COMP9319 Web Data Compression and Search

An Occ Implementation,
RLFM (Compressed FM Index) Revisit

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An example Occ implementation

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FM Index (L(x)=c)

	F	L	c	C
0	#	i		
1	i	p		
2	i	s		
3	i	s		
4	i	m		
5	m	#	0	
6	p	p	1	
7	p	i	1	
8	s	s	2	
9	s	s	3	
10	s	i	2	
11	s	i	3	

3

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FM Index (when reversing from L[5])

	F	L	c	C
			0	# 0
			0	i 1
			0	m 5
			1	p 6
			0	s 8
5	m	#	0	
			1	
			1	
			2	
			3	
10	s	i	2	
11	s	i	3	

LF[5] = 0+0 = 0, i

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FM Index (when reversing from L[5])

	F	L	c	C
0	#	i	0	# 0
1	i	p	0	i 1
2	i	s	0	m 5
3	i	s	1	p 6
4	i	m	0	s 8
5	m	#	0	
6	p	p	1	
7	p	i	1	
8	s	s	2	
9	s	s	3	
10	s	i	2	
11	s	i	3	

LF[5] = 0+0 = 0, i
LF[0] = 1+0 = 1, p
LF[1] = 6+0 = 6, p
LF[6] = 6+1 = 7, i
LF[7] = 1+1 = 2, s
LF[2] = 8+0 = 8, s
LF[8] = 8+2 = 10, i
LF[10] = 1+2 = 3, s
LF[3] = 8+1 = 9, s
LF[9] = 8+3 = 11, i
LF[11] = 1+3 = 4, m

5

5

FM Index (L(x) ≠ c)

	F	L	i	m	p	s	C
0	#	i	1	0	0	0	# 0
1	i	p	1	0	1	0	i 1
2	i	s	1	0	1	1	m 5
3	i	s	1	0	1	2	p 6
4	i	m	1	1	1	2	s 8
5	m	#	1	1	1	2	
6	p	p	1	1	2	2	
7	p	i	2	1	2	2	
8	s	s	2	1	2	3	
9	s	s	2	1	2	4	
10	s	i	3	1	2	4	
11	s	i	4	1	2	4	

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FM Index (con't)

pssi

	F	L	i	m	p	s	C
0	#	i	1	0	0	0	# 0
➡ 1	i	p	1	0	1	0	i 1
2	i	s	1	0	1	1	m 5
3	i	s	1	0	1	2	p 6
➡ 4	i	m	1	1	1	2	s 8
5	m	#	1	1	1	2	
6	p	p	1	1	2	2	
7	p	i	2	1	2	2	
8	s	s	2	1	2	3	
9	s	s	2	1	2	4	
10	s	i	3	1	2	4	
11	s	i	4	1	2	4	

Fst=1
Lst=4

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FM Index (con't)

pssi

	F	L	i	m	p	s	C
0	#	i	1	0	0	0	# 0
➡ 1	i	p	1	0	1	0	i 1
2	i	s	1	0	1	1	m 5
3	i	s	1	0	1	2	p 6
➡ 4	i	m	1	1	1	2	s 8
5	m	#	1	1	1	2	
6	p	p	1	1	2	2	
7	p	i	2	1	2	2	
8	s	s	2	1	2	3	
9	s	s	2	1	2	4	
10	s	i	3	1	2	4	
11	s	i	4	1	2	4	

Fst=8+0
Lst=(8+2)-1

8

8

FM Index (con't)

pssi

	F	L	i	m	p	s	C
0	#	i					
1	i	p					
2	i	s					
3	i	s					
4	i	m					
5	m	#	1	1	1	2	
6	p	p	1	1	2	2	
7	p	i	2	1	2	2	
➡ 8	s	s	2	1	2	3	
➡ 9	s	s	2	1	2	4	
10	s	i	3	1	2	4	
11	s	i	4	1	2	4	

