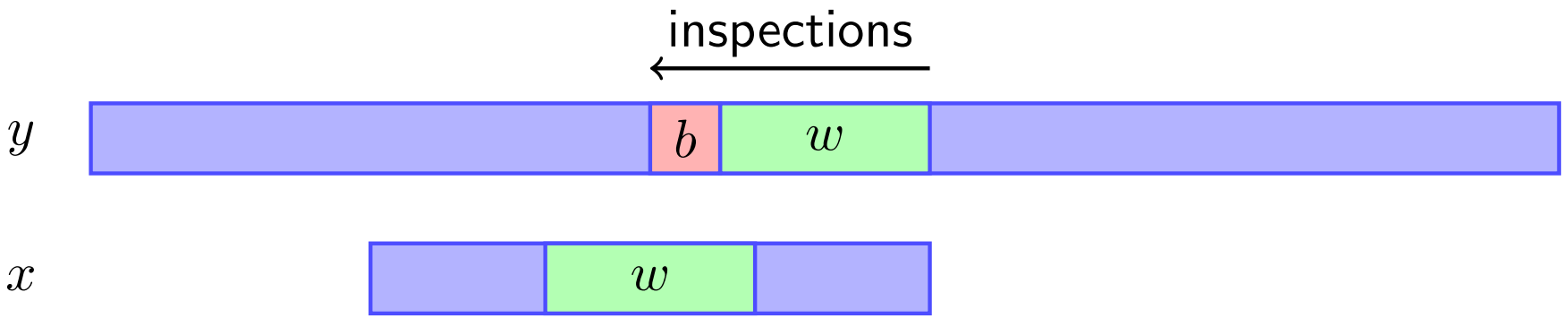

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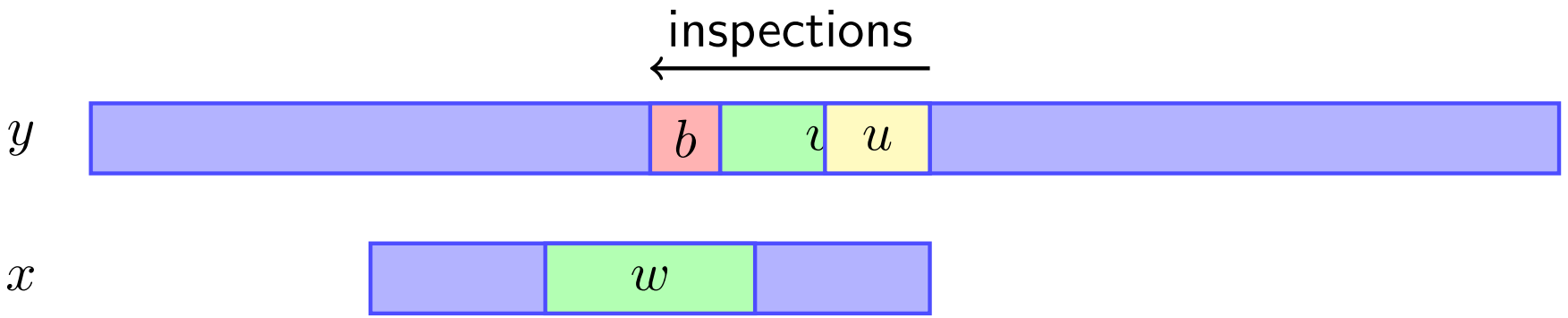

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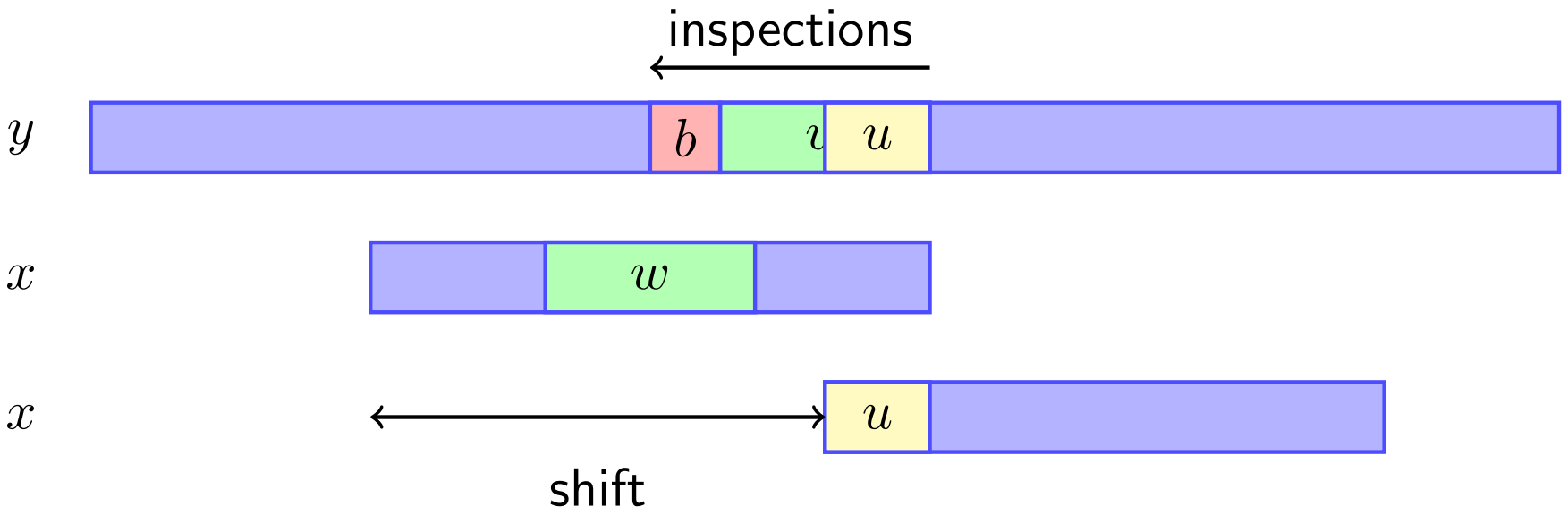

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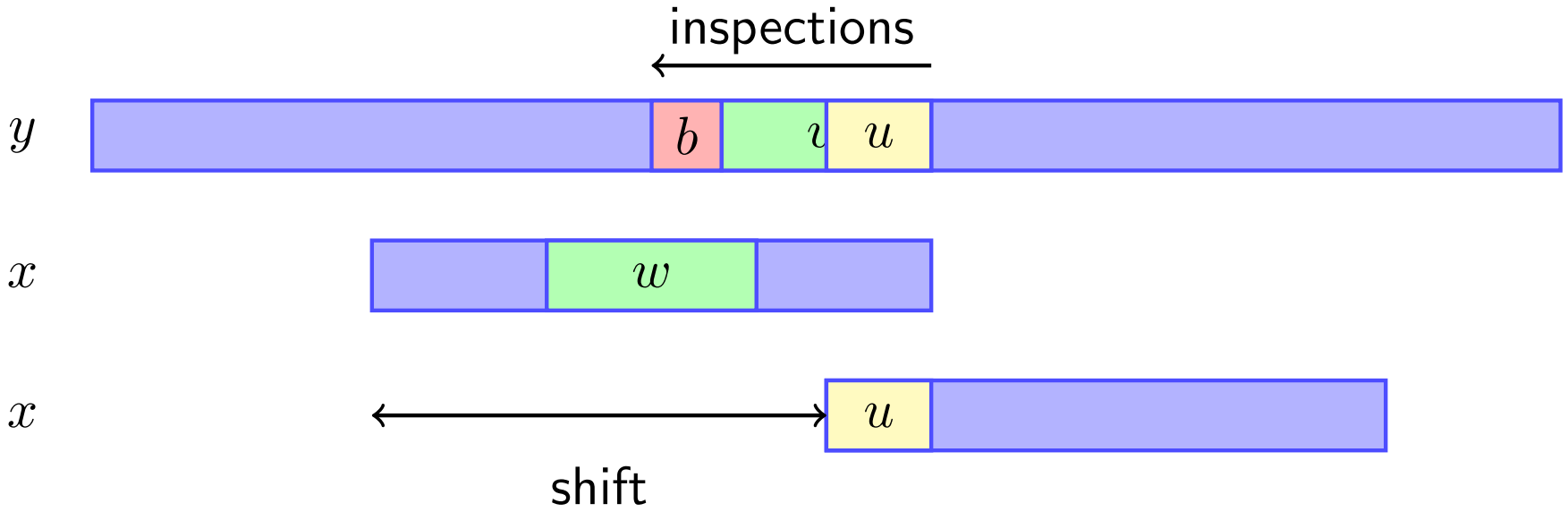

with Factor Oracle: BSOM
(Backward Suffix Oracle Matching, Allauzen, Crochemore & Raffinot, 1999)

Shift Or (Baeza-Yates & Gonnet 1992)

x C A T A

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C A T A C

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y	C	C	A	T	A	C
		1	1	1	1	

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C A T A C

	1	1	1	1

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C A T A C

1	1	1	1	
0	1	1	1	Shift

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y = **C** C A T A C

1	1	1	1
0	1	1	1
0	1	1	1

Shift
Or with S_C

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y = **C** C A T A C

	1	1	1	1
Shift	0	1	1	1
Or with S_C	0	1	1	1
$=$	0	1	1	1

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C **C** A T A C

0 1 1 1

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C **C** A T A C

0	1	1	1
0	0	1	1

Shift

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C **C** A T A C

0	1	1	1
0	0	1	1
0	1	1	1

Shift
Or with S_C

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A	y	C	C	A	T	A	C
S_A	1	0	1	0		0	1	1	1		
S_C	0	1	1	1		0	0	1	1		
S_G	1	1	1	1		0	1	1	1		
S_T	1	1	0	1		0	1	1	1		

Shift

Or with S_C

$=$

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C **A** T A C

	0	1	1	1

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C **A** T A C

0	1	1	1
0	0	1	1

Shift

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C **A** T A C

0	1	1	1	
0	0	1	1	Shift
1	0	1	0	Or with S_C

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C **A** T A C

	0	1	1	1
	0	0	1	1
	1	0	1	0
	1	0	1	1

Shift

Or with S_C

$=$

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y	C	C	A	T	A	C
			1	0	1	1

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C A **T** A C

1	0	1	1	
0	1	0	1	Shift

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C A **T** A C

1	0	1	1
0	1	0	1
1	1	0	1

Shift
Or with S_C

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A	y	C	C	A	T	A	C
S_A	1	0	1	0		1	0	1	1		
S_C	0	1	1	1		0	1	0	1		Shift
S_G	1	1	1	1		1	1	0	1		Or with S_C
S_T	1	1	0	1		1	1	0	1		$=$

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y	C	C	A	T	A	C
		1	1	0	1	

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C A T A C

1	1	0	1	
0	1	1	0	Shift

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y	C	C	A	T	A	C
	1	1	0	1		
	0	1	1	0		
	1	0	1	0		

Shift

Or with S_C

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y	C	C	A	T	A	C
		1	1	0	1	
		0	1	1	0	
		1	0	1	0	
		1	1	1	0	

Shift
Or with S_C
$=$

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y	C	C	A	T	A	C
			1	1	1	0

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C **A T A C**

1	1	1	0	
0	1	1	1	Shift

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y C C **A T A C**

1	1	1	0	
0	1	1	1	Shift
0	1	1	1	Or with S_C

Shift Or (Baeza-Yates & Gonnet 1992)

x	C	A	T	A
S_A	1	0	1	0
S_C	0	1	1	1
S_G	1	1	1	1
S_T	1	1	0	1

y	C	C	A	T	A	C
			1	1	1	0
			0	1	1	1
			0	1	1	1
			0	1	1	1

Shift

Or with S_C

$=$

BNDM (Navarro & Raffinot, 1998)

x C A T A

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y C C A T A C

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	1	1	1	1		

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	1	1	1	1		

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	1	1	1	1		
	0	0	1	0		

And with S_T

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	1	1	1	1		
	0	0	1	0		
	0	0	1	0		

And with S_T

$=$

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	1	1	1	1		
	0	0	1	0		
	0	0	1	0		
	0	1	0	0		

And with S_T

$=$

Shift

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	0	1	0	0		

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	0	1	0	0		
	0	1	0	1		

And with S_A

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	0	1	0	0		
	0	1	0	1		
	0	1	0	0		

And with S_A

$=$

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	0	1	0	0		
	0	1	0	1		
	0	1	0	0		
	1	0	0	0		

And with S_A

$=$

Shift

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
		1	0	0	0	

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y C C A T A C

1	0	0	0
1	0	0	0

And with S_C

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y C C A T A C

1	0	0	0	
1	0	0	0	And with S_C
1	0	0	0	$=$

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A	y	C	C	A	T	A	C
S_A	0	1	0	1		1	0	0	0	
S_C	1	0	0	0		1	0	0	0	And with S_C
S_G	0	0	0	0		1	0	0	0	$=$
S_T	0	0	1	0		0	0	0	0	Shit

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	0	0	0	0		

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	0	0	0	0		
	1	0	0	0		

And with S_C

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	0	0	0	0		
	1	0	0	0		
	0	0	0	0		

And with S_C

$=$

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
		1	1	1	1	

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x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
		1	1	1	1	
		0	1	0	1	

And with S_A

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
		1	1	1	1	
		0	1	0	1	
		0	1	0	1	

And with S_A

$=$

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
		1	1	1	1	
		0	1	0	1	
		0	1	0	1	
		1	0	1	0	

And with S_A

$=$

Shift

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
		1	0	1	0	

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
		1	0	1	0	
		0	0	1	0	

And with S_T

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	1	0	1	0		
	0	0	1	0		
	0	0	1	0		

And with S_T

$=$

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
	1	0	1	0		
	0	0	1	0		
	0	0	1	0		
	0	1	0	0		

