Sliding a Suffix Array Along a Text

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Introduction

Suffix Array

- Text index introduced in 1990.
- Lexicographically sorted suffixes.
- Matching a pattern of length m in a text T of length n in $O(m \log n)$ worst-case time.

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Example

$$T = \overset{0}{\mathrm{C}}\ \overset{1}{\mathrm{T}}\ \overset{2}{\mathrm{C}}\ \overset{3}{\mathrm{T}}\ \overset{4}{\mathrm{A}}\ \overset{5}{\mathrm{C}}\ \overset{6}{\mathrm{A}}\ \overset{7}{\mathrm{C}}\ \overset{8}{\mathrm{T}}\ \overset{9}{\mathrm{A}}\ \overset{10}{\$}$$

$$\mathrm{SA}(T) = 10\ 9\ 4\ 6\ 5\ 7\ 2\ 0\ 8\ 3\ 1$$

Problem

Question

Consider a sliding window, and a suffix array computed on it.
How to update the suffix array when the window slides?

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- Avoid decrements by computing a *displaced* suffix array.

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- Avoid decrements by computing a *displaced* suffix array.

Displaced suffix array

Values range from k to $k + n - 1$ instead of 1 to n for the original suffix array.

- k: starting position of the window in the text;
- n: length of the window.

Algorithm

Big picture

- Store a list *Disp* of modifications, in position order, that have to be computed for updating the displaced suffix array.
- Update the displaced suffix array accordingly.

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- Store a list *Disp* of modifications, in position order, that have to be computed for updating the displaced suffix array.
- Update the displaced suffix array accordingly.

What is stored in the list?

Three types of modification:

- insertion of value j at position i, denoted by (i, j);
- deletion of the value at position i, denoted by $(i, 0)$;
- substitution of the value at position i by j, denoted by $(i, -j)$.

Algorithm

Remark

When sliding a window by s characters, we delete a prefix of length s and insert a suffix of the same length.

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Deletion of the prefix

Suffixes starting at positions $[k, \ldots, k+s-1]$ should not exist anymore in SA. Binary search over the suffix array SA to identify positions of these suffixes in SA. Add the corresponding entries to *Disp*.

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Insertion of the suffix

Suffixes starting at positions $[k+n, \ldots, k+n+s-1]$ do not exist yet in SA. Binary search over SA to find their positions of insertion. Add the corresponding entries to *Disp*.

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When sliding a window by s characters, we delete a prefix of length s and insert a suffix of the same length.

Deletion of the prefix

Suffixes starting at positions $[k, \ldots, k+s-1]$ should not exist anymore in SA. Binary search over the suffix array SA to identify positions of these suffixes in SA. Add the corresponding entries to *Disp*.

Insertion of the suffix

Suffixes starting at positions $[k+n, \ldots, k+n+s-1]$ do not exist yet in SA. Binary search over SA to find their positions of insertion. Add the corresponding entries to *Disp*.

Reorder suffixes

Proceed from right to left, starting by suffix at position $k+n-1$. Let j be the position of the current suffix in SA. Compute using binary search the new position $j' \geq j$ of this suffix.
Remark: $j' - j$ is not greater than at the previous step.

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Example: creating *Disp* list

$$T = \begin{array}{c} \begin{array}{cccccccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \end{array} \\ \mathsf{G\,A\,C\,T\,C\,T\,A\,C\,A\,C\,T\,A\,T\,C\,A} \end{array}$$

Example: creating *Disp* list

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$T =$	G	A	C	T	C	T	A	C	A	C	T	A	T	C	A

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp

Example: creating *Disp* list

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
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	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp

Example: creating *Disp* list

$$T = \underset{}{\overset{1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10\ 11\ 12\ 13\ 14\ 15}{\mathrm{G\,A\,\underbrace{C\,T}_{\text{deleted}}\,C\,T\,A\,C\,A\,C\,T\,A\,\underbrace{T\,C}_{\text{inserted}}\,A}}}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp

Example: creating *Disp* list

$$T = \begin{array}{cccccccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & \\ G & A & \underbrace{C}_{\text{deleted}} & \underbrace{T}_{\text{deleted}} & C & T & A & C & A & C & T & A & \underbrace{T}_{\text{inserted}} & \underbrace{C}_{\text{inserted}} & A & \end{array}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp

Deleting suffix 3.

