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Comparing Suffix Automata Against Suffix Arrays For Longest Common Substring Queries

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Abstract

The objective of this paper was to compare the performance of two algorithms, the Suffix Automaton and the Enhanced Suffix Array, for solving the Longest Common Substring problem **between two strings** in a pure Python implementation.

The algorithms were tested on multiple scenarios, from best case to worst case, and on multiple string lengths, from 100 to 10,000 characters, with multiple runs for each scenario and string length to ensure statistical significance of the results. Both the build time and the query time were measured, as well as the memory used both for building the data structure and for querying it.

The results showed that **so long as one is programming in pure Python, and so long as only two strings are involved**, an Enhanced Suffix Array offers practically zero advantages over a Suffix Automaton. The Suffix Automaton was substantially faster to build and to query in all but one scenario, and although the Enhanced Suffix Array had an overall smaller index size, this would do very little in real-life memory-constrained applications, as its peak memory usage was either comparable to the Suffix Automaton or only barely smaller in all scenarios and string lengths. Not to mention that the Suffix Automaton is much simpler to implement.

This is potentially due to the nature of Python, as it is a high level interpreted language where the memory management is abstracted away from the programmer, leading to even simple data types like integers and lists having a much higher memory overhead than in lower level languages. Due to Python's memory management, the Enhanced Suffix Array would also lose its cache locality, which is the main reason for its compactness in lower level languages like C.

Abstrakt

Das Ziel dieser Arbeit war es, die Leistung von zwei Algorithmen, dem Suffix Automaton und dem Enhanced Suffix Array, bei der Lösung des Longest Common Substring-Problems **zwischen zwei Zeichenketten (Strings)** *in einer reinen Python-Implementierung zu vergleichen.*

Die Algorithmen wurden in verschiedenen Szenarien getestet, von besten bis zu schlechtesten Fällen, und auf verschiedenen Stringlängen, von 100 bis 10.000 Zeichen, mit mehreren Durchläufen für jedes Szenario und jede Stringlänge, um die statistische Signifikanz der Ergebnisse sicherzustellen. Sowohl die Aufbauzeit als auch die Abfragezeit wurden gemessen, ebenso wie der für den Aufbau der Datenstruktur und für die Abfrage verwendete Speicher.

Die Ergebnisse zeigten, dass **solange man in reinem Python programmiert und nur zwei Zeichenketten beteiligt sind**, *ein Enhanced Suffix Array praktisch keine Vorteile gegenüber einem Suffix Automaton bietet. Der Suffix Automaton war wesentlich schneller im Aufbau und in der Abfrage in allen bis auf einer der Szenarien, und obwohl der Enhanced Suffix Array insgesamt eine kleinere Indexgröße hatte, würde dies in realen, speicherbeschränkten Anwendungen nur sehr wenig ausmachen, da sein Spitzen-Speicherverbrauch in allen Szenarien und Stringlängen entweder vergleichbar mit dem des Suffix Automatons oder nur ein wenig kleiner war. Auch von Vorteil ist, dass der Suffix Automaton viel einfacher zu implementieren ist.*

Dies liegt vermutlich an der Natur von Python, da es eine hochstufige interpretierte Sprache ist, bei der die Speicherverwaltung von der Programmierer/in abstrahiert wird, was dazu führt, dass selbst einfache Datentypen wie Ganzzahlen und Listen einen viel höheren Speicher-Overhead haben als in kompilierten Sprachen. Aufgrund der Speicherverwaltung von Python würde der Enhanced Suffix Array auch seine Cache-Lokalität verlieren, was der Hauptgrund für seine Kompaktheit in Sprachen wie C ist.

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Glossary

base The building blocks of DNA and RNA, represented by the letters A, C, G, T (for DNA) and A, C, G, U (for RNA). 5

DNA Deoxyribonucleic Acid, the molecule that carries genetic information in living organisms. 1

RNA Ribonucleic Acid, a molecule that is transcribed from DNA and which then gets translated into proteins. 1

sentinel A unique character used to separate concatenated strings in a suffix array or suffix tree, which is lexicographically smaller than any other character in the strings. Usually characters like \0 (null character), $, or # are used as sentinels, as they are ahead of all other characters in the ASCII table. 3

1 Introduction

1.1 Background

The Longest Common Substring (LCS) problem is a fundamental problem in computer science, with applications in multiple domains, bioinformatics being one of the most prominent. This is due to the fact that DNA and RNA sequences are usually encoded as strings for bioinformatics workflows, in a format called FASTA, originally described by Pearson and Lipman in 1985[1].

The LCS problem is defined as follows:

> Given two strings S and T, each of length at most n, the longest common substring (LCS) problem is to find a longest substring common to S and T.[2]

For example, given the strings "AG**CTAGC**" and "T**CTAGC**TA", the longest common substring is "CTAGC", which has a length of 5. The LCS problem can be solved using various algorithms, such as dynamic programming, suffix trees, suffix arrays, and suffix automata, each with different time and space complexities.

Of particular interest are the Suffix Automaton (SAM) (also known as Directed Acyclic Word Graph (DAWG)) and the Suffix Array (SA) with Longest Common Prefix (LCP) Array (also known as an Enhanced Suffix Array (ESA)), which both yield the search result in linear time, but differ in their construction time and space requirements.

Both of these data structures are derived from the Suffix Tree, the first linear time and space data structure for solving the LCS problem, which was introduced by Peter Weiner in 1973[3] as "bi-trees", although the uncompressed version he introduced is currently referred to as a *trie* in order to differentiate it from the modern definition of a Suffix Tree, which corresponds to the compressed version as described by McCreight in 1976[4].

1.1.1 Suffix Tree

A (compressed) Suffix Tree is constructed from a string S using an algorithm, originally called Algorithm M, mapping a finite string S of characters into an auxiliary index to S in the form of a digital search tree T whose paths are the suffixes of S, and whose terminal nodes correspond uniquely to positions within S[4].

As the Suffix Automaton and the Enhanced Suffix Array are both further refinements of the Suffix Tree, a Suffix Tree implementation will not be included in the comparisons done in this paper.

1.1.2 Suffix Automaton

A Suffix Automaton (SAM) is a data structure that represents all the substrings of a given string in a compact way.

> An efficient and compact data structure for representing a full index of a set of strings is a Suffix Automaton, a minimal deterministic automaton representing the set of all suffixes of a set of strings. Since a substring is a prefix of a suffix, a suffix automaton can be used to determine if a string x is a substring in time linear in its length $O(|x|)$, which is optimal.[5]

The SAM was first introduced by Blumer et al. in 1985[6], and its use in solving the LCS problem has been explored in various works, such as in the book *Text Algorithms* by Crochemore and Rytter, in chapter 6[7].

A notable feature of the Suffix Automaton is that it can be constructed with just one string, and in fact, the same automaton can then be reused to find the Longest Common Substring of that string and any other string, by traversing the automaton with the second string and keeping track of the longest match found. The same automaton can therefore be used to find the LCS of the first string and any number of other strings, without having to reconstruct it every time.

1.1.3 Enhanced Suffix Array

> The generic name *enhanced suffix array* stands for data structures consisting of the suffix array and additional tables.[8]

In this implementation, a Enhanced Suffix Array (ESA) consists of a Suffix Array (SA) and an Longest Common Prefix (LCP) Array, which is all that's necessary to solve the

LCS problem in linear time because the LCS can be solved by finding the maximum value in the LCP Array corresponding to suffixes (from the SA) that belong to different strings.

A SA is an array of integers that represent the starting positions of the suffixes of a string in lexicographical order, while the LCP Array is an array of integers that represent the length of the longest common prefix between adjacent suffixes in the SA[8].

Currently, there are algorithms to construct both the SA and the LCP Array in $O(m+n)$ time for two strings S and T of lengths m and n respectively, such as the Suffix Array with Induced Sorting (SA-IS) algorithm for the SA[9] and Kasai's algorithm for the LCP Array[10].

A notable feature of the ESA is that it can be constructed with more than two strings at once, by concatenating the strings together with unique delimiters (sentinels), and then constructing the ESA for the concatenated string. This allows for finding the LCS of all the strings at once.

1.2 Motivation

Although there have been many papers comparing either the SAM or the ESA to the Suffix Tree[5,6,7,8,11], there is a lack of direct comparisons between these two data structures, even though they both fundamentally solve the same problem using the same underlying principle of representing the suffixes of a string in a compact way.

Moreover, there is a lack of practical comparisons between these two structures in the context of specific programming languages, even though the obtuse memory management of languages like Python[12] could potentially lead to real-world results not matching up with theoretical expectations, especially when it comes to space usage.

