Text Indexing

Lecture 05: Burrows-Wheeler Transform

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PINGO

https://pingo.scc.kit.edu/886630

Recap: Text-Compression

Definition: LZ77 Factorization [ZL77]

Given a text T of length n over an alphabet Σ, the **LZ77 factorization** is

- a set of z factors $f_1, f_2, \ldots, f_z \in \Sigma^+$, such that
- $T = f_1 f_2 \ldots f_z$ and for all $i \in [1, z]$ f_i is
- single character not occurring in $f_1 \ldots f_{i-1}$ or
- longest substring occurring ≥ 2 times in $f_1 \ldots f_i$

$T =$ abababbbbaba\$

- $f_1 =$ a
- $f_2 =$ b
- $f_3 =$ abab
- $f_4 =$ bbb
- $f_5 =$ aba
- $f_6 =$ \$

Definition: LZ78 Factorization [ZL78]

Given a text T of length n over an alphabet Σ, the **LZ78 factorization** is

- a set of z factors $f_1, f_2, \ldots, f_z \in \Sigma^+$, such that
- $T = f_1 f_2 \ldots f_z$, $f_0 = \epsilon$ and for all $i \in [1, z]$
- if $f_1 \ldots f_{i-1} = T[1..j-1]$, then f_i is the longest prefix of $T[j..n]$, such that

$$\exists k \in [0, i), \alpha \in \Sigma \cup \{\$\} \colon f_k = f_i \alpha$$

$T =$ abababbbbaba\$

- $f_1 =$ a
- $f_2 =$ b
- $f_3 =$ ab
- $f_4 =$ abb
- $f_5 =$ bb
- $f_6 =$ aba
- $f_7 =$ \$

Burrows-Wheeler Transform [BW94] (1/2)

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Definition: Burrows-Wheeler Transform

Given a text T of length n and its suffix array SA, for $i \in [1, n]$ the **Burrows-Wheeler transform** is

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

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	1	2	3	4	5	6	7	8	9	10	11	12	13
T	a	b	a	b	c	a	b	c	a	b	b	a	$
SA	13	12	1	9	6	3	11	2	10	7	4	8	5
LCP	0	0	1	2	2	5	0	2	1	1	4	0	3
BWT	a	b	$	c	c	b	b	a	a	a	a	b	b

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- character before the suffix in *SA*-order
- choose characters cyclic ℹ \$ for first suffix

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LCP	0	0	1	2	2	5	0	2	1	1	4	0	3
BWT	a	b	\$	c	c	b	b	a	a	a	a	b	b

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

- character before the suffix in SA-order
- choose characters cyclic ℹ \$ for first suffix

- can compute BWT in $O(n)$ time
- for binary alphabet $O(n/\sqrt{\lg n})$ time and $O(n/\lg n)$ words space is possible [KK19]

	1	2	3	4	5	6	7	8	9	10	11	12	13
T	a	b	a	b	c	a	b	c	a	b	b	a	\$
SA	13	12	1	9	6	3	11	2	10	7	4	8	5
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BWT	a	b	\$	c	c	b	b	a	a	a	a	b	b

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BWT	a	b	$	c	c	b	b	a	a	a	a	b	b

- definition is not very descriptive
- easy way to compute BWT
- what can we do with the BWT

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BWT	a	b	$	c	c	b	b	a	a	a	a	b	b

- definition is not very descriptive
- easy way to compute BWT
- what can we do with the BWT

- **PINGO** can the BWT be reversed?

Burrows-Wheeler Transform (2/2)

Definition: Cyclic Rotation

Given a text T of length n, the i-th **cyclic rotation** is

$$T^{(i)} = T[i..n]T[1..i)$$

- i-th cyclic rotation is concatenation of i-th suffix and $(i-1)$-th prefix

$T = \texttt{ababcabcabba\$}$

$T^{(1)}$	$T^{(2)}$	$T^{(3)}$	$T^{(4)}$	$T^{(5)}$	$T^{(6)}$	$T^{(7)}$	$T^{(8)}$	$T^{(9)}$	$T^{(10)}$	$T^{(11)}$	$T^{(12)}$	$T^{(13)}$
a	b	a	b	c	a	b	c	a	b	b	a	$
b	a	b	c	a	b	c	a	b	b	a	$	a
a	b	c	a	b	c	a	b	b	a	$	a	b
b	c	a	b	c	a	b	b	a	$	a	b	a
c	a	b	c	a	b	b	a	$	a	b	a	b
a	b	c	a	b	b	a	$	a	b	a	b	c
b	c	a	b	b	a	$	a	b	a	b	c	a
c	a	b	b	a	$	a	b	a	b	c	a	b
a	b	b	a	$	a	b	a	b	c	a	b	c
b	b	a	$	a	b	a	b	c	a	b	c	a
b	a	$	a	b	a	b	c	a	b	c	a	b
a	$	a	b	a	b	c	a	b	c	a	b	b
$	a	b	a	b	c	a	b	c	a	b	b	a

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Definition: Burrows-Wheeler Transform (alt.)

