FM-index of an alignment: A compressed index for highly similar strings

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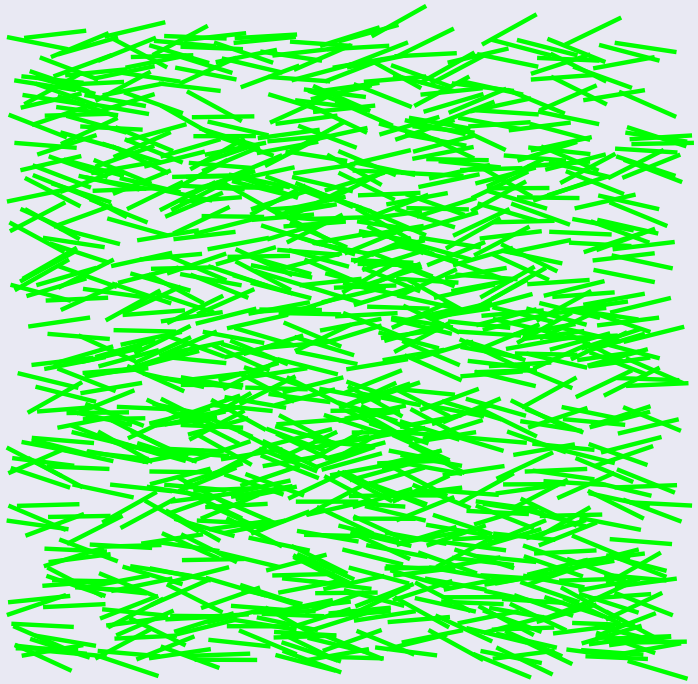
Next Generation Sequencing (NGS)

- millions of sort (length ~ 150) fragments called *reads*
- 2 types of projects:
  - re-sequencing: (*mapping*) reads on a reference gnome
  - *de novo* (*assembling*) reads