1.3 Research Question

The primary research question of this paper is:

> How do the SAM and the ESA compare in terms of time and space complexity
> when solving the Longest Common Substring problem **between two strings**
> in an everyday programming context?

Python[12] was chosen as the programming language for this paper due to the fact that it is by far the most popular programming language for bioinformatics[13].

2 Methods

2.1 Hardware Specifications

The tests were run on a laptop with the following specifications:

- CPU Model: Intel Core i5-10210U

- CPU Cores: 4^{14}

- CPU Threads: 8^{14}

- CPU Base Frequency: 1.60 GHz[14]

- CPU Max Turbo Frequency: 4.20 GHz[14]

- RAM: 16 GB DDR4 2933 MT/s

- Storage: 512 GB NVMe SSD

In order to ensure minimal interference, the tests were run with no other applications (other than the IDE itself) running, and with the laptop plugged in and heavy background processes like Windows Update disabled.

2.2 Python Environment

Here are the details of the Python environment used for the implementation and testing of the algorithms:

Python Version	3.13.12
Operating System	Windows 11 Pro 64-bit (version 25H2)
IDE	Visual Studio Code (version 1.109.5)
Environment Manager	Miniforge (conda version 26.1.0)
Packages Used	**Package** **Version** time built-in tracemalloc built-in sys built-in matplotlib 3.10.8 pandas 3.0.1 jupyter 1.1.1 Jinja2 3.1.6

Table 2.1: Details of the Python environment used for implementation and testing

2.3 Test Data

To ensure a comprehensive evaluation of the algorithms, synthetic test data was generated using three different alphabets and five different scenarios, each designed to cover a wide range of cases that could be encountered in real-world applications, with a particular focus on the field of bioinformatics, where the LCS problem is particularly relevant due to the nature of DNA and RNA sequences being represented as strings.

The alphabets used for the test data were as follows:

Alphabet Name	Description	Characters
Full	Every lowercase letter	a, b, c, ..., z
DNA	The four DNA bases	A, C, G, T
Disjoint	Two disjoint sets of the lower-case letters	String 1: a, b, c, ..., m String 2: n, o, p, ..., z

Table 2.2: Description of the alphabets used for generating test data

Five separate scenarios were tested, in order to cover as wide a range of cases as possible:

Scenario Name	Description	Alphabet
random_uniform	Both strings are generated randomly with a uniform distribution of characters	Full
mutated_implant	A common motif is implanted in both strings with mutations	DNA
repetitive_with_noise	Strings are formed by repeating a pattern with some mutations	DNA
near_identical	Strings are nearly identical, with minor mutations preferentially at the edges	Full
disjoint_alphabet	Strings are generated from completely disjoint alphabets	Disjoint

Table 2.3: Description of test scenarios used for benchmarking

The justifications for the choice of these scenarios are:

- The *random_uniform* scenario serves as a baseline for the performance of the algorithms on completely random data.

- The *mutated_implant* scenario simulates a common real-world case in bioinformatics, where two otherwise unrelated long sequences share a relatively short common motif between them at unrelated positions[15,16]. It's basically the "needle in a haystack" scenario.

- The *repetitive_with_noise* scenario simulates another common case in bioinformatics, where sequences are formed by repeating a pattern (tandem repeats[17]) with some mutations, which can lead to multiple short LCSs.

- The *near_identical* scenario tests the performance of the algorithms on strings that are nearly identical, so that there would be one very long LCS which would have to be held in memory.

- The *disjoint_alphabet* scenario tests the case where the two strings have no common characters, which should result in an LCS of length 0. The algorithms would have to traverse the entire data structure to determine this. It also serves as a sanity check to ensure that the algorithms are correctly identifying the lack of common substrings.

2.4 Design

The algorithms themselves were implemented in pure Python (version 3.13.12), without the aid of any external libraries (although external libraries were used for gathering the results and plotting the graphs).

The SAM was implemented using the standard on-line construction algorithm[18]. To find the LCS of the first string and the second string, the SAM was created with the first string, and then traversed through by the second string, keeping track of the longest match found.

To give the Suffix Array (SA) the best chance possible, the SA was constructed using the Suffix Array with Induced Sorting (SA-IS) algorithm, the current state-of-the-art algorithm for constructing it in linear time[9]. The SA was constructed for the concatenated string of the two strings being compared, with a sentinel character in between them (\0 in this case) to separate them. The LCP Array was constructed using Kasai's algorithm[10], which is a linear time algorithm for constructing it from the SA. The ESA was essentially implemented as a combination of the SA and the LCP Array.

25 string pairs each of lengths 100, 500, 1000, 5000, and 10,000 characters were generated for each scenario, and each string pair was tested on both algorithms **20 times** to try and ensure statistical significance of the results. To ensure reproducibility, the random seed used for generating the string pairs was fixed at 42 for all scenarios and string lengths.

The testing code was designed to run both algorithms on the same string pairs, and to measure both the time taken and the peak memory usage for each run. The time taken was measured using the `time` module, while the peak memory usage was measured using the `tracemalloc` module, which is a built-in Python module for tracking memory allocations. The index size for each algorithm was computed using the `sys.getsizeof` function, which returns the size of an object by recursively summing the sizes of all referenced objects.

The full testing code, including a requirements file and instructions for running it, is provided in the supplementary materials. A complete list of generated string pairs with their corresponding LCS values, as well as the raw test results, are also included. Additionally, the code used for plotting the results (using the `matplotlib` library) is provided.

3 Results

3.1 Choice of Central Tendency

The data collected seems to be heavily right-skewed, with some outliers. This is irrespective of the scenario, string length, algorithm, or even the type of measurement (build time, query time, total time, or memory usage).

This is likely due to cache misses, other background processes running on the computer, or other random factors that can affect the performance of the algorithms in a non-deterministic way. Therefore, the **median** was chosen as the measure of central tendency for the results, as the data is not normally distributed and the median is more robust to outliers than the mean. And since the median is being used, the interquartile range (IQR) was chosen as the measure of variability.

Tables with the exact values of the median and IQR for all measurements are included in the appendix (page iv) grouped by scenario, and the plots in the main text are based on these values. An even more detailed summary is available as a CSV file in the supplementary materials, which includes other statistics such as the mean and standard deviation.
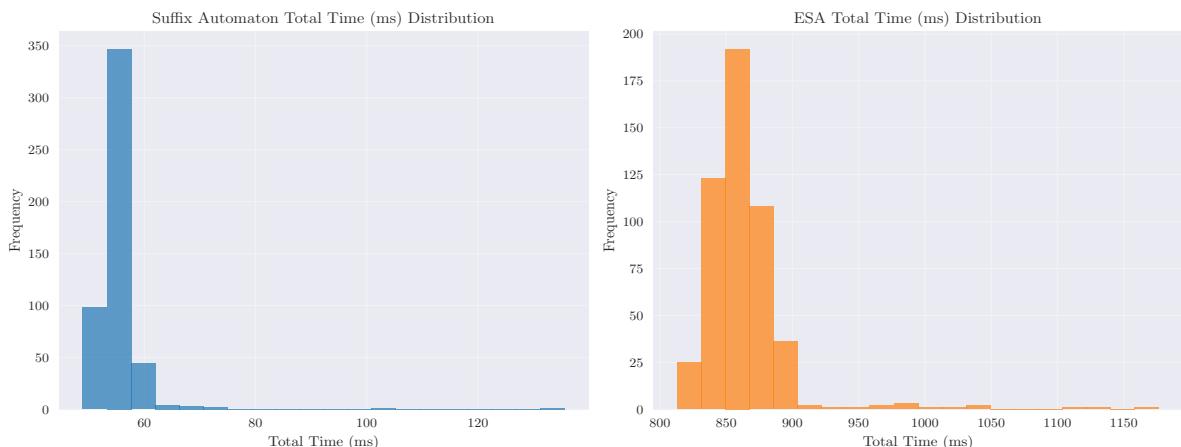
Figure 3.1: Distribution of total time for the SAM and the ESA for the random uniform scenario and string length 10000, as an example of the right-skewed nature of the data

3.2 Time

The time taken to construct the SAM and the ESA and to find the LCS was measured for each scenario and string length, and the results are shown in the following plots.

The build time, query time, and total time are shown separately to give a more detailed view of the performance of the algorithms. The median is shown as a line, and the IQR is shown as a shaded area around the line. Because the IQR is very small for most of the data points, it may not be visible in the plots.

