Language-Agnostic Subtitle Synchronization

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Contents

Introduction

Motivation

- understanding quiet, fast speech
- foreign movies
- language learning

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Subtitles online often badly synchronized!

Error patterns in subtitle synchronization

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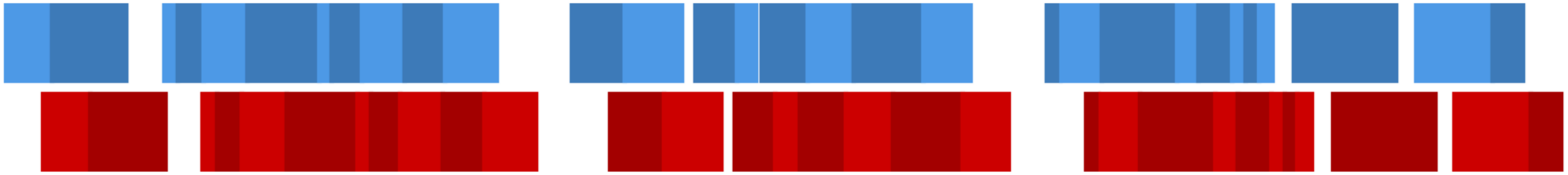
- Constant Shift



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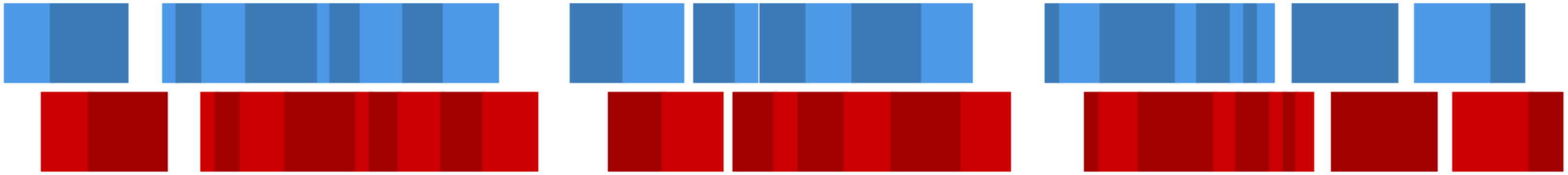

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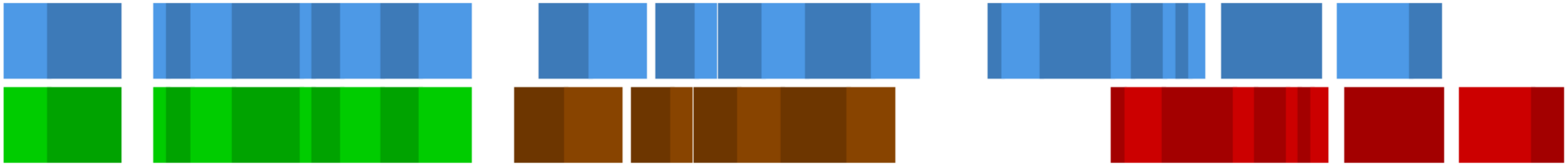

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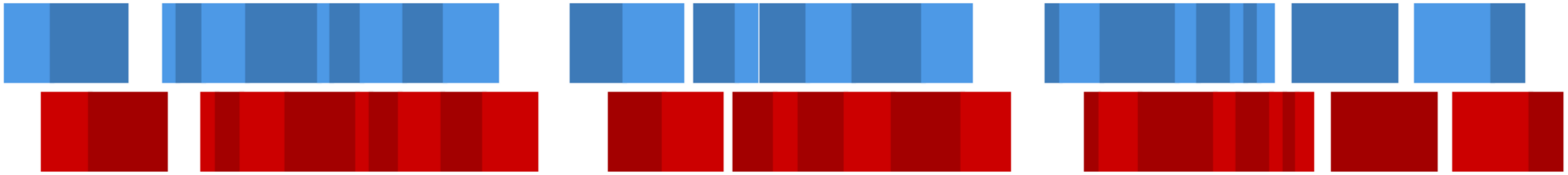

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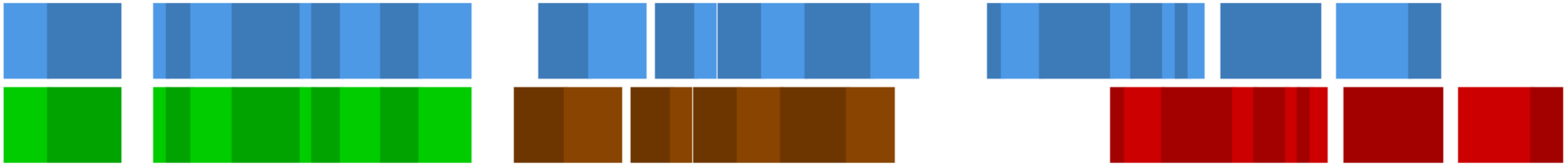
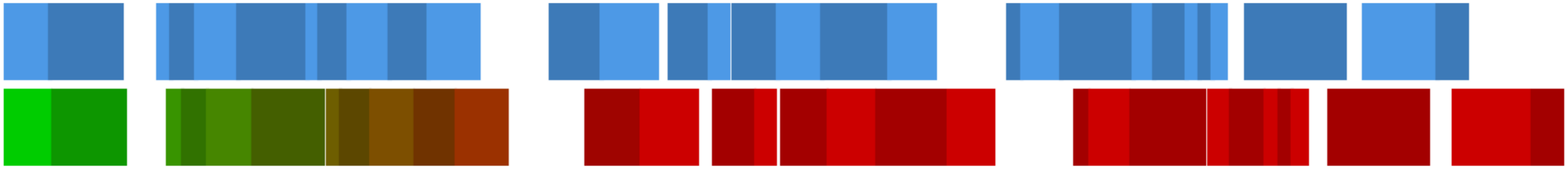


- Framerate Differences



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Process overview

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4. Align subtitle intervals to speech intervals.

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WebRTC voice-activity-detection:

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4. Compare with threshold

Optimal no-split alignment

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Given two time spans $a = [a_1, a_2)$ and $b = [b_1, b_2)$:

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\texttt{iscore}(a, b) &= \frac{\texttt{overlap}(a, b)}{\texttt{min}(\texttt{length}(a), \texttt{length}(b))}
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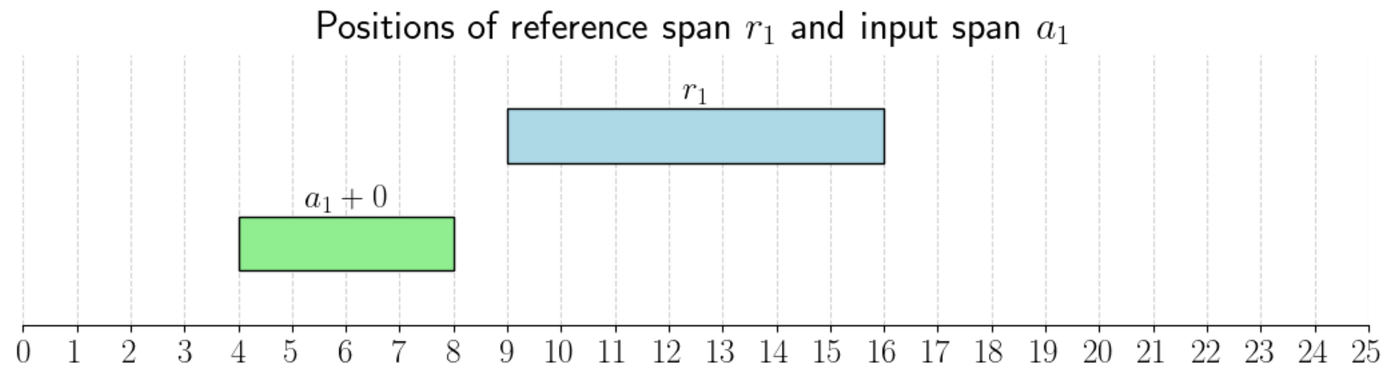