Given a text T and a matrix containing all its cyclic rotations in lexicographical order as columns, then the **Burrows-Wheeler transform** of the text is the last row of the matrix

$T = \texttt{ababcabcabba\$}$

$T^{(1)}$	$T^{(2)}$	$T^{(3)}$	$T^{(4)}$	$T^{(5)}$	$T^{(6)}$	$T^{(7)}$	$T^{(8)}$	$T^{(9)}$	$T^{(10)}$	$T^{(11)}$	$T^{(12)}$	$T^{(13)}$
a	b	a	b	c	a	b	c	a	b	b	a	$
b	a	b	c	a	b	c	a	b	b	a	$	a
a	b	c	a	b	c	a	b	b	a	$	a	b
b	c	a	b	c	a	b	b	a	$	a	b	a
c	a	b	c	a	b	b	a	$	a	b	a	b
a	b	c	a	b	b	a	$	a	b	a	b	c
b	c	a	b	b	a	$	a	b	a	b	c	a
c	a	b	b	a	$	a	b	a	b	c	a	b
a	b	b	a	$	a	b	a	b	c	a	b	c
b	b	a	$	a	b	a	b	c	a	b	c	a
b	a	$	a	b	a	b	c	a	b	c	a	b
a	$	a	b	a	b	c	a	b	c	a	b	b
$	a	b	a	b	c	a	b	c	a	b	b	a

Burrows-Wheeler Transform (2/2)

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$	a	a	a	a	a	b	b	b	b	b	c	c
a	$	b	b	b	b	a	a	b	c	c	a	a
b	a	a	b	c	c	$	b	a	a	a	b	b
a	b	b	a	a	a	a	c	$	b	b	b	c
b	a	c	$	b	b	b	a	a	b	c	a	a
c	b	a	a	b	c	a	b	b	a	a	$	b
a	c	b	b	a	a	b	c	a	$	b	a	b
b	a	c	a	$	b	c	a	b	a	b	b	a
c	b	a	b	a	b	a	b	c	b	a	a	$
a	c	b	c	b	a	b	b	a	a	$	b	a
b	a	b	a	a	$	c	a	b	b	a	c	b
b	b	a	b	b	a	a	$	c	c	b	a	a
a	b	$	c	c	b	b	a	a	a	a	b	b

Burrows-Wheeler Transform (2/2)

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$	a	a	a	a	a	b	b	b	b	b	c	c
a	$	b	b	b	b	a	a	b	c	c	a	a
b	a	a	b	c	c	$	b	a	a	a	b	b
a	b	b	a	a	a	a	c	$	b	b	b	c
b	a	c	$	b	b	b	a	a	b	c	a	a
c	b	a	a	b	c	a	b	b	a	a	$	b
a	c	b	b	a	a	b	c	a	$	b	a	b
b	a	c	a	$	b	c	a	b	a	b	b	a
c	b	a	b	a	b	a	b	c	b	a	a	$
a	c	b	c	b	a	b	b	a	a	$	b	a
b	a	b	a	a	$	c	a	b	b	a	c	b
b	b	a	b	b	a	a	$	c	c	b	a	a
a	b	$	c	c	b	b	a	a	a	a	b	b

First and Last Row

- two important rows in the matrix
- other rows are not needed at all
- there is a special relation between the two rows
  ℹ later this lecture

First Row F

- contains all characters or the text in sorted order

Last Row L

- is the *BWT* itself

T = ababcabcabba$

	$T^{(13)}$	$T^{(12)}$	$T^{(1)}$	$T^{(9)}$	$T^{(6)}$	$T^{(3)}$	$T^{(11)}$	$T^{(2)}$	$T^{(10)}$	$T^{(7)}$	$T^{(4)}$	$T^{(8)}$	$T^{(5)}$
F	$	a	a	a	a	a	b	b	b	b	b	c	c
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
	b	b	a	b	b	a	a	$	c	c	b	a	a
L	a	b	$	c	c	b	b	a	a	a	a	b	b

Properties of the BWT: Rank of Characters

Definition: Rank

Given a text T over an alphabet *Sigma*, the **rank** of a character at position $i \in [1, n]$ is

$$rank(i) = |\{j \in [1, i] \colon T[i] = T[j]\}|$$

- rank is number of same characters that occur before in the text
- mark ranks of characters w.r.t. text not *BWT*