3.2.1 Build Time

The build time is the time taken to construct the data structure (the SAM or the ESA) from the string(s).
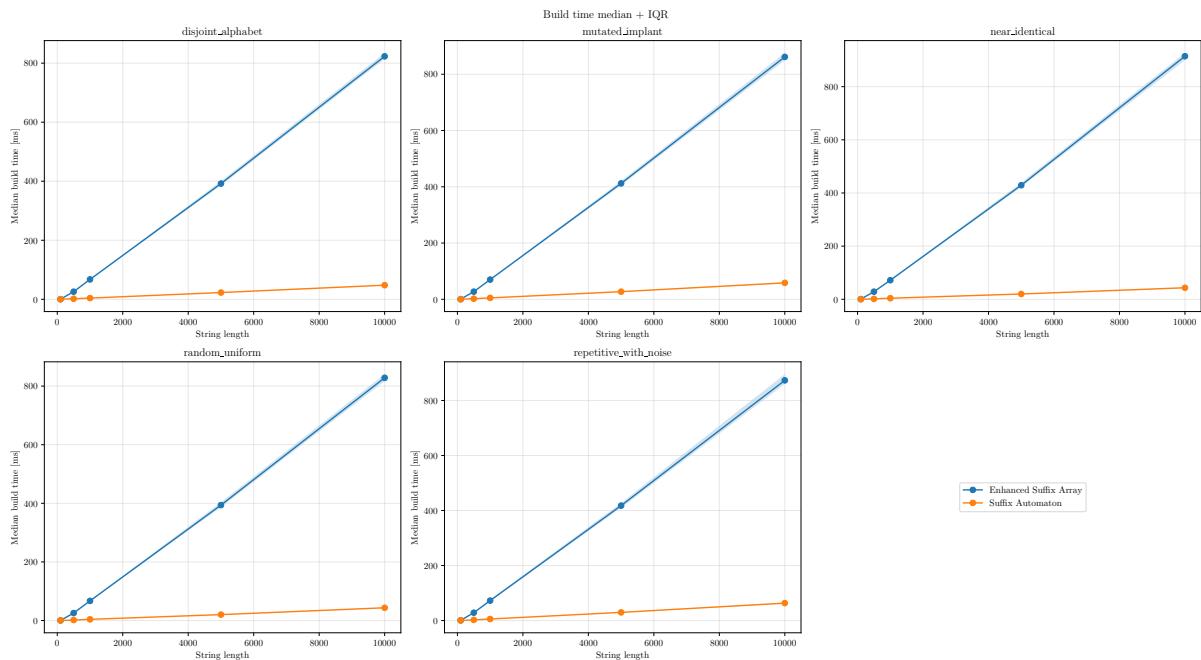
Figure 3.2: Median and interquartile range (IQR) of build time for the SAM and the ESA across different scenarios and string lengths

As can be seen from the plot, the build time for both algorithms tend to follow a linear trend with respect to the string length (as is to be expected), but the ESA has a much higher build time than the SAM, especially as the string length increases.

3.2.2 Query Time

The query time is the time taken to find the LCS of the two strings using the constructed data structure.
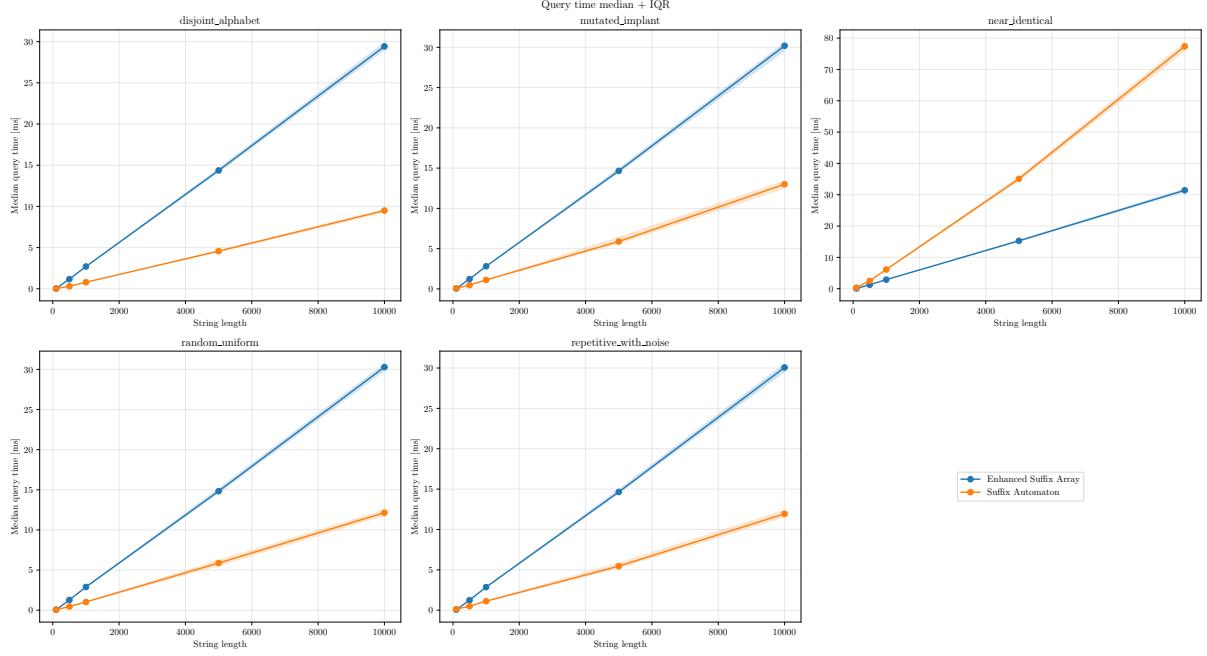
Figure 3.3: Median and interquartile range (IQR) of query time for the SAM and the ESA across different scenarios and string lengths

The query time for both algorithms also tends to follow a linear trend with respect to the string length, and for most cases, the SAM has a shorter query time than the ESA, with near_identical being the only exception. This outlier can be explained by the fact that in the near_identical scenario, where the LCS is singular and very long, causing the SAM to have to traverse a long path in the automaton, whereas the ESA can find the LCS by directly inspecting the LCP between the relevant suffixes, and that too, only once. This leads to the interesting observation that *the query time of the SAM grows in proportion to the length of the LCS*, at least in Python.

Also note that the query time for both algorithms is extremely small compared to the build time, and even with string pairs that are each 10,000 characters long, the median query time remained under 0.1 seconds.

3.2.3 Total Time

The total time represents the time from the start of the construction of the data structure to the end of finding the LCS, so it is essentially the sum of the build time and the query time.
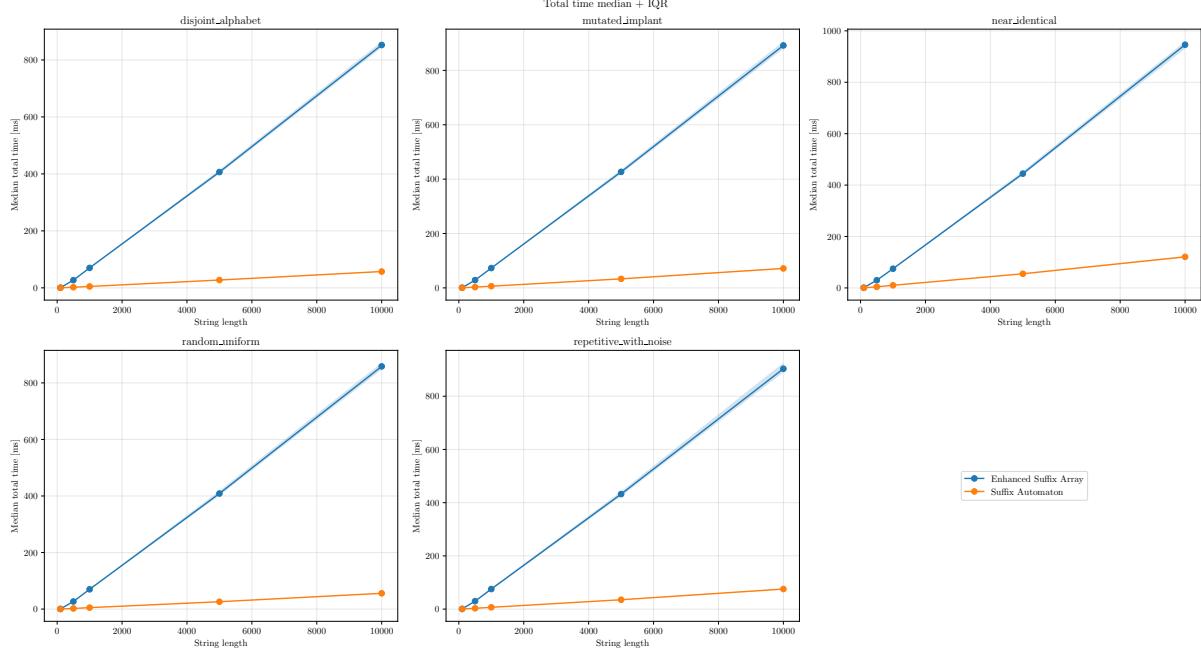
Figure 3.4: Median and interquartile range (IQR) of total time for the SAM and the ESA across different scenarios and string lengths

Because the build time was so high for the ESA compared to the SAM, the total time for the ESA is also much higher than that of the SAM across all scenarios and string lengths, with the difference becoming more pronounced as the string length increases.