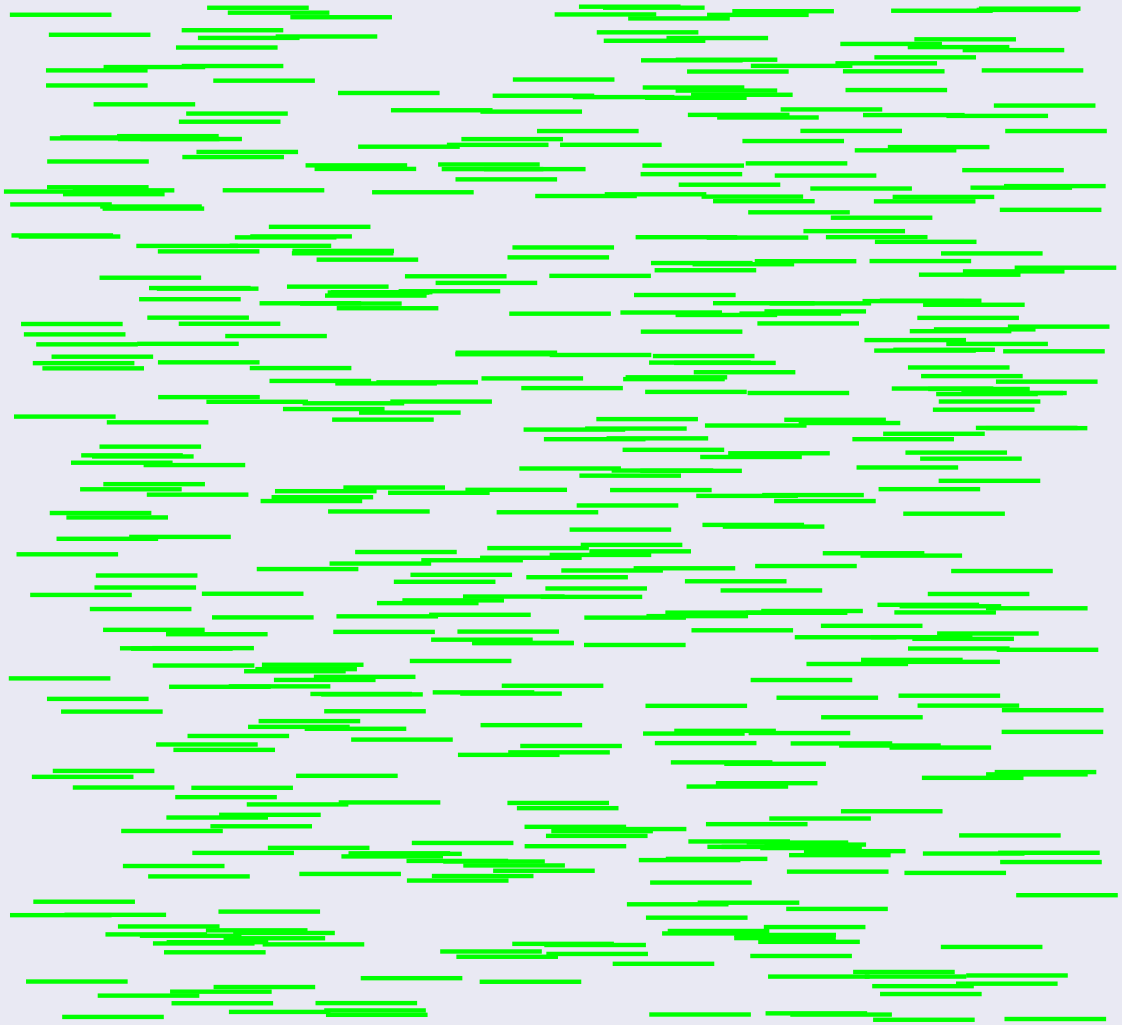
Sequencer

Reads

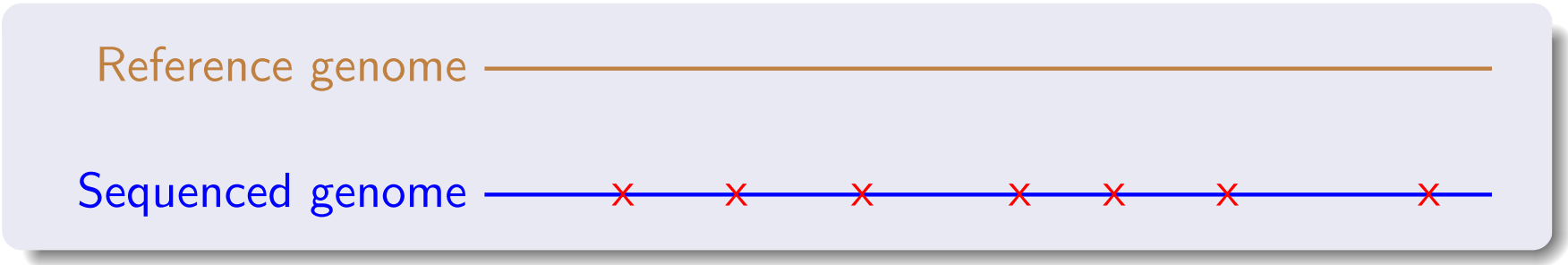


Re-sequencing

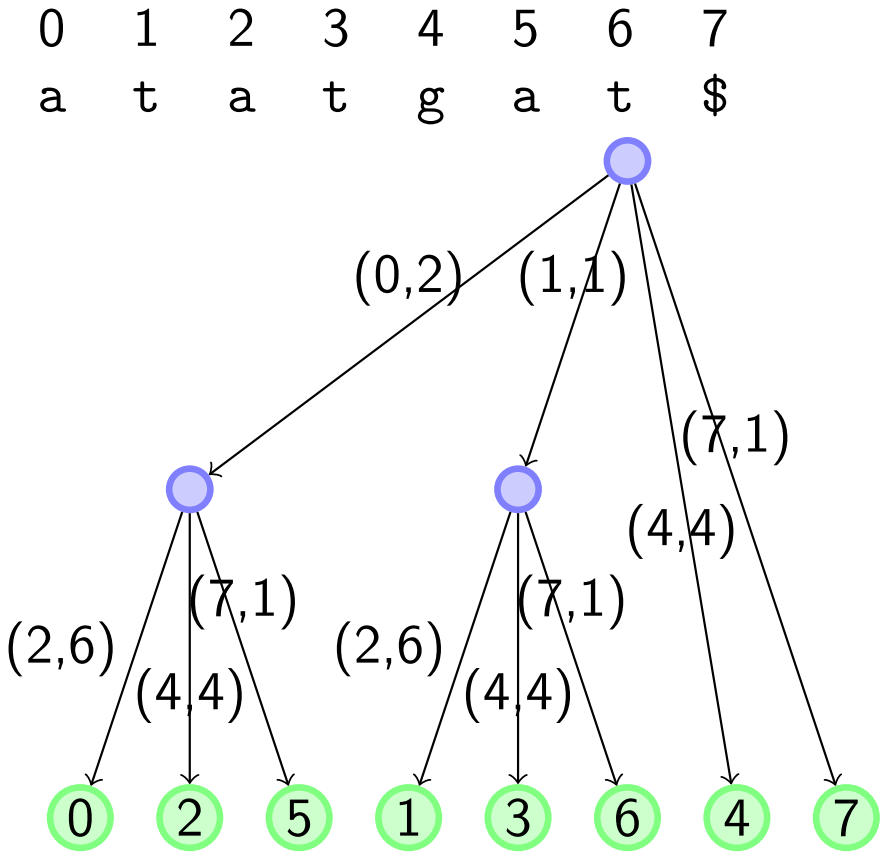
Reference genome



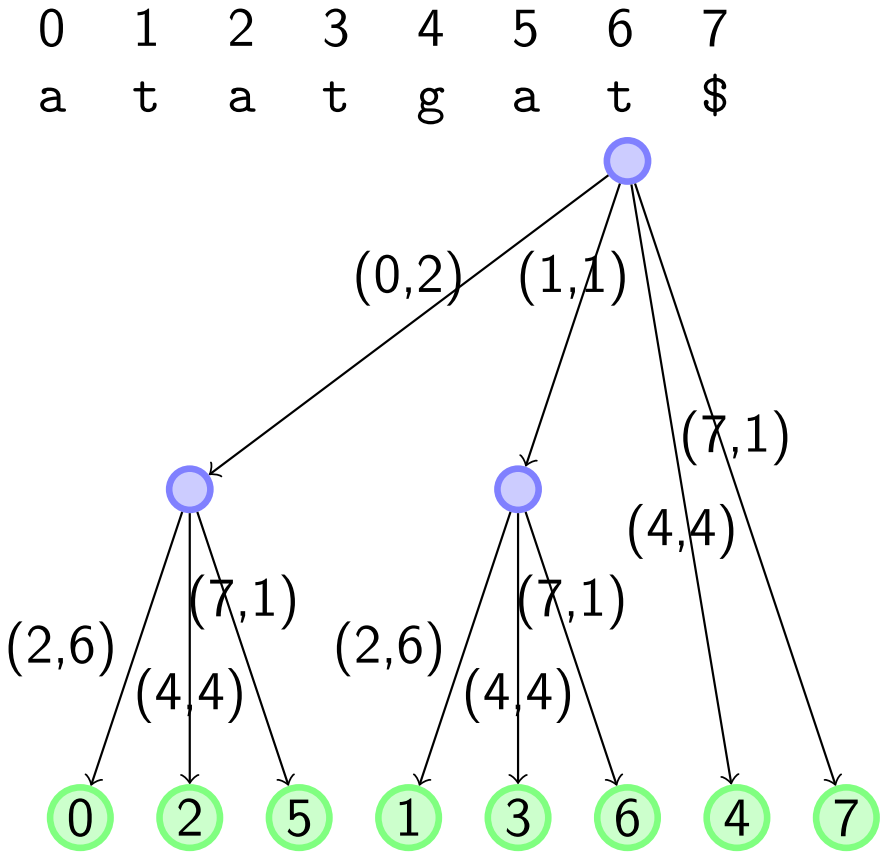
Variations



Suffix Tree



Suffix Tree



Human genome 3.3 Gbp

3.3 Gbp $\times$ 12.5 bytes $\rightarrow$ 41.25 GB

Suffix Array

		0	1	2	3	4	5	6	7
y	=	a	t	a	t	g	a	t	$

SA	sort of the suffixes
7	$
5	at$
0	atatgat$
2	atgat$
4	gat$
6	t$
1	tatgat$
3	tgat$

Suffix Array

		0	1	2	3	4	5	6	7
y	$=$	a	t	a	t	g	a	t	$

SA	sort of the suffixes
7	$
5	at$
0	atatgat$
2	atgat$
4	gat$
6	t$
1	tatgat$
3	tgat$

$n \log n$ bits

Burrows-Wheeler Transform (BWT)

		0	1	2	3	4	5	6	7
y	=	a	t	a	t	g	a	t	$

sort of the conjugates

F		L
$	atatga	t
a	t$atat	g
a	tatgat	$
a	tgat$a	t
g	at$ata	t
t	$atatg	a
t	atgat$	a
t	gat$at	a

BWT = tg$ttaaa

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y	$=$	a	t	a	t	g	a	t	$

sort of the conjugates

F		L
$	atatga	t
a	t$atat	g
a	tatgat	$
a	tgat$a	t
g	at$ata	t
t	$atatg	a
t	atgat$	a
t	gat$at	a

BWT $=$ tg$ttaaa

$n \log \sigma$ bits

Burrows-Wheeler Transform (BWT)

	0	1	2	3	4	5	6	7
y =	a	t	a	t	g	a	t	$

	a	c	g	t
C	1	1	4	5

a	c	g	t
0	0	0	1
0	0	1	0
0	0	0	0
0	0	0	1
0	0	0	1
1	0	0	0
1	0	0	0
1	0	0	0

$\sigma \log n + \sigma n$ bits

FM-index

Self-index

sampled suffix array + BWT

FM-index

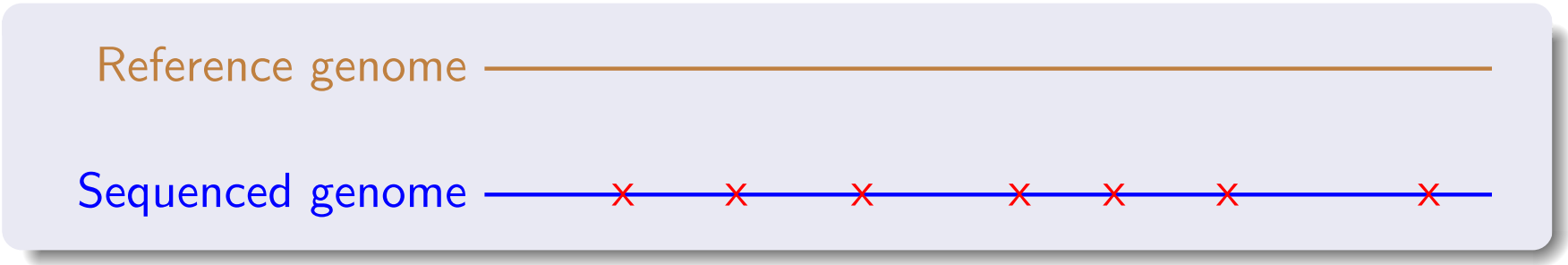
Self-index

sampled suffix array + BWT

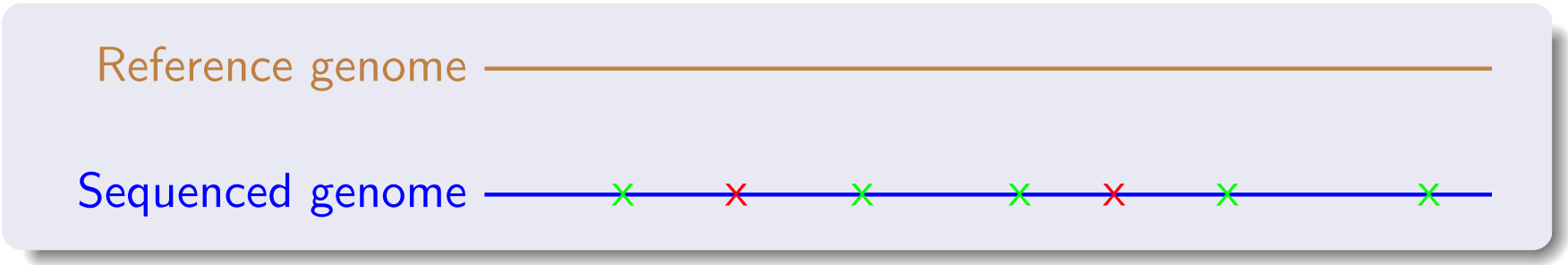
Human genome

less than 2GB

After sequencing



After sequencing



Reference genomes

Similar sequences

Example with 4 sequences

$S^1 = \texttt{atccaactccc\$}$
$S^2 = \texttt{attcaactcac\$}$
$S^3 = \texttt{atcttactcac\$}$
$S^4 = \texttt{atacaactccc\$}$