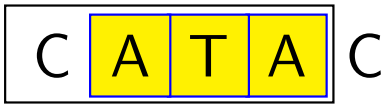
And with S_T

$=$

Shift

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0



	0	1	0	0

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y C C A T A C

0	1	0	0
0	1	0	1

And with S_A

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y C C A T A C

0	1	0	0
0	1	0	1
0	1	0	0

And with S_A

$=$

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y C C A T A C

0	1	0	0	
0	1	0	1	And with S_A
0	1	0	0	$=$
1	0	0	0	Shift

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
		1	0	0	0	

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y	C	C	A	T	A	C
		1	0	0	0	
		1	0	0	0	

And with S_C

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y C C A T A C

1	0	0	0
1	0	0	0
1	0	0	0

And with S_C

$=$

BNDM (Navarro & Raffinot, 1998)

x	C	A	T	A
S_A	0	1	0	1
S_C	1	0	0	0
S_G	0	0	0	0
S_T	0	0	1	0

y C C A T A C

1	0	0	0
1	0	0	0
1	0	0	0

And with S_C

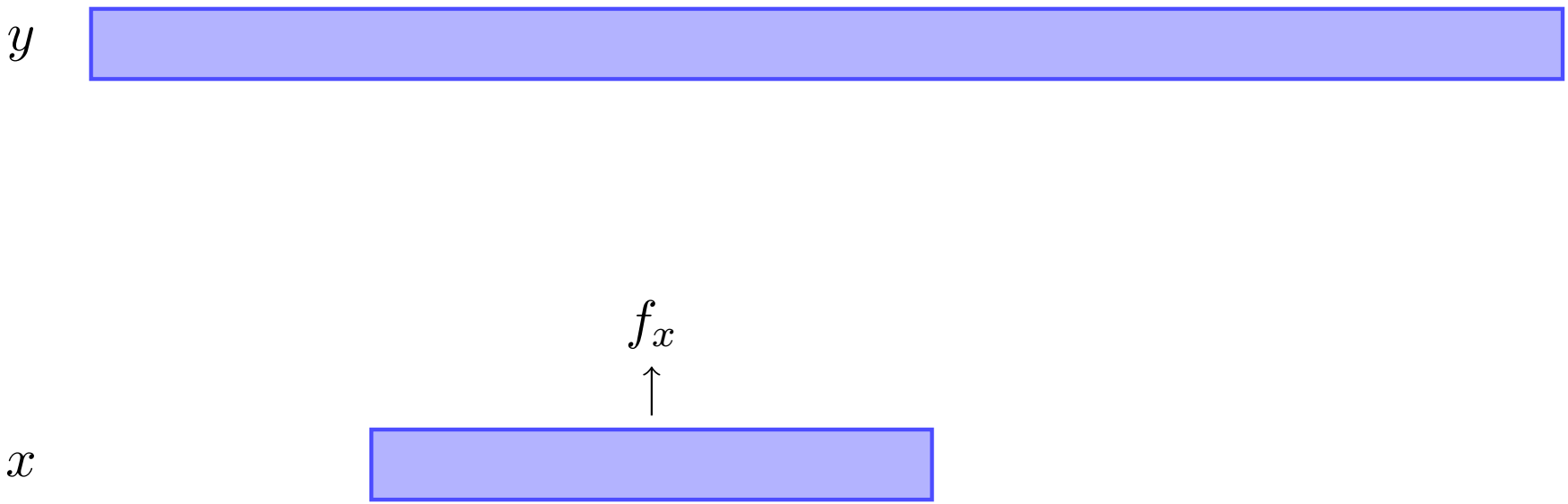
$=$

SO and BNDM

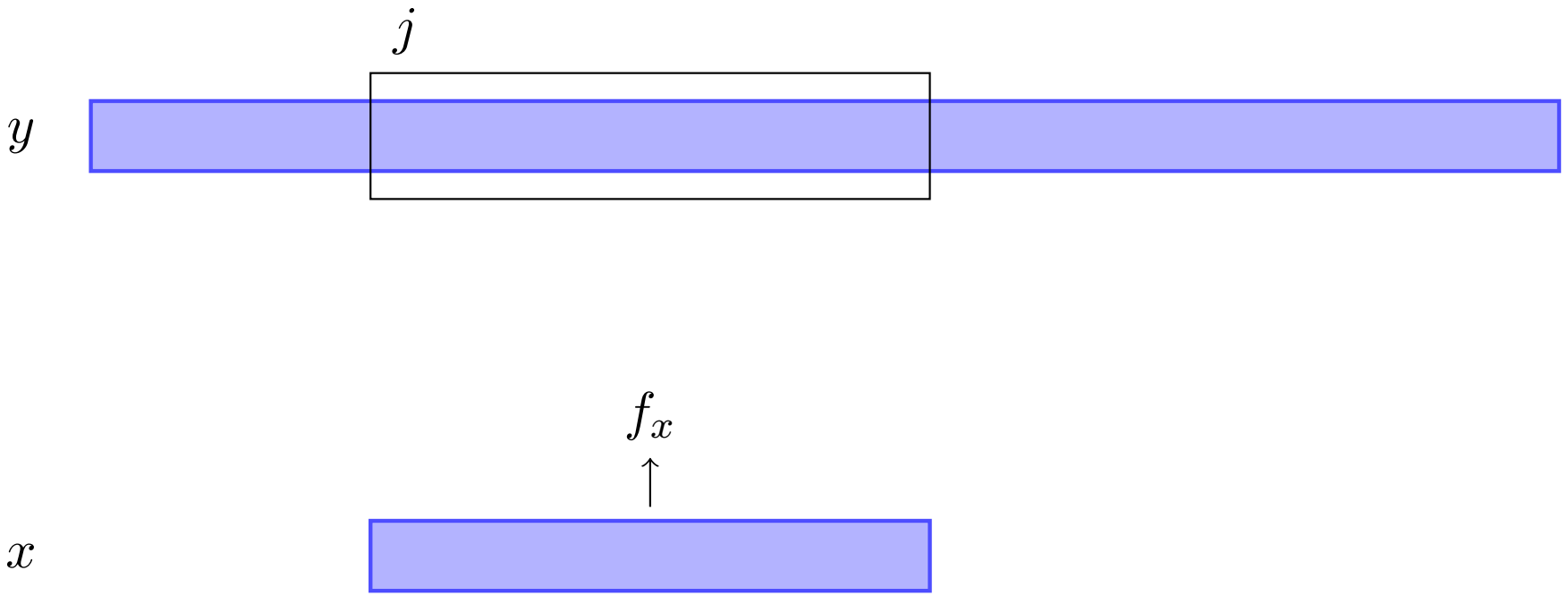
Easily adapt to approximate string matching

Karp-Rabin (1987)

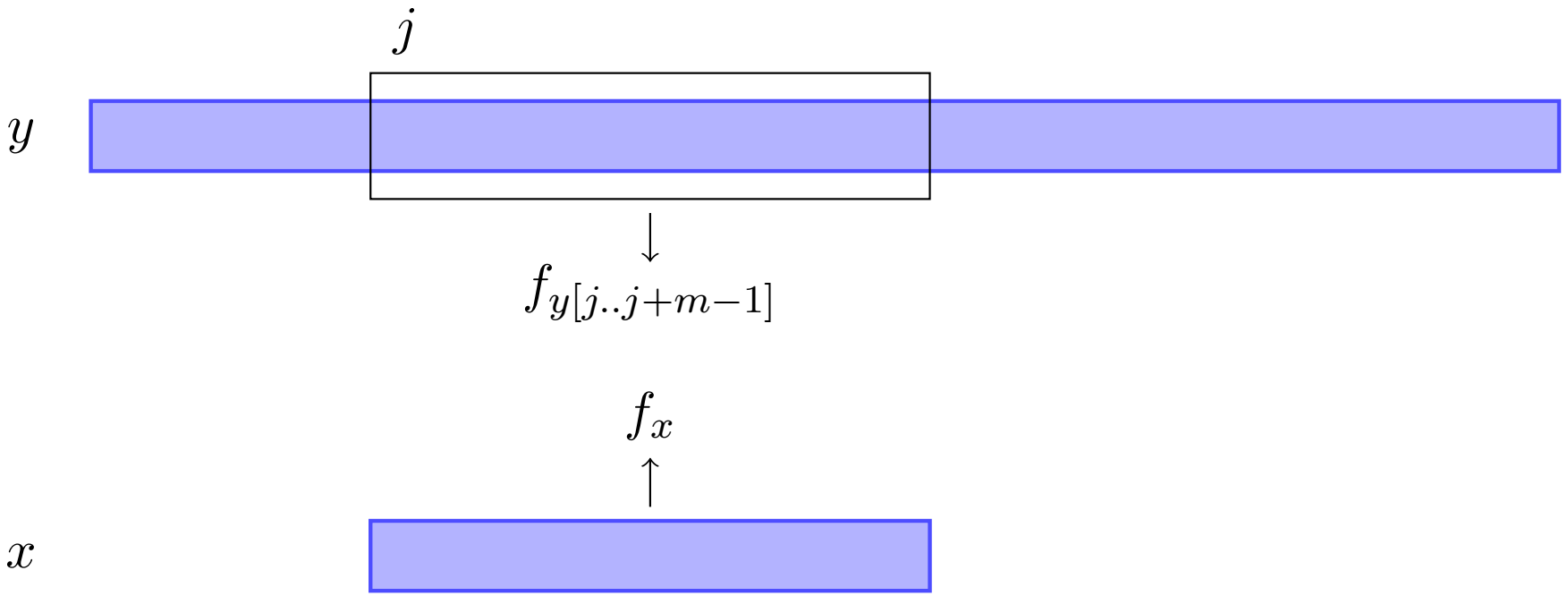
Karp-Rabin (1987)



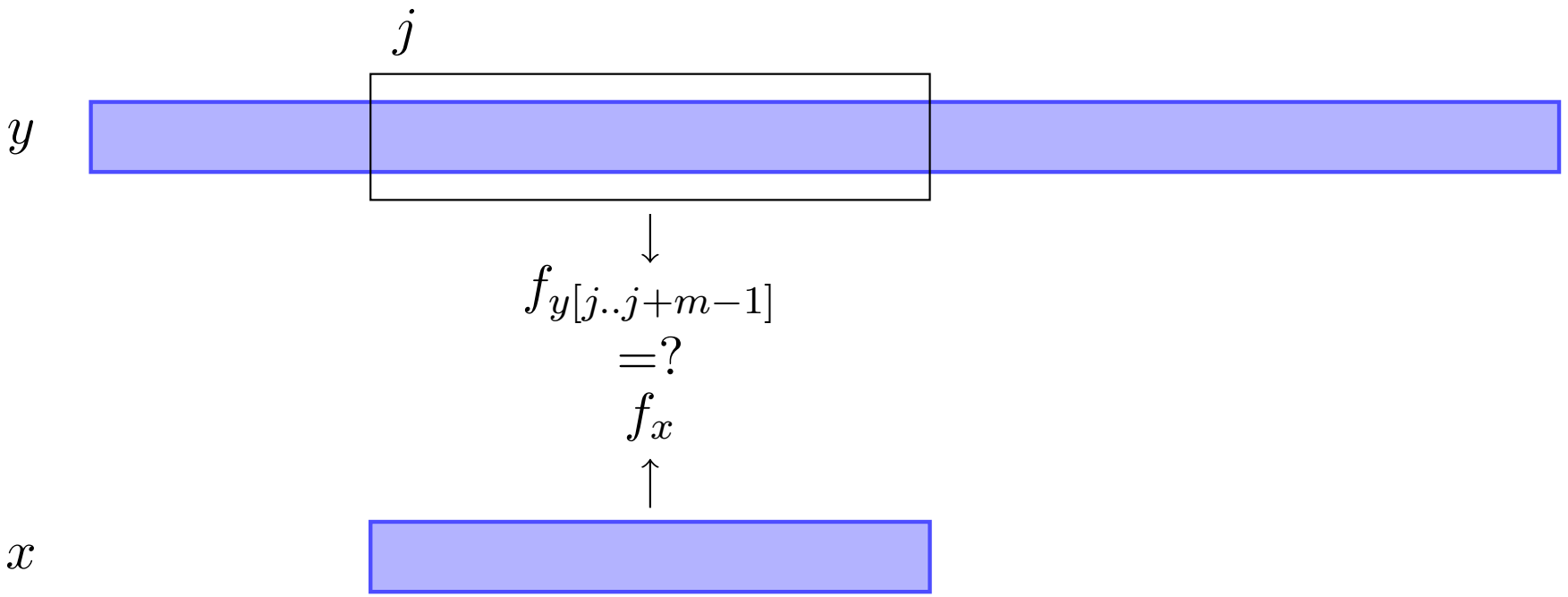
Karp-Rabin (1987)



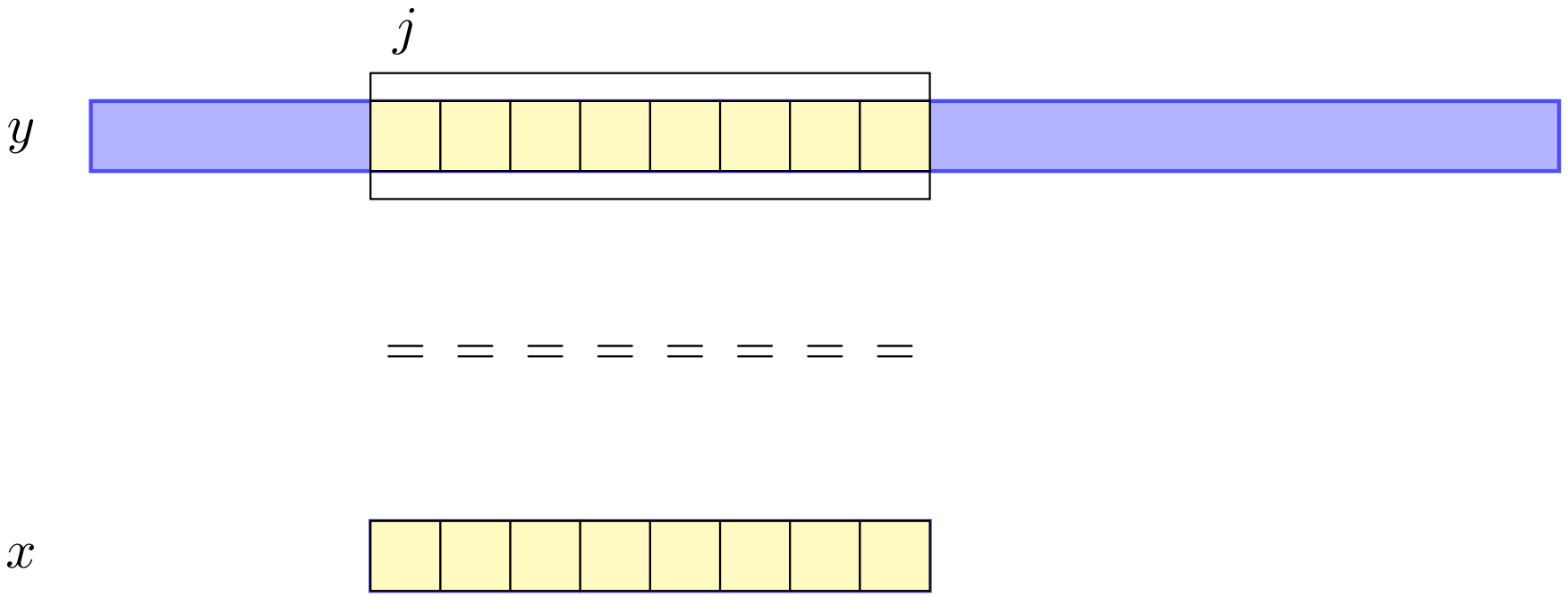
Karp-Rabin (1987)