This is in spite of the fact that the ESA was built with the SA-IS and Kasai's algorithms, avoiding the traditional naive algorithms which would have used Python's built-in sorting, rendering the time complexity to be $O(n\log n)$ for a combined string of length n.

4 Conclusion

In this paper, two algorithms for solving the longest common substring (LCS) problem **between two strings** were compared: the Suffix Automaton (SAM) and the Enhanced Suffix Array (ESA). The algorithms were implemented in pure Python and tested on a variety of scenarios and string lengths, with the results measured in terms of build time, query time, total time, peak memory usage, and index size.

The results showed that the SAM generally outperformed the ESA in terms of build time and total time, while the query time was more variable depending on the scenario. The SAM had a shorter query time than the ESA in most cases, except for the near_identical scenario where the ESA had a shorter query time due to the nature of the LCS being singular and very long.

In terms of memory usage, while SAM had a much larger index size than the ESA, with the SAM reaching above 4 MiB median for strings of length 10,000, (compared to the ESA which stayed barely above 1 MiB median for the same string length), the peak memory usage of the SAM and the ESA were more comparable in most scenarios, negating any potential benefit of the ESA in memory-constrained environments.

The reason the ESA didn't save even more memory could be chalked up to the idiosyncrasies of Python's memory management system and its huge object overhead, given that it is a dynamically typed, interpreted language.

Another interesting observation was that the query time of the SAM seemed to grow in proportion to the length of the LCS, at least in Python, which could be a potential area for further investigation.

It has to be reasserted that this paper does not claim to be conclusive proof that the SAM is *always* better than the ESA for solving the LCS problem in general, because the individual strengths of the two algorithms are still valid.

For instance, if multiple strings need to compared against the same "reference" string, the SAM would have to be constructed only once, and then reused for all the comparisons, which would give it a significant advantage over the ESA, which would have to be reconstructed every time.

On the other hand, if the LCS of more than two strings needs to be found at once, the ESA would have a significant advantage over the SAM, as it can be constructed with an indefinite number of strings, so long as one can find enough unique sentinel characters to separate them which are not present in the strings themselves and are lexicographically smaller than any other character in the strings. The equivalent of this for the SAM would be to construct a "General Suffix Automaton"[5] which is a substantially more complex data structure that can represent the suffixes of multiple strings at once, requiring the same $O(|\sum_{i=1}^{k} n_i|)$ for construction (where n_i is the length of string i and k is the number of strings), the same as the ESA.

Due to the narrow scope of this paper, more advanced algorithms like the FM-Index[19] were not included in the comparisons, but it could be interesting to compare against in future work, especially given that it is built on top of the ESA idea and optimized for using minimal space.

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Appendix

Disjoint Alphabet

Enhanced Suffix Array (Build Time)

Condensed results for Enhanced Suffix Array in scenario disjoint_ alphabet.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.5106	0.1265	0.4583	0.1391	500
500	26.2949	3.0448	25.8245	1.1181	500
1000	67.9895	4.1817	67.3458	3.2995	500
5000	394.3566	15.9704	392.0425	14.0880	500
10000	827.6511	29.0246	823.1218	20.5804	500

Suffix Automaton (Build Time)

Condensed results for Suffix Automaton in scenario disjoint_ alphabet.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.2354	0.0501	0.2236	0.0222	500
500	1.9801	0.3657	1.8739	0.2254	500
1000	4.1412	0.2445	4.1075	0.2836	500
5000	23.0649	3.3611	22.9133	1.4102	500
10000	47.9052	4.0663	47.7820	2.2490	500

Enhanced Suffix Array (Query Time)

Condensed results for Enhanced Suffix Array in scenario disjoint_ alphabet.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.0338	0.0076	0.0319	0.0023	500
500	1.2148	0.1354	1.1702	0.0906	500
1000	2.7226	0.1462	2.7022	0.1424	500
5000	14.4301	0.6275	14.3621	0.5594	500
10000	29.5849	1.2168	29.4213	0.9918	500

Suffix Automaton (Query Time)

Condensed results for Suffix Automaton in scenario disjoint_ alphabet.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.0331	0.0096	0.0312	0.0029	500
500	0.3170	0.1573	0.2997	0.0154	500
1000	0.7997	0.0366	0.7935	0.0381	500
5000	4.6049	0.6684	4.5716	0.2821	500
10000	9.5072	0.7182	9.4911	0.4564	500

Enhanced Suffix Array (Total Time)

Condensed results for Enhanced Suffix Array in scenario disjoint_ alphabet.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.5444	0.1309	0.4907	0.1391	500
500	27.5098	3.1136	27.0282	1.1357	500
1000	70.7121	4.2814	70.0603	3.5061	500
5000	408.7867	16.3983	406.4943	14.3276	500
10000	857.2359	29.6781	852.5146	21.4592	500

Suffix Automaton (Total Time)

Condensed results for Suffix Automaton in scenario disjoint_ alphabet.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.2684	0.0566	0.2555	0.0253	500
500	2.2971	0.4194	2.1760	0.2493	500
1000	4.9409	0.2572	4.9126	0.3063	500
5000	27.6698	3.5782	27.4650	1.7086	500
10000	57.4125	4.6418	57.2604	2.6455	500

Enhanced Suffix Array (Memory Overall)

Condensed results for Enhanced Suffix Array in scenario disjoint_ alphabet.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	16.4984	1.3383	16.0645	0.4219
500	124.0991	0.9039	124.1738	0.6562
1000	292.9397	2.6246	292.0293	3.4922
5000	1660.4448	3.4893	1660.0254	2.7266
10000	3313.2738	5.5712	3313.4707	7.4297

Suffix Automaton (Memory Overall)

Condensed results for Suffix Automaton in scenario disjoint_ alphabet.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	15.0475	0.3781	15.0781	0.5469
500	152.8589	1.3059	152.6641	1.4688
1000	324.0625	2.1525	324.2812	3.3789
5000	1796.1284	3.5084	1796.5352	5.7578
10000	3546.4630	5.2843	3546.0664	6.7695

Enhanced Suffix Array (Build Peak Memory)

Condensed results for Enhanced Suffix Array in scenario disjoint_ alphabet.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	16.4984	1.3383	16.0645	0.4219
500	124.0991	0.9039	124.1738	0.6562
1000	292.9397	2.6246	292.0293	3.4922
5000	1660.4448	3.4893	1660.0254	2.7266
10000	3313.2738	5.5712	3313.4707	7.4297

Suffix Automaton (Build Peak Memory)

Condensed results for Suffix Automaton in scenario disjoint_ alphabet.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	14.7741	0.3781	14.8047	0.5469
500	152.5581	1.3059	152.3633	1.4688
1000	323.7617	2.1525	323.9805	3.3789
5000	1795.8277	3.5084	1796.2344	5.7578
10000	3546.1622	5.2843	3545.7656	6.7695

Enhanced Suffix Array (Query Peak Memory)

Condensed results for Enhanced Suffix Array in scenario disjoint_ alphabet.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	4.5784	0.0285	4.5723	0.0000
500	41.6934	0.0000	41.6934	0.0000
1000	88.8960	0.0310	88.8887	0.0000
5000	476.5762	0.0000	476.5762	0.0000
10000	962.7518	0.0697	962.7480	0.0000

Suffix Automaton (Query Peak Memory)

Condensed results for Suffix Automaton in scenario disjoint_ alphabet.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	15.0475	0.3781	15.0781	0.5469
500	152.8589	1.3059	152.6641	1.4688
1000	324.0625	2.1525	324.2812	3.3789
5000	1796.1284	3.5084	1796.5352	5.7578
10000	3546.4630	5.2843	3546.0664	6.7695

Enhanced Suffix Array (Query Extra Memory)

Condensed results for Enhanced Suffix Array in scenario disjoint_ alphabet.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	0.5938	0.0000	0.5938	0.0000
500	0.6250	0.0000	0.6250	0.0000
1000	0.6250	0.0000	0.6250	0.0000
5000	0.6250	0.0000	0.6250	0.0000
10000	0.6250	0.0000	0.6250	0.0000

