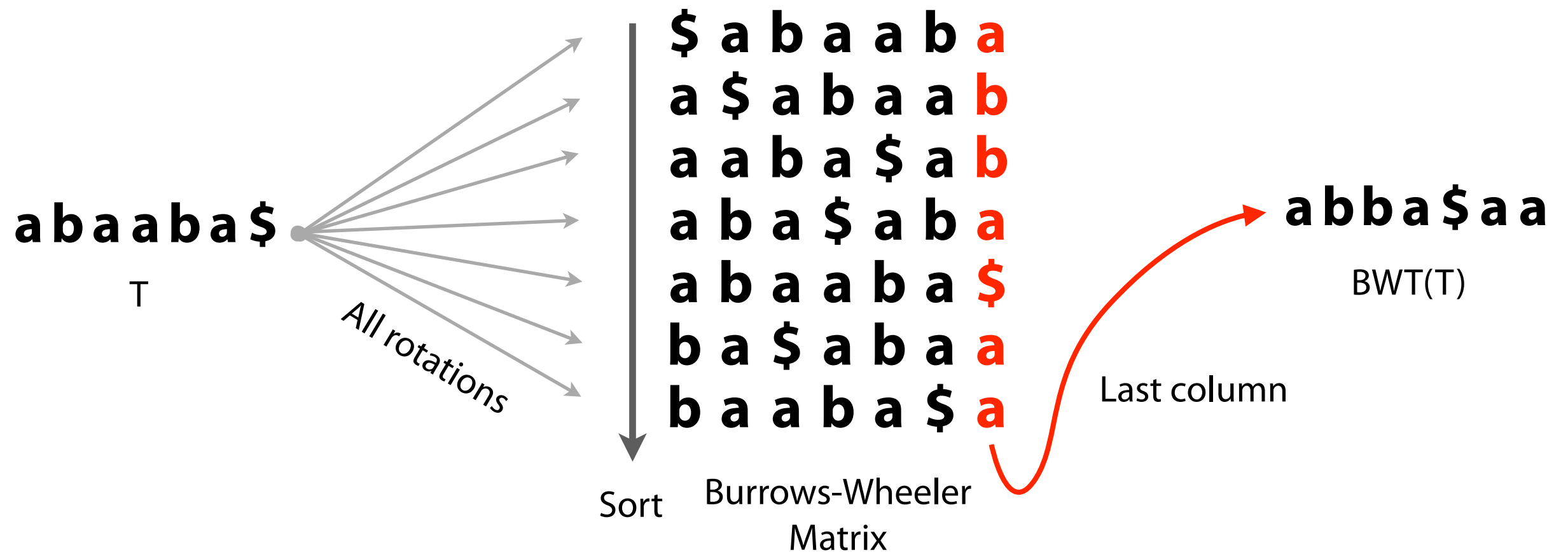


BWT & FM-index

Burrows-Wheeler Transform

Reversible permutation of the characters of a string, used originally for compression



How is it useful for compression?

How is it reversible?

How is it an index?

Burrows M, Wheeler DJ: A block sorting lossless data compression algorithm.
Digital Equipment Corporation, Palo Alto, CA 1994, Technical Report 124; 1994

Burrows-Wheeler Transform

```
def rotations(t):  
    """ Return list of rotations of input string t """  
    tt = t * 2  
    return [ tt[i:i+len(t)] for i in xrange(0, len(t)) ]  
  
def bwm(t):  
    """ Return lexicographically sorted list of t's rotations """  
    return sorted(rotations(t))  
  
def bwtViaBwm(t):  
    """ Given T, returns BWT(T) by way of the BWM """  
    return ''.join(map(lambda x: x[-1], bwm(t)))
```

Make list of all rotations

Sort them

Take last column

```
>>> bwtViaBwm("Tomorrow_and_tomorrow_and_tomorrow$")  
'w$wwdd__nnoooaattTmmrrrrrrrooo__ooo'  
  
>>> bwtViaBwm("It_was_the_best_of_times_it_was_the_worst_of_times$")  
's$esttssfftteww_hhmmbootttt_ii__woeeaaressi_____  
  
>>> bwtViaBwm('in_the_jingle_jangle_morning_Ill_come_following_you$')  
'u_gleeeengj_mlh1_nnnnt$nwj__lggIolo_iiiiarfcmlylo_oo_'
```

Burrows-Wheeler Transform

BWM bears a resemblance to the suffix array

\$ a b a a b a
a **\$** a b a a b
a a b a **\$** a b
a b a **\$** a b a
a b a a b a **\$**
b a **\$** a b a a
b a a b a **\$** a

BWM(T)

6	\$
5	a \$
2	a a b a \$
3	a b a \$
0	a b a a b a \$
4	b a \$
1	b a a b a \$

SA(T)

Sort order is the same whether rows are rotations or suffixes

Burrows-Wheeler Transform

In fact, this gives us a new definition / way to construct BWT(T):

$$BWT[i] = \begin{cases} T[SA[i] - 1] & \text{if } SA[i] > 0 \\ \$ & \text{if } SA[i] = 0 \end{cases}$$

“BWT = characters just to the left of the suffixes in the suffix array”

\$ a b a a b a
 a **\$** a b a a b
 a a b a **\$** a b
 a b a **\$** a b a
 a b a a b a **\$**
 b a **\$** a b a a
 b a a b a **\$** a

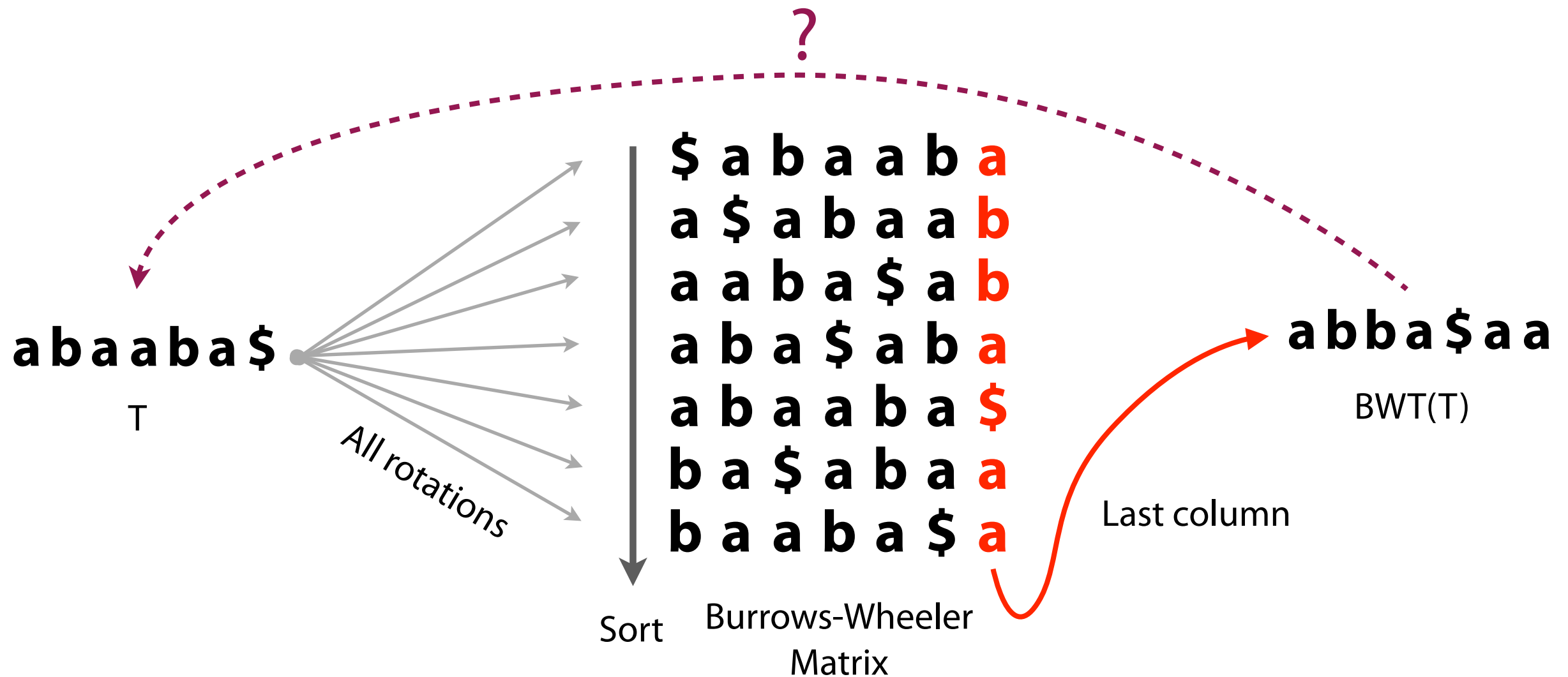
BWM(T)

6	\$
5	a \$
2	a a b a \$
3	a b a \$
0	a b a a b a \$
4	b a \$
1	b a a b a \$

SA(T)

Burrows-Wheeler Transform

How to reverse the BWT?