Fst=8+0
Lst=(8+2)-1

9

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FM Index (con't)

	F	L	i	m	p	s	C
			1	0	0	0	# 0
			1	0	1	0	i 1
			1	0	1	1	m 5
			1	0	1	2	p 6
			1	1	1	2	s 8
5	m	#	1	1	1	2	
			1	1	2	2	
			2	1	2	2	
➡			2	1	2	3	
➡			2	1	2	4	
10	s	i	3	1	2	4	
11	s	i	4	1	2	4	

Fst=8+2
Lst=(8+4)-1

10

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FM Index (con't)

pssi

	F	L	i	m	p	s	C
0	#	i	1	0	0	0	# 0
1	i	p	1	0	1	0	i 1
2	i	s	1	0	1	1	m 5
3	i	s	1	0	1	2	p 6
4	i	m	1	1	1	2	s 8
5	m	#	1	1	1	2	
6	p	p	1	1	2	2	
7	p	i	2	1	2	2	
8	s	s	2	1	2	3	
9	s	s	2	1	2	4	
➡ 10	s	i	3	1	2	4	
➡ 11	s	i	4	1	2	4	

Fst=8+2
Lst=(8+4)-1

11

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FM Index (con't)

pssi

	F	L	i	m	p	s	C
0	#	i	1	0	0	0	# 0
1	i	p	1	0	1	0	i 1
2	i	s	1	0	1	1	m 5
3	i	s	1	0	1	2	p 6
4	i	m	1	1	1	2	s 8
5	m	#	1	1	1	2	
6	p	p	1	1	2	2	
7	p	i	2	1	2	2	
8	s	s	2	1	2	3	
9	s	s	2	1	2	4	
➡ 10	s	i	3	1	2	4	
➡ 11	s	i	4	1	2	4	

Fst=6+2
Lst=(6+2)-1

12

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FM Index (con't)

		F	L	i	m	p	s	C
pssi	0	#	i	1	0	0	0	# 0
	1	i	p	1	0	1	0	i 1
	2	i	s	1	0	1	1	m 5
	3	i	s	1	0	1	2	p 6
	4	i	m	1	1	1	2	s 8
	5	m	#	1	1	1	2	
	6	p	p	1	1	2	2	
	7	p	i	2	1	2	2	
	8	s	s	2	1	2	3	
	9	s	s	2	1	2	4	
➡	10	s	i	3	1	2	4	
➡	11	s	i	4	1	2	4	

Fst=6+2
Lst=(6+2)-1

Fst > Lst => No match

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FM Index (con't)

		F	L	i	m	p	s	C
pssi	0	#	i					# 0
	1	i	p					i 1
	2	i	s					m 5
	3	i	s	1	0	1	2	p 6
	4	i	m					s 8
	5	m	#					
	6	p	p					
	7	p	i	2	1	2	2	
	8	s	s					
	9	s	s					
	10	s	i					
	11	s	i	4	1	2	4	

To reduce space

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FM Index (con't)

		F	L	i	m	p	s	C
pssi	0	#	i					# 0
	1	i	p					i 1
	2	i	s					m 5
	3	i	s					p 6
	4	i	m					s 8
	5	m	#					
	6	p	p					
	7	p	i	2	1	2	2	
	8	s	s					
	9	s	s					
	10	s	i					
	11	s	i	4	1	2	4	

To reduce space

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FM Index (con't) Similar when L(x) = c

		F	L	i	m	p	s	C
pssi	0	#	i					# 0
	1	i	p					i 1
	2	i	s					m 5
	3	i	s	1	0	1	2	p 6
	4	i	m					s 8
	5	m	#					
	6	p	p					
	7	p	i	2	1	2	2	
	8	s	s					
	9	s	s					
	10	s	i					
	11	s	i	4	1	2	4	

To reduce space

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RLFM Index (Revisit)

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RLFM Index (Derive B' from LF)