Suffix Automaton (Query Extra Memory)

Condensed results for Suffix Automaton in scenario disjoint_ alphabet.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	0.5938	0.0000	0.5938	0.0000
500	0.6211	0.0000	0.6211	0.0000
1000	0.6211	0.0000	0.6211	0.0000
5000	0.6211	0.0000	0.6211	0.0000
10000	0.6211	0.0000	0.6211	0.0000

Enhanced Suffix Array (Index)

Condensed results for Enhanced Suffix Array in scenario disjoint_ alphabet.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	9.2715	0.0000	9.2715	0.0000	0.0000
500	44.9863	0.0000	44.9863	0.0000	0.0000
1000	88.2754	0.0000	88.2754	0.0000	0.0000
5000	444.7129	0.0000	444.7129	0.0000	0.0000
10000	891.8223	0.0000	891.8223	0.0000	0.0000

Suffix Automaton (Index)

Condensed results for Suffix Automaton in scenario disjoint_ alphabet.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	32.8057	0.4383	32.8613	0.6562	0.0000
500	172.9945	1.3058	172.8027	1.4688	0.0000
1000	342.2449	2.1524	342.4668	3.3789	0.0000
5000	1798.6859	3.5084	1799.0957	5.7578	0.0000
10000	3529.4888	5.2840	3529.0957	6.7695	0.0000

Mutated Implant

Enhanced Suffix Array (Build Time)

Condensed results for Enhanced Suffix Array in scenario mutated_implant.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.6661	0.1265	0.6247	0.0627	500
500	27.1928	1.2921	27.2298	1.1035	500
1000	71.3355	6.8086	70.1016	3.1516	500
5000	415.2829	23.5458	412.0689	14.8760	500
10000	865.6591	31.8575	861.7277	26.2638	500

Suffix Automaton (Build Time)

Condensed results for Suffix Automaton in scenario mutated_implant.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.2973	0.0793	0.2797	0.0240	500
500	2.3592	0.2918	2.2537	0.2469	500
1000	5.1489	0.3975	5.0725	0.3247	500
5000	27.3212	2.6246	27.1847	1.8712	500
10000	58.4598	5.7681	58.5074	3.6106	500

Enhanced Suffix Array (Query Time)

Condensed results for Enhanced Suffix Array in scenario mutated_implant.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.0560	0.0146	0.0524	0.0089	500
500	1.2555	0.1061	1.2248	0.0565	500
1000	2.8705	0.2707	2.8104	0.1426	500
5000	14.7844	0.8281	14.6585	0.6375	500
10000	30.1891	1.1744	30.1899	1.1141	500

Suffix Automaton (Query Time)

Condensed results for Suffix Automaton in scenario mutated_implant.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.0913	0.0282	0.0855	0.0164	500
500	0.4909	0.0938	0.4693	0.1025	500
1000	1.1618	0.1691	1.1134	0.1440	500
5000	6.0820	0.8923	5.8926	0.9030	500
10000	13.0033	1.1745	12.9978	1.0177	500

Enhanced Suffix Array (Total Time)

Condensed results for Enhanced Suffix Array in scenario mutated_ implant.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.7221	0.1348	0.6763	0.0653	500
500	28.4484	1.3192	28.4662	1.1225	500
1000	74.2060	7.0157	72.9203	3.2408	500
5000	430.0673	24.2207	426.7509	15.3301	500
10000	895.8482	32.6771	891.7958	27.0631	500

Suffix Automaton (Total Time)

Condensed results for Suffix Automaton in scenario mutated_ implant.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.3886	0.0987	0.3665	0.0330	500
500	2.8501	0.3401	2.7365	0.3251	500
1000	6.3107	0.4960	6.2280	0.4621	500
5000	33.4031	3.2867	33.1946	2.3144	500
10000	71.4631	6.7327	71.5134	4.3611	500

Enhanced Suffix Array (Memory Overall)

Condensed results for Enhanced Suffix Array in scenario mutated_ implant.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	17.0411	0.3534	17.0176	0.3594
500	117.1639	0.8303	116.9473	0.5703
1000	257.0182	1.8227	256.4395	3.7500
5000	1398.2211	6.0046	1400.7363	2.4062
10000	2807.9716	5.8384	2807.3301	3.4141

Suffix Automaton (Memory Overall)

Condensed results for Suffix Automaton in scenario mutated_ implant.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	19.3906	0.7071	19.4209	0.8154
500	174.6112	1.1849	174.5752	1.2686
1000	380.2407	1.8273	380.5127	2.1729
5000	2001.6002	4.5429	2001.8057	5.8643
10000	4045.0428	5.3404	4045.3662	7.7617

Enhanced Suffix Array (Build Peak Memory)

Condensed results for Enhanced Suffix Array in scenario mutated_ implant.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	17.0411	0.3534	17.0176	0.3594
500	117.1639	0.8303	116.9473	0.5703
1000	257.0182	1.8227	256.4395	3.7500
5000	1398.2211	6.0046	1400.7363	2.4062
10000	2807.9716	5.8384	2807.3301	3.4141

Suffix Automaton (Build Peak Memory)

Condensed results for Suffix Automaton in scenario mutated_ implant.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	18.6140	0.6739	18.7109	0.7344
500	173.6980	1.0974	173.9102	1.4492
1000	379.1989	1.7619	379.3945	1.8633
5000	2000.5287	4.5416	2000.8320	5.7969
10000	4043.5930	5.1033	4043.3828	7.8672

Enhanced Suffix Array (Query Peak Memory)

Condensed results for Enhanced Suffix Array in scenario mutated_ implant.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	4.6695	0.0523	4.6562	0.0605
500	41.7860	0.0382	41.7783	0.0488
1000	88.9845	0.0241	88.9756	0.0283
5000	476.7691	0.1685	476.7236	0.0674
10000	963.0100	0.1976	962.9443	0.0850

Suffix Automaton (Query Peak Memory)

Condensed results for Suffix Automaton in scenario mutated_ implant.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	19.3906	0.7071	19.4209	0.8154
500	174.6112	1.1849	174.5752	1.2686
1000	380.2407	1.8273	380.5127	2.1729
5000	2001.6002	4.5429	2001.8057	5.8643
10000	4045.0428	5.3404	4045.3662	7.7617

Enhanced Suffix Array (Query Extra Memory)

Condensed results for Enhanced Suffix Array in scenario mutated_ implant.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	0.6797	0.0330	0.6777	0.0303
500	0.7175	0.0382	0.7100	0.0488
1000	0.7208	0.0241	0.7119	0.0283
5000	0.8057	0.1702	0.7617	0.0527
10000	0.8486	0.1877	0.7793	0.0674

Suffix Automaton (Query Extra Memory)

Condensed results for Suffix Automaton in scenario mutated_ implant.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	1.0971	0.3216	0.8506	0.5898
500	1.2336	0.3407	1.4072	0.6475
1000	1.3621	0.3226	1.4932	0.6387
5000	1.3918	0.2856	1.4893	0.1494
10000	1.7701	0.6790	1.6328	0.2930

Enhanced Suffix Array (Index)

Condensed results for Enhanced Suffix Array in scenario mutated_ implant.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	9.2715	0.0000	9.2715	0.0000	12.3200
500	44.9863	0.0000	44.9863	0.0000	22.5200
1000	88.2754	0.0000	88.2754	0.0000	31.4000
5000	444.7129	0.0000	444.7129	0.0000	41.2400
10000	891.8223	0.0000	891.8223	0.0000	43.4000

Suffix Automaton (Index)

Condensed results for Suffix Automaton in scenario mutated_ implant.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	36.9114	0.7756	37.0273	0.8281	12.3200
500	193.7652	1.0974	193.9805	1.4492	22.5200
1000	397.3130	1.7619	397.5117	1.8633	31.4000
5000	2003.0178	4.5416	2003.3242	5.7969	41.2400
10000	4026.5508	5.1033	4026.3438	7.8672	43.4000

Near Identical

Enhanced Suffix Array (Build Time)
Condensed results for Enhanced Suffix Array in scenario near_identical.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.8973	0.2670	0.8299	0.0721	500
500	28.7797	3.8677	28.6069	1.2660	500
1000	72.0393	3.9829	71.6989	3.5016	500
5000	436.3448	32.8775	429.1522	15.7043	500
10000	917.2661	32.8563	914.5540	27.2977	500