BWM has a key property called the *LF Mapping*...

Burrows-Wheeler Transform: T-ranking

Give each character in T a rank, equal to # times the character occurred previously in T . Call this the *T-ranking*.

a₀ b₀ a₁ a₂ b₁ a₃ \$

Now let's re-write the BWM including ranks...

Note: we *do not* actually write this information in the text / BWM, we Are simply including it here to help us track “which” occurrences of each character in the BWM correspond to the occurrences in the text.

Burrows-Wheeler Transform

BWM with T-ranking:

	<i>F</i>						<i>L</i>
	\$	a ₀	b ₀	a ₁	a ₂	b ₁	a₃
	a₃	\$	a ₀	b ₀	a ₁	a ₂	b ₁
	a₁	a ₂	b ₁	a ₃	\$	a ₀	b ₀
	a₂	b ₁	a ₃	\$	a ₀	b ₀	a₁
	a₀	b ₀	a ₁	a ₂	b ₁	a ₃	\$
	b ₁	a ₃	\$	a ₀	b ₀	a ₁	a₂
	b ₀	a ₁	a ₂	b ₁	a ₃	\$	a₀

Look at first and last columns, called *F* and *L*

And look at just the **a**s

as occur in the same order in *F* and *L*. As we look down columns, in both cases we see: **a₃**, **a₁**, **a₂**, **a₀**

Burrows-Wheeler Transform

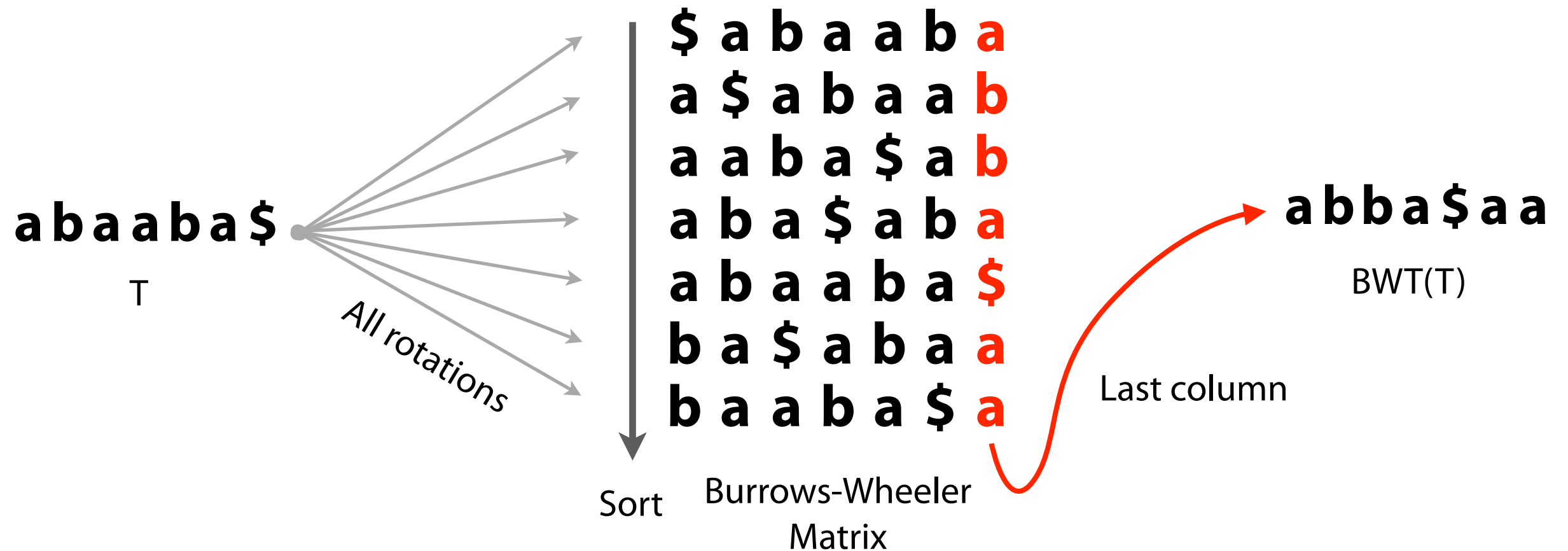
BWM with T-ranking:

<i>F</i>							<i>L</i>
\$	a ₀	b ₀	a ₁	a ₂	b ₁	a ₃	
a ₃	\$	a ₀	b ₀	a ₁	a ₂	b₁	
a ₁	a ₂	b ₁	a ₃	\$	a ₀	b₀	
a ₂	b ₁	a ₃	\$	a ₀	b ₀	a ₁	
a ₀	b ₀	a ₁	a ₂	b ₁	a ₃	\$	
b₁	a ₃	\$	a ₀	b ₀	a ₁	a ₂	
b₀	a ₁	a ₂	b ₁	a ₃	\$	a ₀	

Same with **b**s: **b₁**, **b₀**

Burrows-Wheeler Transform

Reversible permutation of the characters of a string, used originally for compression



How is it useful for compression?

How is it reversible?

How is it an index?

Burrows M, Wheeler DJ: A block sorting lossless data compression algorithm.
Digital Equipment Corporation, Palo Alto, CA 1994, Technical Report 124; 1994

Burrows-Wheeler Transform: LF Mapping

BWM with T-ranking:

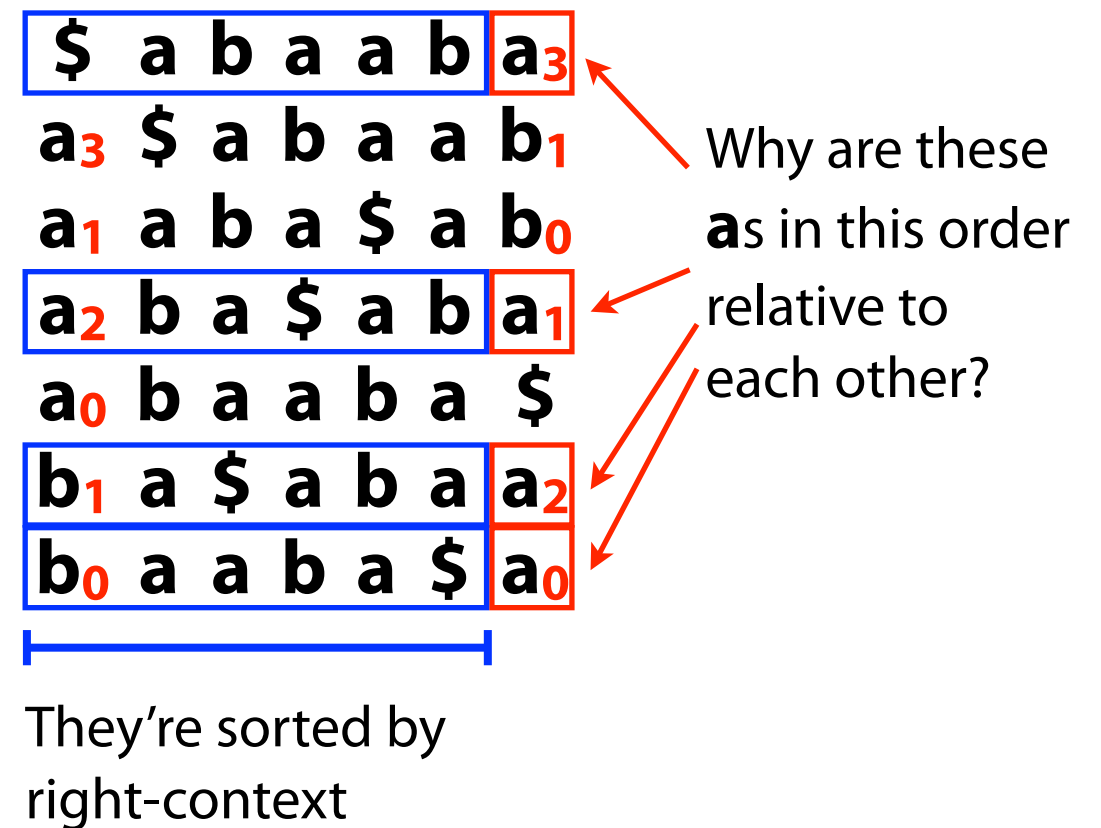
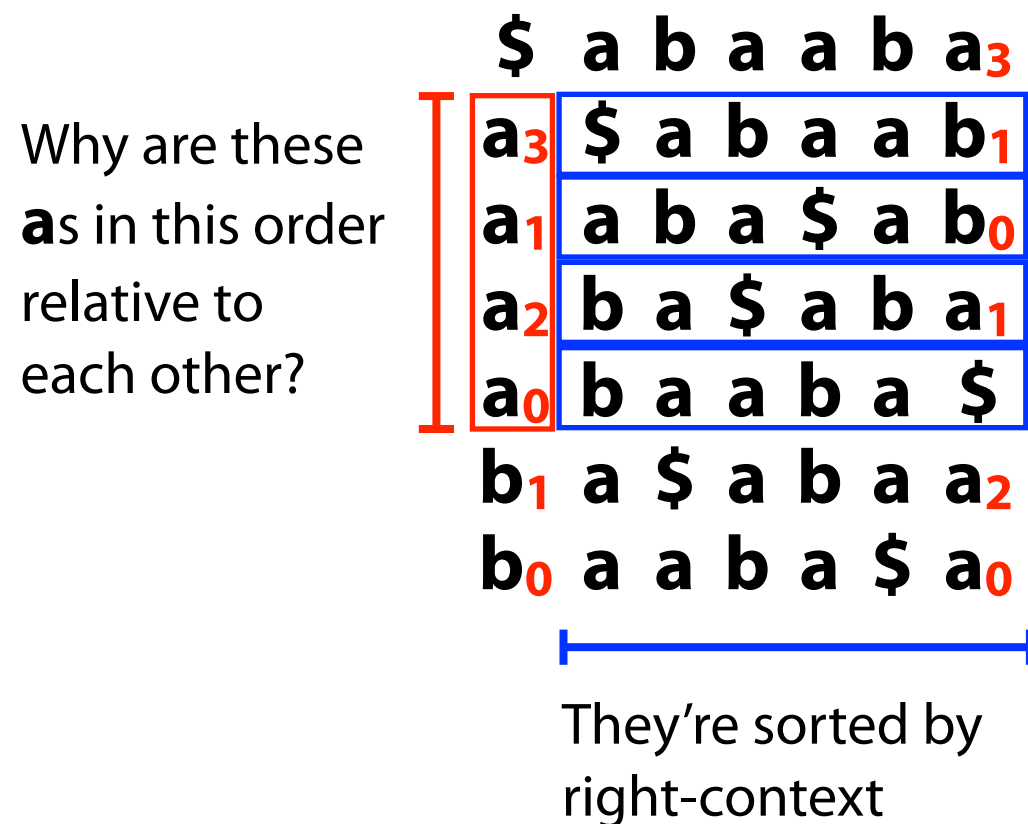
F	L
\$	a₀ b₀ a₁ a₂ b₁ a₃
a₃	\$ a₀ b₀ a₁ a₂ b₁
a₁ a₂ b₁ a₃	\$ a₀ b₀
a₂ b₁ a₃	\$ a₀ b₀ a₁
a₀ b₀ a₁ a₂ b₁ a₃	\$
b₁ a₃	\$ a₀ b₀ a₁ a₂
b₀ a₁ a₂ b₁ a₃	\$ a₀

LF Mapping: The i^{th} occurrence of a character c in L and the i^{th} occurrence of c in F correspond to the *same* occurrence in T

However we rank occurrences of c , ranks appear in the same order in F and L

Burrows-Wheeler Transform: LF Mapping

Why does the LF Mapping hold?



Occurrences of c in F are sorted by right-context. Same for L !

Whatever ranking we give to characters in T , rank orders in F and L will match

Burrows-Wheeler Transform: LF Mapping

BWM with T-ranking:

<i>F</i>							<i>L</i>
\$	a ₀	b ₀	a ₁	a ₂	b ₁	a ₃	
a ₃	\$	a ₀	b ₀	a ₁	a ₂	b ₁	
a ₁	a ₂	b ₁	a ₃	\$	a ₀	b ₀	
a ₂	b ₁	a ₃	\$	a ₀	b ₀	a ₁	
a ₀	b ₀	a ₁	a ₂	b ₁	a ₃	\$	
b ₁	a ₃	\$	a ₀	b ₀	a ₁	a ₂	
b ₀	a ₁	a ₂	b ₁	a ₃	\$	a ₀	

We'd like a different ranking so that for a given character, ranks are in ascending order as we look down the F / L columns...

Burrows-Wheeler Transform: LF Mapping

BWM with B-ranking:

F							L	
	\$	a ₃	b ₁	a ₁	a ₂	b ₀	a ₀	
	a ₀	\$	a ₃	b ₁	a ₁	a ₂	b ₀	
	a ₁	a ₂	b ₀	a ₃	\$	a ₃	b ₁	
	a ₂	b ₀	a ₀	\$	a ₃	b ₁	a ₁	
	a ₃	b ₁	a ₁	a ₂	b ₀	a ₀	\$	
	b ₀	a ₀	\$	a ₃	b ₁	a ₁	a ₂	
	b ₁	a ₁	a ₂	b ₀	a ₀	\$	a ₃	

Ascending rank

F now has very simple structure: a **\$**, a block of **a**s with ascending ranks, a block of **b**s with ascending ranks

Burrows-Wheeler Transform

<i>F</i>	<i>L</i>	
\$	a ₀	
a ₀	b ₀	
a ₁	b ₁	← Which BWM row <i>begins</i> with b ₁ ?
a ₂	a ₁	Skip row starting with \$ (1 row)
a ₃	\$	Skip rows starting with a (4 rows)
b ₀	a ₂	Skip row starting with b ₀ (1 row)
row 6 → b ₁	a ₃	Answer: row 6

Burrows-Wheeler Transform

Say T has 300 **A**s, 400 **C**s, 250 **G**s and 700 **T**s and $\$ < \mathbf{A} < \mathbf{C} < \mathbf{G} < \mathbf{T}$

Which BWM row (0-based) begins with **G**₁₀₀? (Ranks are B-ranks.)

Skip row starting with **\$** (1 row)

Skip rows starting with **A** (300 rows)

Skip rows starting with **C** (400 rows)

Skip first 100 rows starting with **G** (100 rows)

Answer: row $1 + 300 + 400 + 100 = \mathbf{row\ 801}$

Burrows-Wheeler Transform: reversing

Reverse BWT(T) starting at right-hand-side of T and moving left

Start in first row. F must have $\$$. L contains character just **prior** to $\$$: **a₀**

a₀: LF Mapping says this is same occurrence of **a** as first **a** in F . **Jump** to row *beginning* with **a₀**. L contains character just **prior** to **a₀**: **b₀**.