Example: creating *Disp* list

$$T = \begin{array}{cccccccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\ G & A & \underbrace{C}_{\text{deleted}} & \underbrace{T}_{} & C & T & A & C & A & C & T & A & \underbrace{T}_{} & \underbrace{C}_{\text{inserted}} & A \end{array}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp $(7, 0)$

Deleting suffix 3.

Example: creating *Disp* list

$$T = \begin{array}{cccccccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\ \mathrm{G} & \mathrm{A} & \underbrace{\mathrm{C}}_{\text{deleted}} & \mathrm{T} & \mathrm{C} & \mathrm{T} & \mathrm{A} & \mathrm{C} & \mathrm{A} & \mathrm{C} & \mathrm{T} & \mathrm{A} & \underbrace{\mathrm{T}}_{\text{inserted}} & \mathrm{C} & \mathrm{A} \end{array}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp $(7, 0)$

Deleting suffix 4.

Example: creating *Disp* list

$$T = \begin{array}{cccccccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & \\ G & A & \underbrace{C}_{\text{deleted}} & \underbrace{T}_{} & C & T & A & C & A & C & T & A & \underbrace{T}_{\text{inserted}} & \underbrace{C}_{} & A & \$ \end{array}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp		$(7, 0)$	$(10, 0)$

Deleting suffix 4.

Example: creating *Disp* list

$$T = \begin{array}{cccccccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & \\ G & A & \underbrace{C}_{\text{deleted}} & \underbrace{T}_{} & C & T & A & C & A & C & T & A & \underbrace{T}_{\text{inserted}} & \underbrace{C}_{} & A & \end{array}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp		$(7, 0)$	$(10, 0)$

Inserting suffix 14: C.

Example: creating *Disp* list

$$T = \underset{\text{deleted}}{\underbrace{\text{GACT}}}\text{CTACACTA}\underset{\text{inserted}}{\underbrace{\text{TC}}}\text{A}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

14

Disp $(4, 14)$ $(7, 0)$ $(10, 0)$

Inserting suffix 14: C.

Example: creating *Disp* list

$$T = \underset{\text{deleted}}{\text{GACT}}\text{CTACACTA}\underset{\text{inserted}}{\text{TC}}\text{A}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp $(4, 14)$ $(7, 0)$ $(10, 0)$

Inserting suffix 13: TC.

Example: creating *Disp* list

$$T = \underset{}{\overset{1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10\ 11\ 12\ 13\ 14\ 15}{G\ A\ \underbrace{C\ T}_{\text{deleted}}\ C\ T\ A\ C\ A\ C\ T\ A\ \underbrace{T\ C}_{\text{inserted}}\ A}}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
									↑	
									13	

Disp $(4, 14)$ $(7, 0)$ $(10, 0)$ $(10, 13)$

Inserting suffix 13: TC.

Example: creating *Disp* list

$$T = \underset{}{\overset{1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10\ 11\ 12\ 13\ 14\ 15}{G\ A\ \underbrace{C\ T}_{\text{deleted}}\ C\ T\ A\ C\ A\ C\ T\ A\ \underbrace{T\ C}_{\text{inserted}}\ A}}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp	$(4, 14)$	$(7, 0)$	$(10, -13)$

Inserting suffix 13: TC.

Example: creating *Disp* list

$$T = \underset{}{\overset{1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10\ 11\ 12\ 13\ 14\ 15}{\mathrm{G\ A\ \underbrace{C\ T}_{\text{deleted}}\ C\ T\ A\ C\ A\ C\ T\ A\ \underbrace{T\ C}_{\text{inserted}}\ A}}}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp	$(4, 14)$	$(7, 0)$	$(10, -13)$

Reordering suffix 12: ATC?

Example: creating *Disp* list

$$T = \begin{array}{c} \scriptstyle 1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10\ 11\ 12\ 13\ 14\ 15 \\ \mathrm{G\,A\,\underbrace{C\,T}_{\text{deleted}}\,C\,T\,A\,C\,A\,C\,T\,A\,\underbrace{T\,C}_{\text{inserted}}\,A} \end{array}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp $(4, 14)$ $(7, 0)$ $(10, -13)$

Reordering suffix 12: ATC?