Suffix Automaton (Build Time)
Condensed results for Suffix Automaton in scenario near_identical.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.2219	0.0571	0.2083	0.0194	500
500	1.7730	0.3135	1.6721	0.1911	500
1000	4.0787	0.3182	4.0387	0.2440	500
5000	20.1832	2.5592	19.9330	1.6187	500
10000	43.1988	2.6354	43.3967	2.8946	500

Enhanced Suffix Array (Query Time)
Condensed results for Enhanced Suffix Array in scenario near_identical.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.0592	0.0214	0.0548	0.0095	500
500	1.3001	0.1472	1.2532	0.0632	500
1000	2.9253	0.3626	2.8856	0.1385	500
5000	15.5071	1.1774	15.2848	0.6238	500
10000	31.5783	1.9220	31.4201	1.1969	500

Suffix Automaton (Query Time)
Condensed results for Suffix Automaton in scenario near_identical.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.3424	0.0579	0.3204	0.0285	500
500	2.5607	0.1944	2.5114	0.1640	500
1000	6.1874	0.4308	6.1105	0.4002	500
5000	35.6452	4.7441	35.0750	1.5872	500
10000	77.5589	3.7466	77.3678	2.9818	500

Enhanced Suffix Array (Total Time)
Condensed results for Enhanced Suffix Array in scenario near_identical.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.9566	0.2782	0.8846	0.0788	500
500	30.0799	3.9293	29.9108	1.2967	500
1000	74.9646	4.0878	74.6613	3.7002	500
5000	451.8520	33.8624	444.4871	16.2480	500
10000	948.8444	34.0679	946.0367	28.3186	500

Suffix Automaton (Total Time)
Condensed results for Suffix Automaton in scenario near_identical.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.5643	0.1049	0.5343	0.0458	500
500	4.3337	0.4158	4.2065	0.4002	500
1000	10.2660	0.6157	10.1860	0.5347	500
5000	55.8285	6.4827	54.9929	2.8518	500
10000	120.7577	6.1184	120.8392	5.2513	500

Enhanced Suffix Array (Memory Overall)
Condensed results for Enhanced Suffix Array in scenario near_identical.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	19.7698	0.4242	19.7598	0.6875
500	122.9600	0.8263	123.2051	0.8828
1000	268.5878	1.5279	268.3926	1.0078
5000	1507.8776	11.8780	1509.4785	18.1016
10000	3048.2410	11.0266	3046.9082	10.7422

Suffix Automaton (Memory Overall)
Condensed results for Suffix Automaton in scenario near_identical.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	14.3064	0.5256	14.4971	0.9219
500	144.3398	1.2458	144.3369	1.8926
1000	324.8686	1.4894	324.5850	1.7168
5000	1655.9121	3.1172	1654.9795	4.7598
10000	3402.6903	4.6552	3402.6357	7.2949

Enhanced Suffix Array (Build Peak Memory)
Condensed results for Enhanced Suffix Array in scenario near_identical.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	19.7698	0.4242	19.7598	0.6875
500	122.9600	0.8263	123.2051	0.8828
1000	268.5878	1.5279	268.3926	1.0078
5000	1507.8776	11.8780	1509.4785	18.1016
10000	3048.2410	11.0266	3046.9082	10.7422

Suffix Automaton (Build Peak Memory)
Condensed results for Suffix Automaton in scenario near_identical.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	13.7309	0.5255	13.9219	0.9219
500	142.9375	1.2450	142.9375	1.8828
1000	322.5197	1.4953	322.2227	1.6875
5000	1645.8894	3.1171	1644.9648	4.7539
10000	3383.0981	4.6633	3383.0508	7.2930

Enhanced Suffix Array (Query Peak Memory)
Condensed results for Enhanced Suffix Array in scenario near_identical.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	4.8014	0.0496	4.7881	0.0020
500	50.0279	0.0776	49.9873	0.0654
1000	113.4915	0.0844	113.4805	0.0664
5000	631.4863	0.3430	631.3613	0.2324
10000	1280.3577	0.6053	1280.2090	0.0791

Suffix Automaton (Query Peak Memory)
Condensed results for Suffix Automaton in scenario near_identical.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	14.3064	0.5256	14.4971	0.9219
500	144.3398	1.2458	144.3369	1.8926
1000	324.8686	1.4894	324.5850	1.7168
5000	1655.9121	3.1172	1654.9795	4.7598
10000	3402.6903	4.6552	3402.6357	7.2949

Enhanced Suffix Array (Query Extra Memory)

Condensed results for Enhanced Suffix Array in scenario near_identical.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	0.8066	0.0093	0.8096	0.0010
500	1.6002	0.0159	1.6064	0.0078
1000	2.5558	0.0223	2.5635	0.0039
5000	10.2275	0.0206	10.2217	0.0068
10000	19.7919	0.0430	19.7900	0.0029

Suffix Automaton (Query Extra Memory)

Condensed results for Suffix Automaton in scenario near_identical.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	0.8958	0.0007	0.8955	0.0000
500	1.7226	0.0043	1.7197	0.0039
1000	2.6792	0.0028	2.6787	0.0039
5000	10.3430	0.0195	10.3350	0.0059
10000	19.9125	0.0334	19.9033	0.0020

Enhanced Suffix Array (Index)

Condensed results for Enhanced Suffix Array in scenario near_identical.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	9.2715	0.0000	9.2715	0.0000	98.1600
500	51.4252	0.0605	51.3848	0.0547	491.4800
1000	108.1062	0.0389	108.0996	0.0547	981.2400
5000	571.8373	0.2732	571.7246	0.0820	4905.1200
10000	1152.9190	0.4672	1152.7910	0.0273	9804.6800

Suffix Automaton (Index)

Condensed results for Suffix Automaton in scenario near_identical.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	32.1459	0.5796	32.3750	0.9727	98.1600
500	163.9070	1.2450	163.9102	1.8828	491.4800
1000	341.5261	1.4898	341.2422	1.7227	981.2400
5000	1649.2808	3.1171	1648.3594	4.7539	4905.1200
10000	3366.9583	4.6633	3366.9141	7.2930	9804.6800

Random Uniform

Enhanced Suffix Array (Build Time)
Condensed results for Enhanced Suffix Array in scenario random_ uniform.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.4797	0.0980	0.4476	0.0406	500
500	25.7370	4.2493	25.5164	1.1177	500
1000	67.5274	3.3034	66.9891	3.0356	500
5000	396.0339	14.3132	393.8816	16.4700	500
10000	832.9461	32.7767	828.3093	23.6200	500

Suffix Automaton (Build Time)
Condensed results for Suffix Automaton in scenario random_ uniform.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.2277	0.0712	0.2094	0.0250	500
500	1.7637	0.2669	1.6816	0.1561	500
1000	4.1209	0.4263	4.0545	0.2428	500
5000	20.1749	2.9370	20.1750	1.4106	500
10000	43.4903	4.1890	43.5015	2.2644	500

Enhanced Suffix Array (Query Time)
Condensed results for Enhanced Suffix Array in scenario random_ uniform.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.0618	0.0136	0.0604	0.0083	500
500	1.3919	1.4714	1.2696	0.1225	500
1000	2.9215	0.2562	2.8963	0.2120	500
5000	14.9142	0.5880	14.8299	0.6740	500
10000	30.4111	1.4659	30.2856	0.9637	500

Suffix Automaton (Query Time)
Condensed results for Suffix Automaton in scenario random_ uniform.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.0712	0.0235	0.0675	0.0143	500
500	0.4728	0.0816	0.4555	0.0810	500
1000	1.0571	0.1328	1.0295	0.1642	500
5000	5.9725	1.1348	5.8729	0.7757	500
10000	12.1748	0.9740	12.1457	0.7932	500

Enhanced Suffix Array (Total Time)

Condensed results for Enhanced Suffix Array in scenario random_ uniform.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.5415	0.1048	0.5071	0.0467	500
500	27.1289	4.5455	26.8161	1.1529	500
1000	70.4489	3.4065	69.8890	3.1449	500
5000	410.9481	14.6772	408.7129	16.9720	500
10000	863.3572	33.8125	858.3702	24.3951	500

Suffix Automaton (Total Time)

Condensed results for Suffix Automaton in scenario random_ uniform.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.2988	0.0874	0.2758	0.0301	500
500	2.2365	0.3149	2.1447	0.2199	500
1000	5.1780	0.4905	5.1077	0.3604	500
5000	26.1474	3.1944	25.9976	1.4997	500
10000	55.6651	4.9964	55.7341	2.7074	500

Enhanced Suffix Array (Memory Overall)

Condensed results for Enhanced Suffix Array in scenario random_ uniform.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	16.0465	0.5712	16.0645	0.4141
500	125.2396	0.5148	125.1348	0.8750
1000	298.8832	3.6421	297.7715	5.8906
5000	1740.3898	10.5886	1742.2676	18.3594
10000	3500.5570	6.7340	3501.4941	9.6562