Similar sequences

Example with 4 sequences

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$S^2 = \texttt{attcaactcac\$}$
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Similar sequences

Example with 4 sequences

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$S^2 = \texttt{attcaactcac\$}$
$S^3 = \texttt{atcttactcac\$}$
$S^4 = \texttt{ataacaactccc\$}$

$\rho = \texttt{at(cca/tca/ctt/aca)actc(c/a/a/c)c\$}$

Similar sequences

Formally

A set of sequences, for $1 \leq j \leq r$:

$$S^j = \alpha_1 \Delta_1^j \cdots \alpha_k \Delta_k^j \alpha_{k+1}$$

the alignment is thus denoted by:

$$\rho = \alpha_1 (\Delta_1^1 / \Delta_1^2 / \cdots / \Delta_1^r) \cdots \alpha_k (\Delta_k^1 / \Delta_k^2 / \cdots / \Delta_k^r) \alpha_{k+1} \$$$

where

- α_is are common parts
- Δ_i^js are non-common parts

Longest repeated suffix of α_is

For each $1 \leq i \leq k$ and $1 \leq j \leq r$

$$\alpha_i = \alpha_i^{\diamond^j} \alpha_i^{*^j}$$

where $\alpha_i^{*^i}$ is the longest suffix of α_i occurring at least twice in S^j

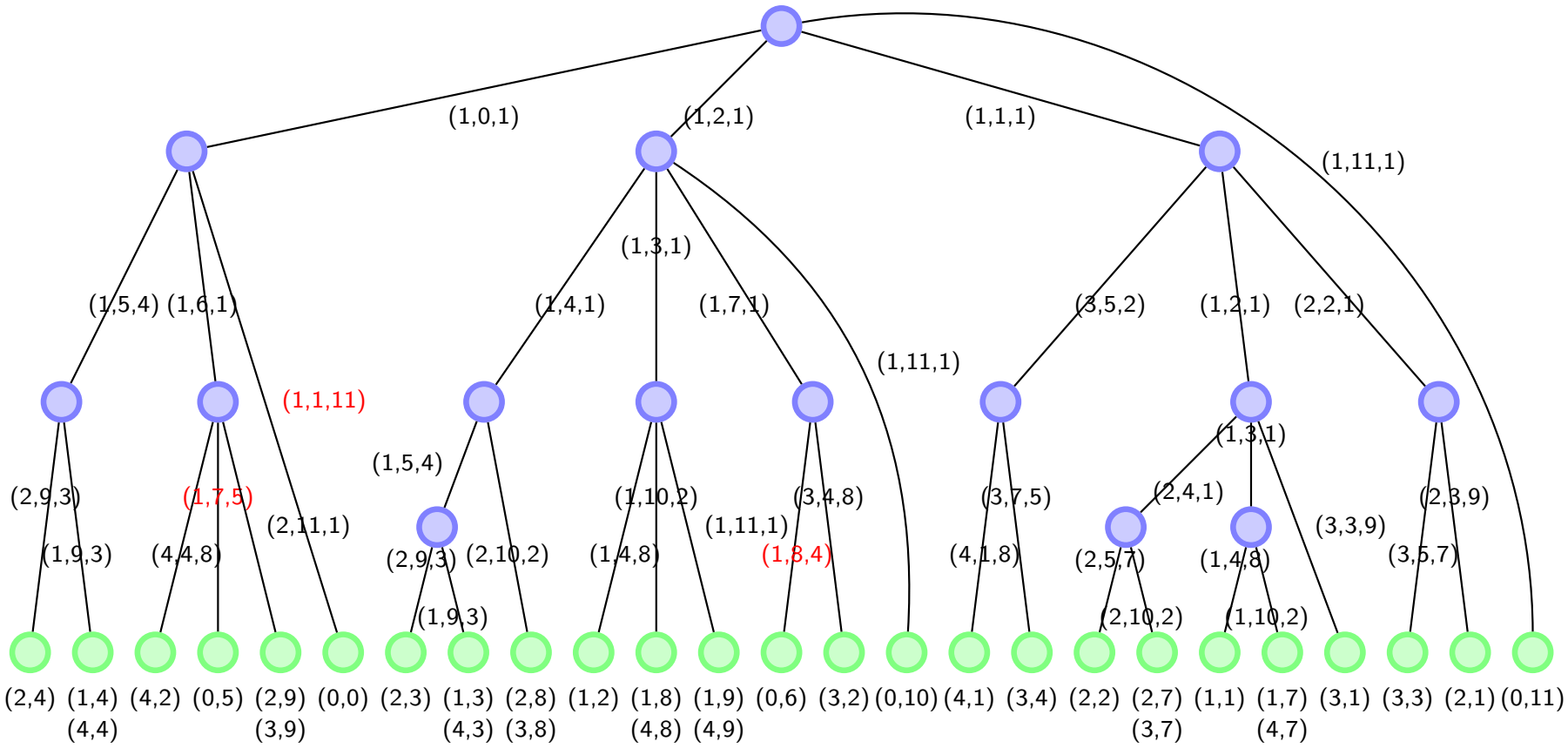
Then

$$\alpha_i = \alpha_i^{\diamond} \alpha_i^{*}$$

where α_i^{*} is the longest among the $\alpha_i^{*^j}$s

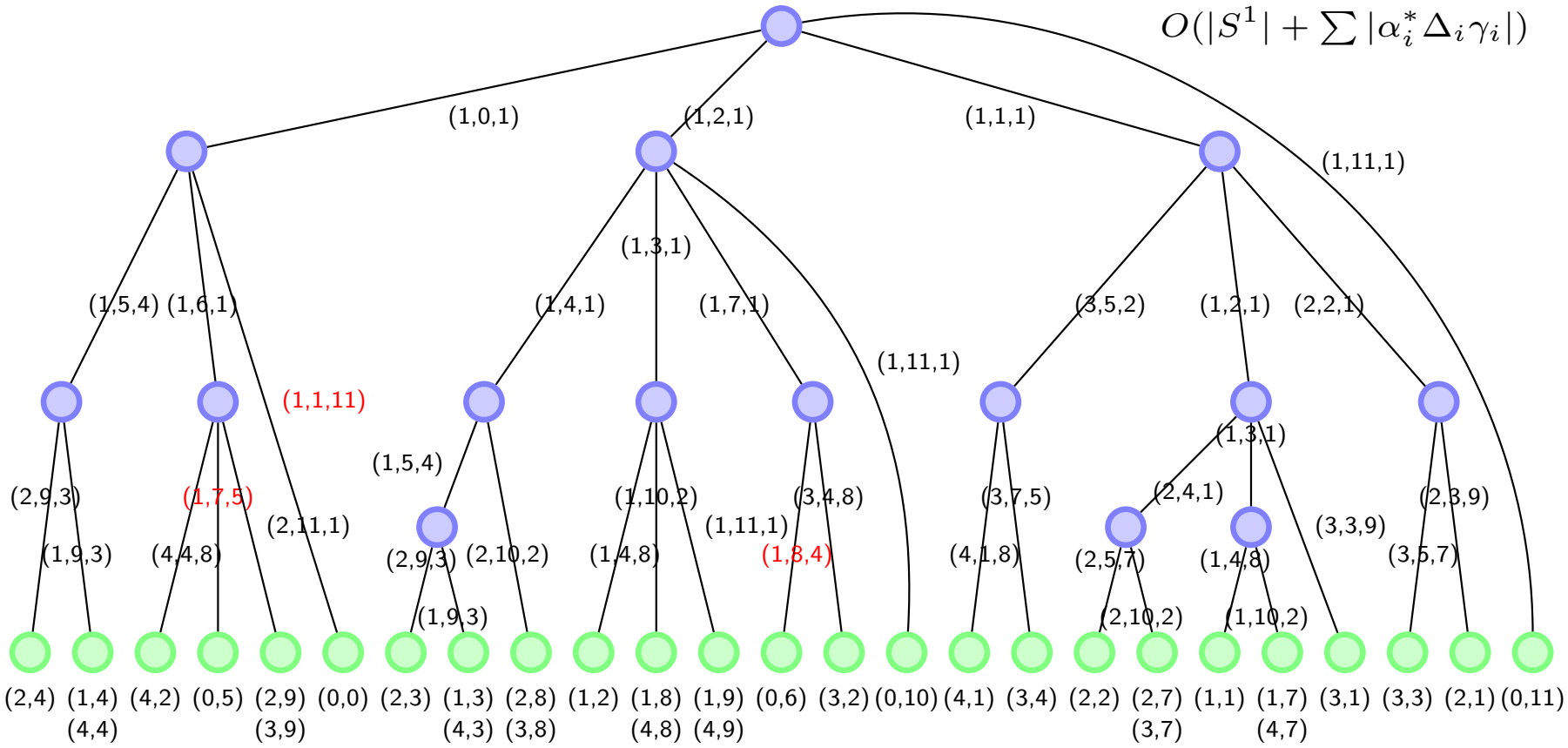
Suffix tree of an alignment

	0	1	2	3	4	5	6	7	8	9	10	11
S_1	a	t	c	c	a	a	c	t	c	c	c	$
S_2	a	t	t	c	a	a	c	t	c	a	c	$
S_3	a	t	c	t	t	a	c	t	c	a	c	$
S_4	a	t	a	c	a	a	c	t	c	c	c	$
	$\alpha_1^\diamond$	α_1^*	Δ_1			$\alpha_2^\diamond$		α_2^*		Δ_2	α_3	