Example: creating *Disp* list

$T =$ G A C T C T A C A C T A T C A

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

C T deleted; T C inserted

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp $(1, 0)$ $(4, 12)$ $(4, 14)$ $(7, 0)$ $(10, -13)$

Reordering suffix 12: ATC?

Example: creating *Disp* list

$$T = \begin{array}{cccccccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & \\ G & A & \underbrace{C}_{\text{deleted}} & \underbrace{T}_{\text{deleted}} & C & T & A & C & A & C & T & A & \underbrace{T}_{\text{inserted}} & \underbrace{C}_{\text{inserted}} & A & \end{array}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp $(1, 0)$ $(4, 12)$ $(4, 14)$ $(7, 0)$ $(10, -13)$

Reordering suffix 11: TATC?

Example: creating *Disp* list

$$T = \underset{}{\overset{1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10\ 11\ 12\ 13\ 14\ 15}{G\ A\ \underbrace{C\ T}_{\text{deleted}}\ C\ T\ A\ C\ A\ C\ T\ A\ \underbrace{T\ C}_{\text{inserted}}\ A}}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp $(1, 0)$ $(4, 12)$ $(4, 14)$ $(7, 0)$ $(8, 0)$ $(10, 11)$ $(10, -13)$

Reordering suffix 11: TATC?

Example: creating *Disp* list

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$T =$	G	A	C	T	C	T	A	C	A	C	T	A	T	C	A

deleted (positions 3–4), inserted (positions 13–14)

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Disp $(1,0)$ $(4,12)$ $(4,14)$ $(5,0)$ $(7,-10)$ $(8,0)$ $(10,11)$ $(10,-13)$

Reordering suffix 10: CTATC?

Example: creating *Disp* list

$$T = \underset{}{\overset{1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10\ 11\ 12\ 13\ 14\ 15}{G\ A\ \underbrace{C\ T}_{\text{deleted}}\ C\ T\ A\ C\ A\ C\ T\ A\ \underbrace{T\ C}_{\text{inserted}}\ A}}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

↑

Disp $(1,0)$ $(4,12)$ $(4,14)$ $(5,0)$ $(7,-10)$ $(8,0)$ $(10,11)$ $(10,-13)$

Reordering suffix 9: ACTATC?

Example: updating SA using *Disp*

Disp	$(1,0)$	$(4,12)$	$(4,14)$	$(5,0)$	$(7,-10)$	$(8,0)$	$(10,11)$	$(10,-13)$

Example: updating SA using *Disp*

$$\underset{\textit{Disp}}{} \underbrace{(1,0)\ (4,12)}_{\text{Left shift}}\ \underbrace{(4,14)\ (5,0)}_{\text{Right shift}}\ \underbrace{(7,-10)}_{\text{Static}}\ \underbrace{(8,0)\ (10,11)}_{\text{Left shift}}\ \underbrace{(10,-13)}_{\text{Static}}$$

Example: updating SA using *Disp*

Disp	$\underbrace{(1,0)\ \ (4,12)}$	$\underbrace{(4,14)\ \ (5,0)}$	$\underbrace{(7,-10)}$	$\underbrace{(8,0)\ \ (10,11)}$	$\underbrace{(10,-13)}$
	Left shift	Right shift	Static	Left shift	Static

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4

Example: updating SA using *Disp*

Disp	$\underbrace{(1,0)\ \ (4,12)}$	$\underbrace{(4,14)\ \ (5,0)}$	$\underbrace{(7,-10)}$	$\underbrace{(8,0)\ \ (10,11)}$	$\underbrace{(10,-13)}$
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	1	2	3	4	5	6	7	8	9	10
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Example: updating SA using *Disp*

Disp	$\underbrace{(1,0)\ \ (4,12)}$	$\underbrace{(4,14)\ \ (5,0)}$	$\underbrace{(7,-10)}$	$\underbrace{(8,0)\ \ (10,11)}$	$\underbrace{(10,-13)}$
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	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
	7	9								

Example: updating SA using *Disp*

Disp	$\underbrace{(1,0)\ \ (4,12)}$	$\underbrace{(4,14)\ \ (5,0)}$	$\underbrace{(7,-10)}$	$\underbrace{(8,0)\ \ (10,11)}$	$\underbrace{(10,-13)}$
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	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
	7	9	12							