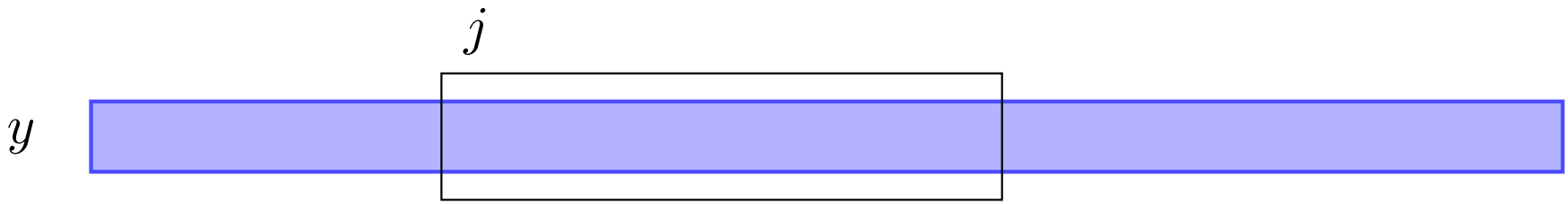
Karp-Rabin (1987)

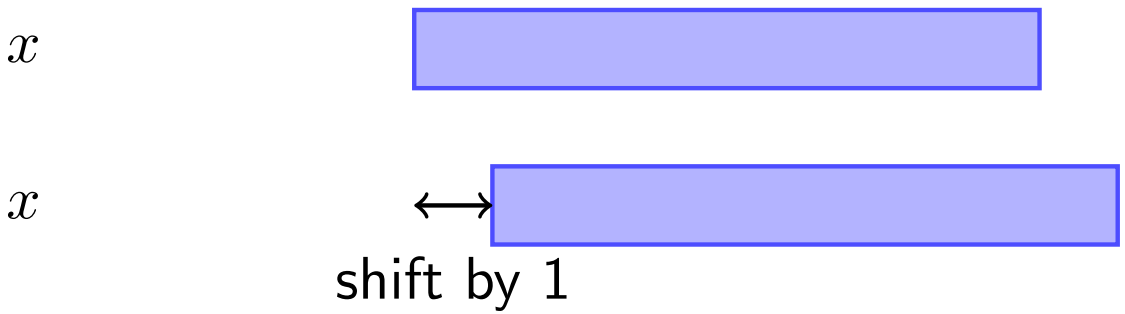


Karp-Rabin (1987)



Karp-Rabin (1987)





Usual tricks

- sentinel: append x at the end of y
- fast loop: locate first one character of x

Usual algorithm

SM(x, m, y, n)

```
1  preprocessing on x
2  position the window at the left end of y
3  while the window is still on y do
4     if x = content of the window then
5        OUTPUT(1 occurrence)
6     shift the window
```

Sentinel

SM(x, m, y, n)

```
1  preprocessing on x
2  append x at the end of y
3  position the window at the left end of y
4  while true do
5     if x = content of the window then
6        if the window is still on y then
7           Output(1 occurrence)
8        else Exit
9     shift the window
```

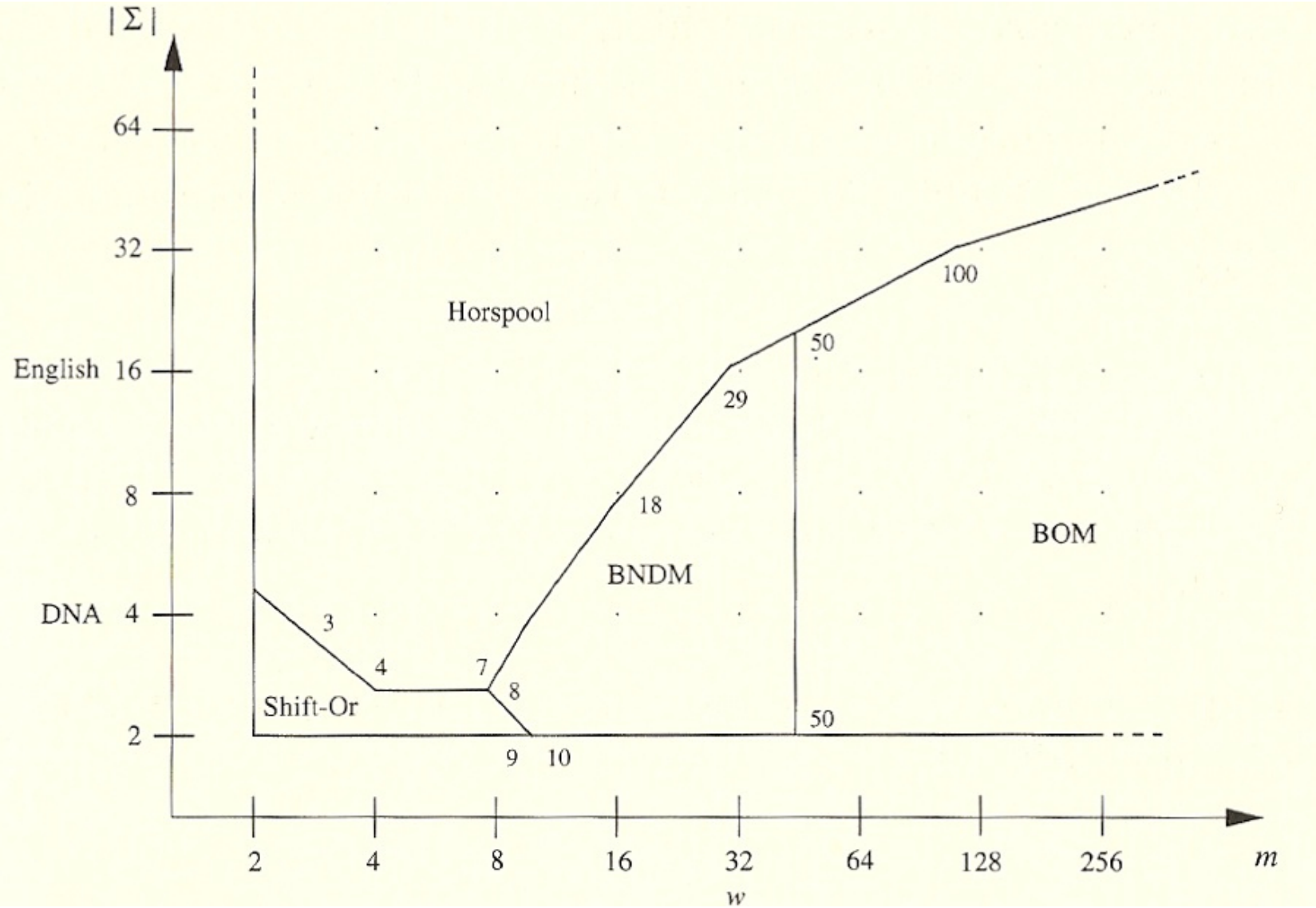
Fast loop

SM(x, m, y, n)

```
1  preprocessing on x
2  append x at the end of y
3  position the window at the left end of y
4  c ← 1 character of x
5  while true do
6     while c is not in the window do
7        shift the window
8     if x = content of the window then
9        if the window is still on y then
10          OUTPUT(1 occurrence)
11       else EXIT
12    shift the window
```

Outline

The XXth Century



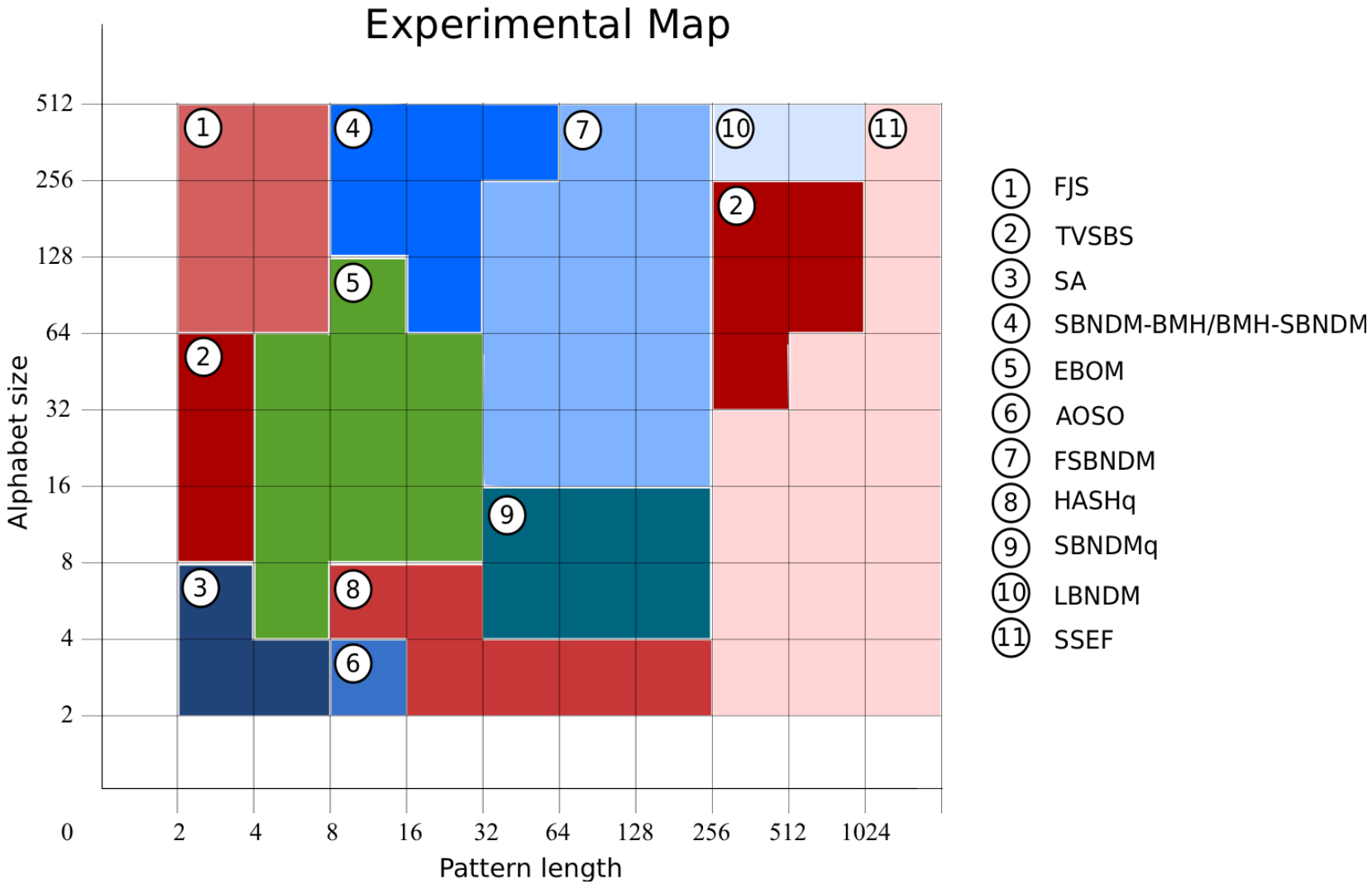
G. Navarro & M. Raffinot, *Flexible Pattern Matching in Strings*, CUP, 2002

The XXIst Century

More than 50 algorithms

- Variants of:
  - BM
  - BOM
  - BNDM
- 2 windows
- 2 automata
- large window
- sample the pattern

The XXIst Century



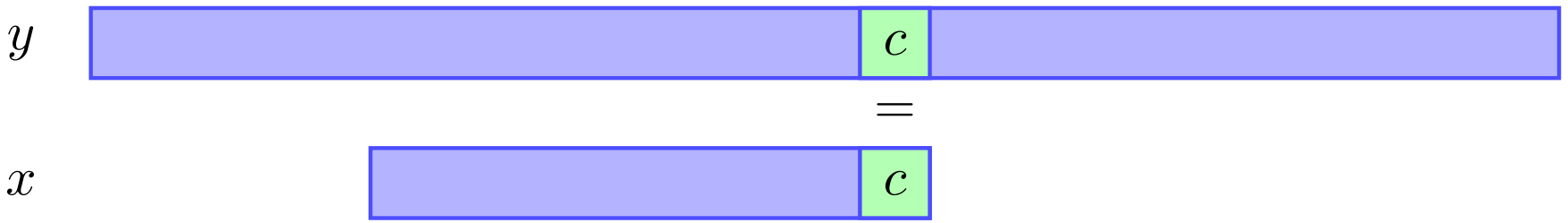
S. Faro & T. Lecroq, *The Exact String Matching Problem: a Comprehensive Experimental Evaluation*, arXiv:1012.2547, 2010