Suffix tree of an alignment

	0	1	2	3	4	5	6	7	8	9	10	11
S_1	a	t	c	c	a	a	c	t	c	c	c	$
S_2	a	t	t	c	a	a	c	t	c	a	c	$
S_3	a	t	c	t	t	a	c	t	c	a	c	$
S_4	a	t	a	c	a	a	c	t	c	c	c	$
	$\alpha_1^\diamond$	α_1^*	Δ_1			$\alpha_2^\diamond$		α_2^*		Δ_2	α_3	



Suffix array of an alignment

i		SA	sort of the suffixes
0	0	11	$
1	2	4	aactcac$
2	1	4	aactccc$
3	4	4	aactccc$
4	2	9	ac$
5	4	9	ac$
6	4	2	acaactccc$
7	0	5	actc(c/a/a/c)c$
8	0	0	at(cca/tca/ctt/aca)actc(c/a/a/c)c$
9	0	10	c$
10	2	3	caaactcac$
11	1	3	caaactccc$
12	4	3	caaactccc$
13	2	8	cac$
14	3	8	cac$
15	1	9	cc$
16	4	9	cc$
17	1	2	ccaactccc$
18	1	8	ccc$
19	4	8	ccc$
20	0	6	ctc(c/a/a/c)c$
21	3	2	cttactcac$
22	4	1	tacaactccc$
23	3	4	tactcac$
24	2	2	tcaactcac$
25	2	7	tcac$
26	3	7	tcac$
27	1	1	tccaactccc$
28	1	7	tccc$
29	4	7	tccc$
30	3	1	tcttactcac$
31	3	3	ttactcac$
32	2	1	ttcaactcac$

Suffix array of an alignment

i		SA	sort of the suffixes
0	0	11	$
1	2	4	aactcac$
2	1	4	aactccc$
3	4	4	aactccc$
4	2	9	ac$
5	4	9	ac$
6	4	2	acaactccc$
7	0	5	actc(c/a/a/c)c$
8	0	0	at(cca/tca/ctt/aca)actc(c/a/a/c)c$
9	0	10	c$
10	2	3	caaactcac$
11	1	3	caaactccc$
12	4	3	caaactccc$
13	2	8	cac$
14	3	8	cac$
15	1	9	cc$
16	4	9	cc$
17	1	2	ccaactccc$
18	1	8	ccc$
19	4	8	ccc$
20	0	6	ctc(c/a/a/c)c$
21	3	2	cttactcac$
22	4	1	tacaactccc$
23	3	4	tactcac$
24	2	2	tcaactcac$
25	2	7	tcac$
26	3	7	tcac$
27	1	1	tccaactccc$
28	1	7	tccc$
29	4	7	tccc$
30	3	1	tcttactcac$
31	3	3	ttactcac$
32	2	1	ttcaactcac$

Burrows-Wheeler Transform of an alignment

i	SA		F		L
0	0	11	$	at(cca/tca/ctt/aca)actc(c/a/a/c)	c
1	1, 2, 4	4	a	actc(c/a/c)$at(c/t/a)	c
2	2, 3	9	a	c$at(tca/ctt)act	c
3	4	2	a	caactccc$a	t
4	0	5	a	ctc(c/a/a/c)c$at(cc/tc/ct/ac)	a,t
5	0	0	a	t(cca/tca/ctt/aca)actc(c/a/a/c)	$
6	0	10	c	$at(cca/tca/ctt/aca)actc	a,c
7	1, 2, 4	3	c	(ca/ca/ca)actc(c/a/c)c$at	a,c,t
8	2, 3	8	c	(a/a)c$at(tca/ctt)ac	t
9	1, 4	9	c	c$at(cca/aca)act	c
10	1	2	c	caactccc$a	t
11	1, 4	8	c	(c/c)c$at(cca/aca)ac	t
12	0	6	c	tc(c/a/a/c)c$at(cca/tca/ctt/aca)	a
13	3	2	c	ttactcac$a	t
14	4	1	t	acaactccc$	a
15	3	4	t	actcac$atc	t
16	2	2	t	caactcac$a	t
17	2, 3	7	t	c(a/a)c$at(tca/aca)ac	c
18	1	1	t	ccaactccc$	a
19	1, 4	7	t	c(c/c)c$at(cca/aca)ac	c
20	3	1	t	cttactcac$	a
21	3	3	t	tactcac$at	c
22	2	1	t	tcaactcac$	a

Burrows-Wheeler Transform of an alignment

i	SA		F		L	a		c		g	t
0	0	11	$	at(cca/tca/ctt/aca)actc(c/a/a/c)	c	0		1		0	0
1	1, 2, 4	4	a	actc(c/a/c)$at(c/t/a)	c	0		1		0	0
2	2, 3	9	a	c$at(tca/ctt)act	c	0		1		0	0
3	4	2	a	caactccc$a	t	0		0		0	1
4	0	5	a	ctc(c/a/a/c)c$at(cc/tc/ct/ac)	a,t	1		0		0	1
5	0	0	a	t(cca/tca/ctt/aca)actc(c/a/a/c)$	$	0		0		0	0
6	0	10	c	$at(cca/tca/ctt/aca)actc	a,c	1		1		0	0
7	1, 2, 4	3	c	(ca/ca/ca)actc(c/a/c)c$at	a,c,t	1		1		0	1
8	2, 3	8	c	(a/a)c$at(tca/ctt)ac	t	0		0		0	1
9	1, 4	9	c	c$at(cca/aca)act	c	0		1		0	0
10	1	2	c	caactccc$a	t	0		0		0	1
11	1, 4	8	c	(c/c)c$at(cca/aca)ac	t	0		0		0	1
12	0	6	c	tc(c/a/a/c)c$at(cca/tca/ctt/aca)	a	1		0		0	0
13	3	2	c	ttactcac$a	t	0		0		0	1
14	4	1	t	acaactccc$	a	1	1	0		0	0
15	3	4	t	actcac$atc	t	0		0		0	1
16	2	2	t	caactcac$a	t	0		0		0	1
17	2, 3	7	t	c(a/a)c$at(tca/aca)a	c	0		1	1	0	0
18	1	1	t	ccaactccc$	a	0	1	0		0	0
19	1, 4	7	t	c(c/c)c$at(cca/aca)a	c	0		0	1	0	0
20	3	1	t	cttactcac$	a	0	1	0		0	0
21	3	3	t	tactcac$at	c	0		1		0	0
22	2	1	t	tcaactcac$	a	0	1	0		0	0