Example: updating SA using *Disp*

Disp

$$\underbrace{(1,0)\ \ (4,12)}_{\text{Left shift}}\ \ \underbrace{(4,14)\ \ (5,0)}_{\text{Right shift}}\ \ \underbrace{(7,-10)}_{\text{Static}}\ \ \underbrace{(8,0)\ \ (10,11)}_{\text{Left shift}}\ \ \underbrace{(10,-13)}_{\text{Static}}$$

	1	2	3	4	5	6	7	8	9	10
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	7	9	12							

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	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
	7	9	12		8					

Example: updating SA using *Disp*

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$\underbrace{(1,0)\ (4,12)}_{\text{Left shift}}\ \underbrace{(4,14)\ (5,0)}_{\text{Right shift}}\ \underbrace{(7,-10)}_{\text{Static}}\ \underbrace{(8,0)\ (10,11)}_{\text{Left shift}}\ \underbrace{(10,-13)}_{\text{Static}}$

	1	2	3	4	5	6	7	8	9	10
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	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
	7	9	12	14	8		10			

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$$\underbrace{(1,0)\ \ (4,12)}_{\text{Left shift}}\ \ \underbrace{(4,14)\ \ (5,0)}_{\text{Right shift}}\ \ \underbrace{(7,-10)}_{\text{Static}}\ \ \underbrace{(8,0)\ \ (10,11)}_{\text{Left shift}}\ \ \underbrace{(10,-13)}_{\text{Static}}$$

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SA	12	7	9	8	10	5	3	11	6	4
	7	9	12	14	8		10			

Example: updating SA using *Disp*

Disp $\underbrace{(1,0)\ (4,12)}_{\text{Left shift}}\ \underbrace{(4,14)\ (5,0)}_{\text{Right shift}}\ \underbrace{(7,-10)}_{\text{Static}}\ \underbrace{(8,0)\ (10,11)}_{\text{Left shift}}\ \underbrace{(10,-13)}_{\text{Static}}$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
	7	9	12	14	8		10	6		

Example: updating SA using *Disp*

Disp

$$\underbrace{(1,0)\ \ (4,12)}_{\text{Left shift}}\ \ \underbrace{(4,14)\ \ (5,0)}_{\text{Right shift}}\ \ \underbrace{(7,-10)}_{\text{Static}}\ \ \underbrace{(8,0)\ \ (10,11)}_{\text{Left shift}}\ \ \underbrace{(10,-13)}_{\text{Static}}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
	7	9	12	14	8		10	6	11	

Example: updating SA using *Disp*

Disp $\underbrace{(1,0)\ (4,12)}_{\text{Left shift}}\ \underbrace{(4,14)\ (5,0)}_{\text{Right shift}}\ \underbrace{(7,-10)}_{\text{Static}}\ \underbrace{(8,0)\ (10,11)}_{\text{Left shift}}\ \underbrace{(10,-13)}_{\text{Static}}$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
	7	9	12	14	8		10	6	11	

Example: updating SA using *Disp*

$$\textit{Disp} \quad \underbrace{(1,0)\ \ (4,12)}_{\text{Left shift}}\ \ \underbrace{(4,14)\ \ (5,0)}_{\text{Right shift}}\ \ \underbrace{(7,-10)}_{\text{Static}}\ \ \underbrace{(8,0)\ \ (10,11)}_{\text{Left shift}}\ \ \underbrace{(10,-13)}_{\text{Static}}$$

	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
	7	9	12	14	8		10	6	11	13

Example: updating SA using *Disp*

$$\underset{\textit{Disp}}{} \underbrace{(1,0)\ (4,12)}_{\text{Left shift}}\ \underbrace{(4,14)\ (5,0)}_{\text{Right shift}}\ \underbrace{(7,-10)}_{\text{Static}}\ \underbrace{(8,0)\ (10,11)}_{\text{Left shift}}\ \underbrace{(10,-13)}_{\text{Static}}$$

