Longest Common Extensions via Fingerprinting

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The DirectComp algorithm

Input

- $s = abbababba$
- $(i, j) = (4, 6)$

The DirectComp algorithm

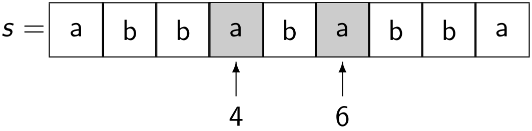
$s =$	a	b	b	a	b	a	b	b	a
				↑		↑			
				4		6			

The DIRECTCOMP algorithm

Input

- $s = abbababba$
- $(i, j) = (4, 6)$

The DIRECTCOMP algorithm



The DirectComp algorithm

Input

- $s = abbababba$
- $(i, j) = (4, 6)$

The DirectComp algorithm

$s =$	a	b	b	a	b	a	b	b	a
				4		6			

1 match

The DirectComp algorithm

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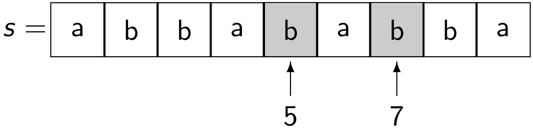
The DirectComp algorithm



1 match

The DirectComp algorithm

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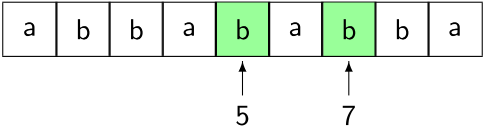
- $s = abbababba$
- $(i, j) = (4, 6)$

The DirectComp algorithm

$s =$



2 matches

The DirectComp algorithm

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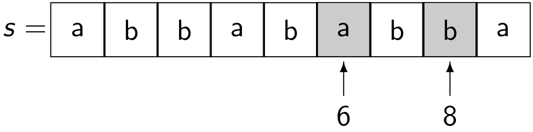
The DirectComp algorithm



2 matches

The DirectComp algorithm

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- $s = abbababba$
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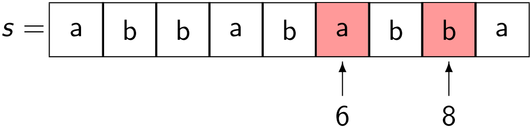
The DirectComp algorithm



2 matches

Result

$LCE_s(4, 6) = 2$

The LCE Problem

LCE value $LCE_s(i, j)$ is the length of the longest common prefix of the two suffixes of s starting at index i and j

LCE problem Efficiently query multiple LCE values on a static string s and varying pairs (i, j)

Existing Algorithm: DirectComp

Preprocessing	None
Space	$O(1) + \|s\|$
Query	$O(LCE(i,j)) = O(n)$
Average query	$O(1)$

For a string length n and alphabet size σ, the average LCE value over all n^σ strings and n^2 query pairs is $O(1)$.

References

L. Ilie, G. Navarro, and L. Tinta. The longest common extension problem revisited and applications to approximate string searching. *J. Disc. Alg.*, 8(4):418-428, 2010.

Existing Algorithms: SuffixNca and LcpRmq

Two algorithms with best known bounds:

SuffixNca Nearest common ancestor queries on a suffix tree

LcpRmq Range minimum queries on a longest common prefix array

Preprocessing	$O(sort(n, \sigma))$
Space	$O(n)$
Query	$O(1)$
Average query	$O(1)$

References

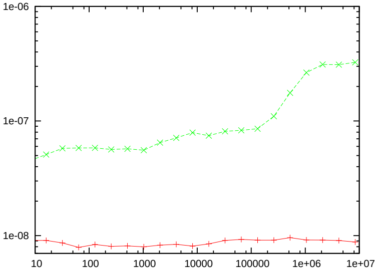
J. Fischer, and V. Heun. Theoretical and Practical Improvements on the RMQ-Problem, with Applications to LCA and LCE. In *Proc. 17th CPM*, pages 36-48, 2006.

D. Harel, R. E. Tarjan. Fast Algorithms for Finding Nearest Common Ancestors. *SIAM J. Comput.*, 13(2):338-355, 1984.

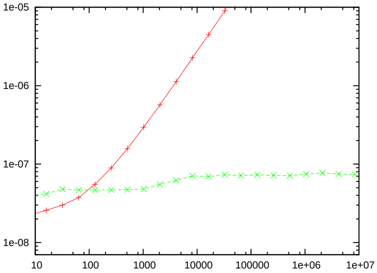
Existing Algorithms: Practical Results

Query times of DirectComp and LcpRmq by string length

Average case



Worst case



The FINGERPRINT$_k$ Algorithm: Data Structure

- For a string $s[1\,..\,n]$, the t-length fingerprints $F_t[1\,..\,n]$ are natural numbers, such that $F_t[i] = F_t[j]$ if and only if $s[i\,..\,i+t-1] = s[j\,..\,j+t-1]$.
- k levels, $1 \leq k \leq \lceil \log n \rceil$
- For each level, $\ell = 0\,..\,k-1$:
  - $t_\ell = \Theta(n^{\ell/k})$, $t_0 = 1$
  - $H_\ell = F_{t_\ell}$