Search for tactcc

Burrows-Wheeler Transform of an alignment

	i	SA		F		L	a	c	g	t
	0	0	11	$	at(cca/tca/ctt/aca)actc(c/a/a/c)	c	0	1	0	0
	1	1, 2, 4	4	a	actc(c/a/c)$at(c/t/a)	c	0	1	0	0
	2	2, 3	9	a	c$at(tca/ctt)act	c	0	1	0	0
	3	4	2	a	caactccc$a	t	0	0	0	1
	4	0	5	a	ctc(c/a/a/c)c$at(cc/tc/ct/ac)	a,t	1	0	0	1
	5	0	0	a	t(cca/tca/ctt/aca)actc(c/a/a/c)$	$	0	0	0	0
→	6	0	10	c	$at(cca/tca/ctt/aca)actc	a,c	1	1	0	0
	7	1, 2, 4	3	c	(ca/ca/ca)actc(c/a/c)c$at	a,c,t	1	1	0	1
	8	2, 3	8	c	(a/a)c$at(tca/ctt)ac	t	0	0	0	1
	9	1, 4	9	c	c$at(cca/aca)act	c	0	1	0	0
	10	1	2	c	caactccc$a	t	0	0	0	1
	11	1, 4	8	c	(c/c)c$at(cca/aca)ac	t	0	0	0	1
	12	0	6	c	tc(c/a/a/c)c$at(cca/tca/ctt/aca)	a	1	0	0	0
→	13	3	2	c	ttactcac$a	t	0	0	0	1
	14	4	1	t	acaactccc$	a	1	1 0	0	0
	15	3	4	t	actcac$atc	t	0	0	0	1
	16	2	2	t	caactcac$a	t	0	0	0	1
	17	2, 3	7	t	c(a/a)c$at(tca/aca)a	c	0	1	1 0	0
	18	1	1	t	ccaactccc$	a	0	1 0	0	0
	19	1, 4	7	t	c(c/c)c$at(cca/aca)a	c	0	0	1 0	0
	20	3	1	t	cttactcac$	a	0	1 0	0	0
	21	3	3	t	tactcac$at	c	0	1	0	0
	22	2	1	t	tcaactcac$	a	0	1 0	0	0

Search for tactcc

c

Burrows-Wheeler Transform of an alignment

	i	SA		F		L	a	c	g	t
	0	0	11	$	at(cca/tca/ctt/aca)actc(c/a/a/c)	c	0	1	0	0
	1	1, 2, 4	4	a	actc(c/a/c)$at(c/t/a)	c	0	1	0	0
	2	2, 3	9	a	c$at(tca/ctt)act	c	0	1	0	0
	3	4	2	a	caactccc$a	t	0	0	0	1
	4	0	5	a	ctc(c/a/a/c)c$at(cc/tc/ct/ac)	a,t	1	0	0	1
	5	0	0	a	t(cca/tca/ctt/aca)actc(c/a/a/c)$	$	0	0	0	0
	6	0	10	c	$at(cca/tca/ctt/aca)actc	a,c	1	1	0	0
	7	1, 2, 4	3	c	(ca/ca/ca)actc(c/a/c)c$at	a,c,t	1	1	0	1
	8	2, 3	8	c	(a/a)c$at(tca/ctt)ac	t	0	0	0	1
→	9	1, 4	9	c	c$at(cca/aca)act	c	0	1	0	0
	10	1	2	c	caactccc$a	t	0	0	0	1
→	11	1, 4	8	c	(c/c)c$at(cca/aca)ac	t	0	0	0	1
	12	0	6	c	tc(c/a/a/c)c$at(cca/tca/ctt/aca)	a	1	0	0	0
	13	3	2	c	ttactcac$a	t	0	0	0	1
	14	4	1	t	acaactccc$	a	1	1 0	0	0
	15	3	4	t	actcac$atc	t	0	0	0	1
	16	2	2	t	caactcac$a	t	0	0	0	1
	17	2, 3	7	t	c(a/a)c$at(tca/aca)a	c	0	1	1 0	0
	18	1	1	t	ccaactccc$	a	0	1 0	0	0
	19	1, 4	7	t	c(c/c)c$at(cca/aca)a	c	0	0	1 0	0
	20	3	1	t	cttactcac$	a	0	1 0	0	0
	21	3	3	t	tactcac$at	c	0	1	0	0
	22	2	1	t	tcaactcac$	a	0	1 0	0	0

Search for tactcc

cc

Burrows-Wheeler Transform of an alignment

	i	SA		F		L	a	c	g	t
	0	0	11	$	at(cca/tca/ctt/aca)actc(c/a/a/c)	c	0	1	0	0
	1	1, 2, 4	4	a	actc(c/a/c)$at(c/t/a)	c	0	1	0	0
	2	2, 3	9	a	c$at(tca/ctt)act	c	0	1	0	0
	3	4	2	a	caactccc$a	t	0	0	0	1
	4	0	5	a	ctc(c/a/a/c)c$at(cc/tc/ct/ac)	a,t	1	0	0	1
	5	0	0	a	t(cca/tca/ctt/aca)actc(c/a/a/c)$	$	0	0	0	0
	6	0	10	c	$at(cca/tca/ctt/aca)actc	a,c	1	1	0	0
	7	1, 2, 4	3	c	(ca/ca/ca)actc(c/a/c)c$at	a,c,t	1	1	0	1
	8	2, 3	8	c	(a/a)c$at(tca/ctt)ac	t	0	0	0	1
	9	1, 4	9	c	c$at(cca/aca)act	c	0	1	0	0
	10	1	2	c	caactccc$a	t	0	0	0	1
	11	1, 4	8	c	(c/c)c$at(cca/aca)ac	t	0	0	0	1
	12	0	6	c	tc(c/a/a/c)c$at(cca/tca/ctt/aca)	a	1	0	0	0
	13	3	2	c	ttactcac$a	t	0	0	0	1
	14	4	1	t	acaactccc$	a	1	1 0	0	0
	15	3	4	t	actcac$atc	t	0	0	0	1
	16	2	2	t	caactcac$a	t	0	0	0	1
	17	2, 3	7	t	c(a/a)c$at(tca/aca)a	c	0	1	1 0	0
→	18	1	1	t	ccaactccc$	a	0	1 0	0	0
→	19	1, 4	7	t	c(c/c)c$at(cca/aca)a	c	0	0	1 0	0
	20	3	1	t	cttactcac$	a	0	1 0	0	0
	21	3	3	t	tactcac$at	c	0	1	0	0
	22	2	1	t	tcaactcac$	a	0	1 0	0	0

Search for tactcc

tcc

Burrows-Wheeler Transform of an alignment

	i	SA		F		L	a	c	g	t
	0	0	11	$	at(cca/tca/ctt/aca)actc(c/a/a/c)	c	0	1	0	0
	1	1, 2, 4	4	a	actc(c/a/c)$at(c/t/a)	c	0	1	0	0
	2	2, 3	9	a	c$at(tca/ctt)act	c	0	1	0	0
	3	4	2	a	caactccc$a	t	0	0	0	1
	4	0	5	a	ctc(c/a/a/c)c$at(cc/tc/ct/ac)	a,t	1	0	0	1
	5	0	0	a	t(cca/tca/ctt/aca)actc(c/a/a/c)$	$	0	0	0	0
	6	0	10	c	$at(cca/tca/ctt/aca)actc	a,c	1	1	0	0
	7	1, 2, 4	3	c	(ca/ca/ca)actc(c/a/c)c$at	a,c,t	1	1	0	1
	8	2, 3	8	c	(a/a)c$at(tca/ctt)ac	t	0	0	0	1
	9	1, 4	9	c	c$at(cca/aca)act	c	0	1	0	0
	10	1	2	c	caactccc$a	t	0	0	0	1
	11	1, 4	8	c	(c/c)c$at(cca/aca)ac	t	0	0	0	1
→	12	0	6	c	tc(c/a/a/c)c$at(cca/tca/ctt/aca)	a	1	0	0	0
	13	3	2	c	ttactcac$a	t	0	0	0	1
	14	4	1	t	acaactccc$	a	1	0	0	0
	15	3	4	t	actcac$atc	t	0	0	0	1
	16	2	2	t	caactcac$a	t	0	0	0	1
	17	2, 3	7	t	c(a/a)c$at(tca/aca)a	c	0	1	0	0
	18	1	1	t	ccaactccc$	a	0	0	0	0
	19	1, 4	7	t	c(c/c)c$at(cca/aca)a	c	0	0	0	0
	20	3	1	t	cttactcac$	a	0	0	0	0
	21	3	3	t	tactcac$at	c	0	1	0	0
	22	2	1	t	tcaactcac$	a	0	0	0	0