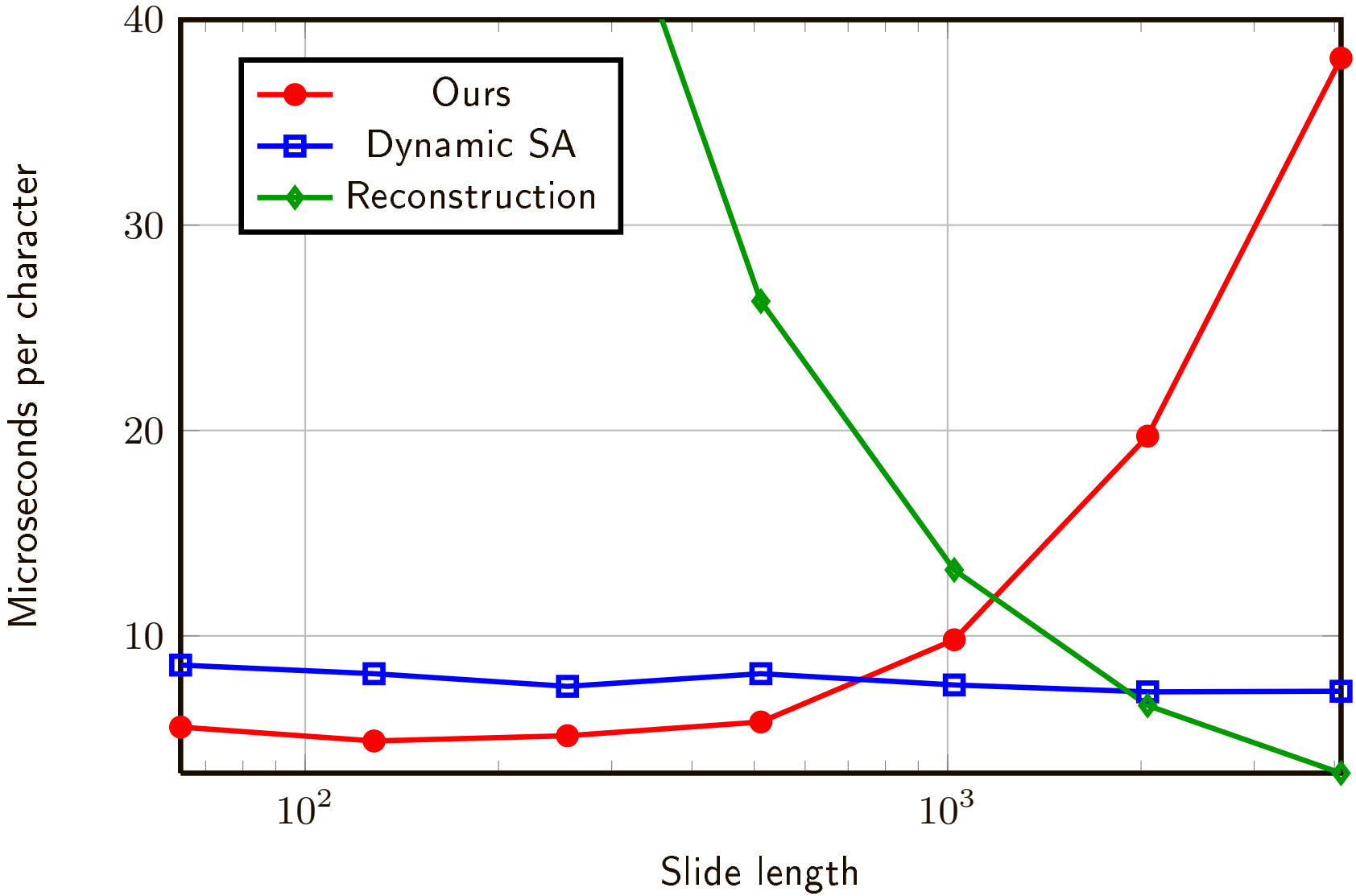
	1	2	3	4	5	6	7	8	9	10
SA	12	7	9	8	10	5	3	11	6	4
	7	9	12	14	8		10	6	11	13

$$T = \overset{1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10\ 11\ 12\ 13\ 14\ 15}{\text{GACTCTACACTATCA}}$$