FJS (Franek-Jennings-Smyth, 2007)

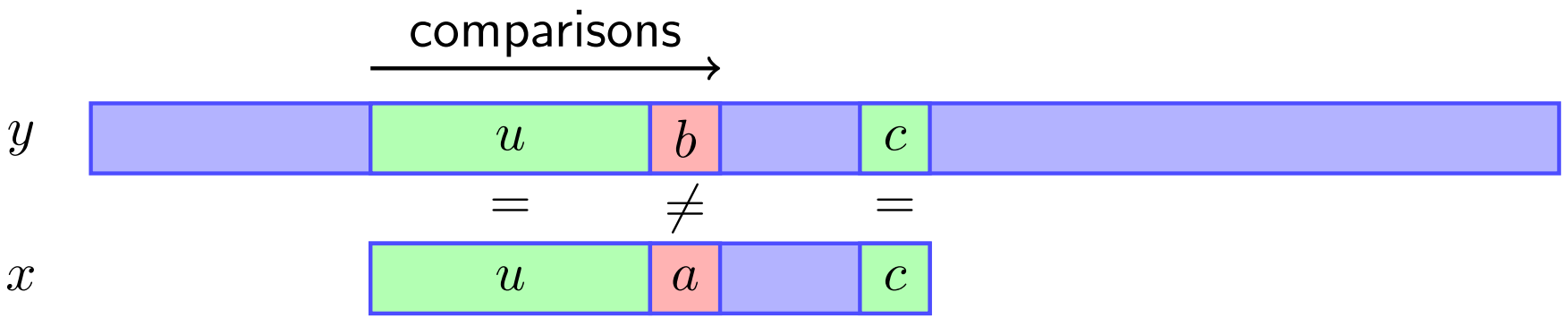
- uses KMP and QS
- $O(m + \sigma)$ time for preprocessing phase
- $3n - 2m$ character comparisons during the searching phase

FJS (Franek-Jennings-Smyth, 2007)

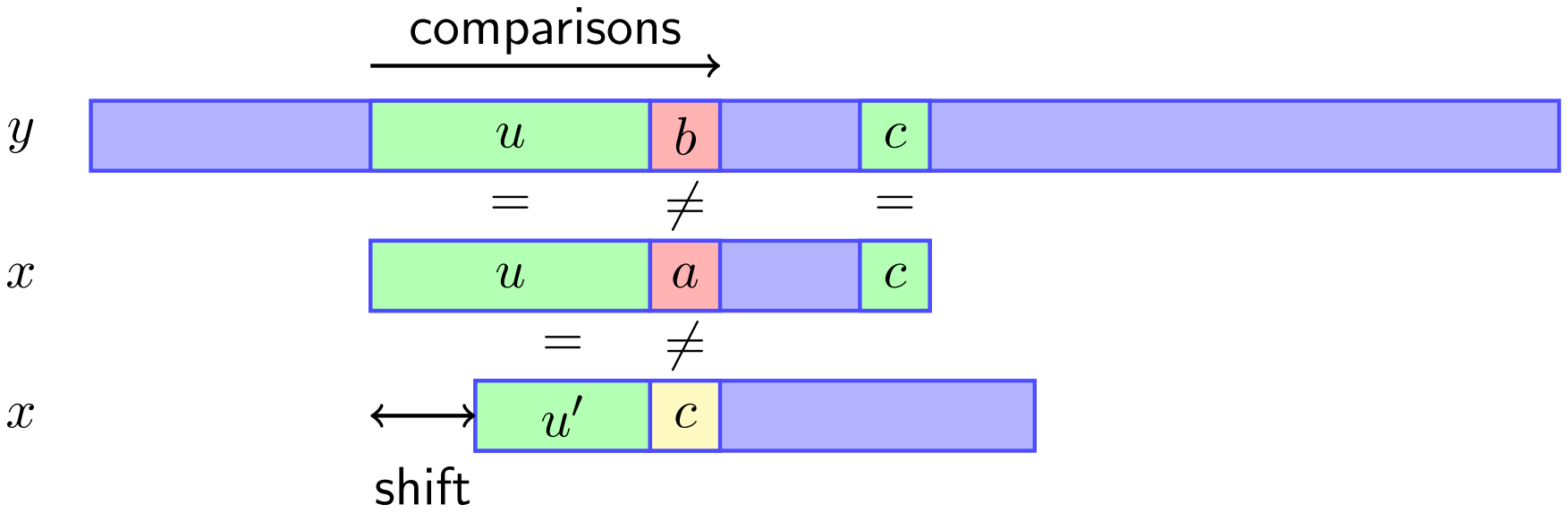
FJS (Franek-Jennings-Smyth, 2007)



FJS (Franek-Jennings-Smyth, 2007)



FJS (Franek-Jennings-Smyth, 2007)



u' is the longest border of u followed by a letter $\neq a$

TVSBS (Thathoo-Virmani-Lakshmi-Balakrishnan-Sekar, 2006)

- compares first the rightmost character of the window then the leftmost, then all the others
- uses the Berry-Ravindran bad character shift
- $O(m + \sigma^2)$ time for the preprocessing phase
- $O(nm)$ time for the searching phase

TVSBS (Thathoo-Virmani-Lakshmi-Balakrishnan-Sekar, 2006)

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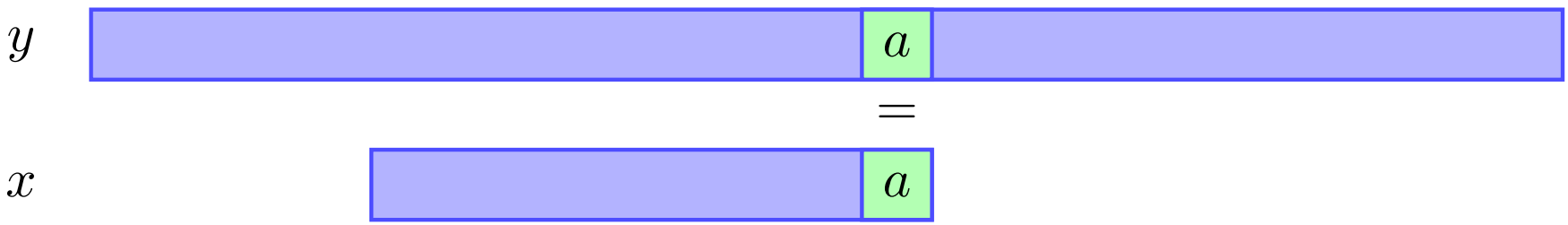
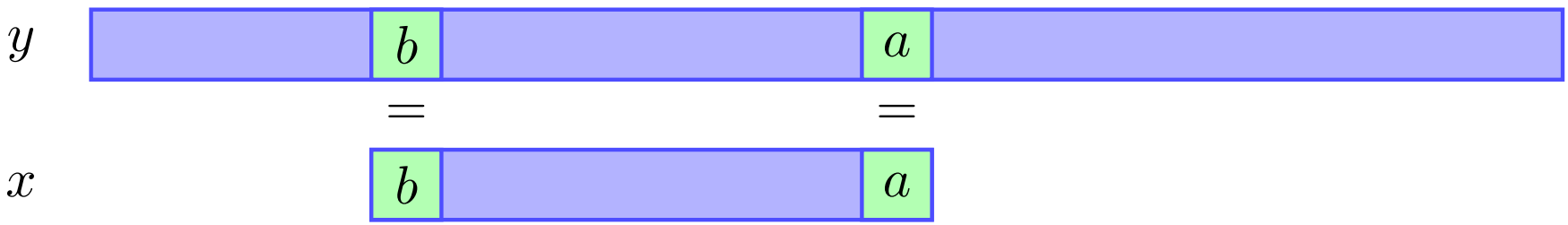
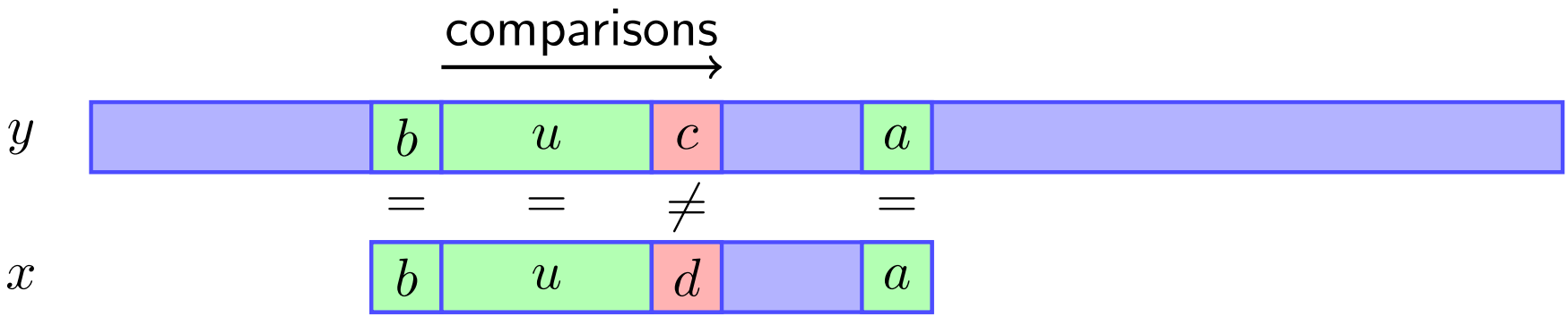


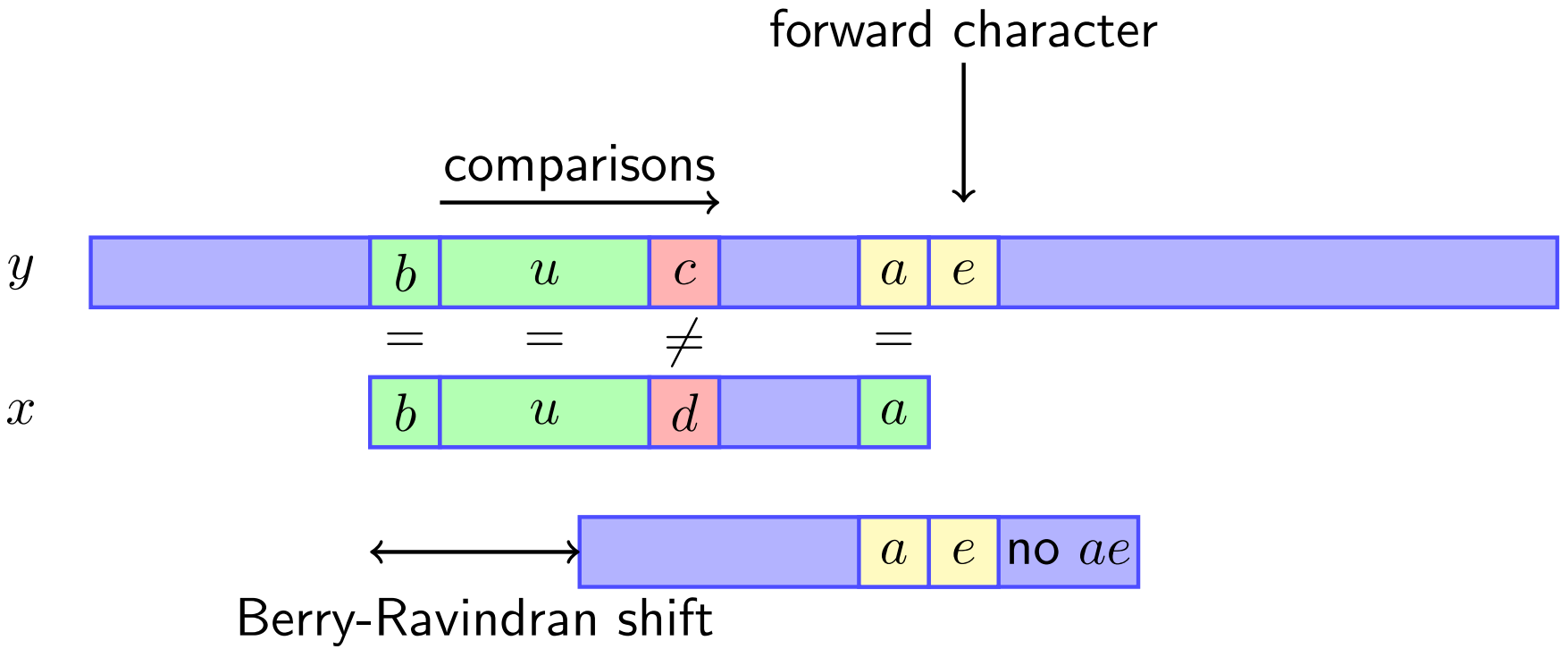
TVSBS (Thathoo-Virmani-Lakshmi-Balakrishnan-Sekar, 2006)



TVSBS (Thathoo-Virmani-Lakshmi-Balakrishnan-Sekar, 2006)



TVSBS (Thathoo-Virmani-Lakshmi-Balakrishnan-Sekar, 2006)



Shift-And (Wu & Manber, 1992)

- Shift-Or with 1 for match and 0 for mismatch

SBNDM-BMH and BMH-SBNDM (Holub & Durian, 2005)

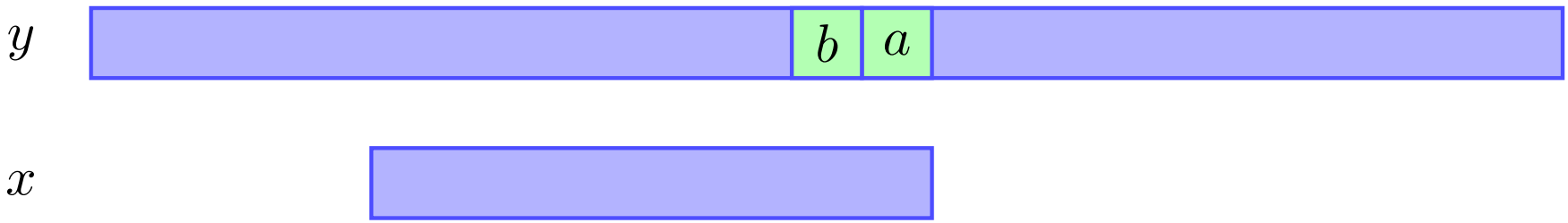
- alternates SBNDM and Horspool strategies