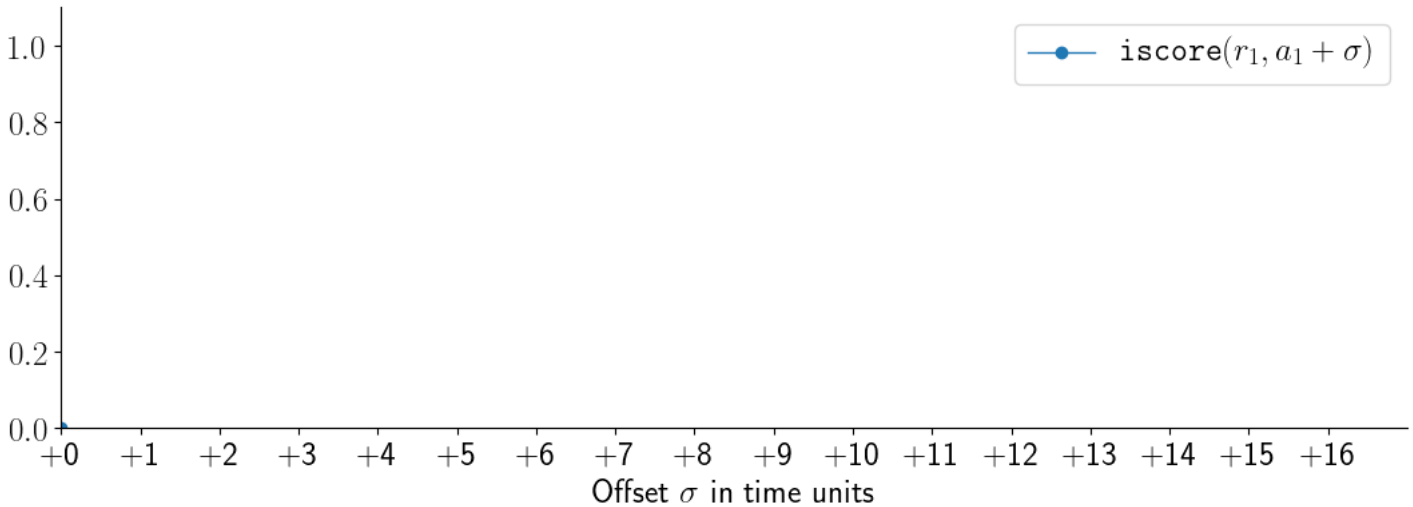

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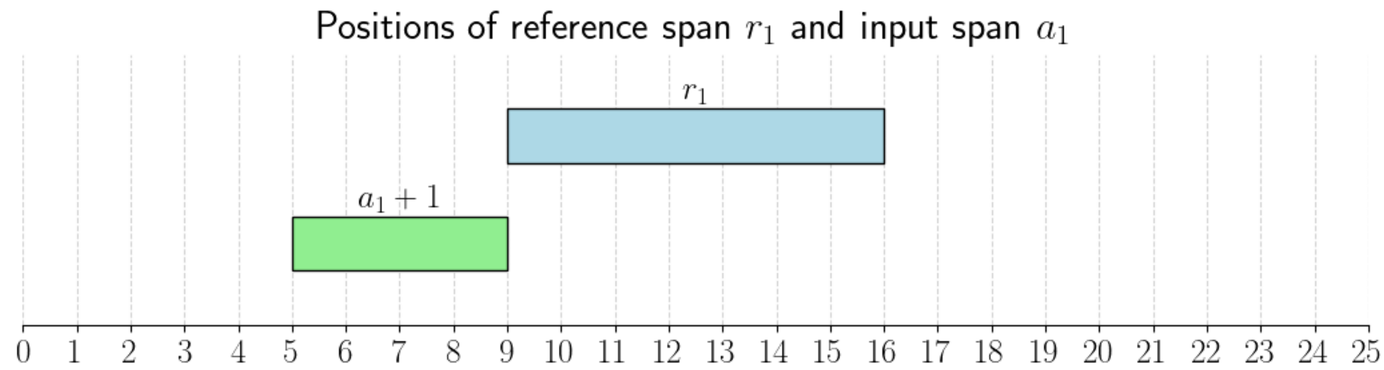

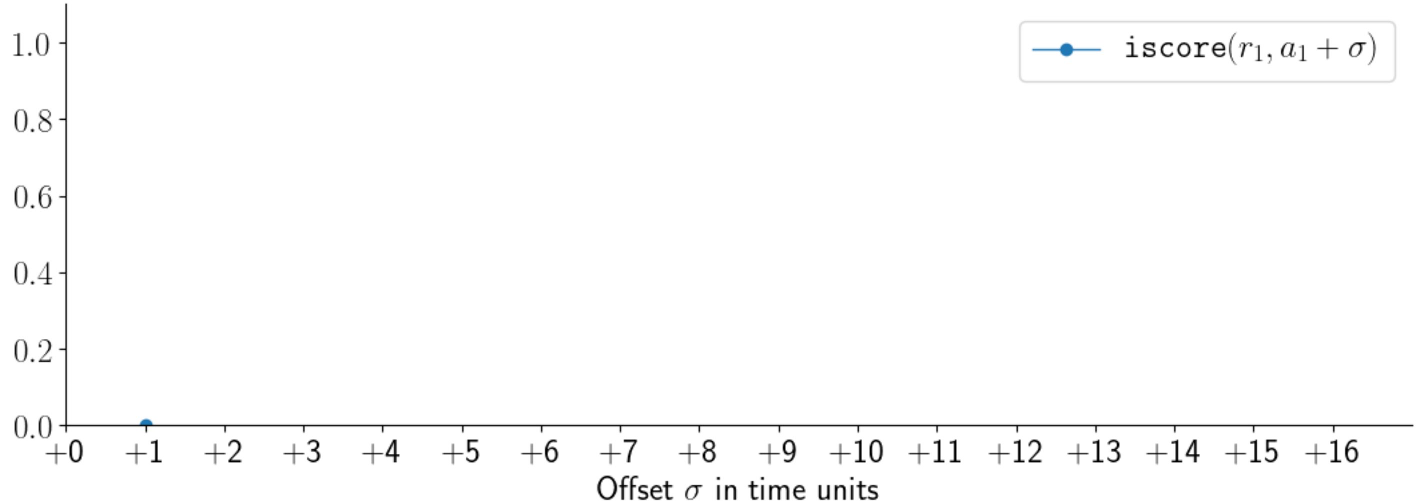

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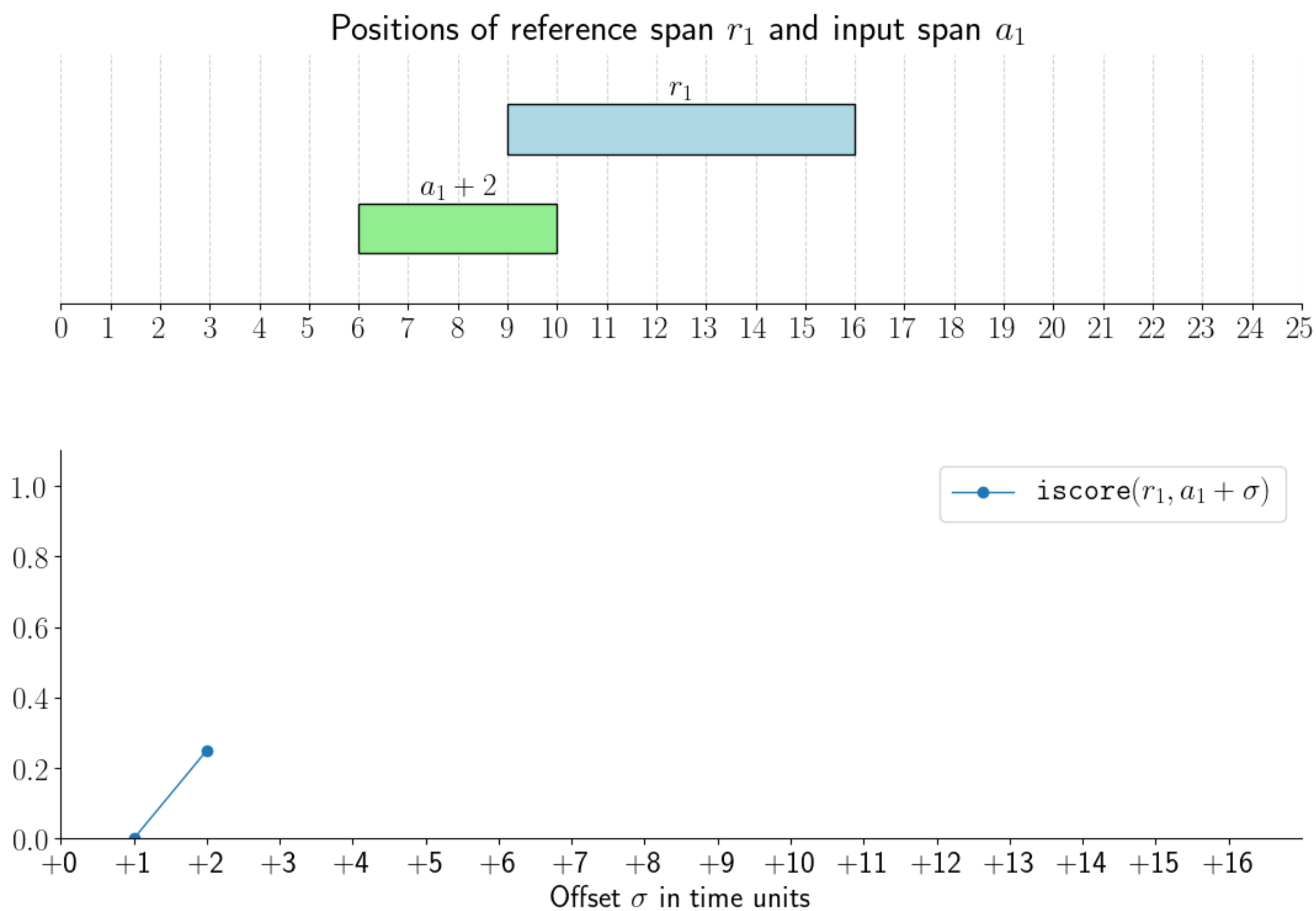