Search for tactcc

ctcc $Z = \{1, 4\}$

Burrows-Wheeler Transform of an alignment

	i	SA		F	L	a	c	g	t
	0	0	11	$ at(cca/tca/ctt/aca)actc(c/a/a/c)	c	0	1	0	0
	1	1, 2, 4	4	a actc(c/a/c)$at(c/t/a)	c	0	1	0	0
	2	2, 3	9	a c$at(tca/ctt)act	c	0	1	0	0
	3	4	2	a caactccc$a	t	0	0	0	1
→	4	0	5	a ctc(c/a/a/c)c$at(cc/tc/ct/ac)	a,t	1	0	0	1
	5	0	0	a t(cca/tca/ctt/aca)actc(c/a/a/c)$	$	0	0	0	0
	6	0	10	c $at(cca/tca/ctt/aca)actc	a,c	1	1	0	0
	7	1, 2, 4	3	c (ca/ca/ca)actc(c/a/c)c$at	a,c,t	1	1	0	1
	8	2, 3	8	c (a/a)c$at(tca/ctt)ac	t	0	0	0	1
	9	1, 4	9	c c$at(cca/aca)act	c	0	1	0	0
	10	1	2	c caactccc$a	t	0	0	0	1
	11	1, 4	8	c (c/c)c$at(cca/aca)ac	t	0	0	0	1
	12	0	6	c tc(c/a/a/c)c$at(cca/tca/ctt/aca)	a	1	0	0	0
	13	3	2	c ttactcac$a	t	0	0	0	1
	14	4	1	t acaactccc$	a	1	0	0	0
	15	3	4	t actcac$atc	t	0	0	0	1
	16	2	2	t caactcac$a	t	0	0	0	1
	17	2, 3	7	t c(a/a)c$at(tca/aca)a	c	0	1	0	0
	18	1	1	t ccaactccc$	a	0	0	0	0
	19	1, 4	7	t c(c/c)c$at(cca/aca)a	c	0	0	0	0
	20	3	1	t cttactcac$	a	0	0	0	0
	21	3	3	t tactcac$at	c	0	1	0	0
	22	2	1	t tcaactcac$	a	0	0	0	0

Search for tactcc

actcc $Z = \{1, 4\}$

Burrows-Wheeler Transform of an alignment

	i	SA		F	L	a	c	g	t
	0	0	11	$ at(cca/tca/ctt/aca)actc(c/a/a/c)	c	0	1	0	0
	1	1, 2, 4	4	a actc(c/a/c)$at(c/t/a)	c	0	1	0	0
	2	2, 3	9	a c$at(tca/ctt)act	c	0	1	0	0
	3	4	2	a caactccc$a	t	0	0	0	1
	4	0	5	a ctc(c/a/a/c)c$at(cc/tc/ct/ac)	a,t	1	0	0	1
	5	0	0	a t(cca/tca/ctt/aca)actc(c/a/a/c)$	$	0	0	0	0
	6	0	10	c $at(cca/tca/ctt/aca)actc	a,c	1	1	0	0
	7	1, 2, 4	3	c (ca/ca/ca)actc(c/a/c)c$at	a,c,t	1	1	0	1
	8	2, 3	8	c (a/a)c$at(tca/ctt)ac	t	0	0	0	1
	9	1, 4	9	c c$at(cca/aca)act	c	0	1	0	0
	10	1	2	c caactccc$a	t	0	0	0	1
	11	1, 4	8	c (c/c)c$at(cca/aca)ac	t	0	0	0	1
	12	0	6	c tc(c/a/a/c)c$at(cca/tca/ctt/aca)	a	1	0	0	0
	13	3	2	c ttactcac$a	t	0	0	0	1
	14	4	1	t acaactccc$	a	1	0	0	0
→	15	3	4	t actcac$atc	t	0	0	0	1
	16	2	2	t caactcac$a	t	0	0	0	1
	17	2, 3	7	t c(a/a)c$at(tca/aca)a	c	0	1	0	0
	18	1	1	t ccaactccc$	a	0	0	0	0
	19	1, 4	7	t c(c/c)c$at(cca/aca)a	c	0	0	0	0
	20	3	1	t cttactcac$	a	0	0	0	0
	21	3	3	t tactcac$at	c	0	1	0	0
	22	2	1	t tcaactcac$	a	0	0	0	0

Search for tactcc

tactcc $Z = \{1, 4\} \cap \{3\} = \emptyset$

Experimental results

Size

Human chromosomes 20 (63 Mbp) from 1000 genomes project

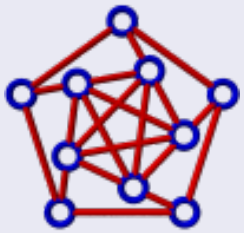
Number of sequences	10	30	60	100
FM-index	223,5	619,6	1111,2	-
RLCSA	104,7	133,0	170,0	209,0
FMA	47,6	60,2	85,7	117,6

Experimental results

Search times

# seq.	Index	Pattern length				
		10	20	30	40	50
10	FM-index	660,92	138,54	6,72	2,63	2,36
	RLCSA	57,4	12,68	0,84	0,31	0,3
	FMA	197,16	34,71	2,19	0,82	0,82
30	FM-index	1735,26	77,17	21,38	9,36	6,17
	RLCSA	151,13	9,68	2,37	1,06	0,7
	FMA	185,73	8,71	2,5	1,3	0,93
60	FM-index	3295,62	108,4	31,38	12,07	8,58
	RLCSA	441,31	13,87	4,16	1,45	0,72
	FMA	158,24	4,08	1,79	0,95	0,62
100	FM-index	-	-	-	-	-
	RLCSA	1286,89	59,54	8,04	2,01	0,98
	FMA	263,38	13,65	2,09	0,65	0,57

References



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Perspectives

- better deal with indels
- plug the method into a read aligner
- propose sets of reference genomes

Thank you for your attention

Backward search: example

i	0	1	2	3	4	5	6	7	8	9	10
y	a	c	a	a	a	c	a	t	a	t	$

	i	SA	F									L	$B^{\$}$	B^{a}	B^{c}	B^{t}
	0	10	$	a	c	a	a	a	c	a	t	a	t	0	0	0	1
	1	2	a	a	a	c	a	t	a	t	$	a	c	0	0	1	0
	2	3	a	a	c	a	t	a	t	$	a	c	a	0	1	0	0
	3	0	a	c	a	a	a	c	a	t	a	t	$	1	0	0	0
	4	4	a	c	a	t	a	t	$	a	c	a	a	0	1	0	0
	5	8	a	t	$	a	c	a	a	a	c	a	t	0	0	0	1
	6	6	a	t	a	t	$	a	c	a	a	a	c	0	0	1	0
	7	1	c	a	a	a	c	a	t	a	t	$	a	0	1	0	0
	8	5	c	a	t	a	t	$	a	c	a	a	a	0	1	0	0
	9	9	t	$	a	c	a	a	a	c	a	t	a	0	1	0	0
	10	7	t	a	t	$	a	c	a	a	a	c	a	0	1	0	0
													BWT				

c	$	a	c	t	#
C	0	1	7	9	11

$x =$ aca

Backward search: example

i	0	1	2	3	4	5	6	7	8	9	10
y	a	c	a	a	a	c	a	t	a	t	$

	i	SA	F										L	$B^{\$}$	B^{a}	B^{c}	B^{t}
	0	10	$	a	c	a	a	a	c	a	t	a	t	0	0	0	1
→	1	2	a	a	a	c	a	t	a	t	$	a	c	0	0	1	0
	2	3	a	a	c	a	t	a	t	$	a	c	a	0	1	0	0
	3	0	a	c	a	a	a	c	a	t	a	t	$	1	0	0	0
	4	4	a	c	a	t	a	t	$	a	c	a	a	0	1	0	0
	5	8	a	t	$	a	c	a	a	a	c	a	t	0	0	0	1
→	6	6	a	t	a	t	$	a	c	a	a	a	c	0	0	1	0
	7	1	c	a	a	a	c	a	t	a	t	$	a	0	1	0	0
	8	5	c	a	t	a	t	$	a	c	a	a	a	0	1	0	0
	9	9	t	$	a	c	a	a	a	c	a	t	a	0	1	0	0
	10	7	t	a	t	$	a	c	a	a	a	c	a	0	1	0	0
													BWT				

c	$	a	c	t	#
C	0	1	7	9	11

$x =$ aca
a $\rightarrow C[\text{a}], C[\text{a}+1]-1 = 1, 6$

Backward search: example

i	0	1	2	3	4	5	6	7	8	9	10
y	a	c	a	a	a	c	a	t	a	t	$

	i	SA	F									L	$B^{\$}$	B^{a}	B^{c}	B^{t}
	0	10	$	a	c	a	a	a	c	a	t	a	t	0	0	0	1
	1	2	a	a	a	c	a	t	a	t	$	a	c	0	0	1	0
	2	3	a	a	c	a	t	a	t	$	a	c	a	0	1	0	0
	3	0	a	c	a	a	a	c	a	t	a	t	$	1	0	0	0
	4	4	a	c	a	t	a	t	$	a	c	a	a	0	1	0	0
	5	8	a	t	$	a	c	a	a	a	c	a	t	0	0	0	1
	6	6	a	t	a	t	$	a	c	a	a	a	c	0	0	1	0
$\rightarrow$	7	1	c	a	a	a	c	a	t	a	t	$	a	0	1	0	0
$\rightarrow$	8	5	c	a	t	a	t	$	a	c	a	a	a	0	1	0	0
	9	9	t	$	a	c	a	a	a	c	a	t	a	0	1	0	0
	10	7	t	a	t	$	a	c	a	a	a	c	a	0	1	0	0
													BWT				

c	$	a	c	t	#
C	0	1	7	9	11

$x =$ aca
a $\rightarrow C[\text{a}], C[\text{a}+1]-1 = 1, 6$
ca $\rightarrow C[\text{c}] + rank_{\text{c}}(BWT, 1-1), C[\text{c}] + rank_{\text{c}}(BWT, 6) - 1 = 7+0, 7+2-1 = 7, 8$