	F	L	C
1	a	c	a 0
2	a	c	c 3
3	a	c	g 6
4	c	a	t 8
5	c	a	
6	c	g	
7	g	g	
8	g	a	
9	t	t	
10	t	t	

	B	S	Fs	Cs
1	1	c	a	a 0
2	0	a	a	c 2
3	0	g	c	g 3
4	1	a	g	t 4
5	0	t	t	
6	1			
7	0			
8	1			
9	1			
10	0			

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RLFM Index (con't from the prev lecture)

	F	L	C
1	a	c	a 0
2	a	c	c 3
3	a	c	g 6
4	c	a	t 8
5	c	a	
6	c	g	
7	g	g	
8	g	a	
9	t	t	
10	t	t	

	B	S	Fs	Cs	B′
1	1	c	a	a 0	
2	0	a	a	c 2	
3	0	g	c	g 3	
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				
8	1				
9	1				
10	0				

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RLFM Index (con't from the prev lecture)

	F	L	C
1	a	c	a 0
2	a	c	c 3
3	a	c	g 6
4	c	a	t 8
5	c	a	
6	c	g	
7	g	g	
8	g	a	
9	t	t	
10	t	t	

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				
8	1				
9	1				
10	0				

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RLFM Index (con't from the prev lecture)

	F	L	C
1	a	c	a 0
2	a	c	c 3
3	a	c	g 6
4	c	a	t 8
5	c	a	
6	c	g	
7	g	g	
8	g	a	
9	t	t	
10	t	t	

	B	S	Fs	Cs	B′
1					
2					
3					
4					
5					
6	1				0
7	0				1
8	1				0
9	1				
10	0				

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RLFM Index (con't from the prev lecture)

	F	L	C
6	c	g	

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6					0
7					1
8					0
9					
10					

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RLFM Index (no L & F, nor LF)

	B	S	B′
1	1	c	
2	0	a	
3	0	g	
4	1	a	
5	0	t	
6	1		
7	0		
8	1		
9	1		
10	0		

If only B and S are stored and given… then how ???

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RLFM Index (no L & F, nor LF)

	B	S	Fs	B′
1	1	c	a	
2	0	a	a	
3	0	g	c	
4	1	a	g	
5	0	t	t	
6	1			
7	0			
8	1			
9	1			
10	0			

If only B and S are stored and given… then how ???

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RLFM Index (no L & F, nor LF)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	
2	0	a	a	c 2	
3	0	g	c	g 3	
4	1	a	g	t 4	
5	0	t	t		
6	1				
7	0				
8	1				
9	1				
10	0				

same

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RLFM Index (No LF mapping)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	
2	0	a	a	c 2	
3	0	g	c	g 3	
4	1	a	g	t 4	
5	0	t	t		
6	1				
7	0				
8	1				
9	1				
10	0				

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RLFM Index (No LF mapping)

	B	S	Fs	Cs	B′
1					
2					
3					
4					
5					
6	1				
7	0				
8	1				
9	1				
10	0				

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27

RLFM Index (No LF mapping)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	
2	0	a	a	c 2	
3	0	g	c	g 3	
4	1	a	g	t 4	
5	0	t	t		

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RLFM Index (No LF mapping)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	
2	0	a	a	c 2	
3	0	g	c	g 3	
4	1	a	g	t 4	
5	0	t	t		
6	1				
7	0				
8	1				
9	1				
10	0				

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RLFM Index (No LF mapping)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	
4	1	a	g	t 4	
5	0	t	t		
6	1				
7	0				
8	1				
9	1				
10	0				

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RLFM Index (No LF mapping)

	B	S	Fs	Cs		B′
1	1	c	a	a	0	1
2	0	a	a	c	2	0
3	0	g	c	g	3	
4	1	a	g	t	4	
5	0	t	t			
6	1					
7	0					
8	1					
9	1					
10	0					

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RLFM Index (No LF mapping)