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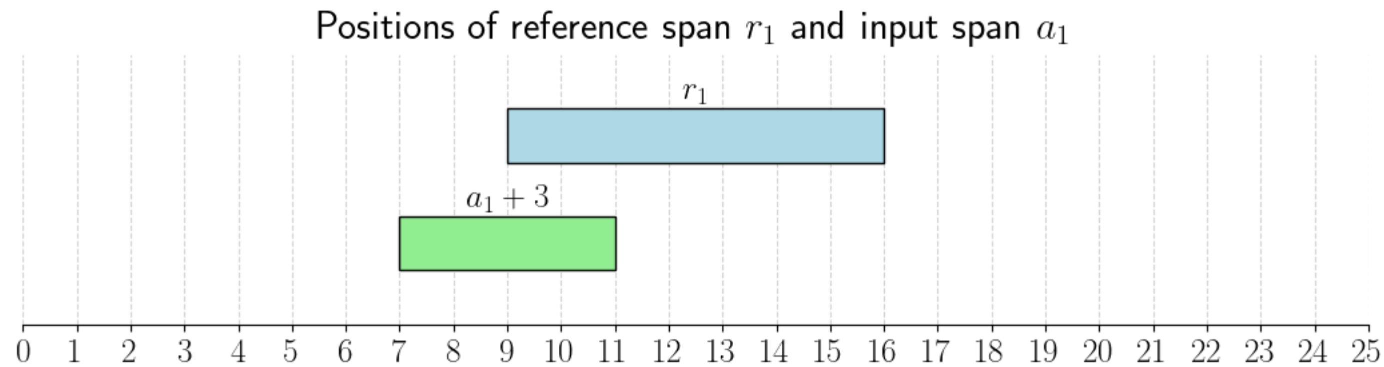

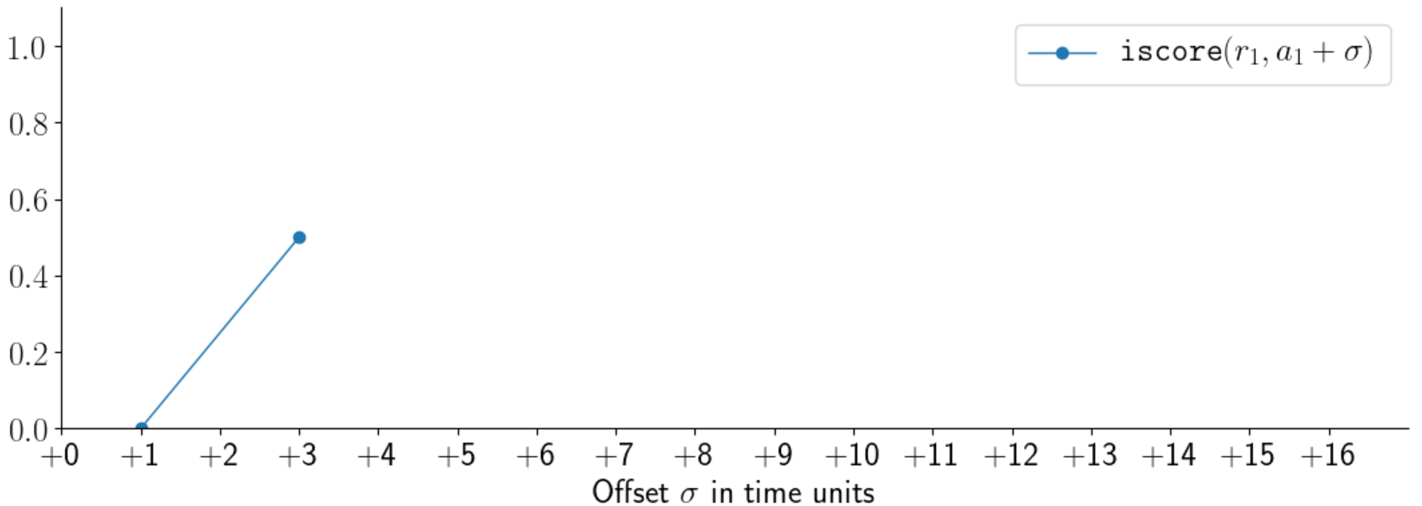

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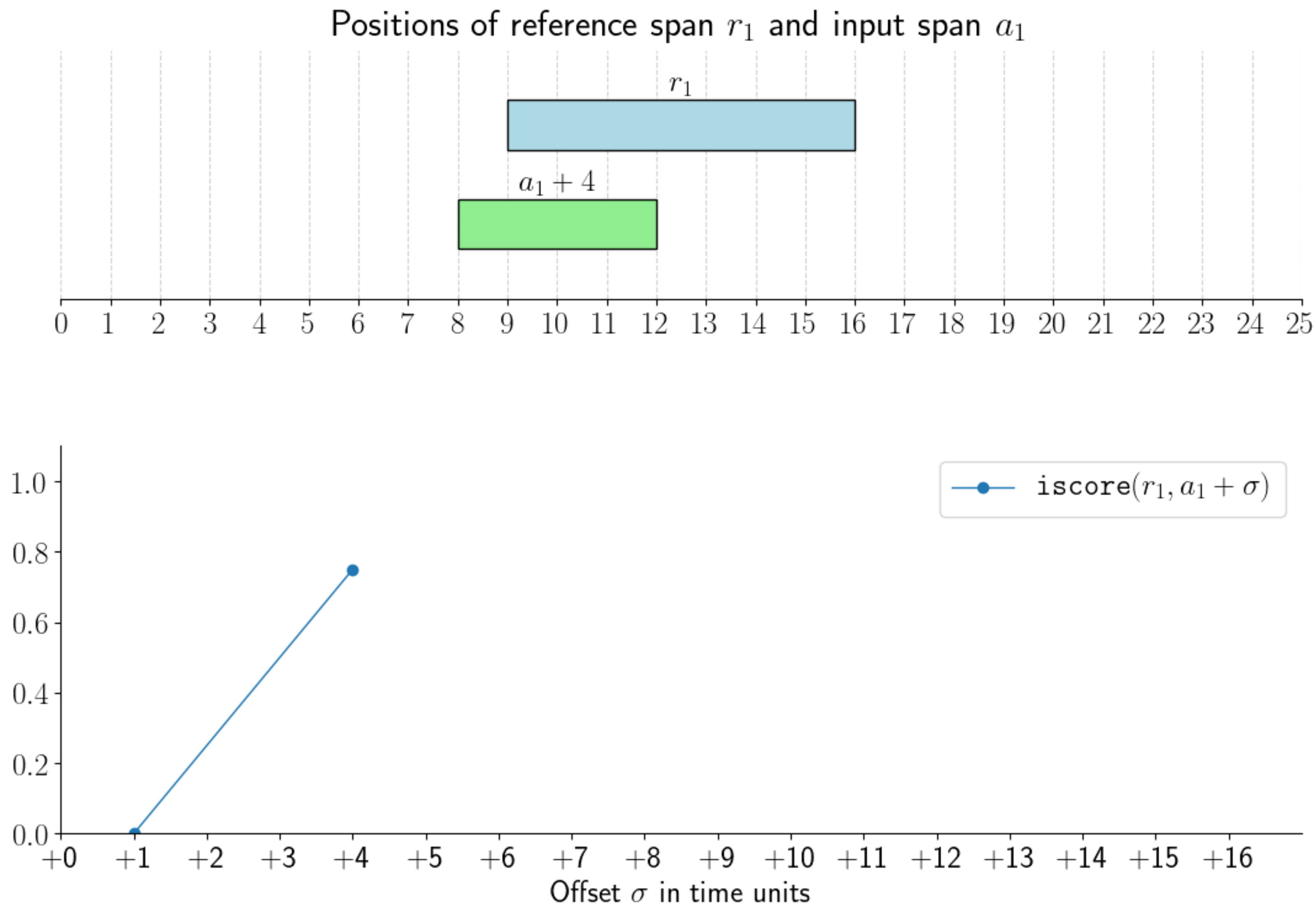