$T = \texttt{ababcabcabba\$}$

	$T^{(13)}$	$T^{(12)}$	$T^{(1)}$	$T^{(9)}$	$T^{(6)}$	$T^{(3)}$	$T^{(11)}$	$T^{(2)}$	$T^{(10)}$	$T^{(7)}$	$T^{(4)}$	$T^{(8)}$	$T^{(5)}$
F	$	a	a	a	a	a	b	b	b	b	b	c	c
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
	b	b	a	b	b	a	a	$	c	c	b	a	a
L	a	b	$	c	c	b	b	a	a	a	a	b	b

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T	a	b	a	b	c	a	b	c	a	b	b	a	$
rank	1	1	2	2	1	3	3	2	4	4	5	5	1

$T = \mathtt{ababcabcabba\$}$

	$T^{(13)}$	$T^{(12)}$	$T^{(1)}$	$T^{(9)}$	$T^{(6)}$	$T^{(3)}$	$T^{(11)}$	$T^{(2)}$	$T^{(10)}$	$T^{(7)}$	$T^{(4)}$	$T^{(8)}$	$T^{(5)}$
F	$	a	a	a	a	a	b	b	b	b	b	c	c
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
	b	b	a	b	b	a	a	$	c	c	b	a	a
L	a	b	$	c	c	b	b	a	a	a	a	b	b

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F	$	a	a	a	a	a	b	b	b	b	b	c	c
	1	5	1	4	3	2	5	1	4	3	2	1	2
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
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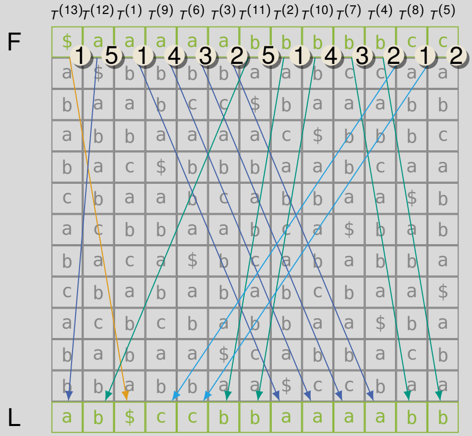
T	a	b	a	b	c	a	b	c	a	b	b	a	$
rank	1	1	2	2	1	3	3	2	4	4	5	5	1

T = ababcabcabba$



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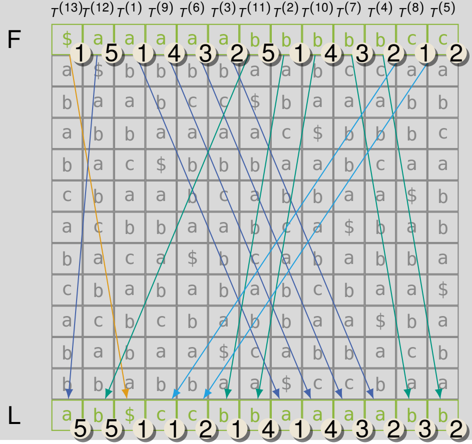

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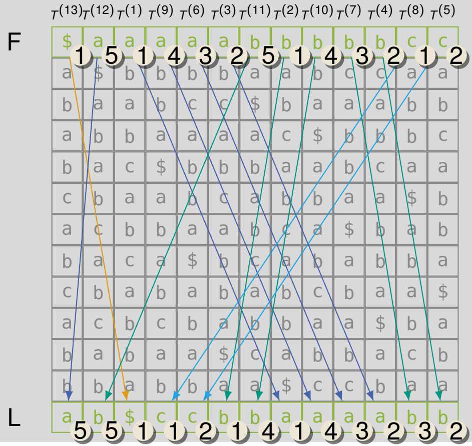
- rank is number of same characters that occur before in the text
- mark ranks of characters w.r.t. text not *BWT*
- order of ranks is the same in first and last row

T	a	b	a	b	c	a	b	c	a	b	b	a	\$
rank	1	1	2	2	1	3	3	2	4	4	5	5	1

T = ababcabcabba\$



LF-Mapping (1/2)

- want to map characters from last to first row
- why do we want this?
  - helps with pattern matching
  - transform *BWT* back to *T*

Definition: *LF*-mapping

Given a text *T* of length *n* and its suffix array *SA*, then the *LF*-mapping is a permutation of $[1, n]$, such that

$$LF(i) = j \iff SA[j] = SA[i] - 1$$

- similar to definition of *BWT*
- requires *SA* or explicitly saving *LF*-mapping