Extended BOM (Faro & Lecroq, 2008)

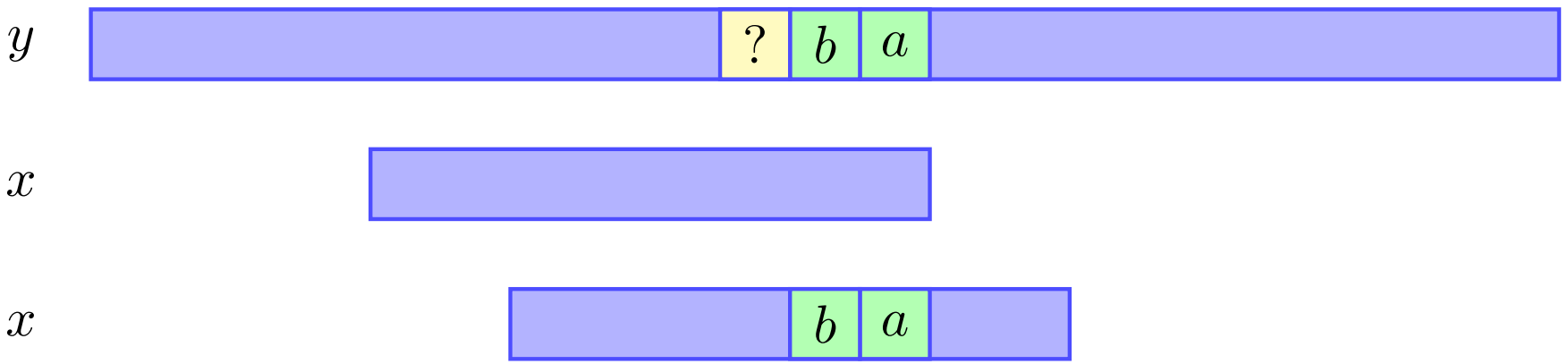
- fast loop with 2 transitions in the factor oracle with a 2-dimensional table
- $O(\sigma^2)$ additional space
- $O(mn)$ worst case time searching phase

Extended BOM (Faro & Lecroq, 2008)

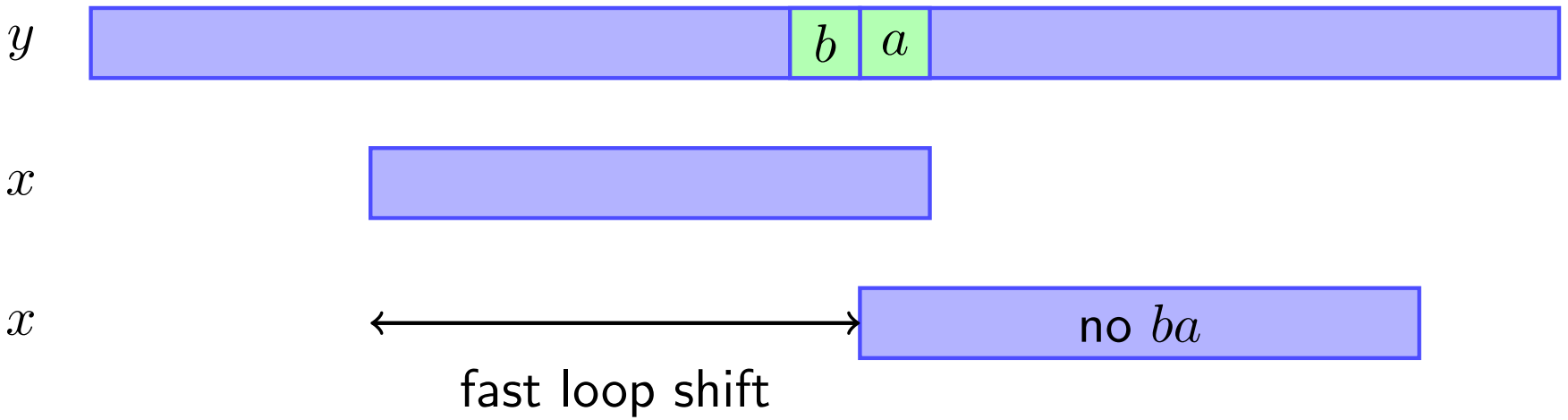
Extended BOM (Faro & Lecroq, 2008)



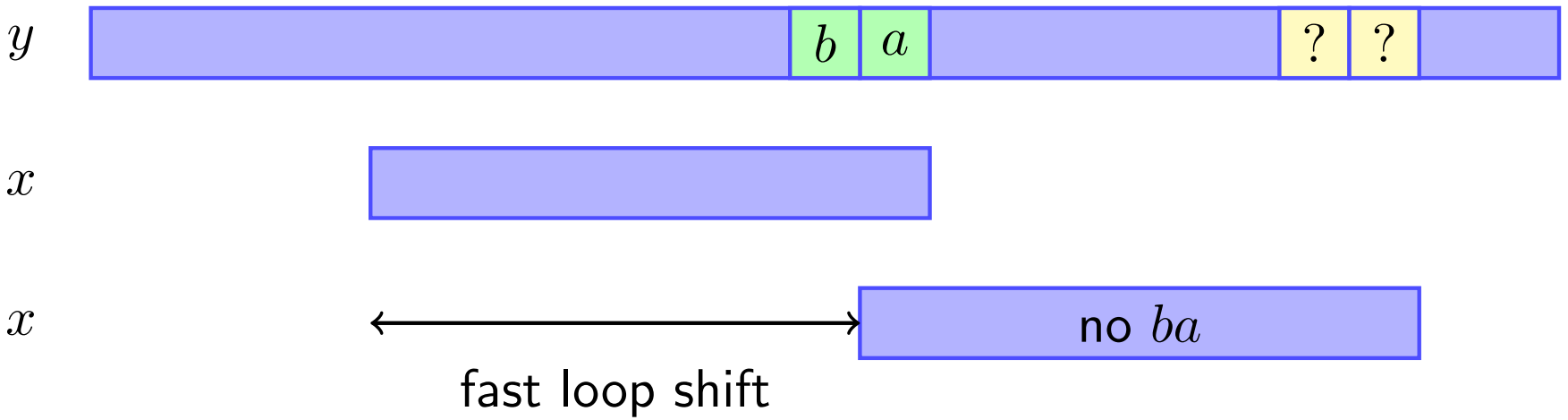
Extended BOM (Faro & Lecroq, 2008)



Extended BOM (Faro & Lecroq, 2008)



Extended BOM (Faro & Lecroq, 2008)



AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)

- considers a set of q patterns $X = \{x^0, x^1, \ldots, x^{q-1}\}$ where $|x^j| = \lfloor m/q \rfloor$ and $x^j[i] = x[j + iq]$
- construct a new pattern $x' = x^0 x^1 \cdots x^{q-1}$
- search for x' in y using the Shift-Or algorithm by considering every q-th character
- if a x^j is found x is naively checked

AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)

x 

AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)

x 

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x 

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x 

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x 

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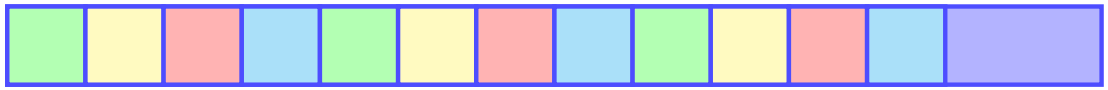
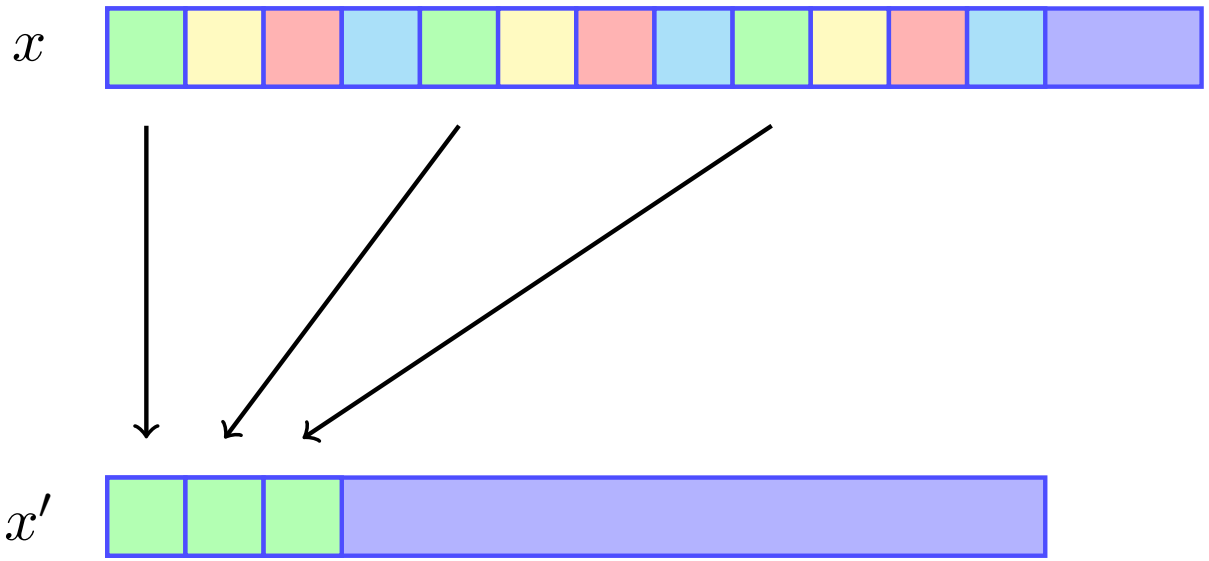
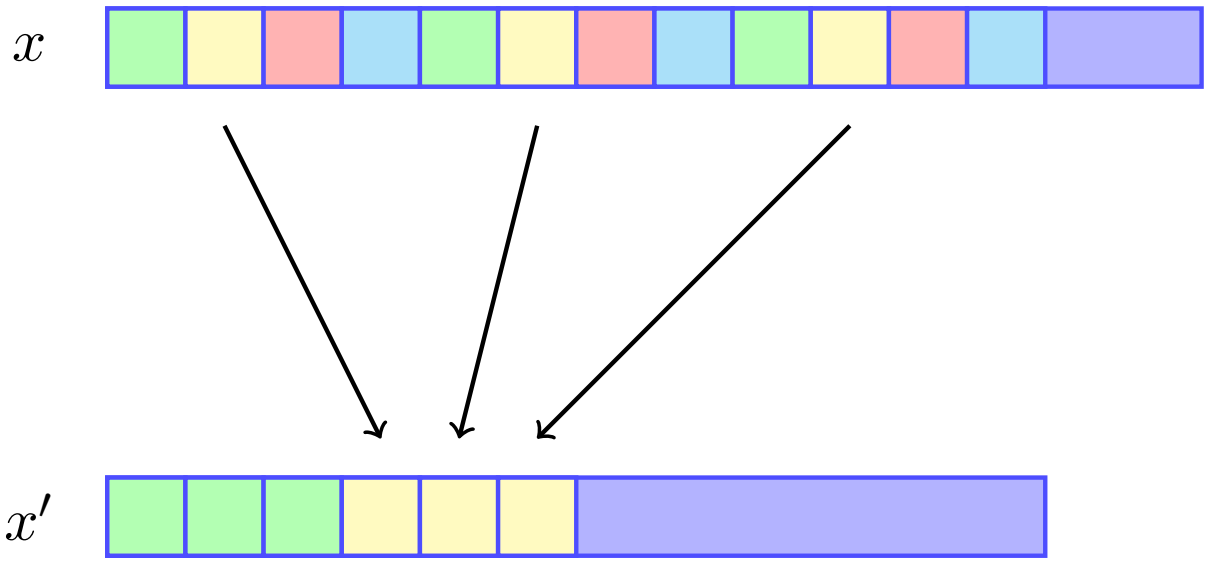
x 

x' 

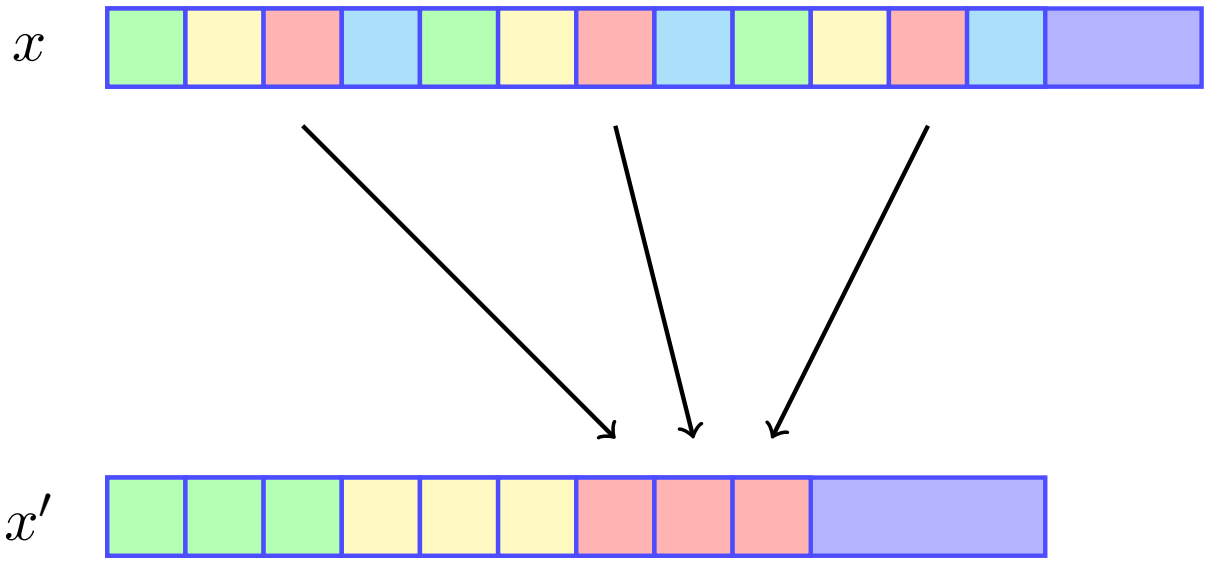
AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