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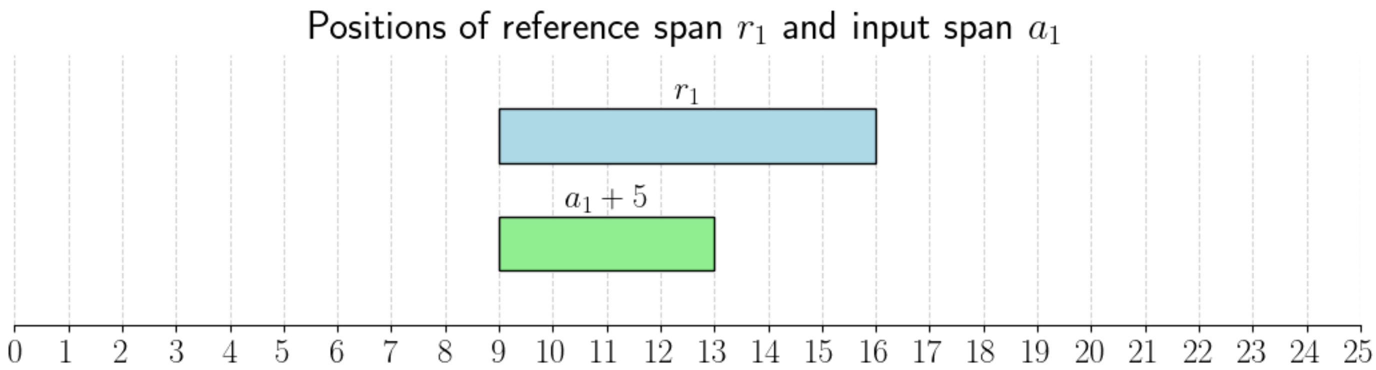

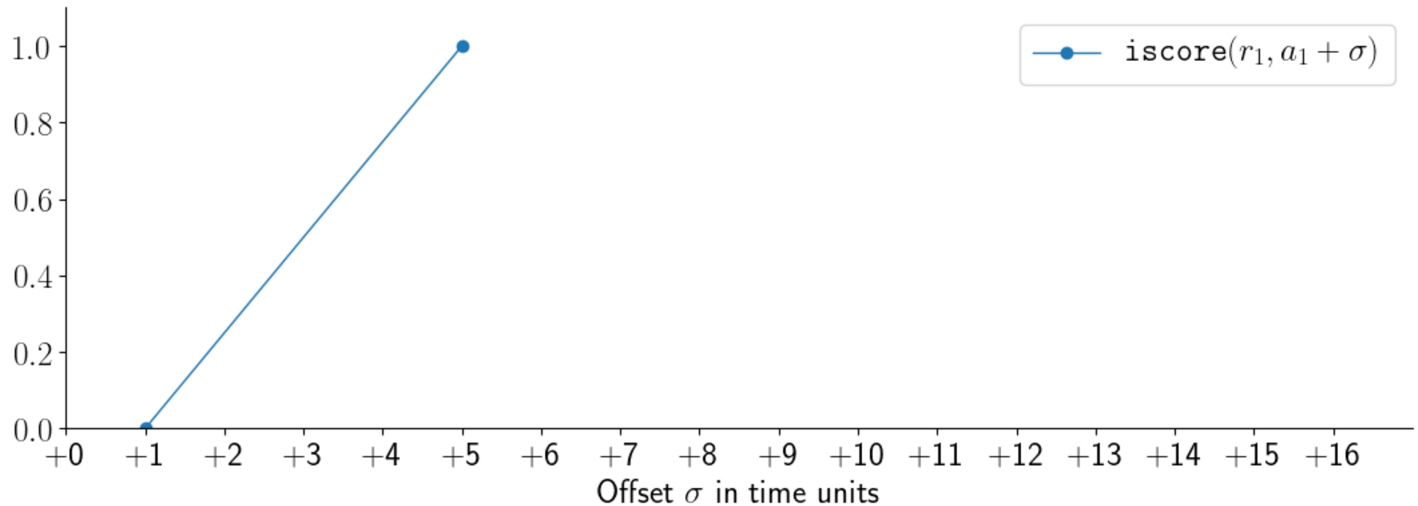

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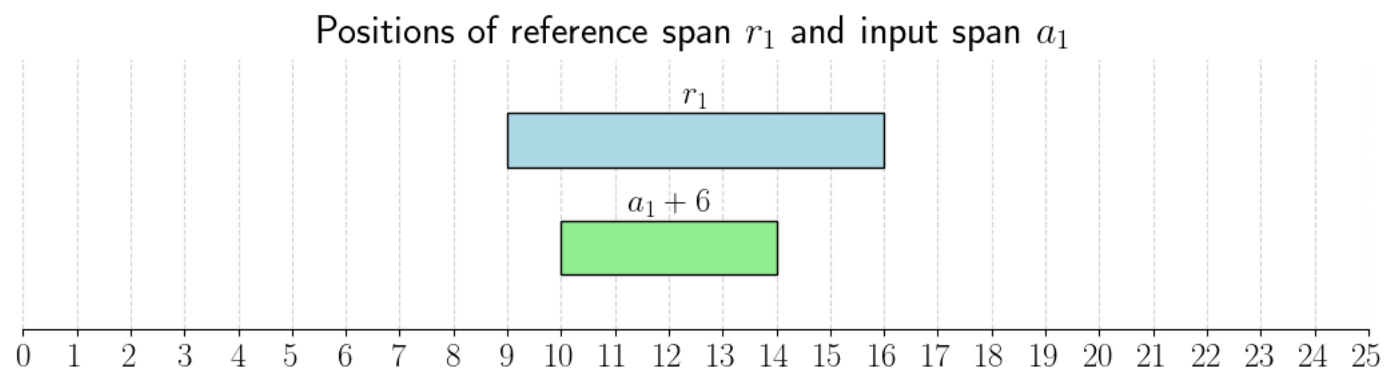