$T = \mathtt{ababcabcabba\$}$

	$T^{(13)}$	$T^{(12)}$	$T^{(1)}$	$T^{(9)}$	$T^{(6)}$	$T^{(3)}$	$T^{(11)}$	$T^{(2)}$	$T^{(10)}$	$T^{(7)}$	$T^{(4)}$	$T^{(8)}$	$T^{(5)}$
F	$	a	a	a	a	a	b	b	b	b	b	c	c
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
	b	b	a	b	b	a	a	$	c	c	b	a	a
L	a	b	$	c	c	b	b	a	a	a	a	b	b

LF-Mapping (1/2)

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$T = \texttt{ababcabcabba\$}$

	$T^{(13)}$	$T^{(12)}$	$T^{(1)}$	$T^{(9)}$	$T^{(6)}$	$T^{(3)}$	$T^{(11)}$	$T^{(2)}$	$T^{(10)}$	$T^{(7)}$	$T^{(4)}$	$T^{(8)}$	$T^{(5)}$
F	$	a	a	a	a	a	b	b	b	b	b	c	c
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
	b	b	a	b	b	a	a	$	c	c	b	a	a
L	a	b	$	c	c	b	b	a	a	a	a	b	b

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F	$	a	a	a	a	a	b	b	b	b	b	c	c
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
	b	b	a	b	b	a	a	$	c	c	b	a	a
L	a	b	$	c	c	b	b	a	a	a	a	b	b

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F	$	a	a	a	a	a	b	b	b	b	b	c	c
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
	b	b	a	b	b	a	a	$	c	c	b	a	a
L	a	b	$	c	c	b	b	a	a	a	a	b	b

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F	$	a	a	a	a	a	b	b	b	b	b	c	c
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
	b	b	a	b	b	a	a	$	c	c	b	a	a
L	a	b	$	c	c	b	b	a	a	a	a	b	b

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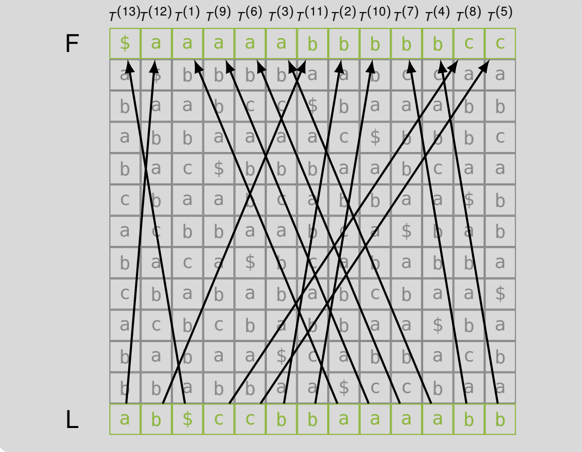

LF-Mapping (2/2)

Definition: *C*-Array and *Rank*-Function

Given a text T of length n over an alphabet Σ, $\alpha \in \Sigma$, and $i \in [1, n]$ then

$$C[\alpha] = |i \in [1, n]\colon\ T[i] < \alpha|$$

and

$$rank_\alpha(i) = |\{j \in [1, i]\colon\ T[j] = \alpha\}|$$

- C contains total number of smaller characters
- $rank_\alpha$ contains number of α's in prefix $T[1..i]$
- $rank_\alpha$ can be computed in $O(1)$ time [FM00]

LF-Mapping (2/2)

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T	a	b	a	b	c	a	b	c	a	b	b	a	\$
$rank$	1	1	2	2	1	3	3	2	4	4	5	5	1

- rank now on BWT
- C is exclusive prefix sum over histogram

LF-Mapping (2/2)

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Definition: *C*-Array and *Rank*-Function

Given a text T of length n over an alphabet Σ, $\alpha \in \Sigma$, and $i \in [1, n]$ then

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T	a	b	a	b	c	a	b	c	a	b	b	a	\$
rank	1	1	2	2	1	3	3	2	4	4	5	5	1

- rank now on *BWT*
- C is exclusive prefix sum over histogram

Definition: *LF*-Mapping (alt.)