Repeat for **b₀**, get **a₂**

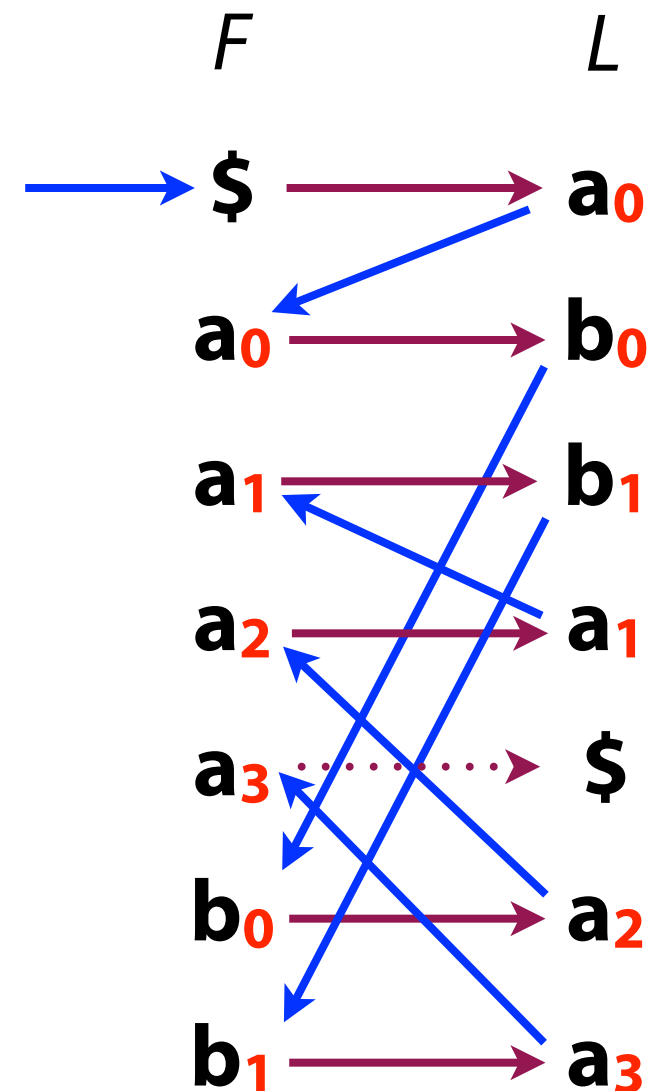
Repeat for **a₂**, get **a₁**

Repeat for **a₁**, get **b₁**

Repeat for **b₁**, get **a₃**

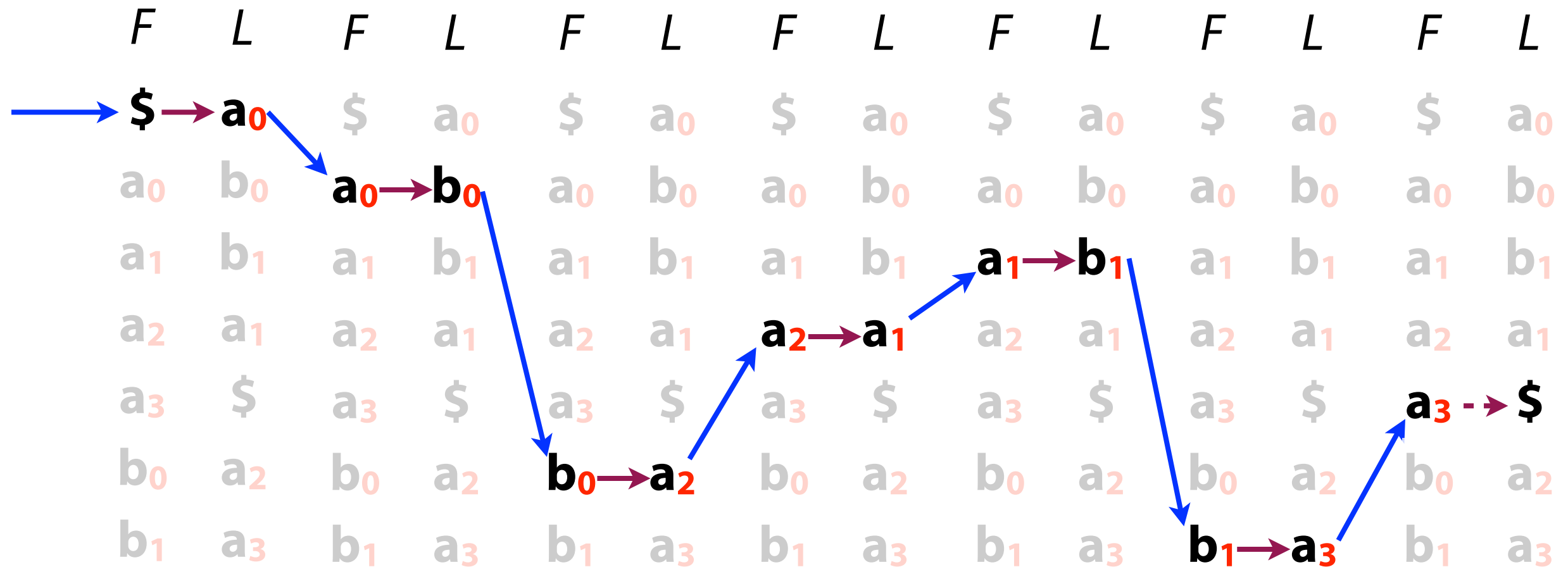
Repeat for **a₃**, get $\$$, done

Reverse of chars we visited = **a₃ b₁ a₁ a₂ b₀ a₀ \$** = T



Burrows-Wheeler Transform: reversing

Another way to visualize reversing BWT(T):



T : $a_3 b_1 a_1 a_2 b_0 a_0 \$$

Burrows-Wheeler Transform: reversing

```
>>> reverseBwt("w$wdd__nnooaattTmmrrrrrrrooo__ooo")
'Tomorrow_and_tomorrow_and_tomorrow$'

>>> reverseBwt("s$esttssfftteww_hhmmbootttt_ii__woeearessIi_____")
'It_was_the_best_of_times_it_was_the_worst_of_times$'

>>> reverseBwt("u_gleeeengj_mlh1_nnnnt$nwj__lggIolo_iiiarfcmylo_oo_")
'in_the_jingle_jangle_morning_Ill_come_following_you$'
```

ranks list is m integers
long! We'll fix later.

```
def reverseBwt(bw):
    ''' Make T from BWT(T) '''
    ranks, tots = rankBwt(bw)
    first = firstCol(tots)
    rowi = 0 # start in first row
    t = '$' # start with rightmost character
    while bw[rowi] != '$':
        c = bw[rowi]
        t = c + t # prepend to answer
        # jump to row that starts with c of same rank
        rowi = first[c][0] + ranks[rowi]
    return t
```

Burrows-Wheeler Transform

We've seen how BWT is useful for compression:

Sorts characters by right-context, making a more compressible string

And how it's reversible:

Repeated applications of LF Mapping, recreating T from right to left

How is it used as an index?

FM Index

FM Index: an index combining the BWT *with a few small auxilliary data structures*

“FM” supposedly stands for “Full-text Minute-space.”
(But inventors are named Ferragina and Manzini)

Core of index consists of F and L from BWM:

F can be represented very simply
(1 integer per alphabet character)

And L is compressible

Potentially very space-economical!

F							L
\$	a	b	a	a	b	a	
a	\$	a	b	a	a	b	
a	a	b	a	\$	a	b	
a	b	a	\$	a	b	a	
a	b	a	a	b	a	\$	
b	a	\$	a	b	a	a	
b	a	a	b	a	\$	a	

└──────────┘
Not stored in index

Paolo Ferragina, and Giovanni Manzini. "Opportunistic data structures with applications." *Foundations of Computer Science, 2000. Proceedings. 41st Annual Symposium on*. IEEE, 2000.

FM Index: querying

Though BWM is related to suffix array, we can't query it the same way

\$	a	b	a	a	b	a
a	\$	a	b	a	a	b
a	a	b	a	\$	a	b
a	b	a	\$	a	b	a
a	b	a	a	b	a	\$
b	a	\$	a	b	a	a
b	a	a	b	a	\$	a



6	\$
5	a \$
2	a a b a \$
3	a b a \$
0	a b a a b a \$
4	b a \$
1	b a a b a \$

We don't have these columns; binary search isn't possible



FM Index: querying

Look for range of rows of BWM(T) with P as prefix

Do this for P 's shortest suffix, then extend to successively longer suffixes until range becomes empty or we've exhausted P

$P = \mathbf{ab}\mathbf{a}$

Easy to find all the rows beginning with \mathbf{a} , thanks to F 's simple structure

F						L
\$	a	b	a	a	b	\mathbf{a}_3
\mathbf{a}_0	\$	a	b	a	a	\mathbf{b}_1
\mathbf{a}_1	a	b	a	\$	a	\mathbf{b}_0
\mathbf{a}_2	b	a	\$	a	b	\mathbf{a}_1
\mathbf{a}_3	b	a	a	b	a	\$
\mathbf{b}_0	a	\$	a	b	a	\mathbf{a}_2
\mathbf{b}_1	a	a	b	a	\$	\mathbf{a}_0

FM Index: querying

We have rows beginning with **a**, now we seek rows beginning with **ba**

$P = \mathbf{aba}$

$P = \mathbf{a} \mathbf{b} \mathbf{a}$

F							L
\$	a	b	a	a	b	a	a_0
a_0	\$	a	b	a	a	b	b_0
a_1	a	b	a	\$	a	b	b_1
a_2	b	a	\$	a	b	a	a_1
a_3	b	a	a	b	a	\$	
b_0	a	\$	a	b	a	a	a_2
b_1	a	a	b	a	\$	a	a_3

← Look at those rows in L .
 b_0, b_1 are **b** s occuring just to left.

Use LF Mapping. Let new range delimit those **bs**

	F		L
	\$	a	b
a_0	\$	a	b
a_1	a	b	\$
a_2	b	a	\$
a_3	b	a	a
b_0	a	\$	a
b_1	a	a	b

Now we have the rows with prefix **ba**

FM Index: querying

We have rows beginning with **ba**, now we seek rows beginning with **aba**

$P = \mathbf{aba}$

F							L
\$	a	b	a	a	b		a_0
a_0	\$	a	b	a	a		b_0
a_1	a	b	a	\$	a		b_1
a_2	b	a	\$	a	b		a_1
a_3	b	a	a	b	a		\$
b_0	a	\$	a	b	a		a_2
b_1	a	a	b	a	\$		a_3

← a_2, a_3 occur just to left.