	B	S	Fs	Cs		B′
1	1	c	a	a	0	1
2	0	a	a	c	2	0
3	0	g	c	g	3	1
4	1	a	g	t	4	
5	0	t	t			
6	1					
7	0					
8	1					
9	1					
10	0					

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RLFM Index (No LF mapping)

	B	S	Fs	Cs	B′
1					
2					
3					
4					
5					
6	1				
7	0				
8	1				
9	1				
10	0				

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RLFM Index (No LF mapping)

	B	S	Fs	Cs		B′
1	1	c	a	a	0	1
2	0	a	a	c	2	0
3	0	g	c	g	3	1
4	1	a	g	t	4	
5	0	t	t			

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RLFM Index (No LF mapping)

	B	S	Fs	Cs		B′
1	1	c	a	a	0	1
2	0	a	a	c	2	0
3	0	g	c	g	3	1
4	1	a	g	t	4	1
5	0	t	t			0
6	1					0
7	0					
8	1					
9	1					
10	0					

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RLFM Index (No LF mapping)

	B	S	Fs	Cs		B′
1	1	c	a	a	0	1
2	0	a	a	c	2	0
3	0	g	c	g	3	1
4	1	a	g	t	4	1
5	0	t	t			0
6	1					0
7	0					
8	1					
9	1					
10	0					

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RLFM Index (No LF mapping)

	B	S	Fs	Cs		B′
1	1	c	a	a	0	1
2	0	a	a	c	2	0
3	0	g	c	g	3	1
4	1	a	g	t	4	1
5	0	t	t			0
6	1					0
7	0					1
8	1					0
9	1					
10	0					

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RLFM Index (No LF mapping)

	B	S	Fs	Cs		B′
1	1	c	a	a	0	1
2	0	a	a	c	2	0
3	0	g	c	g	3	1
4	1	a	g	t	4	1
5	0	t	t			0
6	1					0
7	0					1
8	1					0
9	1					1
10	0					0

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Now we h

Let's **reverse (decode)** using LF mapping

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apply these formulas to do reversing & ard search.

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CHANGES TO FORMULAS

- Recall that we need to compute $C_T[c]+rank_c(L,i)$ in the backward search.
- **Theorem:** $C[c]+rank_c(L,i)$ is equivalent to $select_1(B',C_S[c]+1+rank_c(S,rank_1(B,i)))-1$, when $L[i] \neq c$ (e.g., when backward search) , and otherwise (e.g., when reverse, sometimes backward search too) to $select_1(B',C_S[c]+rank_c(S,rank_1(B,i)))+i-select_1(B,rank_1(B,i))$.

But I promised that I would explain why/how these formulas actually work

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RLFM Index (con't from the prev lecture)

	F	L	C		B	S	Fs	Cs		B′
1	a	c	a	0	1	c	a	a	0	1
2	a	c	c	3	0	a	a	c	2	0
3	a	c	g	6	0	g	c	g	3	1
4	c	a	t	8	1	a	g	t	4	1
5	c	a			0	t	t			0
6	c	g			1					0
7	g	g			0					1
8	g	a			1					0
9	t	t			1					1
10	t	t			0					0

Suppose reverse from L[8]

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RLFM Index (con't from the prev lecture)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$\text{rank}_a(S, \text{rank}_1(B, 8)) = 2$

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RLFM Index (con't from the prev lecture)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$\text{rank}_a(S, \text{rank}_1(B, 8)) = 2$

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RLFM Index (con't from the prev lecture)

	B	S	Fs	Cs	B′
1					
2					
3					
4					
5					
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$\text{select}_1(B', C_s[a]+\text{rank}_a(S, \text{rank}_1(B, 8)))$

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RLFM Index (con't from the prev lecture)

	F	L	C
6	c	g	

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$\text{select}_1(B', C_s[a]+\text{rank}_a(S, \text{rank}_1(B, 8))) = 3$