Given a *BWT*, its *C*-array, and its *rank*-Function, then

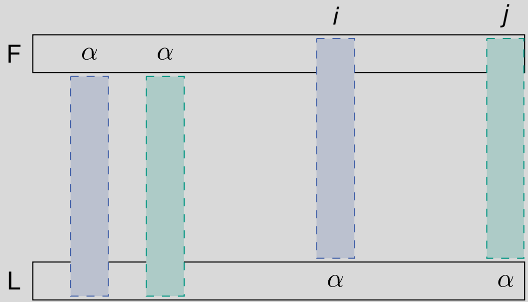
$$LF(i) = C[BWT[i]] + rank_{BWT[i]}(i)$$

Reversing the BWT (1/2)

- characters (w.r.t. text) preserve order in L and F
- LF-mapping returns previous character in text

Reversing the BWT (1/2)

- characters (w.r.t. text) preserve order in *L* and *F*
- *LF*-mapping returns previous character in text



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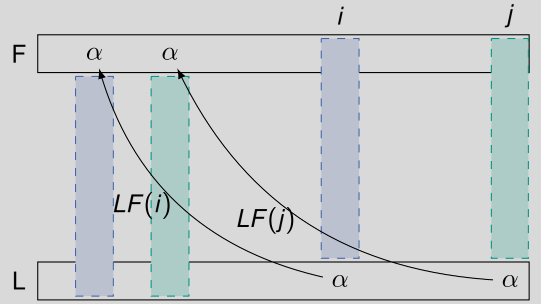

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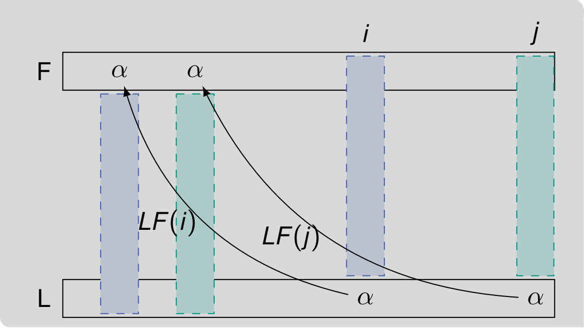
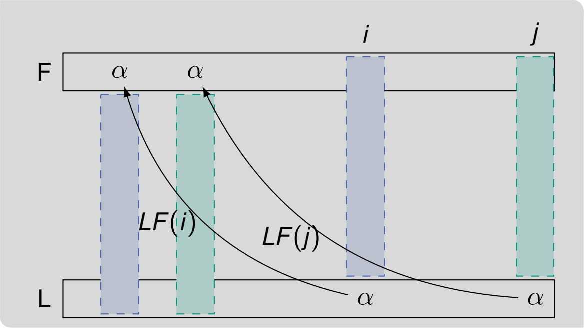


$T = \texttt{ababcabcabba\$}$

F	$	a	a	a	a	a	b	b	b	b	b	c	c
	a	$	b	b	b	b	a	a	b	c	c	a	a
	b	a	a	b	c	c	$	b	a	a	a	b	b
	a	b	b	a	a	a	a	c	$	b	b	b	c
	b	a	c	$	b	b	b	a	a	b	c	a	a
	c	b	a	a	b	c	a	b	b	a	a	$	b
	a	c	b	b	a	a	b	c	a	$	b	a	b
	b	a	c	a	$	b	c	a	b	a	b	b	a
	c	b	a	b	a	b	a	b	c	b	a	a	$
	a	c	b	c	b	a	b	b	a	a	$	b	a
	b	a	b	a	a	$	c	a	b	b	a	c	b
	b	b	a	b	b	a	a	$	c	c	b	a	a
L	a	b	$	c	c	b	b	a	a	a	a	b	b
LF	2	7	1	12	13	8	9	3	4	5	6	10	11

Reversing the BWT (1/2)

- characters (w.r.t. text) preserve order in L and F
- LF-mapping returns previous character in text



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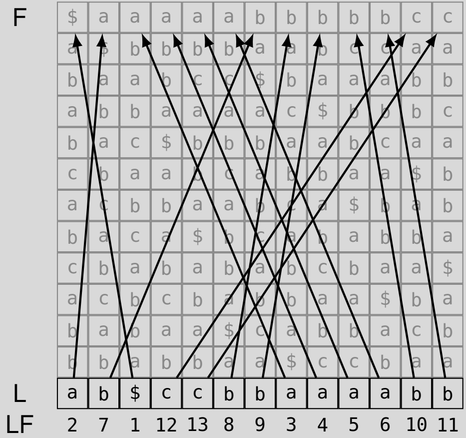

Reversing the BWT (2/2)

- characters (w.r.t. text) preserve order in L and F
- LF-mapping returns previous character in text

	1	2	3	4	5	6	7	8	9	0	11	12	13
L	a	b	$	c	c	b	b	a	a	a	a	b	b
LF	2	7	1	12	13	8	9	3	4	5	6	10	11

Reversing the BWT (2/2)

- characters (w.r.t. text) preserve order in L and F
- LF-mapping returns previous character in text