Use LF Mapping →

$P = \mathbf{aba}$

F							L
\$	a	b	a	a	b		a_0
a_0	\$	a	b	a	a		b_0
a_1	a	b	a	\$	a		b_1
a_2	b	a	\$	a	b		a_1
a_3	b	a	a	b	a		\$
b_0	a	\$	a	b	a		a_2
b_1	a	a	b	a	\$		a_3

Now we have the rows with prefix **aba**

FM Index: querying

$P = \text{aba}$

Now we have the same range, $[3, 5)$, we would have got from querying suffix array

F		L
\$	a b a a b	a₀
a₀	\$ a b a a	b₀
a₁	a b a \$ a	b₁
$[3, 5)$	a₂ b a \$ a b	a₁
	a₃ b a a b a	\$
	b₀ a \$ a b a	a₂
	b₁ a a b a \$	a₃

Where are these?

6	\$
5	a \$
2	a a b a \$
$[3, 5)$	a b a \$
	a b a a b a \$
4	b a \$
1	b a a b a \$

Unlike suffix array, we don't immediately know *where* the matches are in T...

FM Index: querying

When P does not occur in T , we will eventually fail to find the next character in L :

$$P = \mathbf{bba}$$

F							L
\$	a	b	a	a	b	a	a₀
a₀	\$	a	b	a	a	b	b₀
a₁	a	b	a	\$	a	b	b₁
a₂	b	a	\$	a	b	a	a₁
a₃	b	a	a	b	a	\$	
Rows with ba prefix	b₀	a	\$	a	b	a	a₂
	b₁	a	a	b	a	\$	a₃

← No **bs**!

FM Index: querying

If we *scan* characters in the last column, that can be very slow, $O(m)$

$P = \mathbf{ab}\mathbf{a}$

F						L
\$	a	b	a	a	b	a₃
a₀	\$	a	b	a	a	b₁
a₁	a	b	a	\$	a	b₀
a₂	b	a	\$	a	b	a₁
a₃	b	a	a	b	a	\$
b₀	a	\$	a	b	a	a₂
b₁	a	a	b	a	\$	a₀

Scan, looking for **b**s

FM Index: lingering issues

(1) Scanning for preceding character is slow

	\$	a	b	a	a	b	a₀
a₀	\$	a	b	a	a	b	b₀
a₁	a	b	a	\$	a	b	b₁
a₂	b	a	\$	a	b	a	a₁
a₃	b	a	a	b	a	\$	
b₀	a	\$	a	b	a	a	a₂
b₁	a	a	b	a	\$	a	a₃

$O(m)$
scan

(2) Storing ranks takes too much space

```
def reverseBwt(bw):
    """ Make T from BWT(T) """
    ranks, tots = rankBwt(bw)
    first = firstCol(tots)
    rowi = 0
    t = "$"
    while bw[rowi] != '$':
        c = bw[rowi]
        t = c + t
        rowi = first[c][0] + ranks[rowi]
    return t
```

m integers

(3) Need way to find where matches occur in T :

Where?

	\$	a	b	a	a	b	a₀
a₀	\$	a	b	a	a	b	b₀
a₁	a	b	a	\$	a	b	b₁
a₂	b	a	\$	a	b	a	a₁
a₃	b	a	a	b	a	\$	
b₀	a	\$	a	b	a	a	a₂
b₁	a	a	b	a	\$	a	a₃

FM Index: fast rank calculations

Is there an $O(1)$ way to determine which **b**s precede the **a**s in our range?

<i>F</i>							<i>L</i>
\$	a	b	a	a	b		a₀
a₀	\$	a	b	a	a		b₀
a₁	a	b	a	\$	a		b₁
a₂	b	a	\$	a	b		a₁
a₃	b	a	a	b	a		\$
b₀	a	\$	a	b	a		a₂
b₁	a	a	b	a	\$		a₃

Occ(*c*, *k*) = # of *c* in the first *k* characters of BWT(*S*), aka the LF mapping.

Tally — also referred to as **Occ**(*c*, *k*)

Idea: pre-calculate # **a**s, **b**s in *L* up to every row:

<i>F</i>	<i>L</i>	a	b
\$	a	1	0
a	b	1	1
a	b	1	2
a	a	2	2
a	\$	2	2
b	a	3	2
b	a	4	2

We infer **b₀** and **b₁** appear in *L* in this range

$O(1)$ time, but requires $m \times |\Sigma|$ integers

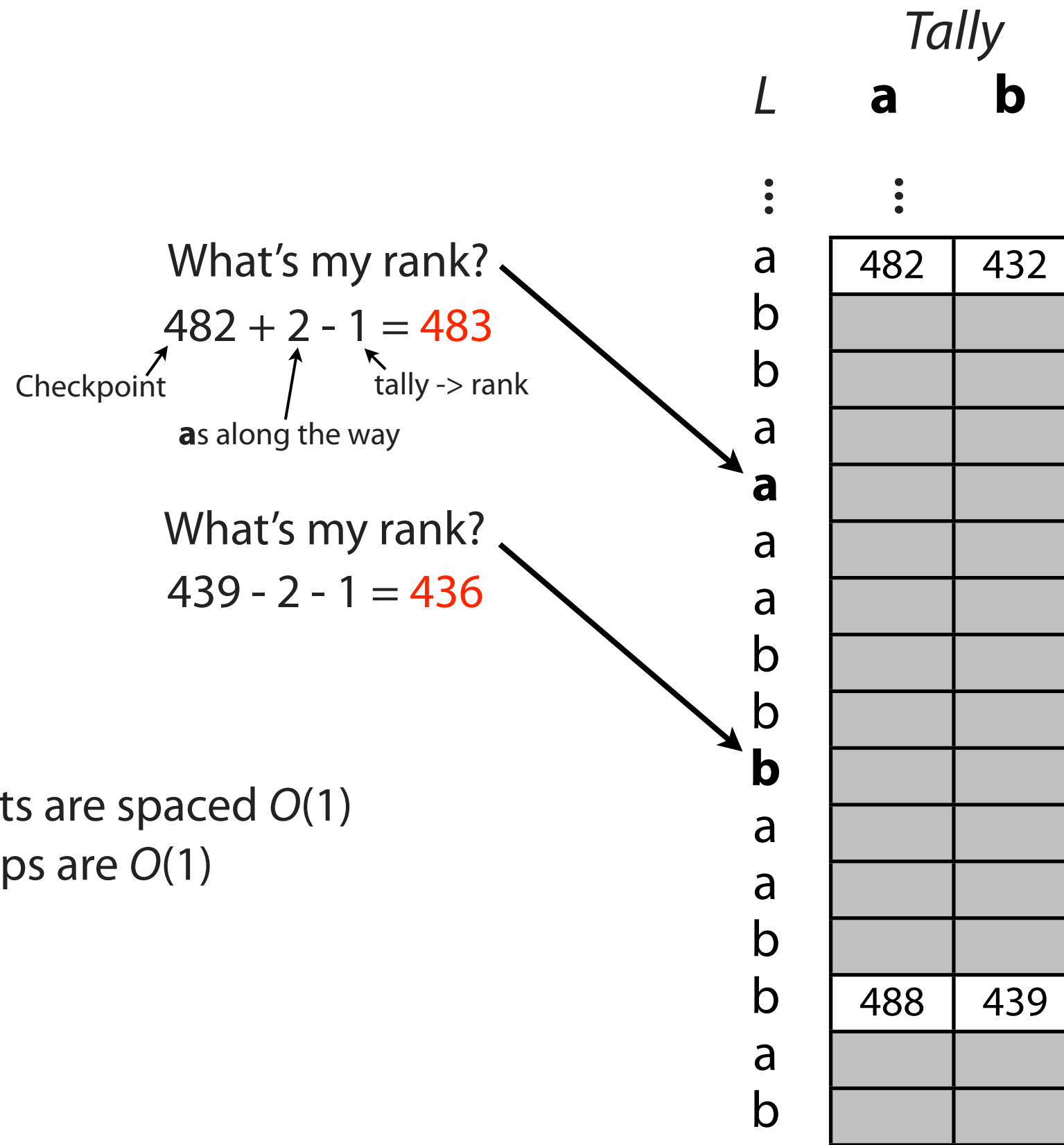
FM Index: fast rank calculations

Another idea: pre-calculate # **a**s, **b**s in L up to *some* rows, e.g. every 5th row.
Call pre-calculated rows *checkpoints*.

		<i>Tally</i>		
F	L	a	b	
\$	a	1	0	← Lookup here succeeds as usual
a	b			
a	b			
a	a			
a	\$			← Oops: not a checkpoint
b	a	3	2	← But there's one nearby
b	a			

To resolve a lookup for character c in non-checkpoint row, scan along L until we get to nearest checkpoint. Use tally at the checkpoint, *adjusted for # of cs we saw along the way*.