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Good, but not good enough

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RLFM Index (con't from the prev lecture)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$\text{select}_1(B', C_c[c]+\text{rank}_c(S, \text{rank}_1(B, 3)))$
$= \text{select}_1(B', 2 + 1) = 4$

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RLFM Index (con't from the prev lecture)

	F	L	C	
1	a	c	a	0
2	a	c	c	3
3	a	c	g	6
4	c	a	t	8
5	c	a		
6	c	g		
7	g	g		
8	g	a		
9	t	t		
10	t	t		

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$select_1(B', C_s[c]+rank_c(S, rank_1(B, 3)))$
$=select_1(B', 2 + 1)=4$

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RLFM Index (con't from the prev lecture)

	F	L	C	
1	a	c	a	0
2	a	c	c	3
3	a	c	g	6
4	c	a	t	8
5	c	a		
6	c	g		
7	g	g		
8	g	a		
9	t	t		
10	t	t		

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$select_1(B', C_s[c]+rank_c(S, rank_1(B, 3)))$
$=select_1(B', 2 + 1)=4 + 2$

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RLFM Index (con't from the prev lecture)

	F	L	C	
1	a	c	a	0
2	a	c	c	3
3	a	c	g	6
4	c	a	t	8
5	c	a		
6	c	g		
7	g	g		
8	g	a		
9	t	t		
10	t	t		

	B	S	Fs	Cs	B′
1					
2					
3					
4					
5					
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$select_1(B', C_s[c]+rank_c(S, rank_1(B, 3)))$
$=select_1(B', 2 + 1)=4 + (i - rank_1(B, i))$

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RLFM Index (con't from the prev lecture)

example, LF[5] = ?

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RLFM Index (con't from the prev lecture)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$select_1(B', C_s[a]+rank_a(S, rank_1(B, 5)))$
$=select_1(B', 0 + 1)=1 + (i - rank_1(B, i))$

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RLFM Index (con't from the prev lecture)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$select_1(B', C_s[a]+rank_a(S, rank_1(B, 5)))$
$=select_1(B', 0 + 1)=1 + (i - rank_1(B, i))$

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RLFM Index (con't from the prev lecture)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$select_1(B', C_s[a]+rank_a(S, rank_1(B, 5)))$
$=select_1(B', 0 + 1)=1 + (i - rank_1(B, i))$

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RLFM Index (con't from the prev lecture)

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$select_1(B', C_s[a]+rank_a(S, rank_1(B, 5)))$
$=select_1(B', 0 + 1)=1 + (i - select_1(B, rank_1(B, i)))$

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RLFM Index (con't from the prev lecture)

	B	S	Fs	Cs	B′
1					
2					
3					
4					
5					
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$select_1(B', C_s[a]+rank_a(S, rank_1(B, 5)))$
$=select_1(B', 0 + 1)=1 + (i - select_1(B, rank_1(B, i)))$

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RLFM Index (con't from the prev lecture)

	F	L	C
1			
2			
3			
4			
5			
6	c	g	

	B	S	Fs	Cs	B′
1	1	c	a	a 0	1
2	0	a	a	c 2	0
3	0	g	c	g 3	1
4	1	a	g	t 4	1
5	0	t	t		0
6	1				0
7	0				1
8	1				0
9	1				1
10	0				0

$select_1(B', C_s[a]+rank_a(S, rank_1(B, 5)))$
$=select_1(B', 0 + 1)=1 + (i - select_1(B, rank_1(B, i)))$

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RLFM Index (con't from the prev lecture)

CHANGES TO FORMULAS

- Recall that we need to compute $C_T[c]+rank_c(L,i)$ in the backward search.
- **Theorem:** $C[c]+rank_c(L,i)$ is equivalent to $select_1(B',C_S[c]+1+rank_c(S,rank_1(B,i)))-1$, when $L[i] \neq c$ (e.g., when backward search) , and otherwise (e.g., when reverse, sometimes backward search too) to $select_1(B',C_S[c]+rank_c(S,rank_1(B,i)))+ i-select_1(B,rank_1(B,i))$.