$H_2[i]$	1	2	3	4	5	6	7	8	9	1	2	3	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$H_1[i]$	1	2	3	4	1	2	5	6	5	1	2	3	4	1	2	5	6	5	6	3	4	6	5	6	7	8	9
$s = H_0[i]$	a	b	b	a	a	b	b	a	b	a	b	b	a	a	b	b	a	b	a	b	a	a	b	a	b	a	$
i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

Space $\quad O(k \cdot n)$

The FINGERPRINT$_k$ Algorithm: Query

1. As long as $H_\ell[i+v] = H_\ell[j+v]$, increment v by t_ℓ, increment ℓ by one, and repeat this step unless and $\ell = k-1$.
2. As long as $H_\ell[i+v] = H_\ell[j+v]$, increment v by t_ℓ and repeat this step.
3. Stop and return v when $\ell = 0$, otherwise decrement ℓ by one and go to step two.

$H_2[i+v]$	1	2	3	4	5	6	7	8	9	1	2	3	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$H_1[i+v]$	1	2	3	4	1	2	5	6	5	1	2	3	4	1	2	5	6	5	6	3	4	6	5	6	7	8	9
$H_0[i+v]$	a	b	b	a	a	b	b	a	b	a	b	b	a	a	b	b	a	b	a	b	a	a	b	a	b	a	$
$i+v$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

$H_2[j+v]$	1	2	3	4	5	6	7	8	9	1	2	3	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$H_1[j+v]$	1	2	3	4	1	2	5	6	5	1	2	3	4	1	2	5	6	5	6	3	4	6	5	6	7	8	9
$H_0[j+v]$	a	b	b	a	a	b	b	a	b	a	b	b	a	a	b	b	a	b	a	b	a	a	b	a	b	a	$
$j+v$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

$$LCE(3, 12) = 9$$

Query	$O(k \cdot n^{1/k})$
Average query	$O(1)$

The FINGERPRINT$_k$ Algorithm: Preprocessing

- For each level ℓ
  - For each t_ℓ-length substring in lexicographically sorted order
    - If the current substring $s[SA[i]\,..\,SA[i] + t_\ell - 1]$ is equal to the previous substring, give it the same fingerprint as the previous substring, otherwise give it a new unused fingerprint. The two substrings are equal when $LCE[i] \geq t_\ell$.

$$s = \text{abbababba}$$

For $t_\ell = 3$:

$$H_\ell = [3, 8, 6, 2, 6, 3, 8, 5, 1]$$

Subst.	$H_l[i]$	i
a	1	9
aba	2	4
abb	3	6
abb	3	1
ba	5	8
bab	6	3
bab	6	5
bba	8	7
bba	8	2

Preprocessing $\quad O(k \cdot n + sort(n, \sigma))$

The $\textsc{Fingerprint}_k$ Algorithm

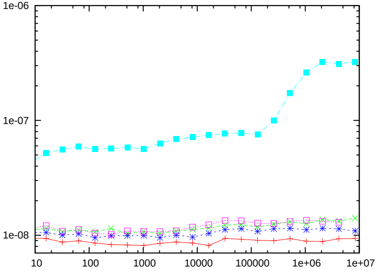
	$1 \leq k \leq \lceil \log n \rceil$
Preprocessing	$O(k \cdot n + sort(n, \sigma))$
Space	$O(k \cdot n)$
Query	$O(k \cdot n^{1/k})$
Average query	$O(1)$

	$k = 1$	$k = 2$	$k = \lceil \log n \rceil$
Preprocessing	$O(sort(n, \sigma))$	$O(sort(n, \sigma))$	$O(n \log n)$
Space	$O(n)$	$O(n)$	$O(n \log n)$
Query	$O(n)$	$O(\sqrt{n})$	$O(\log n)$
Average query	$O(1)$	$O(1)$	$O(1)$

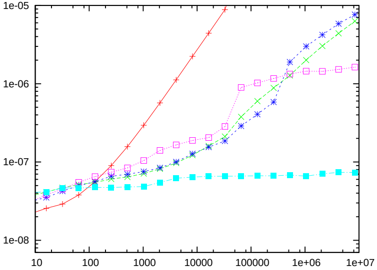
Practical Results

Query times of DIRECTCOMP, FINGERPRINT$_2$, FINGERPRINT$_3$, FINGERPRINT$_{\lceil \log n \rceil}$ and LCPRMQ by string length

Average case



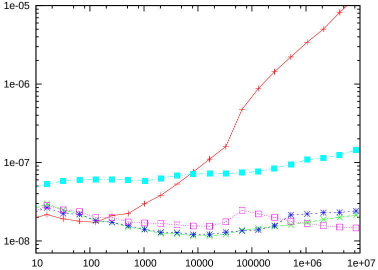
Worst case



Practical Results

Query times of DIRECTCOMP, FINGERPRINT$_2$, FINGERPRINT$_3$, FINGERPRINT$_{\lceil \log n \rceil}$ and LCPRMQ by string length