- $T[n] = \$$ and $T^{(n)}$ in first row
- apply LF-mapping on result to obtain any character

$$T[n-i] = L[\underbrace{LF(LF(\ldots(}_{i-1 \text{ times}}LF(1))\ldots))]$$

	1	2	3	4	5	6	7	8	9	0	11	12	13
L	a	b	$	c	c	b	b	a	a	a	a	b	b
LF	2	7	1	12	13	8	9	3	4	5	6	10	11

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L	a	b	$	c	c	b	b	a	a	a	a	b	b
LF	2	7	1	12	13	8	9	3	4	5	6	10	11

- $T[13] = \$$ and $k = 1$

Reversing the BWT (2/2)

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- $T[13] = \$$ and $k = 1$
- $T[12] = L[1] = \mathrm{a}$ and $k = LF(1) = 2$

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- $T[11] = L[2] = \texttt{b}$ and $k = LF(2) = 7$

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	1	2	3	4	5	6	7	8	9	0	11	12	13
L	a	b	$	c	c	b	b	a	a	a	a	b	b
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- $T[13] = \$$ and $k = 1$
- $T[12] = L[1] = \mathtt{a}$ and $k = LF(1) = 2$
- $T[11] = L[2] = \mathtt{b}$ and $k = LF(2) = 7$
- $T[10] = L[7] = \mathtt{b}$ and $k = LF(7) = 9$

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	1	2	3	4	5	6	7	8	9	0	11	12	13
L	a	b	$	c	c	b	b	a	a	a	a	b	b
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- $T[10] = L[7] = \mathtt{b}$ and $k = LF(7) = 9$
- $T[9] = L[9] = \mathtt{a}$ and $k = LF(9) = 4$

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- $T[10] = L[7] = \mathtt{b}$ and $k = LF(7) = 9$
- $T[9] = L[9] = \mathtt{a}$ and $k = LF(9) = 4$
- $T[9] = L[4] = \mathtt{c}$ and $k = LF(4) = 12$

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	1	2	3	4	5	6	7	8	9	0	11	12	13
L	a	b	$	c	c	b	b	a	a	a	a	b	b
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- $T[9] = L[9] = \mathtt{a}$ and $k = LF(9) = 4$
- $T[9] = L[4] = \mathtt{c}$ and $k = LF(4) = 12$
- ...

Properties of the BWT: Runs

- *BWT* is reversible
- can be used for lossless compression

Definition: Run (simplified)

Given a text T of length n, we call its substring $T[i..j]$ a **run**, if

- $T[k] = T[\ell]$ for all $k, \ell \in [i, j]$ and
- $T[i-1] \neq T[i]$ and $T[j+1] \neq T[j]$

ℹ (To be more precise, this is a definition for a run of a periodic substring with smallest period 1, but this is not important for this lecture)

	1	2	3	4	5	6	7	8	9	0	11	12	13
L	a	b	$	c	c	b	b	a	a	a	a	b	b

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- *BWT* contains lots of runs
- same context is often grouped together

Compressing the BWT: Run-Length Compression

Definition: Run-Length Encoding

Given a text T, represent each run $T[i..i+\ell)$ as tuple

$$(T[i], \ell)$$

$T = $ `ababcabcabba$`

	1	2	3	4	5	6	7	8	9	0	11	12	13
BWT	a	b	$	c	c	b	b	a	a	a	a	b	b

- $(\texttt{a}, 1)$
- $(\texttt{b}, 1)$
- $(\texttt{\$}, 1)$
- $(\texttt{c}, 2)$
- $(\texttt{b}, 2)$
- $(\texttt{a}, 4)$
- $(\texttt{b}, 2)$

Compressing the BWT: Move-to-Front

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Definition: Move-To-Front Encoding

Given a text T over an alphabet $\Sigma = [1, \sigma]$, the **MTF encoding** $MTF(T)$ of the text is computed as follows

- start with a list $X = \Sigma[1], \Sigma[2], \ldots, \Sigma[\sigma]$
- scan text from left to right, for character $T[i]$
  - append position of $T[i]$ in X to $MTF(T)$ and
  - move $T[i]$ to front of X

- MTF encoding can easily be reverted
- consists of many small numbers
- runs are preserved
- use Huffman on encoding no theoretical improvement but good in practice

Compressing the BWT: Move-to-Front

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Definition: Move-To-Front Encoding

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- $\ldots$
- $MTF = 2\,3\,3\,4\,1\,1\,3\,1\,4\,1\,1\,1\,2\,1$

Pattern Matching using the BWT

Recap

Given a text T of length n over an alphabet Σ, $\alpha \in \Sigma$, and $i \in [1, n]$ then

$$C[\alpha] = |i \in [1, n]\colon\ T[i] < \alpha|$$

and

$$rank_\alpha(i) = |\{j \in [1, i]\colon\ T[j] = \alpha\}|$$

- find interval of occurrences in *SA* using *BWT*
- *SA* is divided into intervals based on first character of suffix as seen during SAIS
- text from *BWT* is backwards
- search pattern backwards