$select_1(B', C_s[a]+rank_a(S, rank_1(B, 5)))$
$=select_1(B', 0 + 1)=1 + (i - select_1(B, rank_1(B, i)))$

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Backward Search

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Backward search for "si"

	B	S	F_s	C		B′
1	1	i	#	#	0	1
2	1	p	i	i	1	1
3	1	s	i	m	4	1
4	0	m	i	p	5	1
5	1	#	m	s	7	0
6	1	p	p			1
7	1	i	p			1
8	1	s	s			1
9	1	i	s			1
10	0					0
11	1					1
12	0					0

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Backward search for "si"

	B	S	F_s	C		B′
1	1	i	#	#	0	1
2	1	p	i	i	1	1
3	1	s	i	m	4	1
4	0	m	i	p	5	1
5	1	#	m	s	7	0
6	1	p	p			1
7	1	i	p			1
8	1	s	s			1
9	1	i	s			1
10	0					0
11	1					1
12	0					0

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Backward search for "si"

	B	S	F_s	C	B′	
1	1					
2	1					
3	1					
4	0					
5	1					
6	1	p	p		1	c = i
7	1	i	p		1	Fst = 2
8	1	s	s		1	Lst = 5
9	1	i	s		1	
10	0				0	
11	1				1	
12	0				0	

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Backward search for "si"

	F	L	C	B	S	F_s	C		B′	
				1	i	#	#	0	1	
➡				1	p	i	i	1	1	
				1	s	i	m	4	1	
➡				0	m	i	p	5	1	
				1	#	m	s	7	0	
6	m	#		6	1	p	p		1	c = i
						i	p		1	Fst = 2
						s	s		1	Lst = 5
						i	s		1	
									0	
									1	
12	s	i		12	0				0	

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Backward search for "si"

	F	L	C	B	S	F_s	C		B′	
1	#	i	#	0	1	#	#	0	1	
➡ 2	i	p	i	1	1	i	i	1	1	
3	i	s	m	5	1	s	m	4	1	
4	i	s	p	6	0	m	p	5	1	
➡ 5	i	m	s	8	1	#	s	7	0	
6	m	#			1	p			1	c = s
7	p	p			1	i			1	Fst =
8	p	i			1	s			1	C[c] + Occ(c,
9	s	s			1	i			1	Fst – 1) + 1
10	s	s			0				0	= ?
11	s	i			1				1	
12	s	i			0				0	

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Backward search for "si"

	F	L	C	B	S	F_s	C		B′	
1	#	i	#	0	1	#	#	0	1	
➡ 2	i	p	i	1	1	i	i	1	1	
3	i	s	m	5	1	s	i	m	4	1
4	i	s	p	6	0	m	i	p	5	1
➡ 5	i	m	s	8	1	#	m	s	7	0
6	m	#			1	p	p			1
7	p	p			1	i	p			1
8	p	i			1	s	s			1
9	s	s			1	i	s			1
10	s	s			0					0
11	s	i			1					1
12	s	i			0					0

T_x → 2

L_r → 5

c = i
Fst = 2
Lst = 5

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Backward search for "si"

	F	L	C
1	#	i	# 0
2	i	p	i 1
3	i	s	m 5
4	i	s	p 6
5	i	m	s 8
6	m	#	
7	p	p	
8	p	i	
9	s	s	
10	s	s	
11	s	i	
12	s	i	

	B	S	F_s	C	B′
1	1	i	#	# 0	1
2	1	p	i	i 1	1
3	1	s	i	m 4	1
4	0	m	i	p 5	1
5	1	#	m	s 7	0
6	1	p	p		1
7	1	i	p		1
8	1	s	s		1
9	1	i	s		1
10	0				0
11	1				1
12	0				0

c = s
Fst = ??