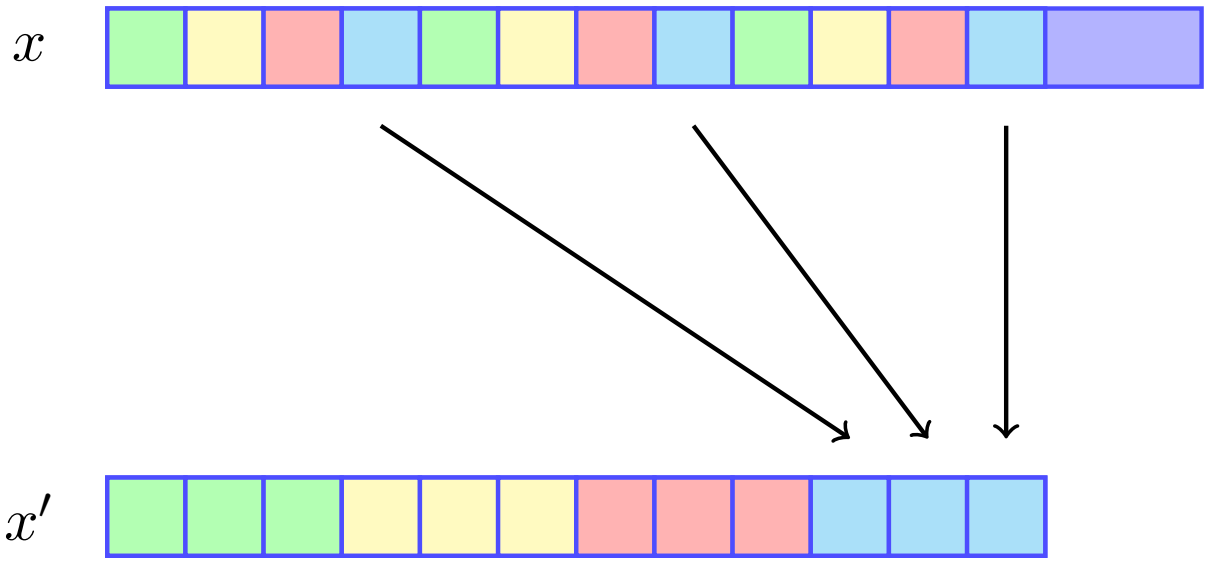
AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)

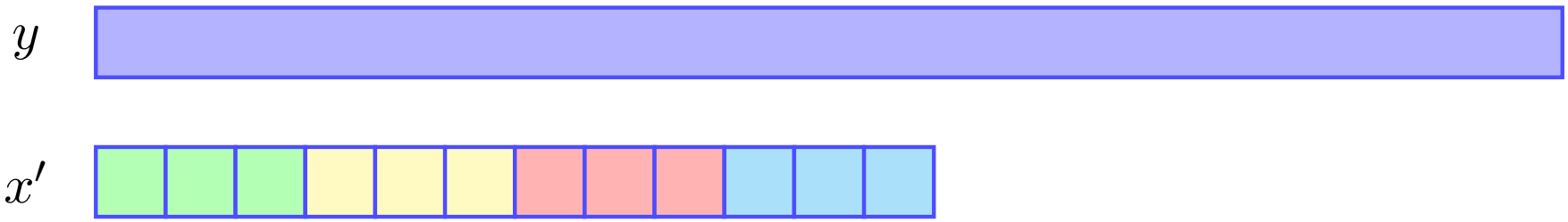


AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)

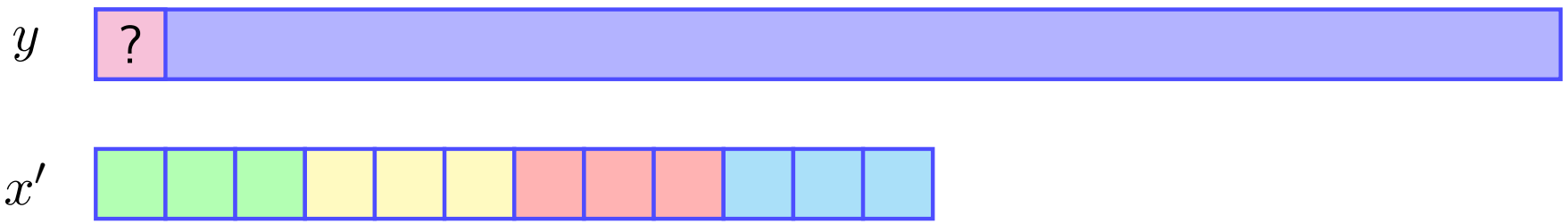
y 

x'

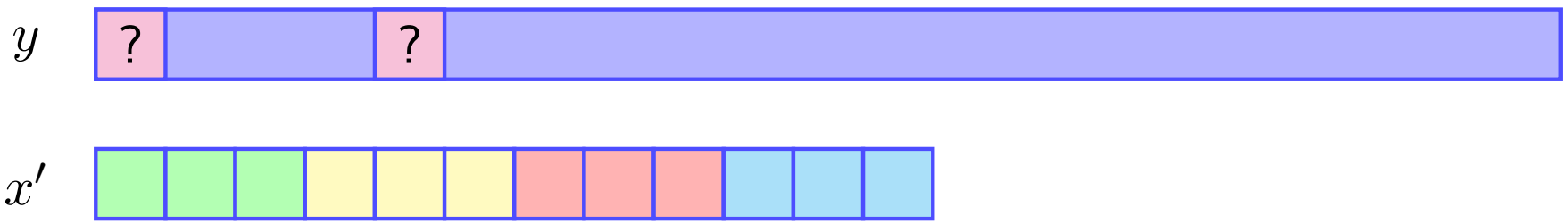
AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



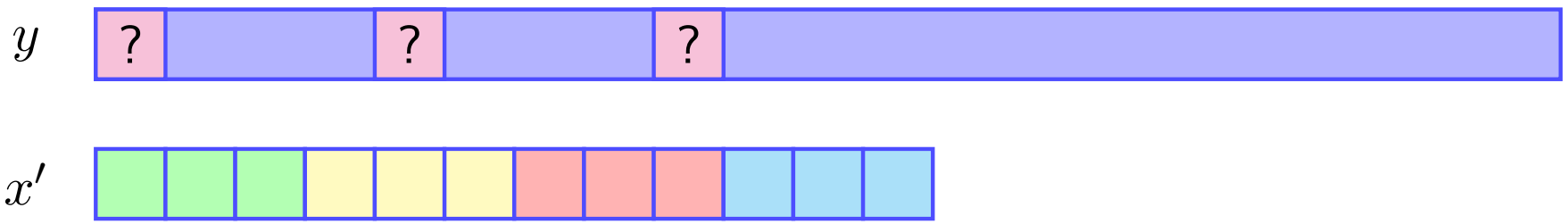
AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



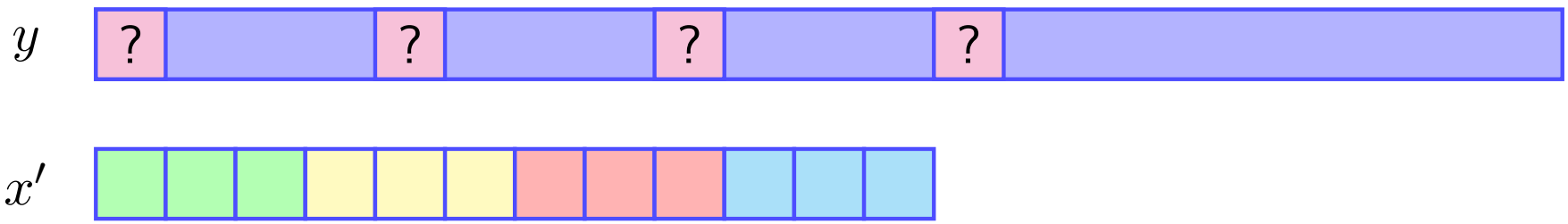
AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



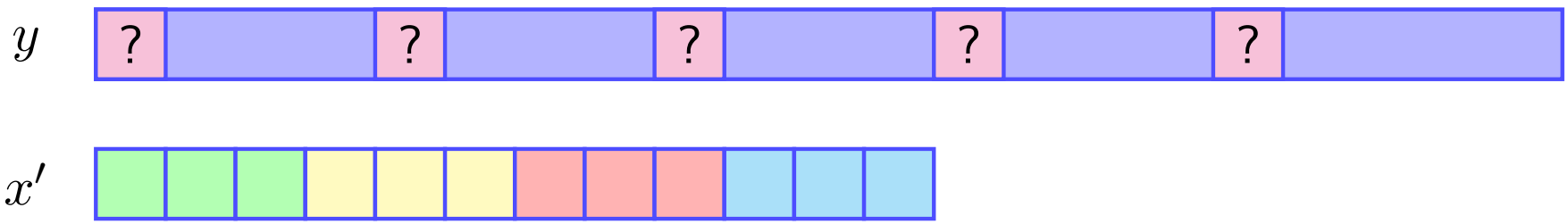
AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



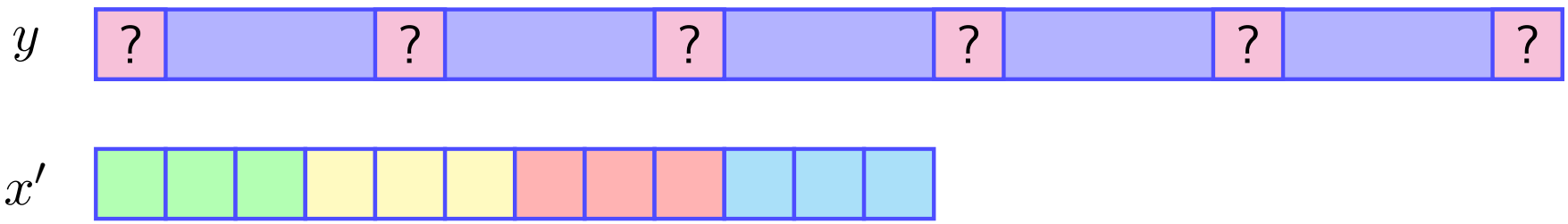
AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)



AOSO (Average Optimal Shift Or, Fredriksson & Grabowski, 2005)

- with $q = O(m/\log_\sigma m)$ average time is $O((n \log_\sigma m)/m)$

Hashing q-grams (Lecroq, 2007)

- Compute a hash value in $[0; 255]$ for every q-grams of the pattern x
- Compute a shift for every hash value
- Unroll the loops as much as possible

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$shift[i] \leftarrow 10$

$\forall i \in [0; 255]$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$$h(\textbf{cat}) = ((rank(\textbf{c}) \times 2 + rank(\textbf{a})) \times 2 + rank(\textbf{t}) = 194$$

$$\mathit{shift}[194] = 10$$

$$\mathit{shift}[194] \leftarrow 9$$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$$h(\textbf{ata}) = ((rank(\textbf{a}) \times 2 + rank(\textbf{a})) \times 2 + rank(\textbf{a}) = 205$$

$$\mathit{shift}[205] = 10$$

$$\mathit{shift}[205] \leftarrow 8$$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$$h(\textbf{tac}) = ((rank(\textbf{t}) \times 2 + rank(\textbf{a})) \times 2 + rank(\textbf{c}) = 245$$

$$shift[245] = 10$$

$$shift[245] \leftarrow 7$$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$h(\textbf{aca}) = ((rank(\textbf{a}) \times 2 + rank(\textbf{c})) \times 2 + rank(\textbf{a}) = 171$

$shift[171] = 10$

$shift[171] \leftarrow 6$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$$h(\textbf{cat}) = ((rank(\textbf{c}) \times 2 + rank(\textbf{a})) \times 2 + rank(\textbf{t}) = 194$$

$$\mathit{shift}[194] = 9$$

$$\mathit{shift}[194] \leftarrow 5$$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$h(\textbf{ata}) = ((rank(\textbf{a}) \times 2 + rank(\textbf{t})) \times 2 + rank(\textbf{a}) = 205$

$shift[205] = 8$

$shift[205] \leftarrow 4$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$h(\textbf{taa}) = ((rank(\textbf{t}) \times 2 + rank(\textbf{a})) \times 2 + rank(\textbf{a}) = 243$

$shift[243] = 10$

$shift[243] \leftarrow 3$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$h(\mathbf{aaa}) = ((rank(\mathbf{a}) \times 2 + rank(\mathbf{a})) \times 2 + rank(\mathbf{a}) = 167$

$shift[167] = 10$

$shift[167] \leftarrow 2$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$h(\mathbf{aat}) = ((rank(\mathbf{a}) \times 2 + rank(\mathbf{a})) \times 2 + rank(\mathbf{t}) = 186$

$shift[186] = 10$

$shift[186] \leftarrow 1$

Hashing q-grams (Lecroq, 2007)

Example

i	0	1	2	3	4	5	6	7	8	9	10	11
$x[i]$	**c**	**a**	**t**	**a**	**c**	**a**	**t**	**a**	**a**	**a**	**t**	**a**

$h(\textbf{ata}) = ((rank(\textbf{a}) \times 2 + rank(\textbf{t})) \times 2 + rank(\textbf{a}) = 205$

$shift[205] = 4 \Longrightarrow sh1 \leftarrow 4$

$shift[205] \leftarrow 0$

Hashing q-grams

Algorithm Hash$q(x, m, y, n)$ for $q = 3$

▷ Preprocessing
for $i \leftarrow 0$ **to** 255 **do** *shift*$[i] \leftarrow m - 2$
for $i \leftarrow 2$ **to** $m - 2$ **do**
    $h \leftarrow ((x[i-2] \times 2 + x[i-1]) \times 2) + x[i]$
    shift$[h \mod 256] \leftarrow m - 1 - i$
$h \leftarrow ((x[m-3] \times 2 + x[m-2]) \times 2) + x[m-1]$
sh1 $\leftarrow$ *shift*$[h \mod 256]$
shift$[h \mod 256] \leftarrow 0$