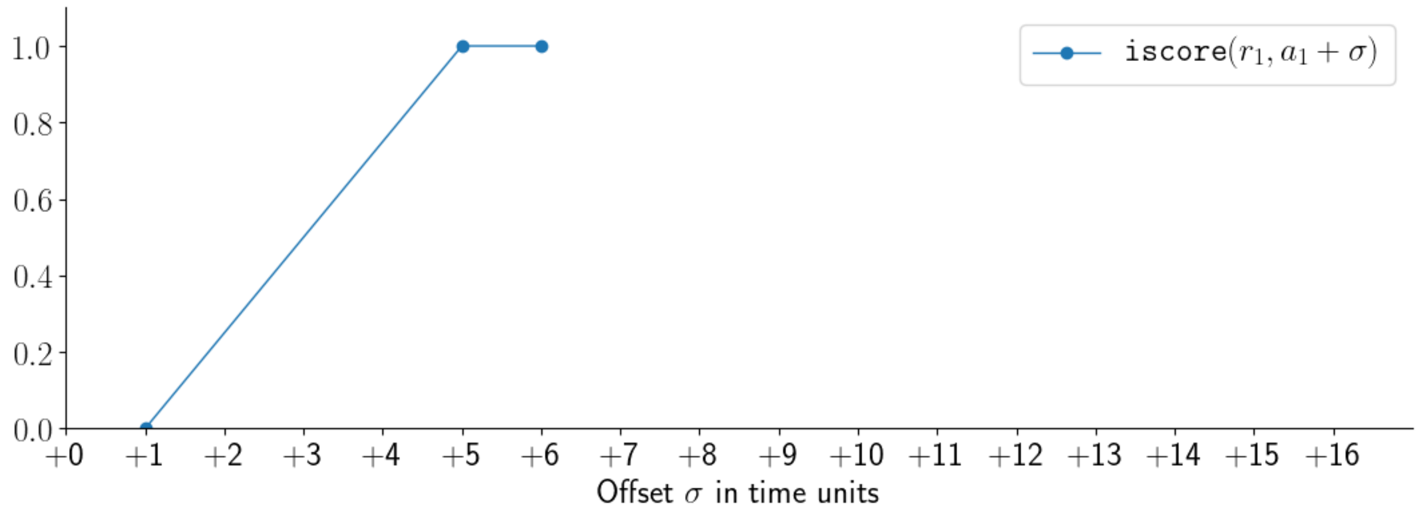

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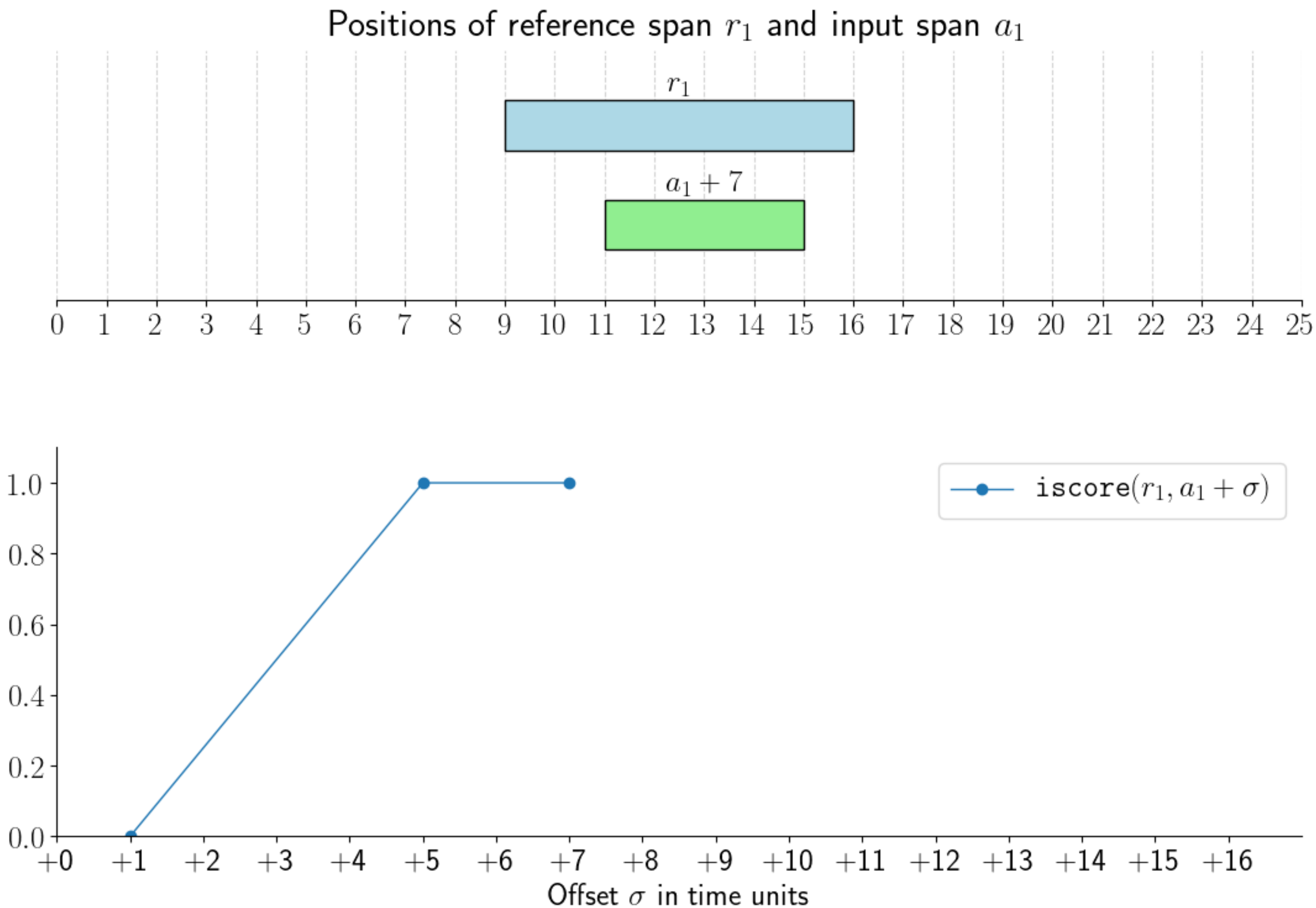

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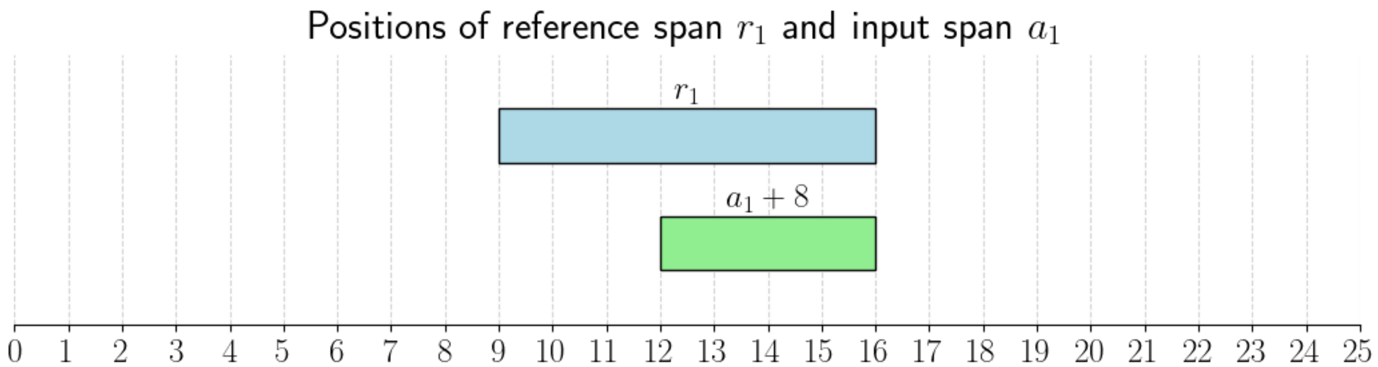