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Backward search for "si"

	F	L	C
1	#	i	# 0
2	i	p	i 1
3	i	s	m 5
4	i	s	p 6
5	i	m	s 8
6	m	#	
7	p	p	
8	p	i	
9	s	s	
10	s	s	
11	s	i	
12	s	i	

	B	S	F_s	C	B′
1	1	i	#	# 0	1
2	1	p	i	i 1	1
3	1	s	i	m 4	1
4	0	m	i	p 5	1
5	1	#	m	s 7	0
6	1	p	p		1
7	1	i	p		1
8	1	s	s		1
9	1	i	s		1
10	0				0
11	1				1
12	0				0

c = s
Fst
Occ of s:
$rank_s(S, rank_1(B,2-1)) = 0$

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Backward search for "si"

	F	L	C
1	#	i	# 0
2	i	p	i 1
3	i	s	m 5
4	i	s	p 6
5	i	m	s 8
6	m	#	
7	p	p	
8	p	i	
9	s	s	
10	s	s	
11	s	i	
12	s	i	

	B	S	F_s	C	B′
1	1	i	#	# 0	1
2	1	p	i	i 1	1
3	1	s	i	m 4	1
4	0	m	i	p 5	1
5	1	#	m	s 7	0
6	1	p	p		1
7	1	i	p		1
8	1	s	s		1
9	1	i	s		1
10	0				0
11	1				1
12	0				0

c = s
Fst
Occ of s:
$rank_s(S, rank_1(B,2-1)) = 0$
$select_1(B',7+1+0)$
So Fst = 9

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Backward search for "si"

	F	L	C
1	#	i	# 0
2	i	p	i 1
3	i	s	m 5
4	i	s	p 6
5	i	m	s 8
6	m	#	
7	p	p	
8	p	i	
9	s	s	
10	s	s	
11	s	i	
12	s	i	

	B	S	F_s	C	B′
1	1	i	#	# 0	1
2	1	p	i	i 1	1
3	1	s	i	m 4	1
4	0	m	i	p 5	1
5	1	#	m	s 7	0
6	1	p	p		1
7	1	i	p		1
8	1	s	s		1
9	1	i	s		1
10	0				0
11	1				1
12	0				0

c = s
Fst
Occ of s:
$rank_s(S, rank_1(B,2-1)) = 0$
$select_1(B',7+1+0)$
So Fst = 9

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Backward search for "si"

	F	L	C
1	#	i	# 0
2	i	p	i 1
3	i	s	m 5
4	i	s	p 6
5	i	m	s 8
6	m	#	
7	p	p	
8	p	i	
9	s	s	
10	s	s	
11	s	i	
12	s	i	

	B	S	F_s	C	B′
1	1	i	#	# 0	1
2	1	p	i	i 1	1
3	1	s	i	m 4	1
4	0	m	i	p 5	1
5	1	#	m	s 7	0
6	1	p	p		1
7	1	i	p		1
8	1	s	s		1
9	1	i	s		1
10	0				0
11	1				1
12	0				0

c = s
Lst
Occ of s:
$rank_s(S, rank_1(B,5)) = 1$

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Backward search for "si"

	F	L	C
1	#	i	# 0
2	i	p	i 1
3	i	s	m 5
4	i	s	p 6
5	i	m	s 8
6	m	#	
7	p	p	
8	p	i	
9	s	s	
10	s	s	
11	s	i	
12	s	i	

	B	S	F_s	C	B′
1	1	i	#	# 0	1
2	1	p	i	i 1	1
3	1	s	i	m 4	1
4	0	m	i	p 5	1
5	1	#	m	s 7	0
6	1	p	p		1
7	1	i	p		1
8	1	s	s		1
9	1	i	s		1
10	0				0
11	1				1
12	0				0

c = s
Lst
Occ of s:
$rank_s(S, rank_1(B,5)) = 1$
$select_1(B',7+1+1) = 11$
$11 - 1 = 10$
So Lst = 10