FM Index: fast rank calculations



Assuming checkpoints are spaced $O(1)$
distance apart, lookups are $O(1)$

FM Index: fast rank calculations

This can also be accomplished using **bit-vector rank** operations. We store one bit-vector for each character of Σ , placing a 1 where this character occurs and a 0 everywhere else:

		<i>Tally</i>	
<i>F</i>	<i>L</i>	a	b
\$	a	1	0
a	b	0	1
a	b	0	1
a	a	1	0
a	\$	0	0
b	a	1	0
b	a	1	0

the operation **rank(x, i)** returns the total number of 1's in a bit-vector up to (and including) index i. **rank(x,i)** is a *constant-time operation*

rank(a,3) = 2

rank(a,5) = 3

rank(b,5) = 2

To resolve the rank for a given character **c** at a given index **i**, we simply issue a **rank(c,i)** query. This is a practically-fast constant-time operation, but we need to keep around Σ bit-vectors, each of $o(m)$ bits.

FM Index: a few problems

Solved! At the expense of adding checkpoints ($O(m)$ integers) to index.

(1)

	F		L
	\$	a b a a b	a_0
a_0	\$	a b a a	b_0
a_1	a	b a \$ a	b_1
a_2	b	a \$ a b	a_1
a_3	b	a a b a	\$
b_0	a	\$ a b a	a_2
b_1	a	a b a \$	a_3

This scan is $O(m)$ work

With checkpoints it's $O(1)$

(2) Ranking takes too much space

m integers

```
def reverseBwt(bw):  
    """ Make T from BWT(T) """  
    ranks, tots = rankBwt(bw)  
    first = firstCol(tots)  
    rowi = 0  
    t = "$"  
    while bw[rowi] != '$':  
        c = bw[rowi]  
        t = c + t  
        rowi = first[c][0] + ranks[rowi]  
    return t
```

With checkpoints, we greatly reduce
integers needed for ranks

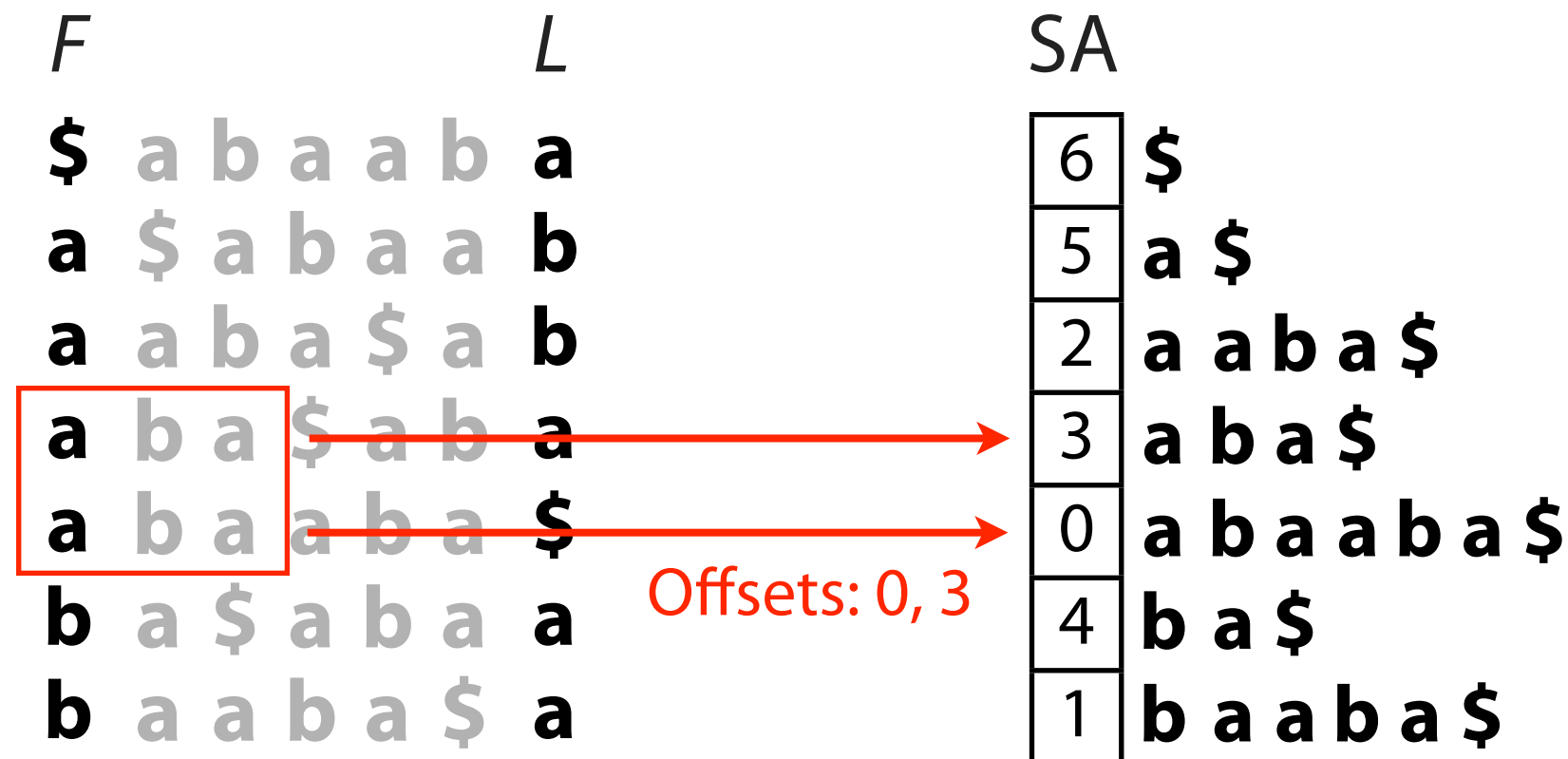
But it's still $O(m)$ space - there's literature
on how to improve this space bound

FM Index: a few problems

Not yet solved: **(3)** Need a way to find where these occurrences are in T :

\$	a	b	a	a	b	a₀
a₀	\$	a	b	a	a	b₀
a₁	a	b	a	\$	a	b₁
a₂	b	a	\$	a	b	a₁
a₃	b	a	a	b	a	\$
b₀	a	\$	a	b	a	a₂
b₁	a	a	b	a	\$	a₃

If suffix array were part of index, we could simply look up the offsets



But SA requires m integers

FM Index: resolving offsets

Idea: store some, but not all, entries of the suffix array

<i>F</i>						<i>L</i>		<i>SA</i>
\$	a	b	a	a	b	a		6
a	\$	a	b	a	a	b		
a	a	b	a	\$	a	b		2
a	b	a	\$	a	b	a		
a	b	a	a	b	a	\$		0
b	a	\$	a	b	a	a		4
b	a	a	b	a	\$	a		

The diagram illustrates a search process for the string "aba". A red box highlights the first three columns of the first four rows. Red arrows point from the third column of each row to the corresponding SA value. The first three rows have SA values of 6, an empty cell, and 2, respectively. The fourth row has an empty cell. The fifth row has an SA value of 0. The first three rows are crossed out with a large red 'X', indicating a failed search. The fourth row is not crossed out, indicating a successful search.

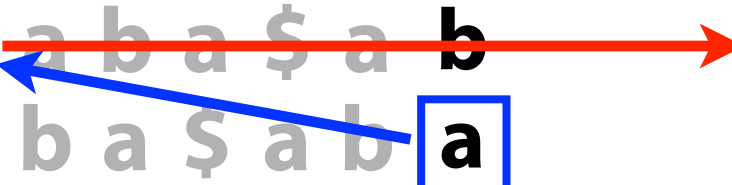
Lookup for row 4 succeeds - we kept that entry of SA

Lookup for row 3 fails - we discarded that entry of SA

FM Index: resolving offsets

But LF Mapping tells us that the **a** at the end of row 3 corresponds to...
...the **a** at the beginning of row 2

<i>F</i>							<i>L</i>		<i>SA</i>
\$	a	b	a	a	b	a			6
a	\$	a	b	a	a	b			
a	a	b	a	\$	a	b			2
a	b	a	\$	a	b	a			
a	b	a	a	b	a	\$			0
b	a	\$	a	b	a	a			4
b	a	a	b	a	\$	a			



And row 2 has a suffix array value = 2

So row 3 has suffix array value = 3 = 2 (row 2's SA val) + 1 (# steps to row 2)

If saved SA values are $O(1)$ positions apart in T , resolving offset is $O(1)$ time