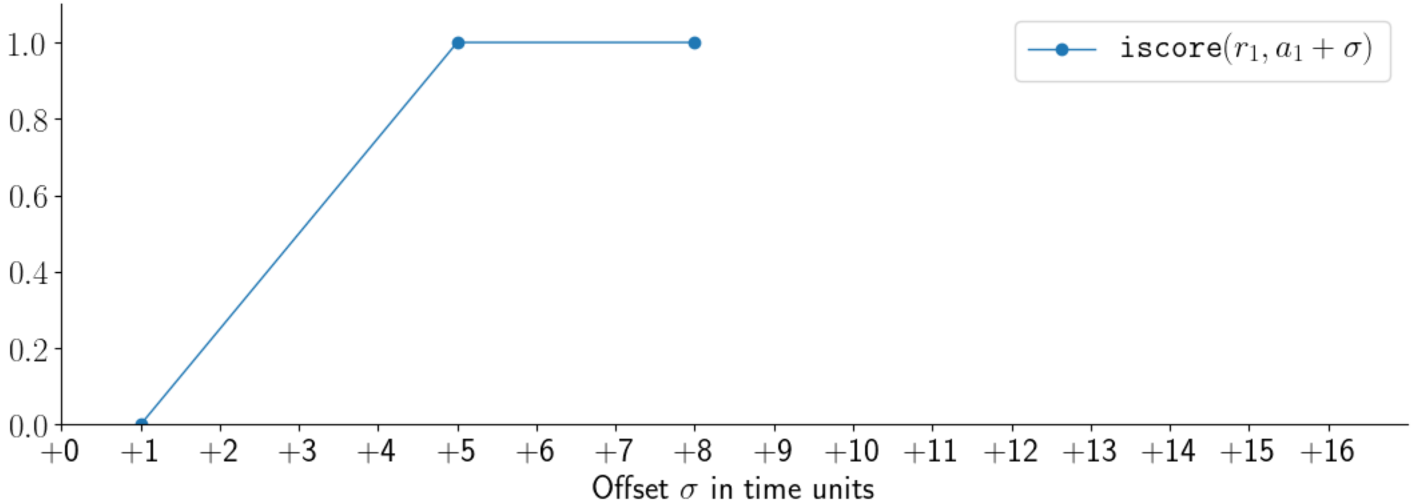

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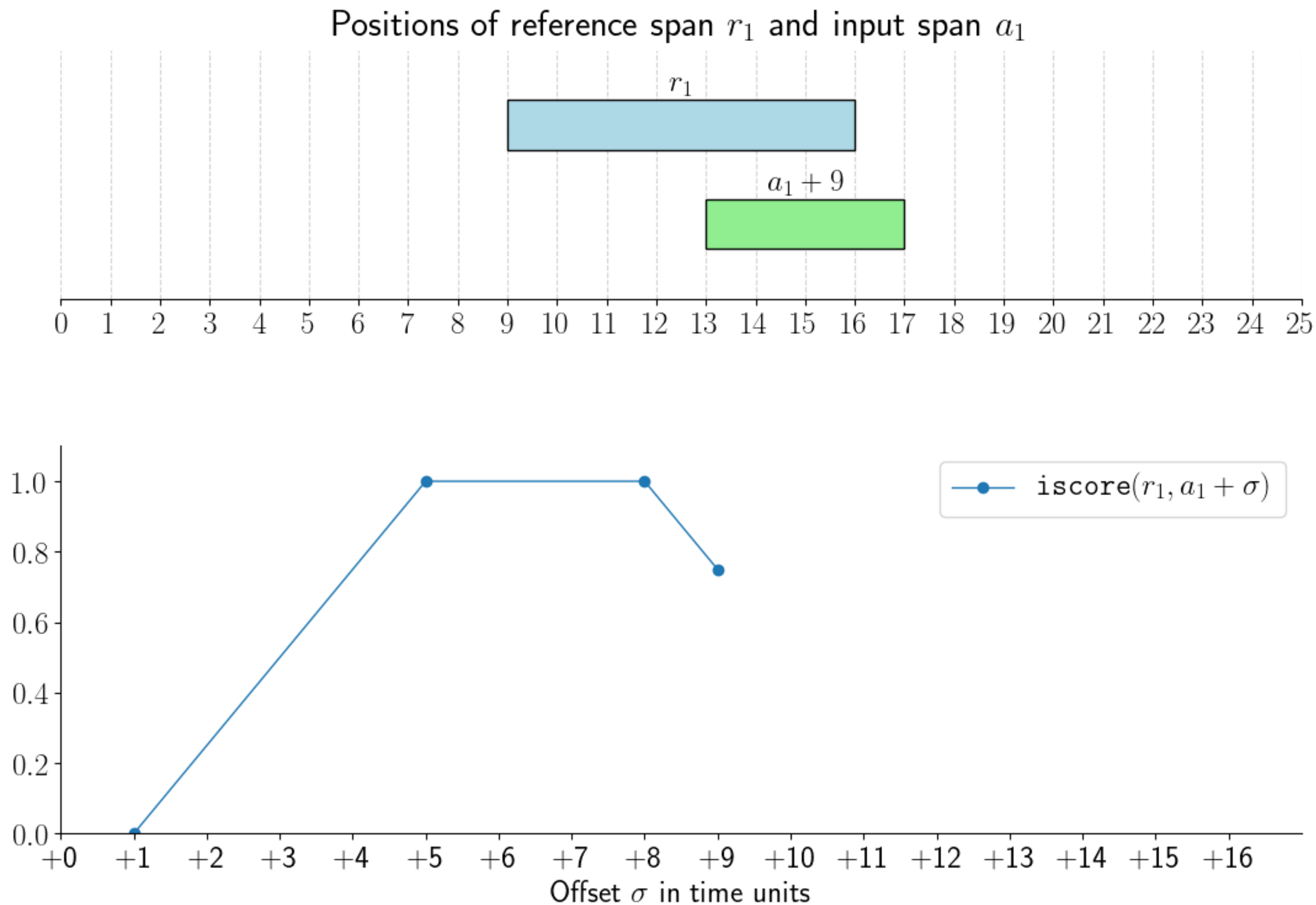

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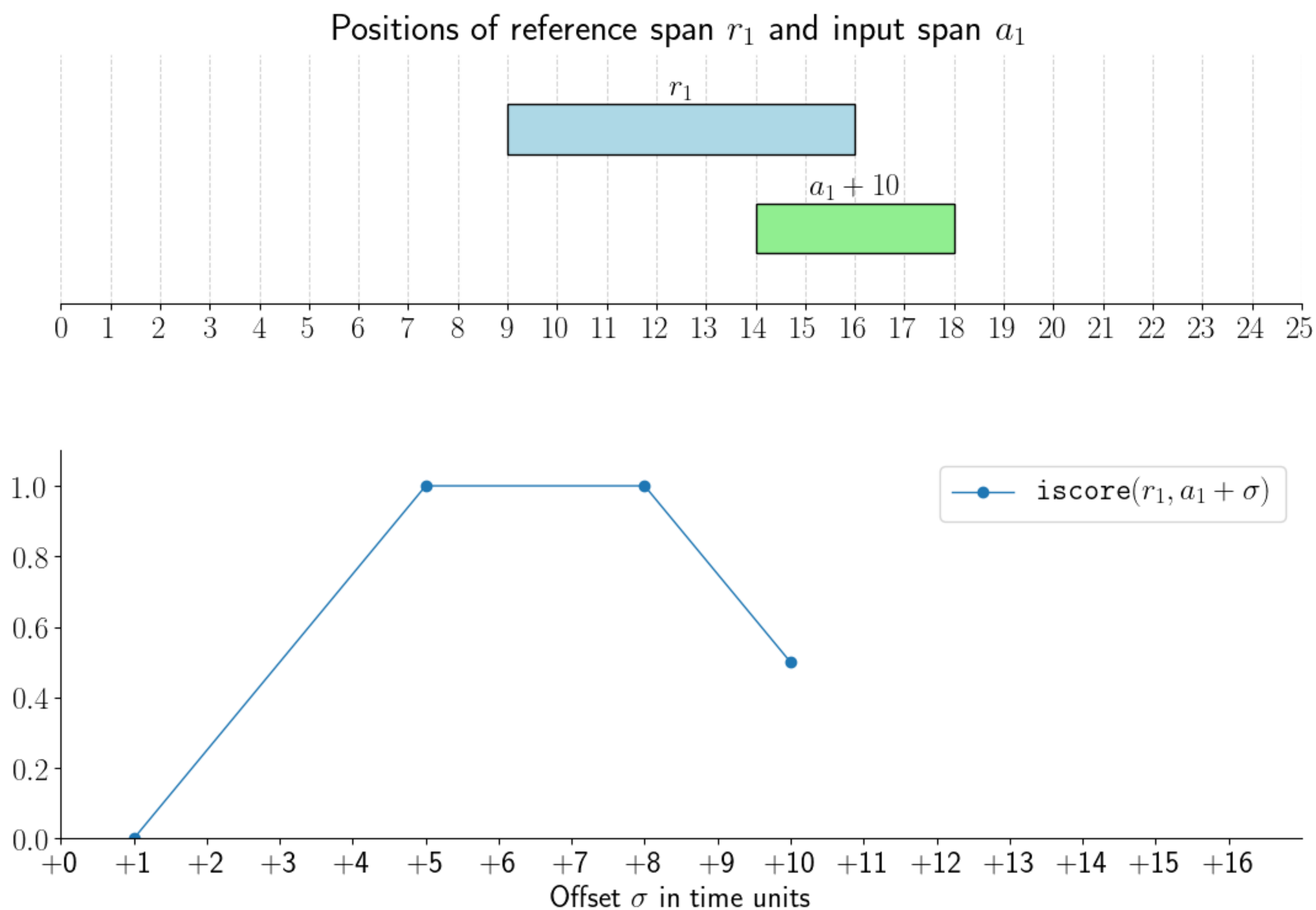