Backward search: example

i	0	1	2	3	4	5	6	7	8	9	10
y	a	c	a	a	a	c	a	t	a	t	$

	i	SA	F									L	$B^{\$}$	B^{a}	B^{c}	B^{t}
	0	10	$	a	c	a	a	a	c	a	t	a	t	0	0	0	1
	1	2	a	a	a	c	a	t	a	t	$	a	c	0	0	1	0
	2	3	a	a	c	a	t	a	t	$	a	c	a	0	1	0	0
→	3	0	a	c	a	a	a	c	a	t	a	t	$	1	0	0	0
→	4	4	a	c	a	t	a	t	$	a	c	a	a	0	1	0	0
	5	8	a	t	$	a	c	a	a	a	c	a	t	0	0	0	1
	6	6	a	t	a	t	$	a	c	a	a	a	c	0	0	1	0
	7	1	c	a	a	a	c	a	t	a	t	$	a	0	1	0	0
	8	5	c	a	t	a	t	$	a	c	a	a	a	0	1	0	0
	9	9	t	$	a	c	a	a	a	c	a	t	a	0	1	0	0
	10	7	t	a	t	$	a	c	a	a	a	c	a	0	1	0	0
													BWT				

c	$	a	c	t	#
C	0	1	7	9	11

$x =$ aca
a $\rightarrow C[\text{a}], C[\text{a}+1]-1 = 1, 6$
ca $\rightarrow C[\text{c}] + rank_{\text{c}}(BWT, 1-1), C[\text{c}] + rank_{\text{c}}(BWT, 6) - 1 = 7+0, 7+2-1 = 7, 8$
aca $\rightarrow C[\text{a}] + rank_{\text{a}}(BWT, 7-1), C[\text{a}] + rank_{\text{a}}(BWT, 8) - 1 = 1+2, 1+4-1 = 3, 4$

BWT

L

t

g

$

t

t

a

a

a

BWT

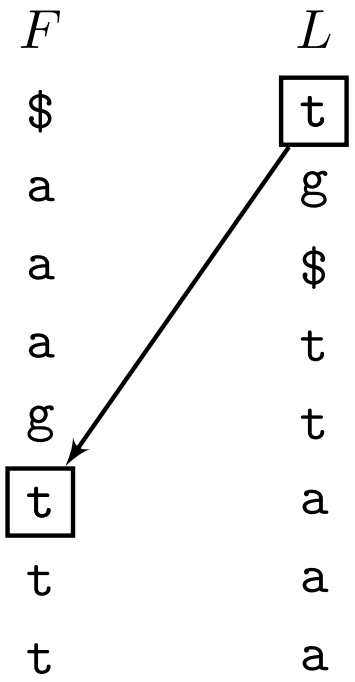
F	L
$	t
a	g
a	$
a	t
g	t
t	a
t	a
t	a

BWT

F	L
$	t
a	g
a	$
a	t
g	t
t	a
t	a
t	a

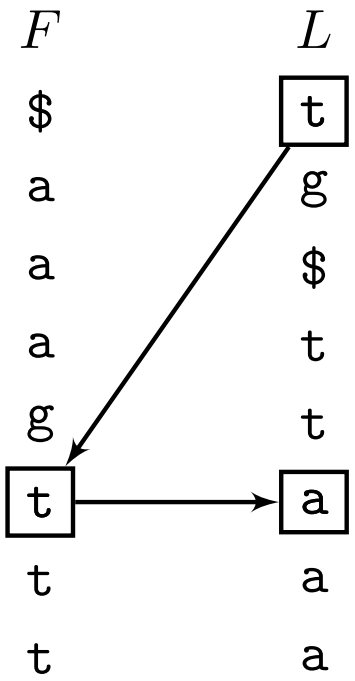
t

BWT



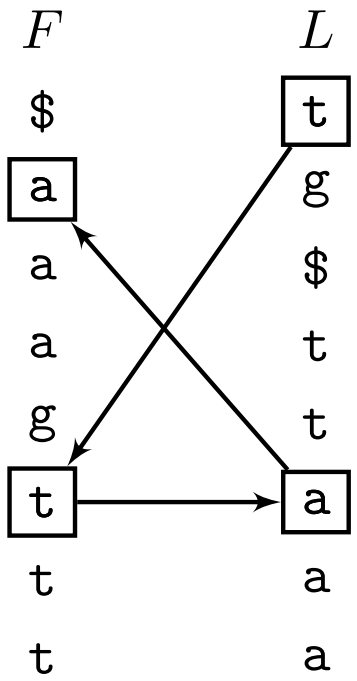
t

BWT



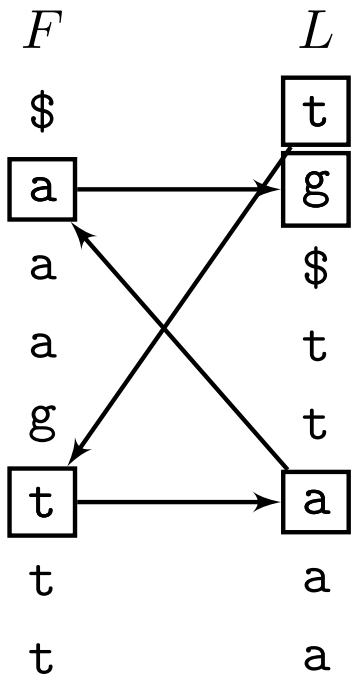
a t

BWT



a t

BWT



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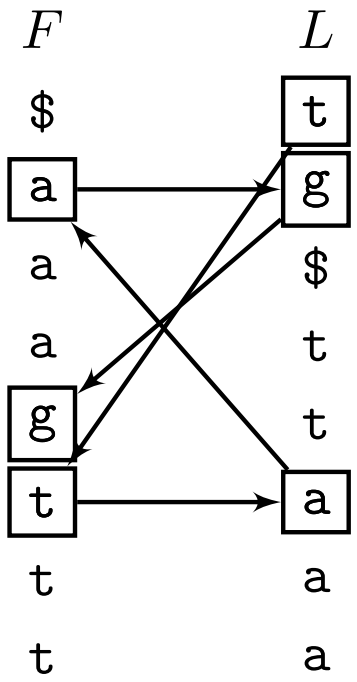
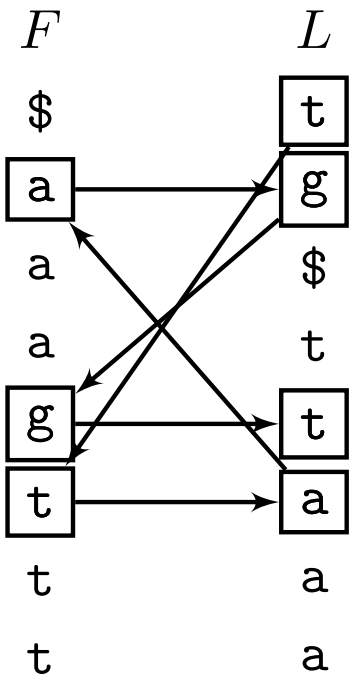