FM Index: problems solved

Solved! At the expense of adding some SA values ($O(m)$ integers) to index
Call this the "SA sample"

(3) Need a way to find where these occurrences are in T :

\$	a	b	a	a	b	a₀
a₀	\$	a	b	a	a	b₀
a₁	a	b	a	\$	a	b₁
a₂	b	a	\$	a	b	a₁
a₃	b	a	a	b	a	\$
b₀	a	\$	a	b	a	a₂
b₁	a	a	b	a	\$	a₃

**With SA sample we can do this in
 $O(1)$ time per occurrence**

FM Index: small memory footprint

Components of the FM Index:

First column (F): $\sim |\Sigma|$ integers

Last column (L): m characters

SA sample: $m \cdot a$ integers, where a is fraction of rows kept

Checkpoints: $m \times |\Sigma| \cdot b$ integers, where b is fraction of rows checkpointed

Example: DNA alphabet (2 bits per nucleotide), T = human genome,
 $a = 1/32$, $b = 1/128$

First column (F): 16 bytes

Last column (L): 2 bits * 3 billion chars = 750 MB

SA sample: 3 billion chars * 4 bytes/char / 32 = ~ 400 MB

Checkpoints: 3 billion * 4 bytes/char * 4 char / 120 = ~400MB

Total ~ 1.5 GB

Computing BWT in $O(n)$ time

- Easy $O(n^2 \log n)$ -time algorithm to compute the BWT (create and sort the BWT matrix explicitly).
- Several direct $O(n)$ -time algorithms for BWT. These are space efficient. (Bowtie e.g. uses [1])
- Also can use suffix arrays or trees:
 Compute the suffix array, use correspondence between suffix array and BWT to output the BWT.
 $O(n)$ -time and $O(n)$ -space, but the constants are large.

[1] Kärkkäinen, Juha. "Fast BWT in small space by blockwise suffix sorting." *Theoretical Computer Science* 387.3 (2007): 249-257.

**Bonus material (not on
exams ... but cool!)**

Actual FM-Index Built on Compressed String

Ferragina, Paolo, and Giovanni Manzini. "Opportunistic data structures with applications." Foundations of Computer Science, 2000. Proceedings. 41st Annual Symposium on. IEEE, 2000.

Data structure has “space occupancy that is a *function of the entropy* of the underlying data set”

Stores text $T[1, u]$ in $O(H_k(T)) + o(1)$ bits for $k \geq 0$ where $H_k(T)$ is the k th order empirical entropy of the text — **sub-linear** for a compressible string

Theorem 1 *Let Z denote the output of the algorithm BW_RLX on input $T[1, u]$. The number of occurrences of a pattern $P[1, p]$ in $T[1, u]$ can be computed in $O(p)$ time on a RAM. The space occupancy is $|Z| + O\left(\frac{u}{\log u} \log \log u\right)$ bits in the worst case. ■*

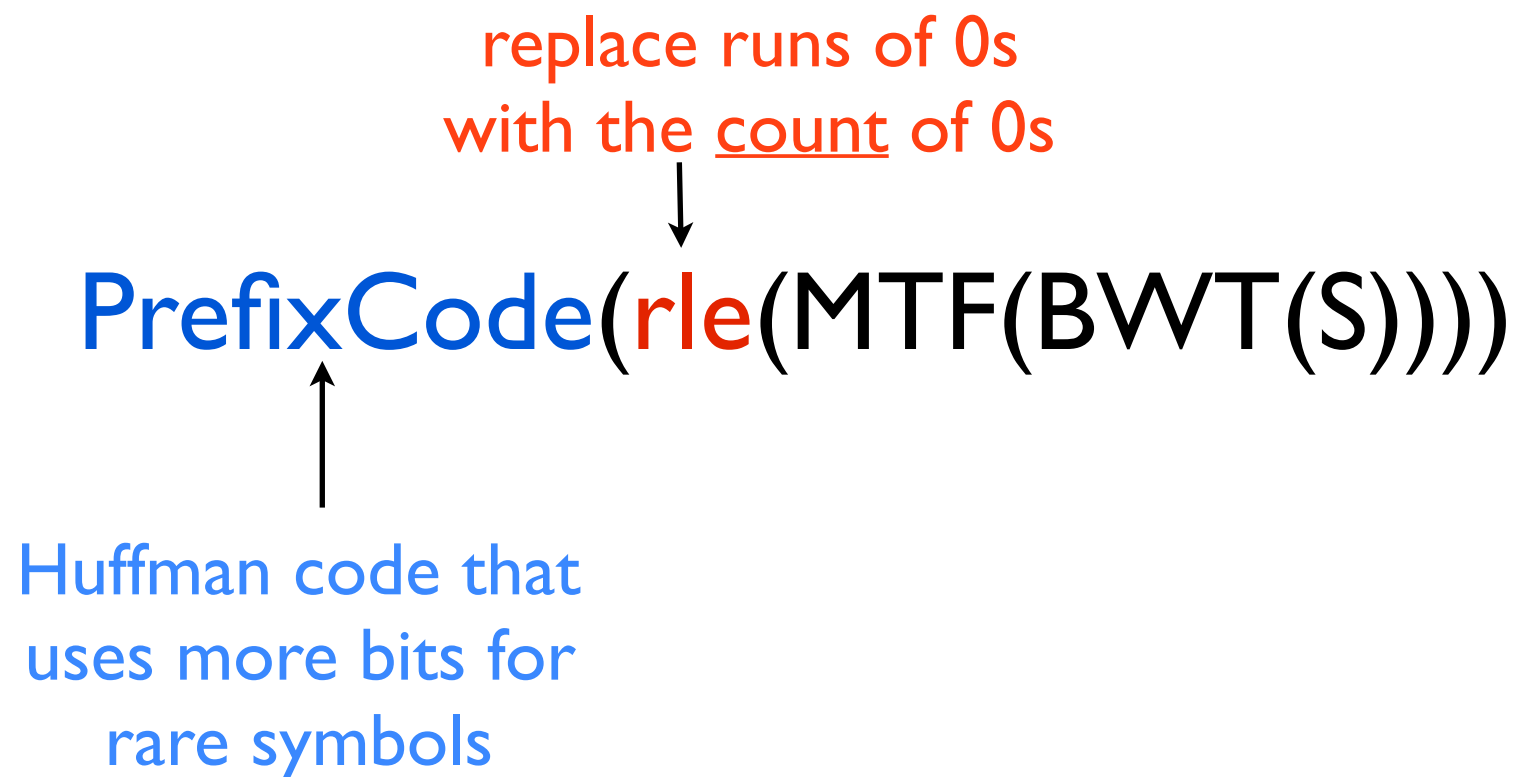
Theorem 2 *A text $T[1, u]$ can be preprocessed in $O(u)$ time so that all the occurrences of a pattern $P[1, p]$ in T can be listed in $O(p + \text{occ} \log^2 u)$ time on a RAM. The space occupancy is bounded by $5H_k(T) + O\left(\frac{\log \log u}{\log u}\right)$ bits per input symbol in the worst case, for any fixed $k \geq 0$. ■*

Theorem 3 *A text $T[1, u]$ can be indexed so that all the occurrences of a pattern $P[1, p]$ in T can be listed in $O(p + \text{occ} \log^\epsilon u)$ time on a RAM. The space occupancy is $O(H_k(T) + \frac{\log \log u}{\log^\epsilon u})$ bits per input symbol in the worst case, for any fixed $k \geq 0$. ■*

Compressing BWT Strings

Lots of possible compression schemes will benefit from preprocessing with BWT (since it tends to group runs of the same letters together).

One good scheme proposed by Ferragina & Manzini:



Move-To-Front Coding

To encode a letter, use its index in the current list, and then move it to the front of the list.

	Σ	do\$oodwg
<i>List with all letters from the allowed alphabet</i> →	\$dgow	1
	d\$gow	1 3
	od\$gw	1 3 2
	\$odgw	1 3 2 1
	o\$dgw	1 3 2 1 0
	o\$dgw	1 3 2 1 0 2
	do\$gw	1 3 2 1 0 2 4
	wdo\$g	1 3 2 1 0 2 4 4 = MTF(do\$oodwg)

Benefits:

- Runs of the same letter will lead to runs of 0s.
- Common letters get small numbers, while rare letters get big numbers.

**slide courtesy of Carl Kingsford*

Move-To-Front Decoding

To encode a letter, use its index in the current list, and then move it to the front of the list.