	1	2	3	4	5	6	7	8	9	10
SA	7	9	12	14	8	5	10	6	11	13

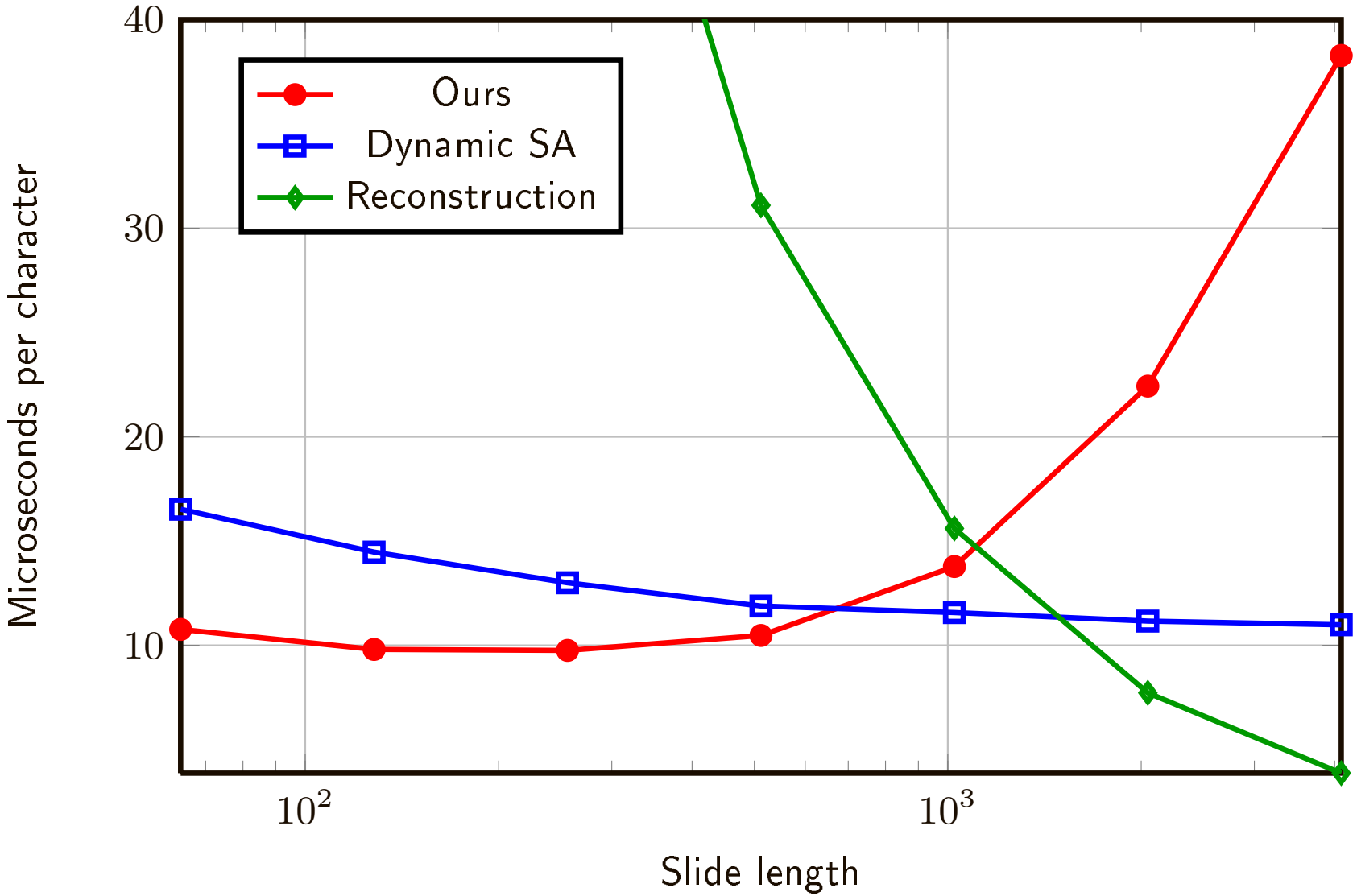
Experiments

On a genome sequence with a 32K-length window.



Experiments

On a XML file with a 32K-length window.



Conclusions and Perspectives

Conclusions

- Constant-time access to any value of the suffix array (rather than logarithmic for the dynamic suffix array);
- More efficient than reconstruction or dynamic suffix array for "small" slides (< 1000)

Perspectives

- Fast Lempel-Ziv factorization?
- Implement and test this LZ approach.