Hashing q-grams

Algorithm Hash$q(x, m, y, n)$ for $q = 3$

▷ Searching
$y[n..n+m-1] \leftarrow x$ ▷ Sentinel
$j \leftarrow m-1$
while TRUE **do**
  $sh \leftarrow 1$
  while $sh \neq 0$ **do**
    $h \leftarrow ((y[j-2] \times 2 + y[j-1]) \times 2) + y[j]$
    $sh \leftarrow shift[h \mod 256]$
    $j \leftarrow j + sh$
  if $j < n$ **then**
    if $x = y[j-m+1..j]$ **then** OUTPUT$(j-m+1)$
    $j \leftarrow j + sh1$
  else RETURN

FSBNDM (Forward Simple BNDM, Faro & Lecroq, 2008)

- incorporate the forward character at each attempt

SBNDMq (Simple BNDM with q grams, Durian, Holub, Peltola & Tarhio, 2009)

- Simple BNDM that considers consecutive q-grams
- shifts of length $m - q + 1$ if the q-gram is not present

LBNDM (Long patterns BNDM, Peltola & Tarhio, 2003)

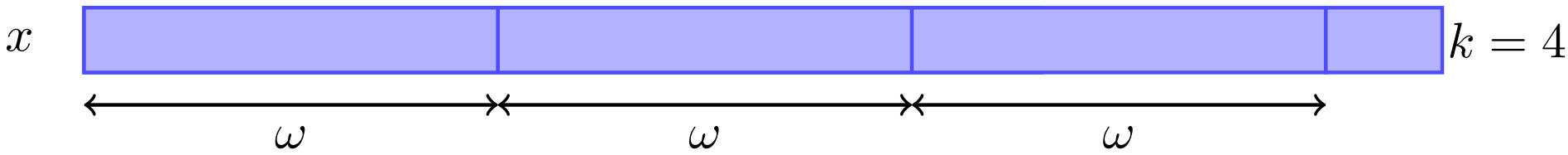
- partition $x = x^0 x^1 \cdots x^{\lfloor m/k \rfloor - 1}$ where $|x^j| = k = \lfloor (m-1)/\omega \rfloor + 1$
- construct a new pattern x' where $x'[j]$ is the set of characters of x^j
- search for x' in y using the BNDM algorithm by considering every k-th character

LBNDM (Long patterns BNDM, Peltola & Tarhio, 2003)

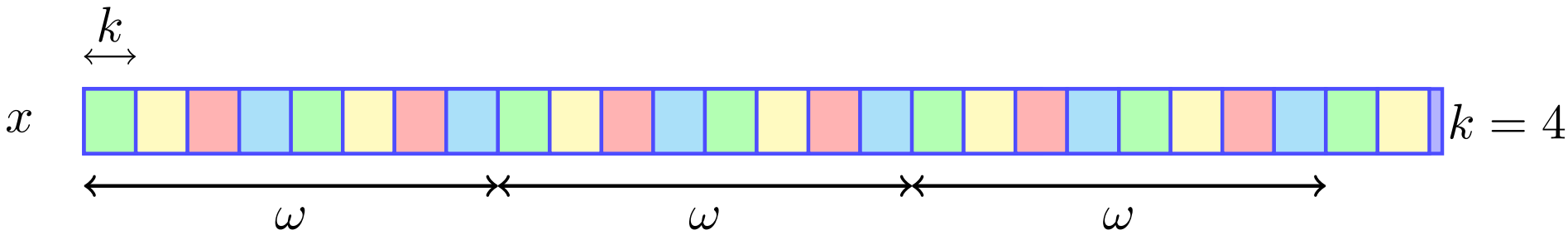
x 

LBNDM (Long patterns BNDM, Peltola & Tarhio, 2003)

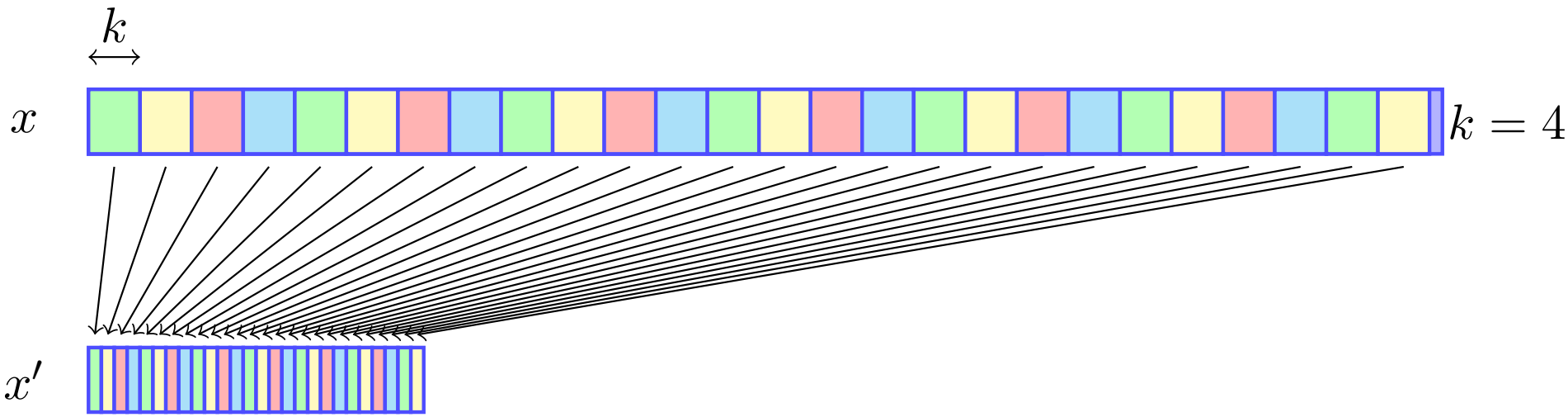
LBNDM (Long patterns BNDM, Peltola & Tarhio, 2003)



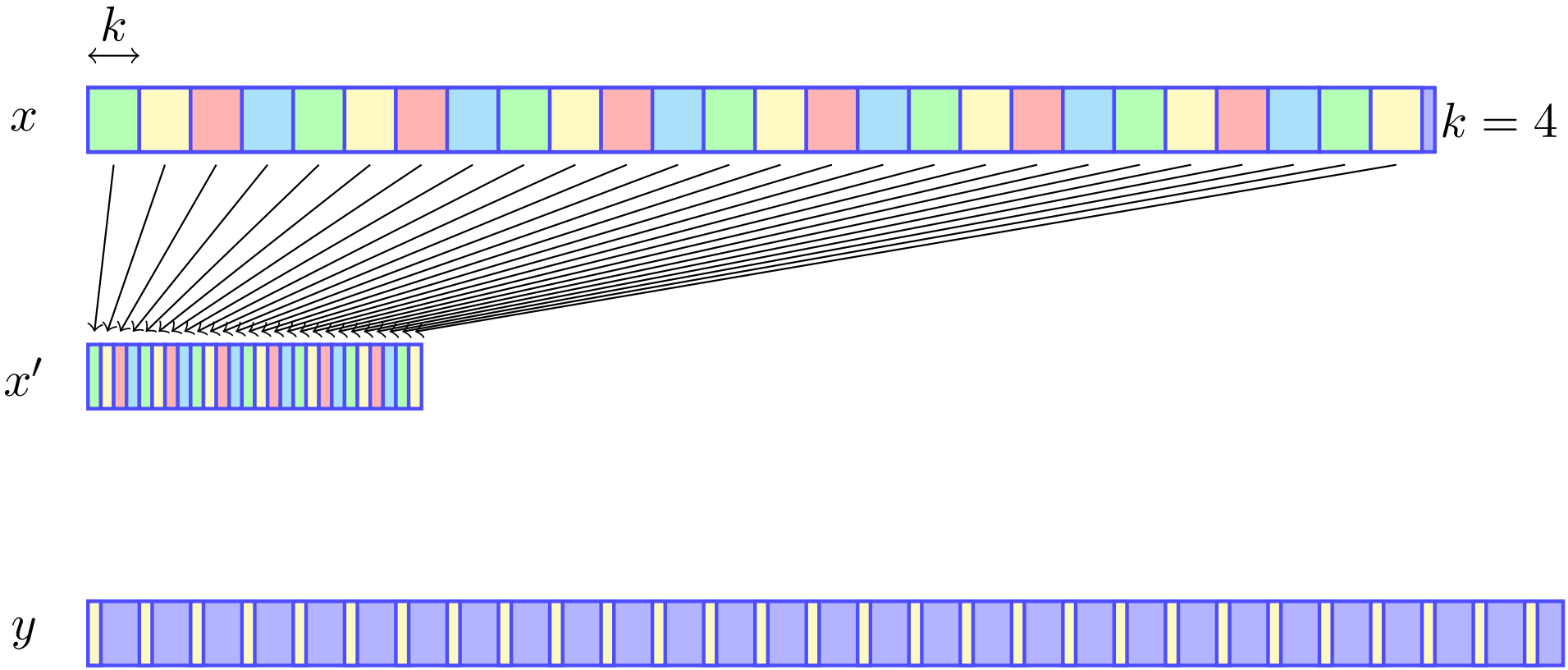
LBNDM (Long patterns BNDM, Peltola & Tarhio, 2003)



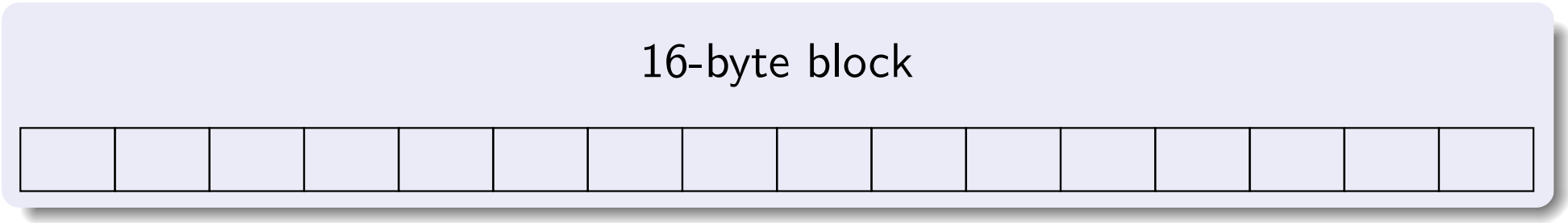
LBNDM (Long patterns BNDM, Peltola & Tarhio, 2003)



LBNDM (Long patterns BNDM, Peltola & Tarhio, 2003)

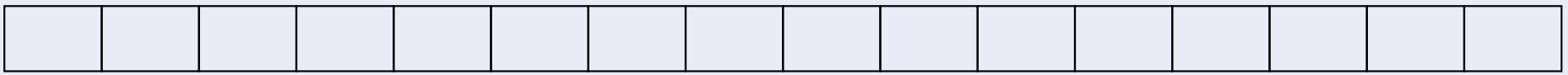


SSEF (Külekci, 2009)

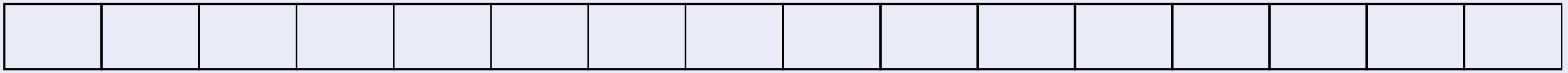


SSEF (Külekci, 2009)