Σ

*List with all
letters from the
allowed alphabet* →

\$dgow	1 3 2 1 0 2 4 4	d
d\$gow	1 3 2 1 0 2 4 4	do
od\$gw	1 3 2 1 0 2 4 4	do\$
\$odgw	1 3 2 1 0 2 4 4	do\$o
o\$dgw	1 3 2 1 0 2 4 4	do\$oo
o\$dgw	1 3 2 1 0 2 4 4	do\$oog
do\$gw	1 3 2 1 0 2 4 4	do\$oogw
wdo\$g	1 3 2 1 0 2 4 4	do\$oogwg

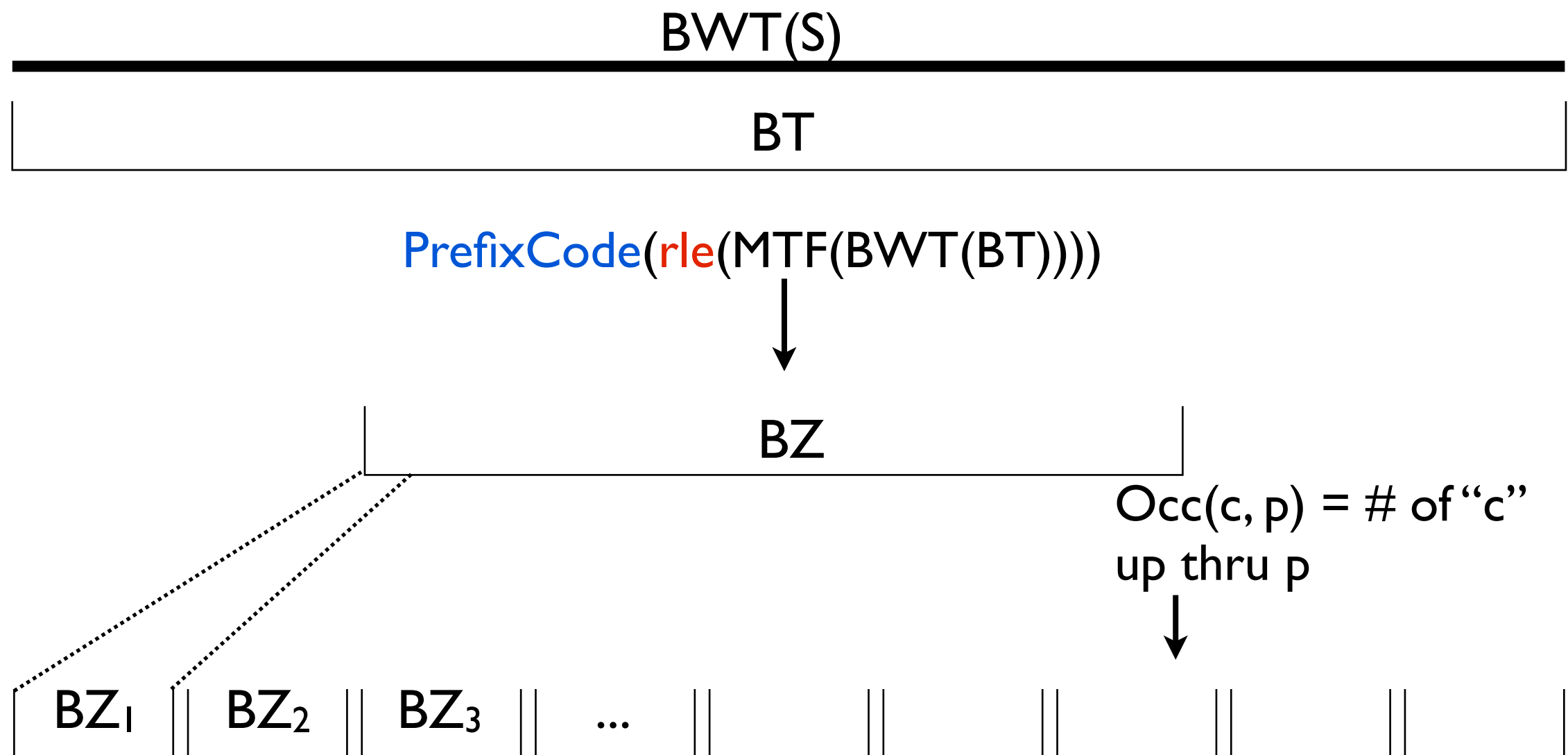
Benefits:

- Runs of the same letter will lead to runs of 0s.
- Common letters get small numbers, while rare letters get big numbers.

**slide courtesy of Carl Kingsford*

Computing Occ in Compressed String

Break BWT(S) into blocks of length L (we will decide on a value for L later):



Assumes every run of 0s is contained in a block [just for ease of explanation].

We will store some extra info for each block (and some groups of blocks) to compute $\text{Occ}(c, p)$ quickly.

Extra Info to Compute Occ

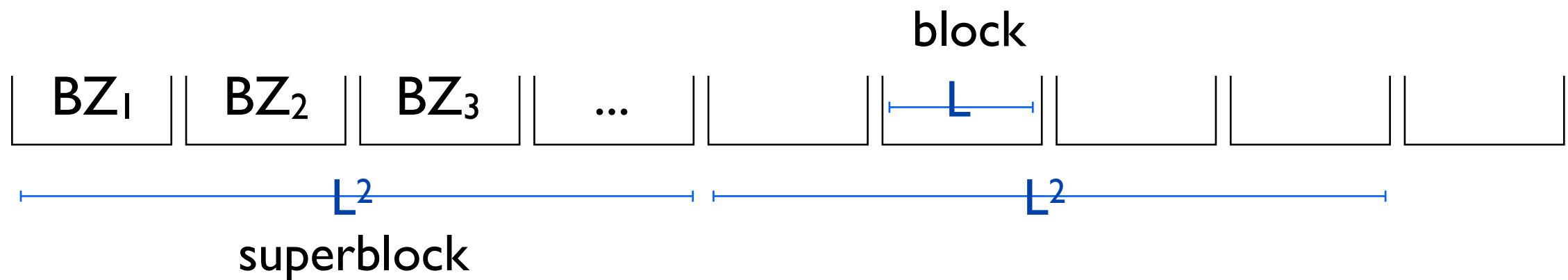
u = compressed length

Choose $L = O(\log u)$

u/L blocks, each array is $|\Sigma| \log L$ space

$\Rightarrow \frac{u}{L} \log L = \frac{u}{\log u} \log \log u$ total space.

block: store $|\Sigma|$ -long array giving # of occurrences of each character up thru and including this block *since the end of the last super block*.



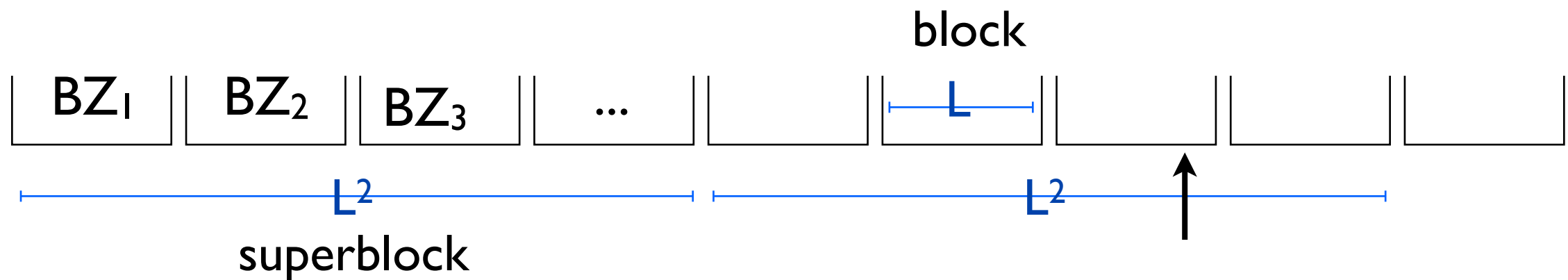
superblock: store $|\Sigma|$ -long array giving # of occurrences of each character up thru *and including* this superblock

u/L^2 superblocks, each array is $|\Sigma| \log u$ long
 $\Rightarrow \frac{u}{(\log u)^2} \log u = \frac{u}{\log u}$ total space.

Extra Info to Compute Occ

u = compressed length

Choose $L = O(\log u)$



$\text{Occ}(c, p) = \# \text{ of "c" up thru } p$:

sum value at last superblock, value at end of previous block, but then need to handle *this block*.

Store an array: $M[\text{c}, \text{k}, \text{BZ}_i, \text{MTF}_i] = \# \text{ of occurrences of } c \text{ through the } k\text{th letter of a block of type } (\text{BZ}_i, \text{MTF}_i)$.

of possible bit patterns of length $\log(u)$

Size: $O(|\Sigma| L^2 |\Sigma|) = O(L^2) = O(u^c \log u)$ for $c < 1$ (since the string is compressed)