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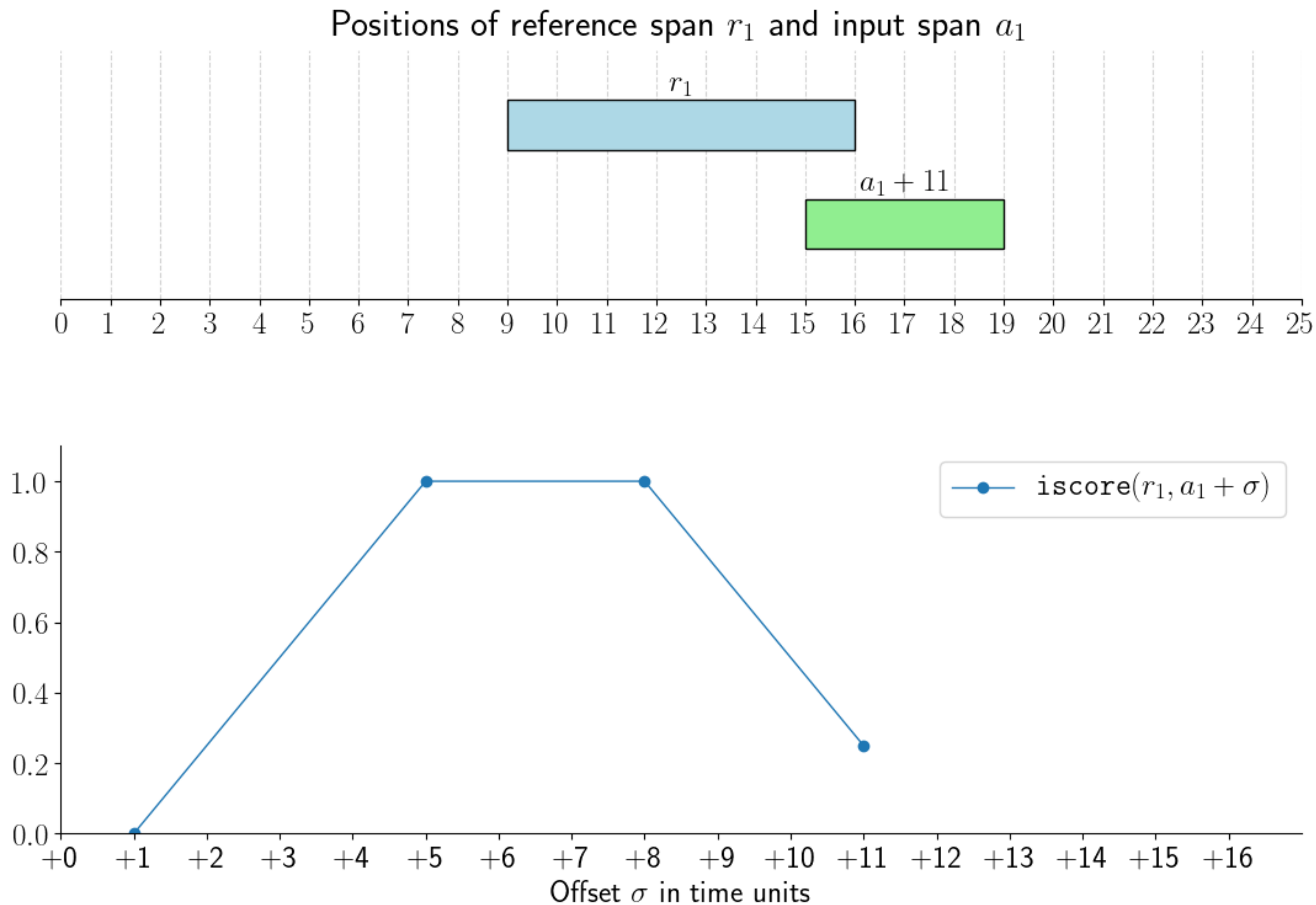

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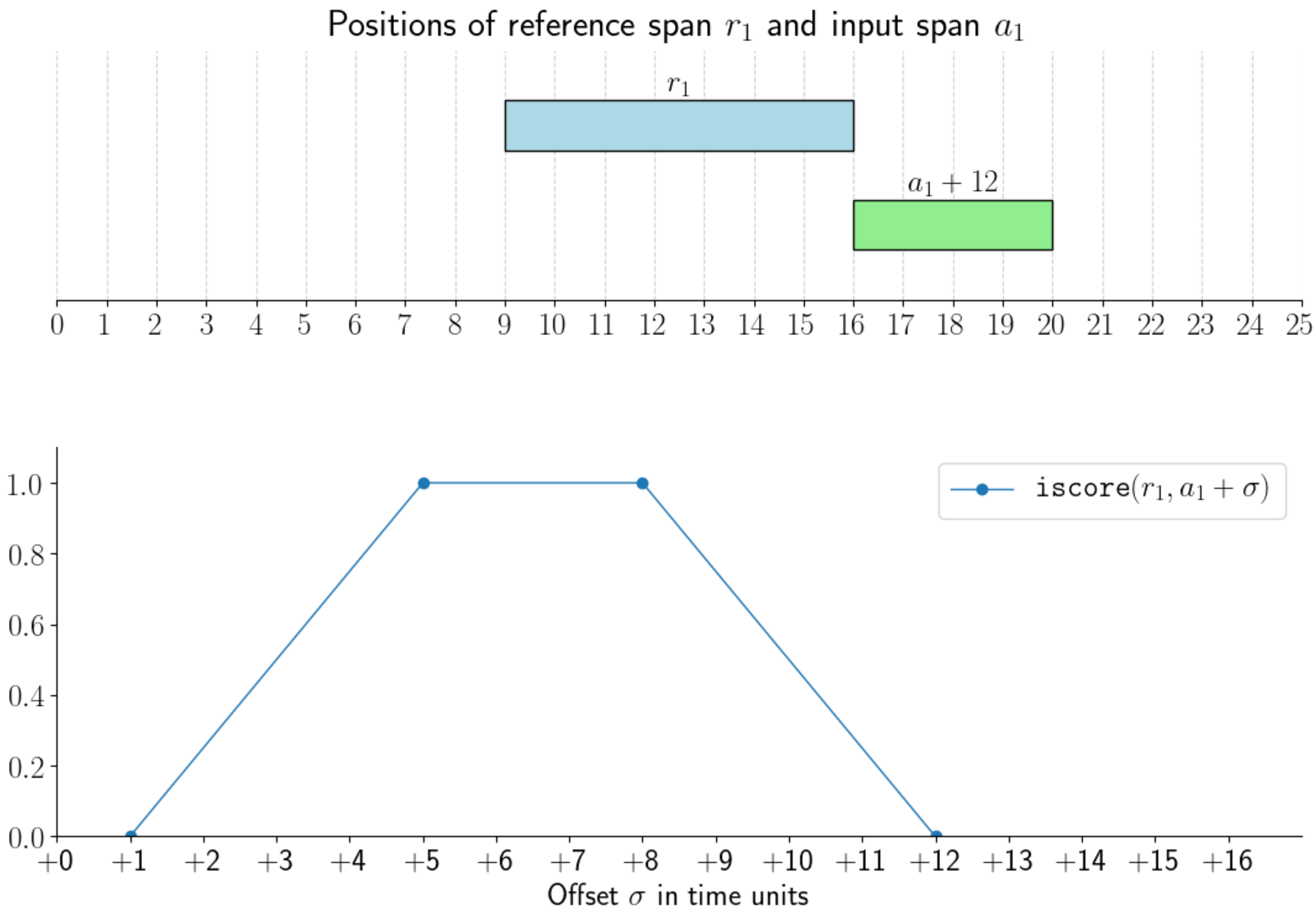

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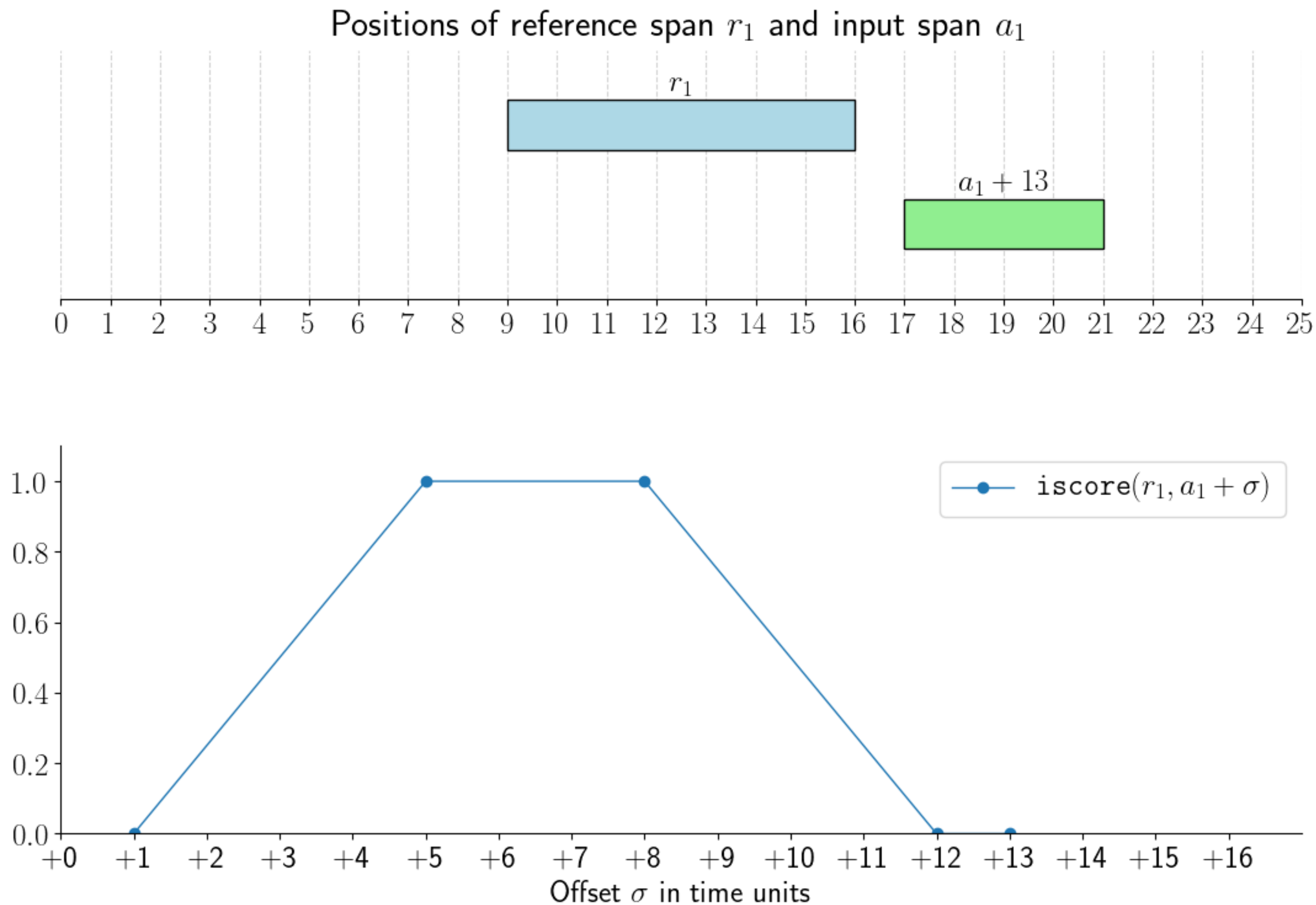