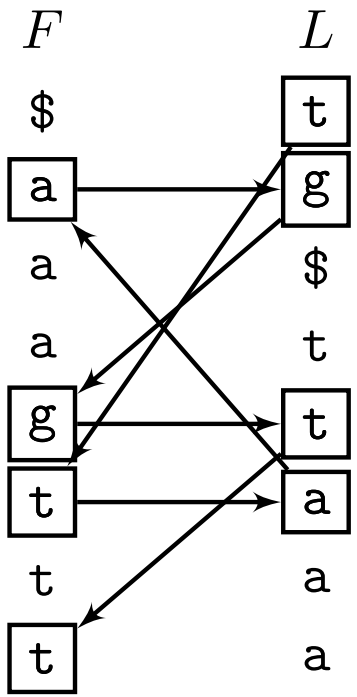
g a t

BWT



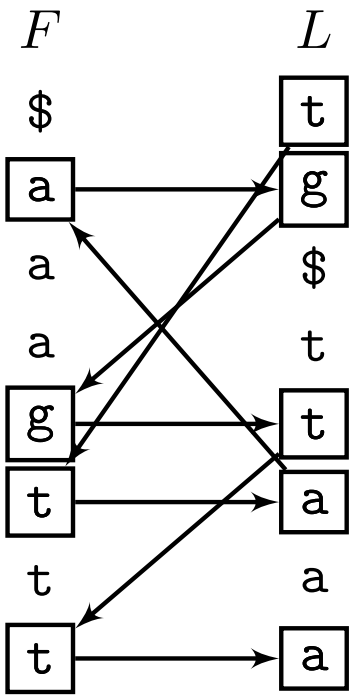
t g a t

BWT



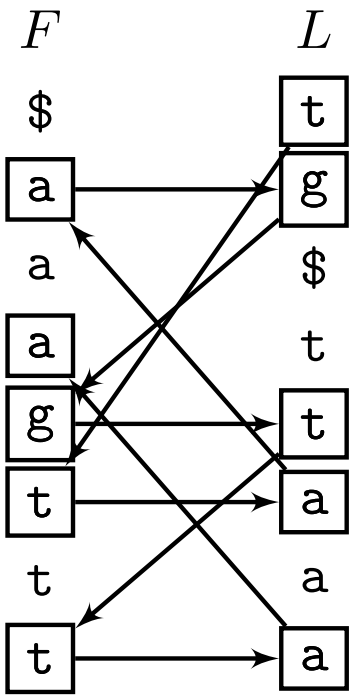
t g a t

BWT



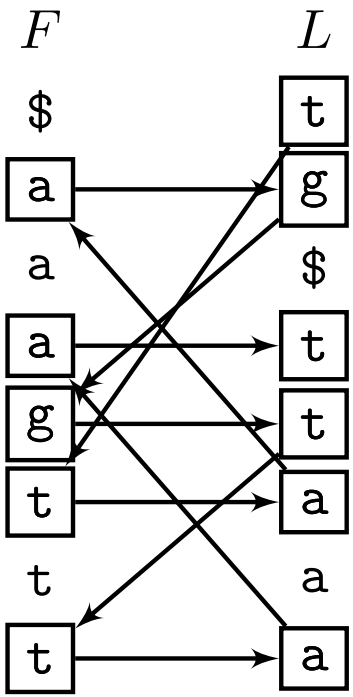
a t g a t

BWT



a t g a t

BWT



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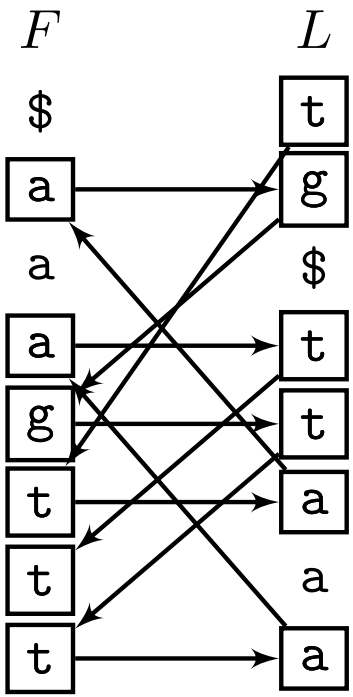
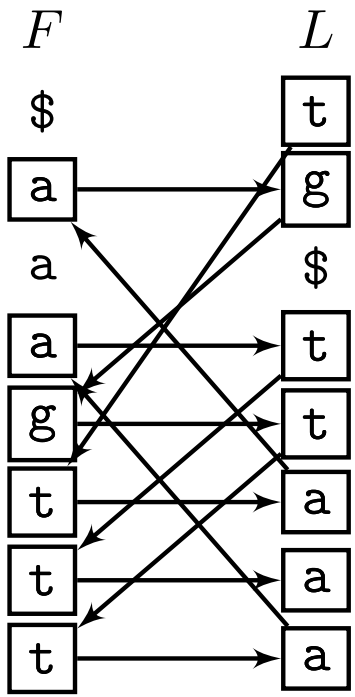
BWT



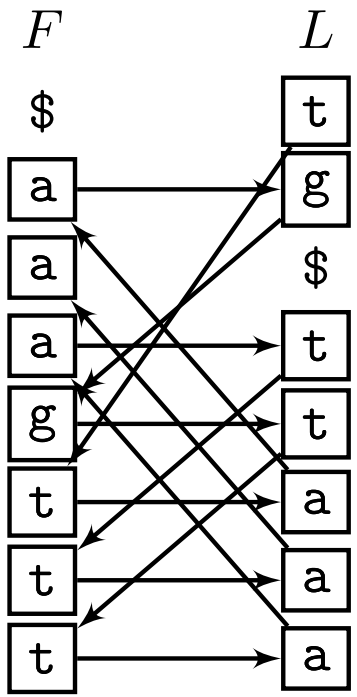
t a t g a t

BWT



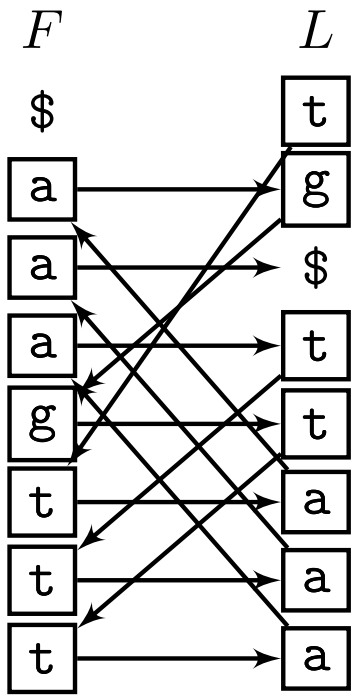
a t a t g a t

BWT



a t a t g a t

BWT



a t a t g a t

LF Function

atatgat$

	$	a	g	t
C	0	1	4	5

$$LF(i) = C[L[i]] + \mathit{rank}_{L[i]}(L, i) - 1$$

LF Function

atatgat$

	$	a	g	t
C	0	1	4	5

$$LF(i) = C[L[i]] + \mathit{rank}_{L[i]}(L, i) - 1$$

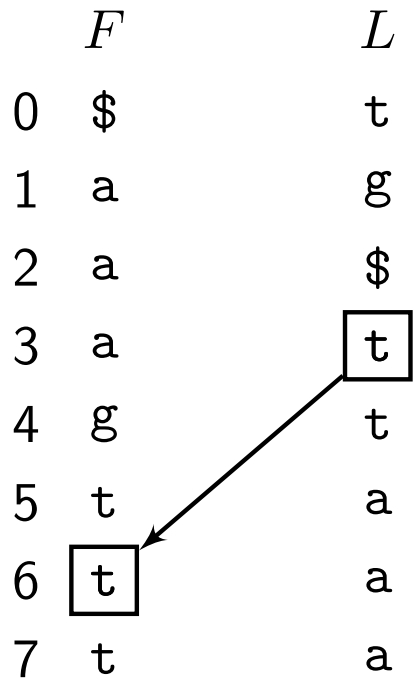
	F	L
0	$	t
1	a	g
2	a	$
3	a	t
4	g	t
5	t	a
6	t	a
7	t	a

LF Function

atatgat$

	$	a	g	t
C	0	1	4	5

$$LF(i) = C[L[i]] + \mathit{rank}_{L[i]}(L, i) - 1$$



$rank$ and $select$

$rank_c(y, i)$: number of symbols c in $y[0\,..\,i]$
and
$select_c(y, i)$: position of the i-th occurrence of symbol c in y

Representation of the BWT

For $c \in A$

$$B^c[i] = \begin{cases} 1 & \text{if } BWT[i] = c \\ 0 & \text{otherwise} \end{cases}$$

then

$rank_c(y, i) = rank_1(B^c, i)$

and

$select_c(y, i) = select_1(B^c, i)$

$rank_1$ and $select_1$ can be computed in constant time by using $n\sigma + o(n\sigma)$ bits