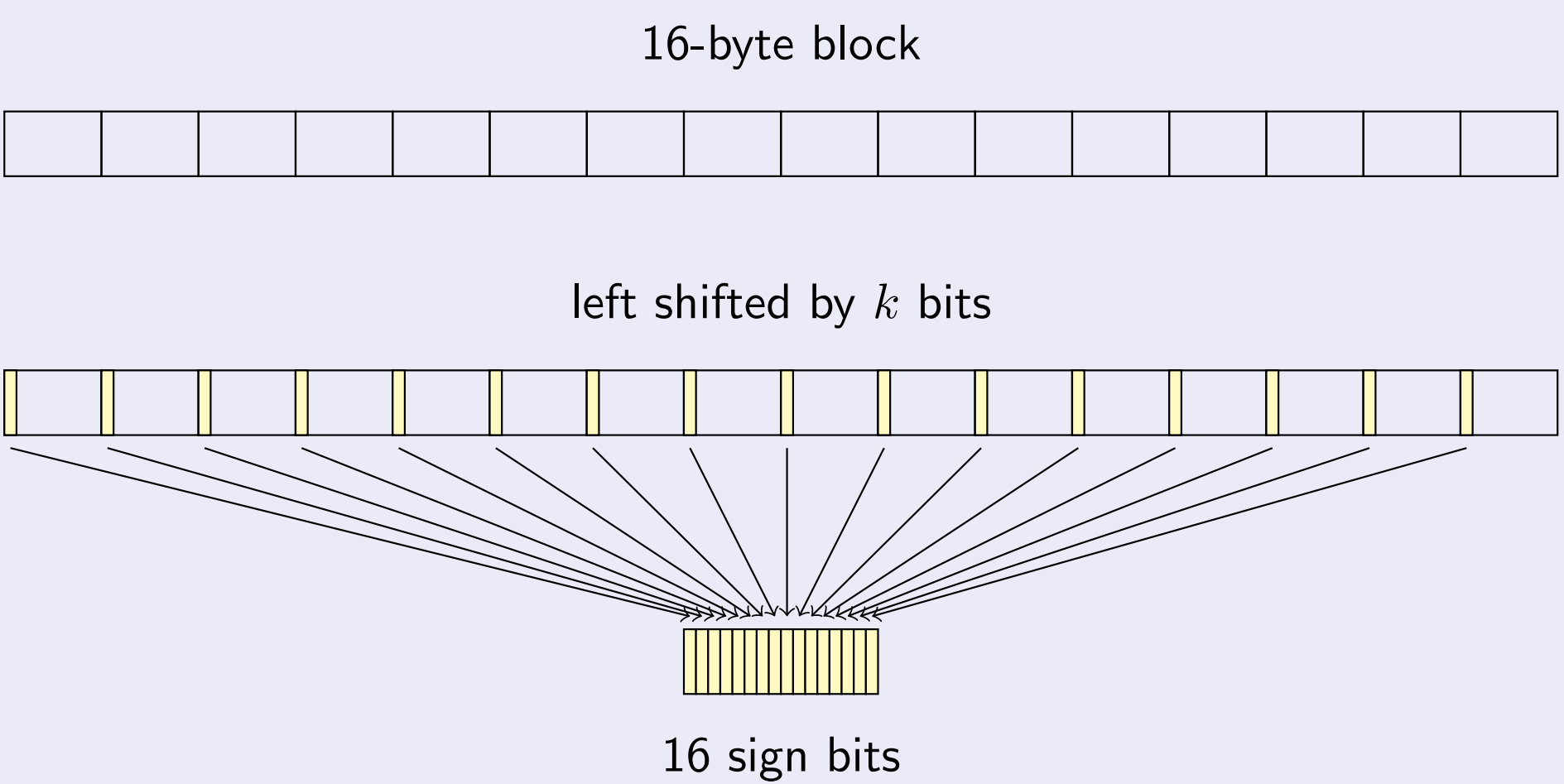
16-byte block



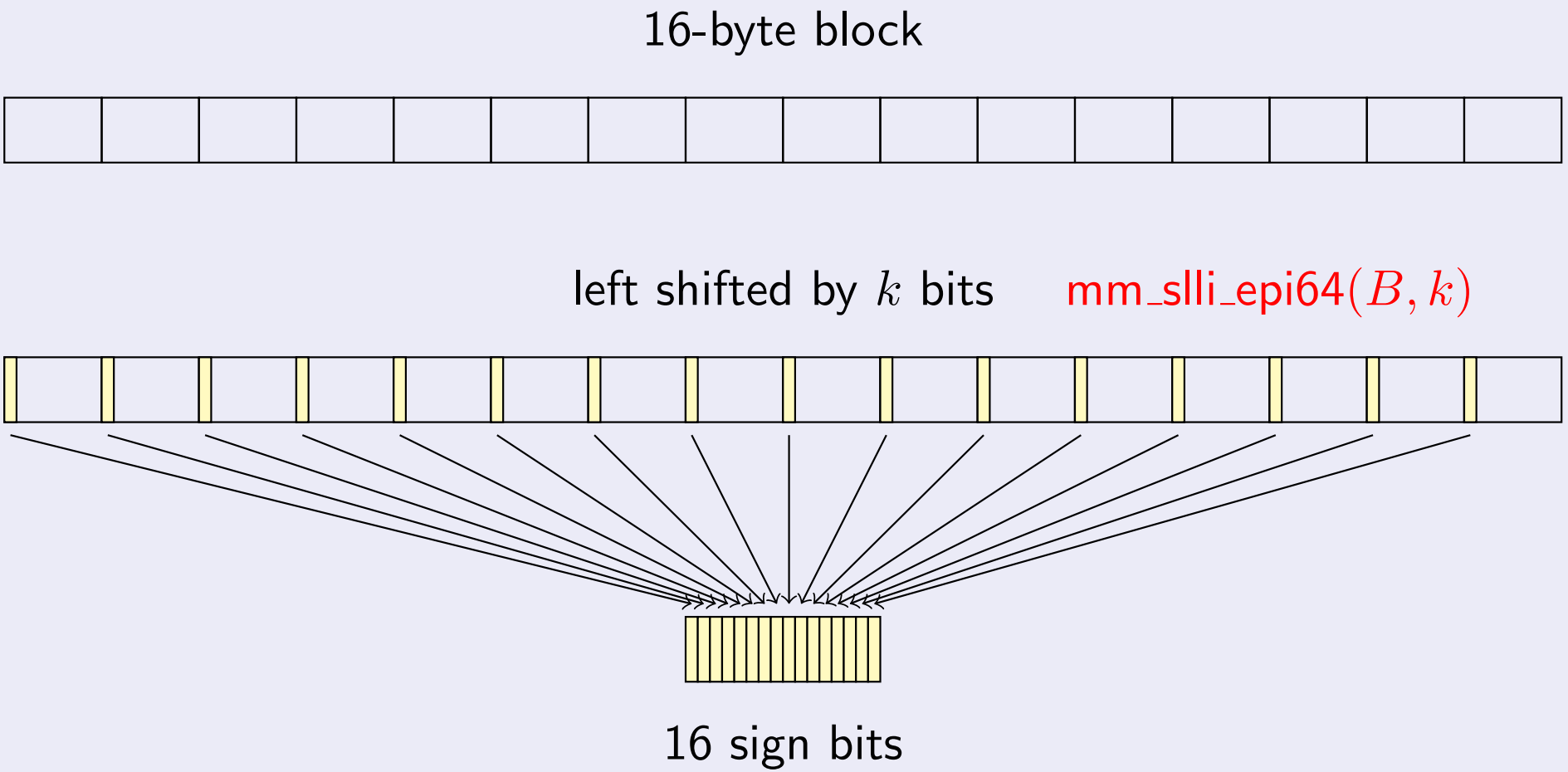
left shifted by k bits



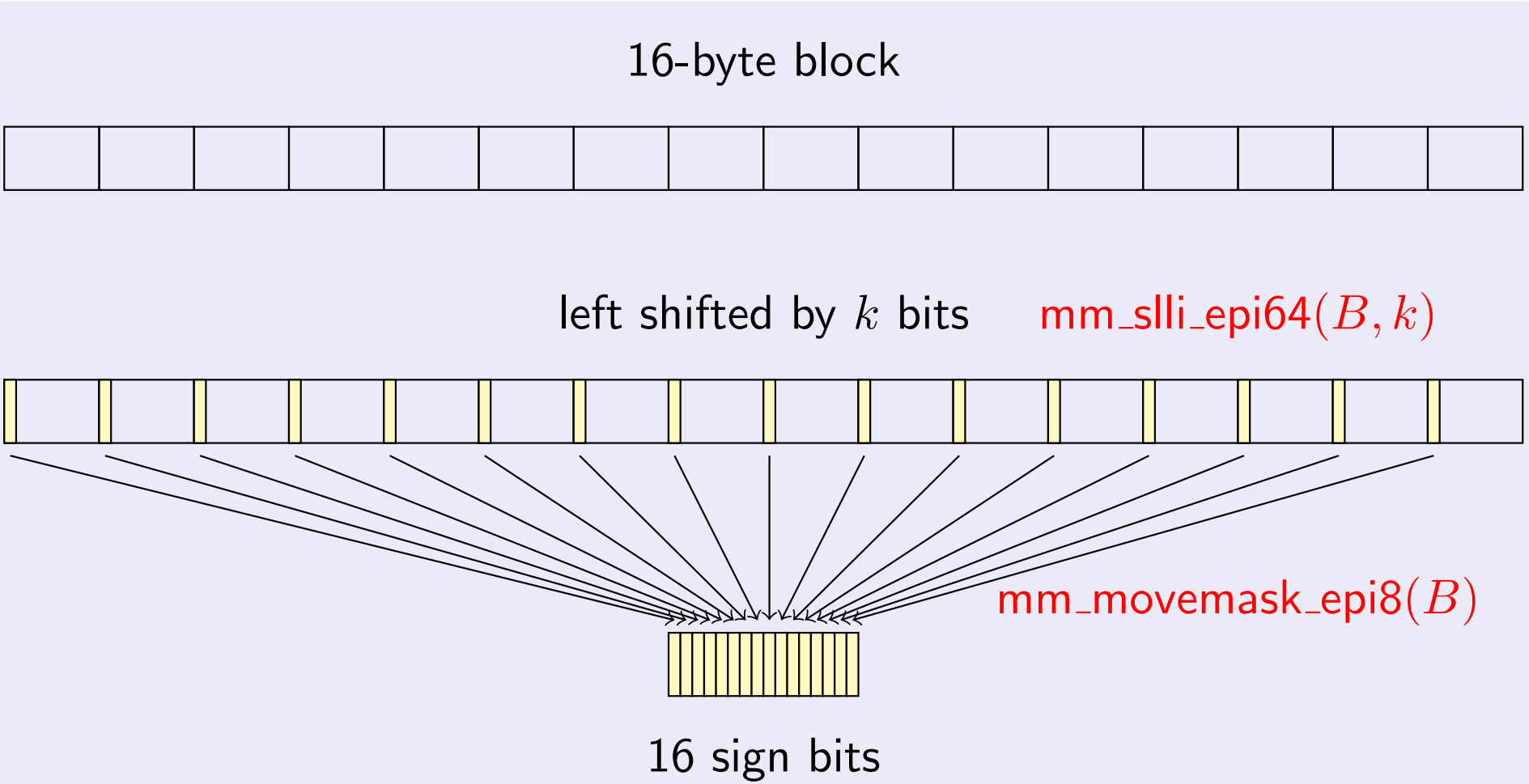
SSEF (Külekci, 2009)



SSEF (Külekci, 2009)



SSEF (Külekci, 2009)



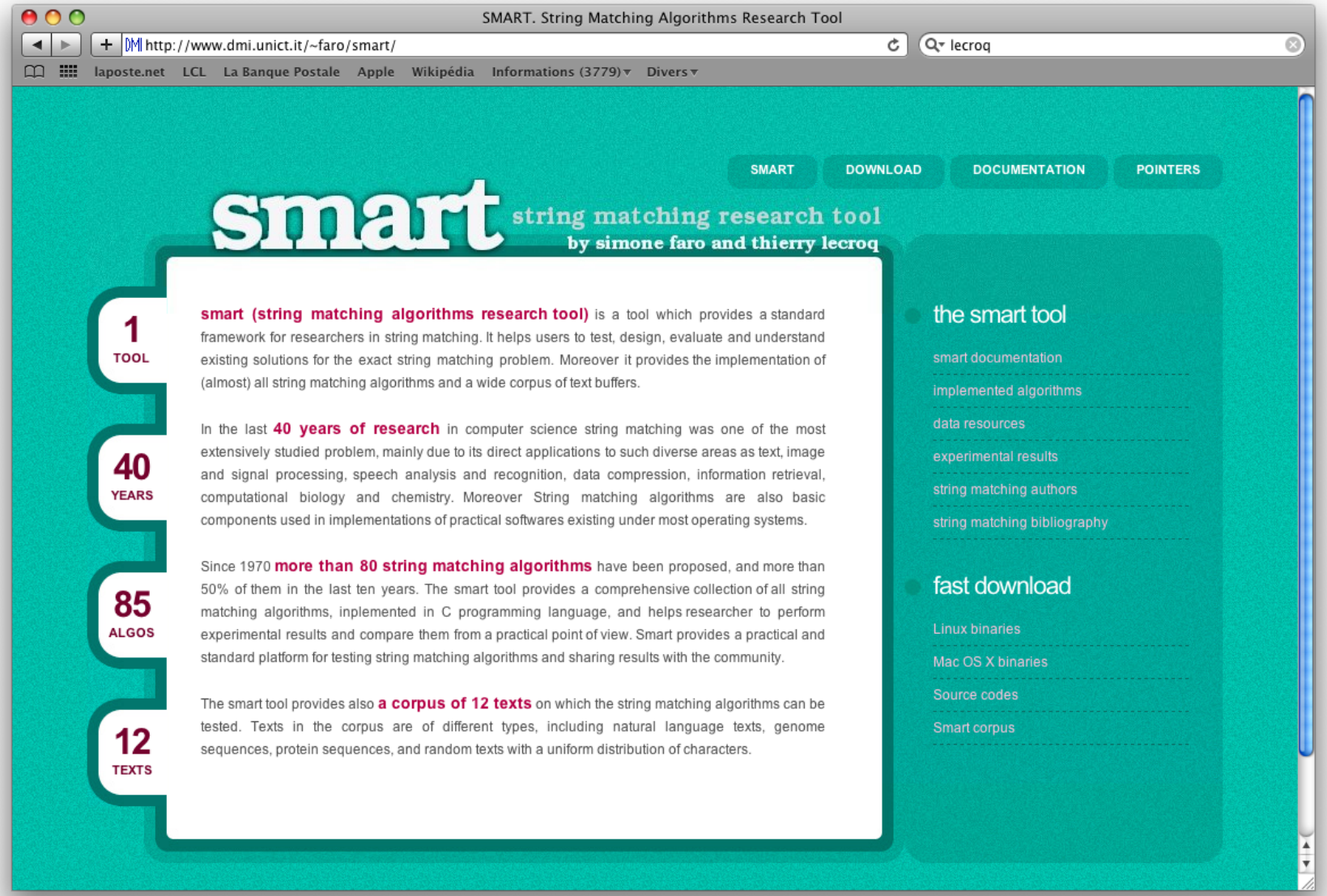
SSEF (Külekci, 2009)

- uses Streaming SIMD Extension instructions
- $O(mn)$ worst case time complexity
- $O(n/m + mn/2^{16})$ average case time complexity
- needs to store at least $2^{16} = 65536$ integers

Outline

SMART: String Matching Algorithm Research Tool

http://www.dmi.unict.it/~faro/smart/



SMART: String Matching Algorithm Research Tool

- more than 80 string matching algorithms
- a corpus of 12 texts
- select/deselect string matching algorithms
- output experimental results in LaTeX, xml, html and txt formats
- easy to plug new algorithms

References


S. Faro and T. Lecroq
The Exact Online String Matching Problem: a Review of the Most Recent Results
Accepted in *ACM Computing Surveys*

What's next

- next session
- sampling

  F. Claude, G. Navarro, H. Peltola, L. Salmela and J. Tarhio
  String Matching with Alphabet Sampling
  To appear in *Journal of Discrete Algorithms*

- constant space

  D. Breslauer, R. Grossi and F. Mignosi
  Simple Real-Time Constant-Space String Matching
  CPM'11

Perspectives

- multicore architecture