- interval for α is $[C[\alpha - 1], C[\alpha + 1]]$
- find sub-interval using $rank_\alpha$

- example on the board

Backwards Search in the BWT

Function *BackwardsSearch*$(P[1..n], C, rank)$**:**

$s = 1, e = n$
for $i = m, \ldots, 1$ **do**
  $s = C[P[i]] + rank_{P[i]}(s-1) + 1$
  $e = C[P[i]] + rank_{P[i]}(e)$
  if $s > e$ **then**
    return $\emptyset$
return $[s, e]$

- no access to text or *SA* required
- no binary search
- existential queries are easy
- counting queries are easy
- reporting queries require additional information
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Sampling the Suffix Array

- reporting queries require *SA*
- storing whole *SA* requires too much space
- better: sample every *s*-th *SA* position in *SA'*

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- if $SA[i] = j$ then $SA[LF(i)] = j - 1$

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- finding a sample requires $O(s \cdot t_{rank})$ time

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std::vector<char/int/...>

- easy access
- very big: $1, 4, \ldots$ bytes per bit

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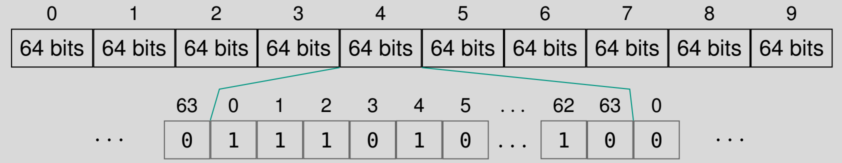

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// There is a bit vector
std::vector<uint64_t> bit_vector;

// access i-th bit
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bool bit = (block >> ( 63 - (i % 64)) )  & 1ULL;
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$\mathrm{select}_\alpha(j)$ position of j-th α

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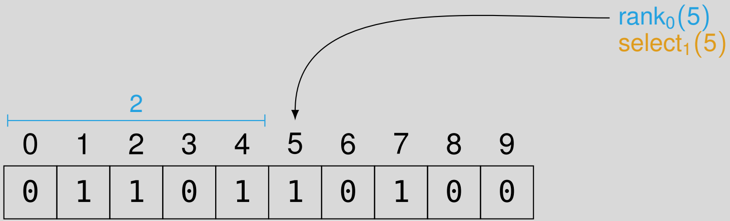

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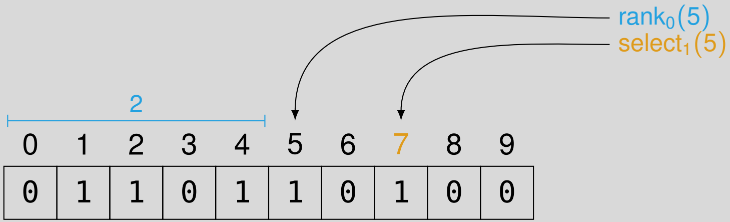

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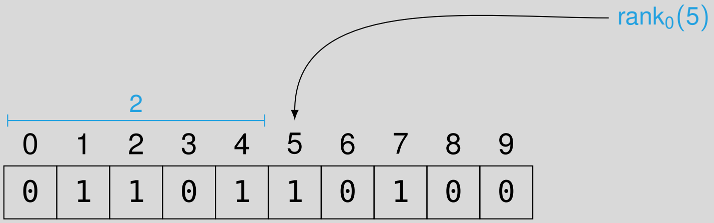

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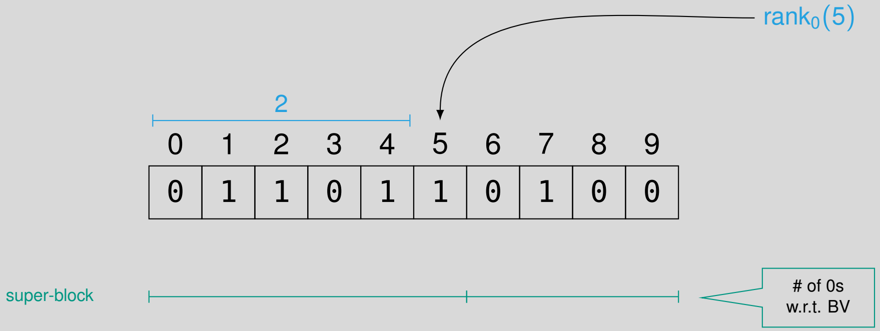