Suffix Automaton (Memory Overall)

Condensed results for Suffix Automaton in scenario random_ uniform.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	14.9186	0.9756	15.1055	1.2656
500	145.6341	3.1733	144.6836	2.4854
1000	325.9029	1.8814	325.8105	2.1445
5000	1649.3546	4.2902	1649.0820	3.6553
10000	3389.3315	5.8528	3388.2588	7.0273

Enhanced Suffix Array (Build Peak Memory)

Condensed results for Enhanced Suffix Array in scenario random_ uniform.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	16.0465	0.5712	16.0645	0.4141
500	125.2396	0.5148	125.1348	0.8750
1000	298.8832	3.6421	297.7715	5.8906
5000	1740.3898	10.5886	1742.2676	18.3594
10000	3500.5570	6.7340	3501.4941	9.6562

Suffix Automaton (Build Peak Memory)

Condensed results for Suffix Automaton in scenario random_ uniform.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	13.7722	0.9011	14.0078	1.1016
500	142.9797	1.2711	142.7109	0.8086
1000	323.2071	1.7084	322.6719	2.2891
5000	1645.7923	3.2911	1646.0859	3.6875
10000	3385.0009	4.8256	3385.0625	5.7070

Enhanced Suffix Array (Query Peak Memory)

Condensed results for Enhanced Suffix Array in scenario random_ uniform.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	5.3109	0.2870	5.3125	0.2100
500	43.1870	1.1188	42.7129	0.2988
1000	91.2228	1.4616	91.9395	2.9180
5000	479.0084	1.3701	479.6514	2.4336
10000	965.8775	2.3907	965.8662	2.6777

Suffix Automaton (Query Peak Memory)

Condensed results for Suffix Automaton in scenario random_ uniform.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	14.9186	0.9756	15.1055	1.2656
500	145.6341	3.1733	144.6836	2.4854
1000	325.9029	1.8814	325.8105	2.1445
5000	1649.3546	4.2902	1649.0820	3.6553
10000	3389.3315	5.8528	3388.2588	7.0273

Enhanced Suffix Array (Query Extra Memory)

Condensed results for Enhanced Suffix Array in scenario random_ uniform.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	1.3143	0.2728	1.3340	0.2100
500	2.1186	1.1188	1.6445	0.2988
1000	2.9540	1.4624	3.6758	2.9180
5000	3.0573	1.3701	3.7002	2.4336
10000	3.7357	2.3906	3.7432	2.6309

Suffix Automaton (Query Extra Memory)

Condensed results for Suffix Automaton in scenario random_ uniform.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	1.4667	0.3255	1.4199	0.2119
500	2.9747	2.4931	1.7979	2.0547
1000	3.0162	1.3717	3.7891	2.4268
5000	3.8826	3.1630	3.7861	2.4883
10000	4.6509	4.0120	3.8291	2.8184

Enhanced Suffix Array (Index)

Condensed results for Enhanced Suffix Array in scenario random_ uniform.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	9.2715	0.0000	9.2715	0.0000	2.4000
500	44.9863	0.0000	44.9863	0.0000	3.4000
1000	88.2754	0.0000	88.2754	0.0000	4.1600
5000	444.7129	0.0000	444.7129	0.0000	5.0800
10000	891.8223	0.0000	891.8223	0.0000	5.3200

Suffix Automaton (Index)

Condensed results for Suffix Automaton in scenario random_ uniform.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	32.1570	0.7439	32.4609	1.2520	2.4000
500	163.9492	1.2710	163.6836	0.8086	3.4000
1000	342.2234	1.7084	341.6914	2.2891	4.1600
5000	1649.1837	3.2911	1649.4805	3.6875	5.0800
10000	3368.8611	4.8256	3368.9258	5.7070	5.3200

Repetitive with Noise

Enhanced Suffix Array (Build Time)
Condensed results for Enhanced Suffix Array in scenario repetitive_ with_ noise.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.7456	0.3978	0.7453	0.2040	500
500	28.8745	4.1395	28.5099	1.6150	500
1000	75.6570	10.9879	72.4695	6.3244	500
5000	420.6713	18.8932	417.7870	17.4356	500
10000	880.0391	33.7104	873.1154	35.8926	500

Suffix Automaton (Build Time)
Condensed results for Suffix Automaton in scenario repetitive_ with_ noise.

Length	Build Mean (ms)	Build SD (ms)	Build Median (ms)	Build IQR (ms)	Runs
100	0.3124	0.0942	0.3029	0.0544	500
500	2.6619	0.7030	2.5061	0.3283	500
1000	5.7827	1.5698	5.5807	0.5132	500
5000	29.8320	2.4029	29.6727	1.8447	500
10000	63.0692	3.5125	63.2876	4.3649	500

Enhanced Suffix Array (Query Time)
Condensed results for Enhanced Suffix Array in scenario repetitive_ with_ noise.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.0667	0.0184	0.0637	0.0213	500
500	1.2991	0.2699	1.2407	0.0803	500
1000	2.9297	0.3893	2.8582	0.2007	500
5000	14.7592	0.6385	14.6447	0.5938	500
10000	30.1369	1.2091	30.0663	1.0998	500

Suffix Automaton (Query Time)
Condensed results for Suffix Automaton in scenario repetitive_ with_ noise.

Length	Query Mean (ms)	Query SD (ms)	Query Median (ms)	Query IQR (ms)	Runs
100	0.1309	0.0288	0.1259	0.0272	500
500	0.5194	0.0943	0.4999	0.0738	500
1000	1.2252	1.0578	1.1130	0.1993	500
5000	5.6016	1.0986	5.4534	0.7179	500
10000	11.9808	0.7847	11.9413	0.9435	500

Enhanced Suffix Array (Total Time)

Condensed results for Enhanced Suffix Array in scenario repetitive_with_noise.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.8122	0.4013	0.8030	0.2064	500
500	30.1736	4.2170	29.8178	1.6146	500
1000	78.5866	11.1725	75.3565	6.5258	500
5000	435.4306	19.3675	432.2704	17.8116	500
10000	910.1760	34.5820	903.2966	36.6330	500

Suffix Automaton (Total Time)

Condensed results for Suffix Automaton in scenario repetitive_with_noise.

Length	Total Mean (ms)	Total SD (ms)	Total Median (ms)	Total IQR (ms)	Runs
100	0.4433	0.1109	0.4202	0.0666	500
500	3.1813	0.7532	3.0233	0.4095	500
1000	7.0080	2.0697	6.7805	0.6139	500
5000	35.4336	3.2577	35.2052	2.1612	500
10000	75.0500	4.1045	75.4318	4.7936	500

Enhanced Suffix Array (Memory Overall)

Condensed results for Enhanced Suffix Array in scenario repetitive_with_noise.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	16.9204	2.1218	15.2129	4.0312
500	116.5432	3.3041	116.4941	6.2852
1000	258.3808	4.4882	259.4238	5.1797
5000	1388.0634	13.1931	1392.7285	22.5469
10000	2806.4719	21.2297	2796.6348	38.2422

Suffix Automaton (Memory Overall)

Condensed results for Suffix Automaton in scenario repetitive_with_noise.

Length	Memory Mean (KiB)	Memory SD (KiB)	Memory Median (KiB)	Memory IQR (KiB)
100	20.8789	3.3049	21.4814	3.6904
500	191.9590	6.0486	192.3955	6.8730
1000	413.2130	8.4098	411.5576	14.3164
5000	2198.2025	9.6755	2197.3115	14.0137
10000	4436.2402	14.3303	4440.3730	18.4805

Enhanced Suffix Array (Build Peak Memory)

Condensed results for Enhanced Suffix Array in scenario repetitive_with_noise.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	16.9204	2.1218	15.2129	4.0312
500	116.5432	3.3041	116.4941	6.2852
1000	258.3808	4.4882	259.4238	5.1797
5000	1388.0634	13.1931	1392.7285	22.5469
10000	2806.4719	21.2297	2796.6348	38.2422

Suffix Automaton (Build Peak Memory)

Condensed results for Suffix Automaton in scenario repetitive_with_noise.