-1: since inclusively, e.g., Lst-Fst+1 = #matches

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Backward search for "ssi"

	F	L	C
1	#	i	# 0
2	i	p	i 1
3	i	s	m 5
4	i	s	p 6
5	i	m	s 8
6	m	#	
7	p	p	
8	p	i	
9	s	s	
10	s	s	
11	s	i	
12	s	i	

	B	S	F_S	C	B′
1	1	i	#	# 0	1
2	1	p	i	i 1	1
3	1	s	i	m 4	1
4	0	m	i	p 5	1
5	1	#	m	s 7	0
6	1	p	p		1
7	1	i	p		1
8	1	s	s		1
9	1	i	s		1
10	0				0
11	1				1
12	0				0

c = s
Fst
Occ of s: $rank_S$(S, $rank_1$(B,9-1)) = 1
$select_1$(B',7+1+1)
So Fst = 11

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Backward search for "ssi"

	F	L	C
1	#	i	# 0
2	i	p	i 1
3	i	s	m 5
4	i	s	p 6
5	i	m	s 8
6	m	#	
7	p	p	
8	p	i	
9	s	s	
10	s	s	
11	s	i	
12	s	i	

	B	S	F_S	C	B′
1	1	i	#	# 0	1
2	1	p	i	i 1	1
3	1	s	i	m 4	1
4	0	m	i	p 5	1
5	1	#	m	s 7	0
6	1	p	p		1
7	1	i	p		1
8	1	s	s		1
9	1	i	s		1
10	0				0
11	1				1
12	0				0

c = s
Lst
Occ of s: $rank_S$(S, $rank_1$(B,10)) = 1
Since L[i]=c, $select_1$(B',Cs[c]+$rank_c$(S,$rank_1$(B,i)))+ i-$select_1$(B,$rank_1$(B,i)).
$select_1$(B',7+2) = 11
11 + 1 = 12
So Lst = 12

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Backward search for "issi"

	F	L	C
1	#	i	# 0
2	i	p	i 1
3	i	s	m 5
4	i	s	p 6
5	i	m	s 8
6	m	#	
7	p	p	
8	p	i	
9	s	s	
10	s	s	
11	s	i	
12	s	i	

	B	S	F_S	C	B′
1	1				
2	1				
3	1				
4	0				
5	1				
6	1	p	p		1
7	1	i	p		1
8	1	s	s		1
9	1	i	s		1
10	0				0
11	1				1
12	0				0

Fst
Occ of i: $rank_S$(S, $rank_1$(B,11)) = 2
$select_1$(B',1+1+2)
So Fst = 4

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Backward search for "issi"

	F	L	C
6	m	#	
12	s	i	

	B	S	F_S	C	B′
1	1	i	#	# 0	1
2	1	p	i	i 1	1
3	1	s	i	m 4	1
4	0	m	i	p 5	1
5	1	#	m	s 7	0
6	1	p	p		1
		i	p		1
		s	s		1
		i	s		1
12	0				0

c = i
Lst
Occ of i: $rank_S$(S, $rank_1$(B,12)) = 3
Since L[i]=c, $select_1$(B',Cs[c]+$rank_c$(S,$rank_1$(B,i)))+ i-$select_1$(B,$rank_1$(B,i)).
$select_1$(B',1+3) = 4
4 + 1 = 5
So Lst = 5

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Therefore ...

CHANGES TO FORMULAS

- Recall that we need to compute $C_T[c]+rank_c(L,i)$ in the backward search.
- **Theorem:** $C[c]+rank_c(L,i)$ is equivalent to $select_1(B',C_S[c]+1+rank_c(S,rank_1(B,i)))-1$, when $L[i] \neq c$ (e.g., when backward search) , and otherwise (e.g., when reverse, sometimes backward search too) to $select_1(B',C_S[c]+rank_c(S,rank_1(B,i)))+$ $i\text{-}select_1(B,rank_1(B,i))$.

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