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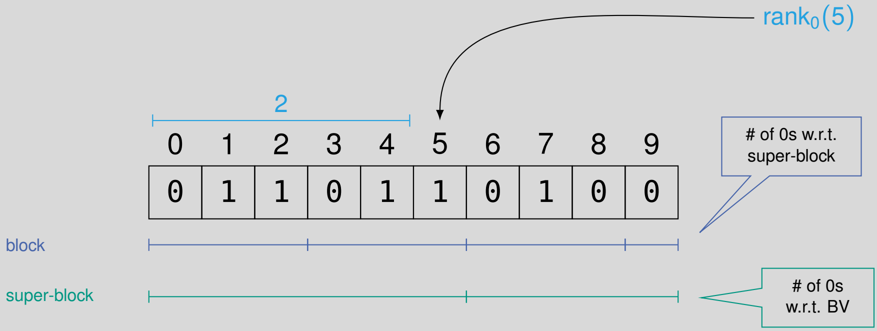

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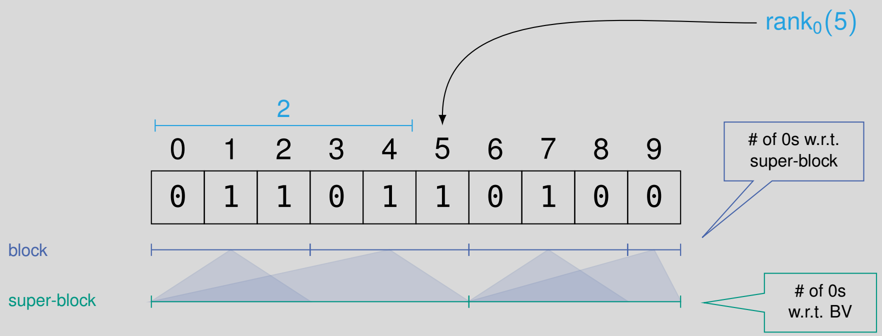

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- for all $\lfloor \frac{n}{s'} \rfloor$ super blocks, store number of 0s from beginning of bit vector to end of super-block
- $n/s' \cdot \lg n = O(\frac{n}{\lg n}) = o(n)$ bits of space

Rank Queries in Bit Vectors (2/2)

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- query in $O(1)$ time
- $rank_0(i) = i - rank_1(i)$

The FM-Index (First Look) [FM00]

Building Blocks of FM-Index

- wavelet tree on BWT providing *rank*-function
  wavelet trees are topic of next lecture!
- C-array
- sampled suffix array with sample rate s
- bit vector marking sampled suffix array positions

Lemma: FM-Index Space Requirements

Given a text T of length n over an alphabet of size σ, the FM-index requires $O(n \lg \sigma)$ bits of space

Space Requirements

- wavelet tree: $n\lceil \lg \sigma \rceil(1 + o(1))$ bits
- C-array: $\sigma \lceil \lg n \rceil$ bits $n(1 + o(1))$ bits if $\sigma \geq \frac{n}{\lg n}$
- sampled suffix array: $\frac{n}{s}\lceil \lg n \rceil$ bits
- bit vector: $n(1 + o(1))$ bits

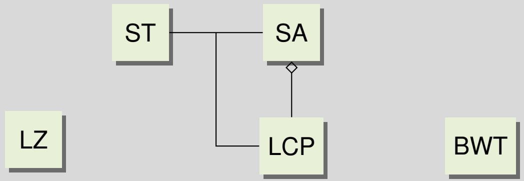
- space and time bounds can be achieved with $s = \lg_\sigma n$

Conclusion and Outlook

This Lecture

- Burrows-Wheeler transform
- introduction to FM-index

Linear Time Construction



Conclusion and Outlook

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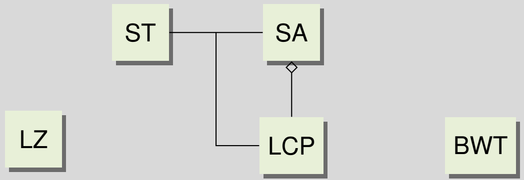
- rank queries on bit vectors

Linear Time Construction



Conclusion and Outlook

This Lecture

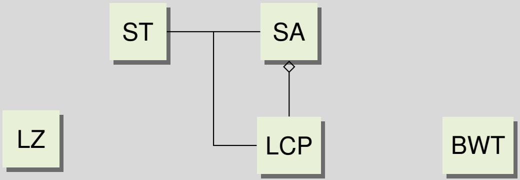
- Burrows-Wheeler transform
- introduction to FM-index

- efficient bit vectors
- rank queries on bit vectors

Next Lecture

- wavelet trees
- more on FM-index

Linear Time Construction



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