Length	BPM Mean (KiB)	BPM SD (KiB)	BPM Median (KiB)	BPM IQR (KiB)
100	20.3926	3.3077	21.0469	3.7109
500	191.3998	6.0547	191.8555	6.8320
1000	412.5785	8.4709	411.0703	14.2461
5000	2197.5287	9.6697	2196.5898	14.0781
10000	4435.5413	14.3320	4439.6953	18.6328

Enhanced Suffix Array (Query Peak Memory)

Condensed results for Enhanced Suffix Array in scenario repetitive_with_noise.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	4.6909	0.0542	4.6641	0.0576
500	41.8202	0.0377	41.8115	0.0215
1000	89.0627	0.1435	89.0342	0.0586
5000	476.7843	0.0511	476.7861	0.0742
10000	962.9840	0.0635	962.9619	0.0811

Suffix Automaton (Query Peak Memory)

Condensed results for Suffix Automaton in scenario repetitive_with_noise.

Length	QPM Mean (KiB)	QPM SD (KiB)	QPM Median (KiB)	QPM IQR (KiB)
100	20.8789	3.3049	21.4814	3.6904
500	191.9590	6.0486	192.3955	6.8730
1000	413.2130	8.4098	411.5576	14.3164
5000	2198.2025	9.6755	2197.3115	14.0137
10000	4436.2402	14.3303	4440.3730	18.4805

Enhanced Suffix Array (Query Extra Memory)

Condensed results for Enhanced Suffix Array in scenario repetitive_with_noise.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	0.6961	0.0276	0.6846	0.0459
500	0.7517	0.0374	0.7432	0.0215
1000	0.7905	0.0533	0.7705	0.0586
5000	0.8204	0.0452	0.8330	0.0781
10000	0.8255	0.0551	0.8008	0.0801

Suffix Automaton (Query Extra Memory)

Condensed results for Suffix Automaton in scenario repetitive_with_noise.

Length	QEM Mean (KiB)	QEM SD (KiB)	QEM Median (KiB)	QEM IQR (KiB)
100	0.8068	0.0302	0.8096	0.0410
500	0.8795	0.0514	0.8643	0.0586
1000	0.9550	0.1439	0.9248	0.0527
5000	0.9941	0.0941	0.9775	0.0352
10000	1.0192	0.1121	1.0068	0.0352

Enhanced Suffix Array (Index)

Condensed results for Enhanced Suffix Array in scenario repetitive_with_noise.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	9.2715	0.0000	9.2715	0.0000	28.8400
500	44.9863	0.0000	44.9863	0.0000	45.3600
1000	88.2754	0.0000	88.2754	0.0000	58.8000
5000	444.7129	0.0000	444.7129	0.0000	67.9600
10000	891.8223	0.0000	891.8223	0.0000	73.7200

Suffix Automaton (Index)

Condensed results for Suffix Automaton in scenario repetitive_with_noise.

Length	IDX Mean (KiB)	IDX SD (KiB)	IDX Median (KiB)	IDX IQR (KiB)	LCS Mean Length
100	38.9295	3.7425	39.7188	4.2168	28.8400
500	211.4670	6.0547	211.9258	6.8320	45.3600
1000	430.6920	8.4712	429.1875	14.2461	58.8000
5000	2200.0178	9.6697	2199.0820	14.0781	67.9600
10000	4418.4991	14.3320	4422.6562	18.6328	73.7200

AI Declaration

The usage of AI tools within this project is documented here. I solemnly declare that I have documented all interactions with AI tools, including the prompts used and the outputs received.

System	Prompt	Usage
GitHub Copilot 1	Asked to delete the existing project and provide a simple LaTeX template with a shared preamble, a Chapters subdirectory, TOC, glossary, abbreviations, and Roman numerals for non-content pages.	Template structure and LaTeX setup provided
GitHub Copilot 2	Requested additional title page lines (WAB header, reviewer, module) for the main document.	Title page metadata and layout updated
GitHub Copilot 3	Requested uppercase Roman numerals for front matter and lowercase Roman numerals for back matter page numbering.	Page numbering adjusted in main and exposee
GitHub Copilot 4	Requested exposee title page to include shared info fields (WAB header, department, module, reviewer).	Exposee title page updated to include shared metadata
GitHub Copilot 5	Requested adding the provadis-hochschule.pdf logo to the top right corner of both main and exposee title pages.	Logo added to top right of both title pages
GitHub Copilot 6	Reported that Glossary and Abbreviations sections were missing from compiled output.	Added example `\newacronym` entries to abbreviations.tex
GitHub Copilot 7	Reported that glossary section still not appearing in final PDF.	Updated settings.tex to include `automake` option in glossaries package to enable automatic glossary generation

System	Prompt	Usage
GitHub Copilot 8	Requested Python benchmark code for LCS comparison with multiple synthetic scenarios (random strings, implanted mutated substrings, etc.)	Created benchmark script and documentation in Code folder
GitHub Copilot 9	Asked to add a progress-bar-like output.	Added optional single-line in-place progress output with percentage, completed/total steps, elapsed time, ETA, and -progress/-no-progress flags
GitHub Copilot 10	Reported that ETA was inaccurate due to varying string lengths	Reworked ETA estimation to be algorithm- and length-aware using observed per-bucket runtimes
GitHub Copilot 11	Requested separate build and query timing (and plots).	Refactored benchmark to record build/query time separately and added total time summaries
GitHub Copilot 12	Requested plots using statistics beyond the mean (median, standard deviation, etc.).	Expanded summary stats and generated mean+std and median+IQR plots alongside memory plots
GitHub Copilot 13	Requested splitting benchmarking and plotting so plot generation can run separately, with a shared CLI entry point and default run-then-plot behavior.	Added CLI mode switch (run/plot/both) to reuse saved CSV results for plotting without rerunning benchmarks
GitHub Copilot 14	Requested an error if the two algorithms return different LCS result strings for the same input.	Added strict substring equality check (in addition to length) and raise an error on mismatch
GitHub Copilot 15	Requested that, in case of multiple valid LCS results, both algorithms return all results and compare the sets.	Updated both algorithms to return all max-length substrings and compare result sets for correctness
GitHub Copilot 16	Requested refactoring the benchmark script into helper modules under a helpers subdirectory, with separate algorithm imports and plotting helper, and clean top-level imports in the main file.	Split benchmark code into dedicated helper modules (SAM, ESA, plotting, generation, statistics, benchmarking) and simplified main script orchestration
GitHub Copilot 17	Requested mean, median, standard deviation, and IQR for memory usage plots as well.	Added memory quartile aggregation and generated memory mean+SD plus median+IQR plots
GitHub Copilot 18	Asked for a practical memory/space-complexity metric and whether build-time and query-time memory can be measured separately.	Added separate build/query phase memory metrics and a persistent index-size metric, with aggregation and plots for comparison

System	Prompt	Usage
GitHub Copilot 19	Asked whether adding total time (build + query) columns and graphs with full statistics would make sense.	Added full total-time statistics (mean, median, std, IQR, Q1, Q3) to summaries and created dedicated total-time plots
GitHub Copilot 20	Requested moving plot legends away from the top center because they obscured titles.	Repositioned all figure legends to the right side outside the plotting area to keep titles unobstructed
GitHub Copilot 21	Requested an additional output file containing both generated strings and their LCS value(s).	Added export of one CSV per generated case with 's', 't', LCS length, and all LCS substrings
GitHub Copilot 22	Asked to replace the lambda with a tuple-key-based approach.	Replaced lambda-based sorting with a tuple-key-based approach for suffix array construction, improving performance
GitHub Copilot 23	Asked to refactor the plotting code to reduce repetition and make it more modular.	Refactored plotting code to use a single generic plotting function
GitHub Copilot 24	Asked to replace the suffix array construction with the SA-IS algorithm.	Replaced doubling-based suffix array construction with an SA-IS implementation (linear-time induced sorting with LMS recursion), keeping the same public API
GitHub Copilot 25	Reported that generated benchmark tables do not fit on the page and requested a smart code-side solution (splitting tables if needed) instead of shrinking them.	Updated the table-export generator to split each algorithm summary into multiple narrower tables (timing, memory, index size)
GitHub Copilot 26	Requested that the generated benchmark tables should not show up in the List of Tables.	Adjusted the generator to avoid captions and instead use a custom numbered title with \refstepcounter{table} and \label for cross-references
GitHub Copilot 27	Requested that the generated tables are still slightly too large and should use a smaller font size.	Wrapped generated tabular blocks in \small within the generator to reduce width without making tables unreadably tiny

Declaration of Authorship

I hereby confirm that I have personally and independently prepared the present work and have not used any sources or aids other than those specified. All passages taken verbatim or in substance from other sources are identified as such. The drawings, illustrations and tables in this work are created by me or have been provided with an appropriate source reference. This work has not been submitted by me to any other university in the same or similar form for the acquisition of an academic degree.

Frankfurt, February 26, 2026 . . . .

Rubin Chempananickal James