Medium LCE size



Cache Optimization of $\textsc{Fingerprint}_k$

- Original:
  - Data structure: $H_\ell[i] = F_{t_\ell}[i]$
  - Size: $|H_\ell| = n$
  - I/O: $O\big(k \cdot n^{1/k}\big)$
- Cache optimized:
  - Data structure:
    $$H_\ell[((i-1) \mod t_\ell) \cdot \lceil n/t_\ell \rceil + \lfloor (i-1)/t_\ell \rfloor + 1] = F_{t_\ell}[i]$$
  - Size: $|H_\ell| = n + t_\ell$
  - I/O: $O\Big(k \cdot \Big(\frac{n^{1/k}}{B} + 1\Big)\Big)$
    - Best when k is small $\implies$ $n^{1/k}$ is large.

$H_2[i+v]$	1	2	3	4	5	6	7	8	9	1	2	3	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$H_1[i+v]$	1	2	3	4	1	2	5	6	5	1	2	3	4	1	2	5	6	5	6	3	4	6	5	6	7	8	9
$H_0[i+v]$	a	b	b	a	a	b	b	a	b	a	b	b	a	a	b	b	a	b	a	b	a	a	b	a	b	a	$
$i+v$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

$H_2[j+v]$	1	2	3	4	5	6	7	8	9	1	2	3	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$H_1[j+v]$	1	2	3	4	1	2	5	6	5	1	2	3	4	1	2	5	6	5	6	3	4	6	5	6	7	8	9
$H_0[j+v]$	a	b	b	a	a	b	b	a	b	a	b	b	a	a	b	b	a	b	a	b	a	a	b	a	b	a	$
$j+v$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

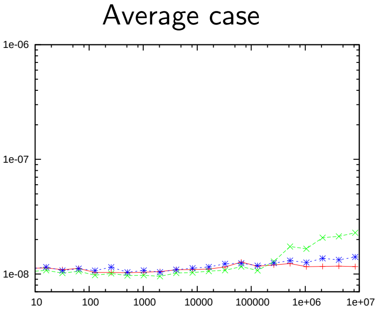
Cache Optimization, Practical Results

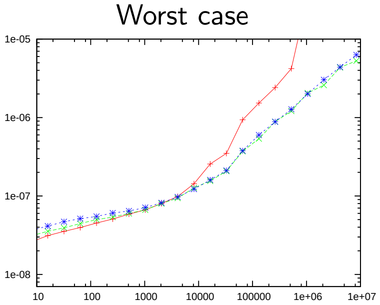
Is I/O optimization good in practice?

- Pro: better cache efficiency
  - Best for small k, no change for $k = \lceil \log n \rceil$
- Con: Calculating memory addresses is more complicated
  - $((i-1) \mod t_\ell) \cdot \lceil n/t_\ell \rceil + \lfloor (i-1)/t_\ell \rfloor + 1$ vs. i

Cache Optimization, Practical Results

Query times of $\textsc{Fingerprint}_2$ without cache optimization and with cache optimization using shift operations vs. multiplication, division and modulo

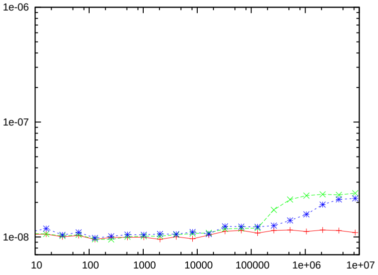




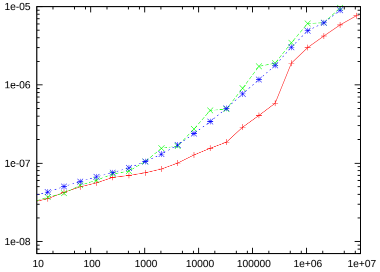
Cache Optimization, Practical Results

Query times of FINGERPRINT$_3$ without cache optimization and with cache optimization using shift operations vs. multiplication, division and modulo

Average case



Worst case



Summary

	DirectComp	LcpRmq / SuffixNca	Fingerprint$_k$
Preprocessing	$O(1)$	$O(sort(n, \sigma))$	$O(k \cdot n + sort(n, \sigma))$
Space	$O(1)$	$O(n)$	$O(k \cdot n)$
Query	$O(n)$	$O(1)$	$O(k \cdot n^{1/k})$
Average query	$O(1)$	$O(1)$	$O(1)$
Query I/O	$O\left(\frac{n}{B}\right)$	$O(1)$	$O\left(k \cdot \left(\frac{n^{1/k}}{B} + 1\right)\right)$

- In practice, the Fingerprint$_k$ algorithm is...
  - ...almost as good as DirectComp and significantly better than LcpRmq in average case
  - ...significantly better than DirectComp but worse than LcpRmq in worst case
- Cache optimization of Fingerprint$_k$ improves query times at $k = 2$ and worsens query times at $k \geq 3$