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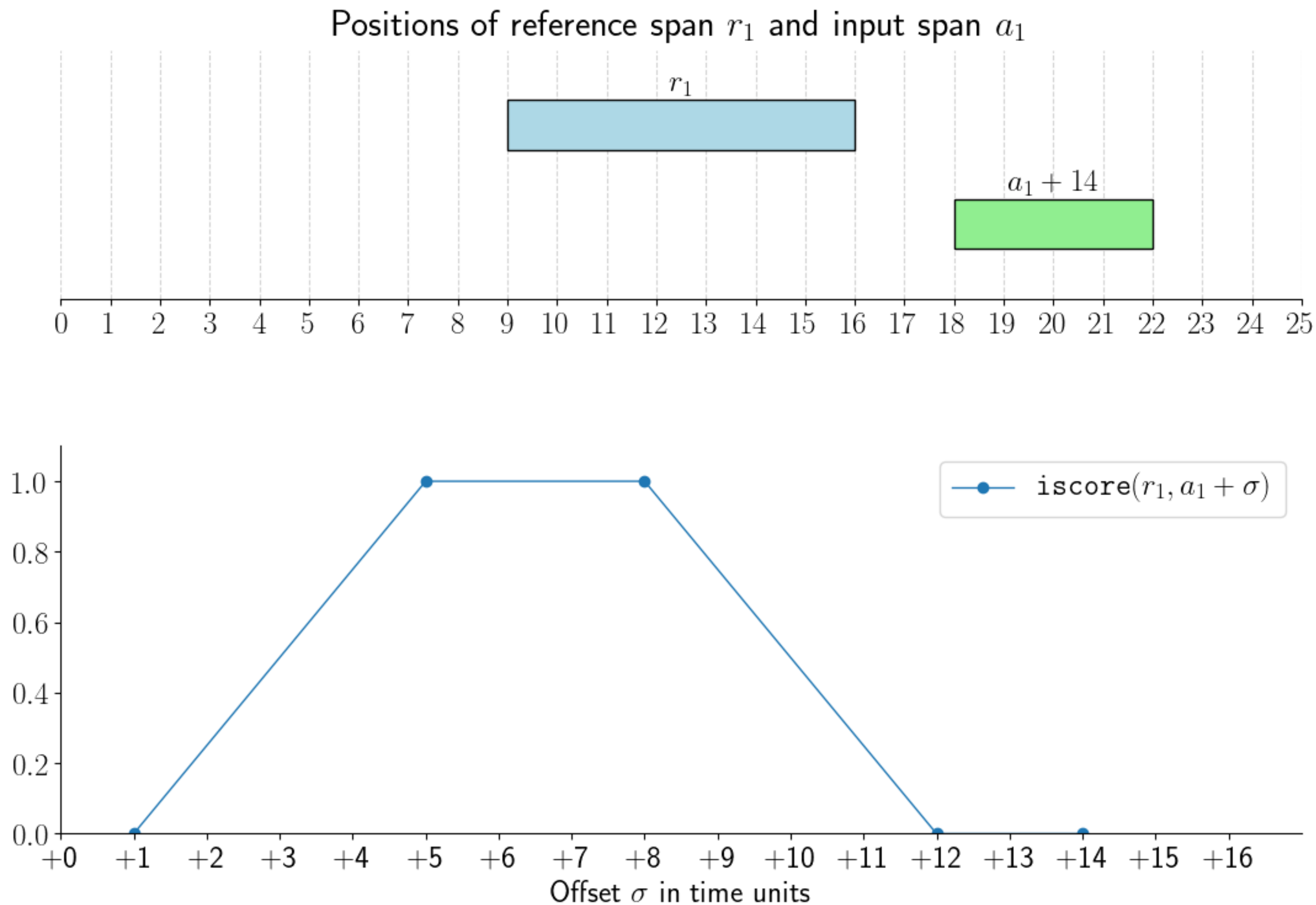

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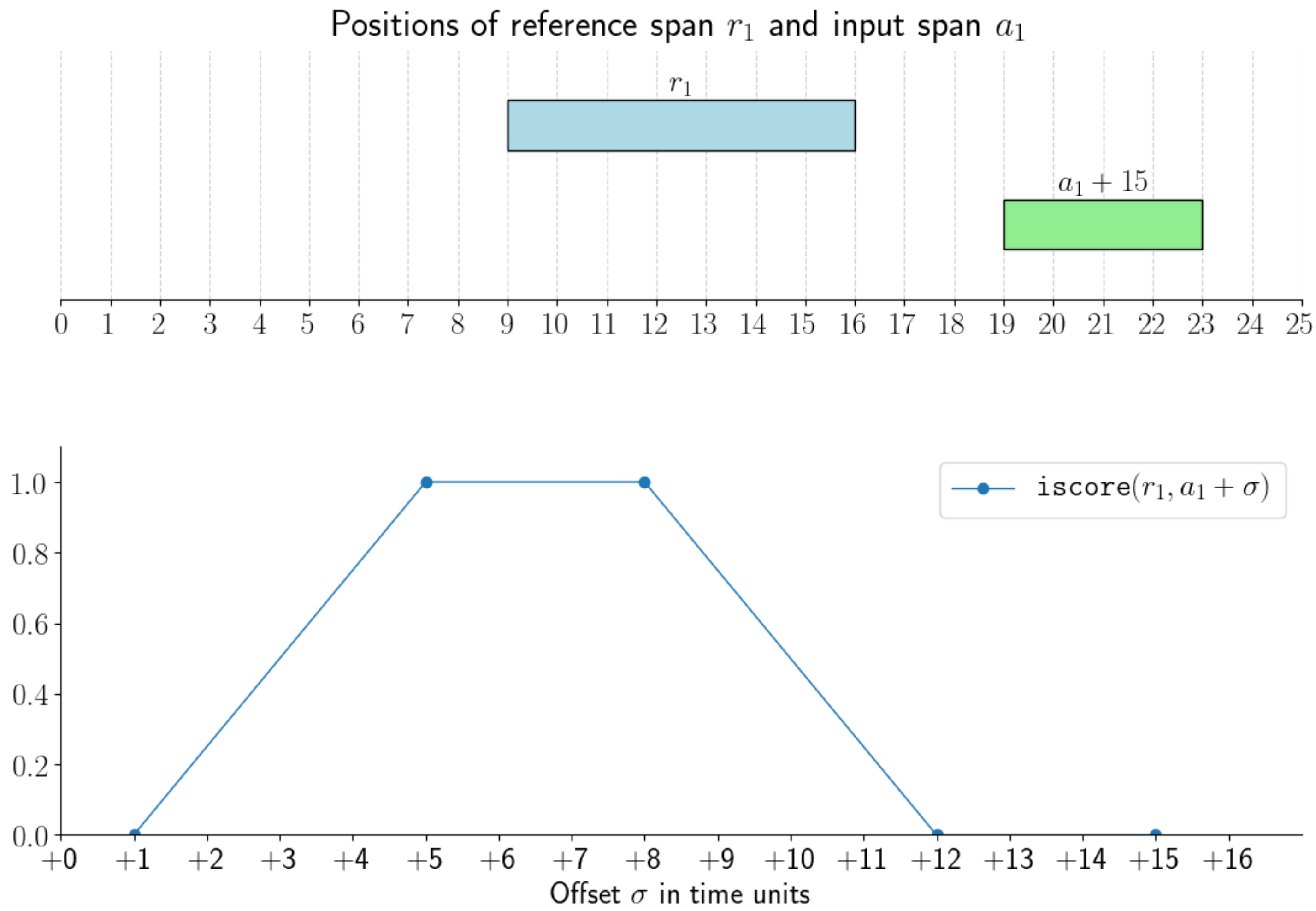

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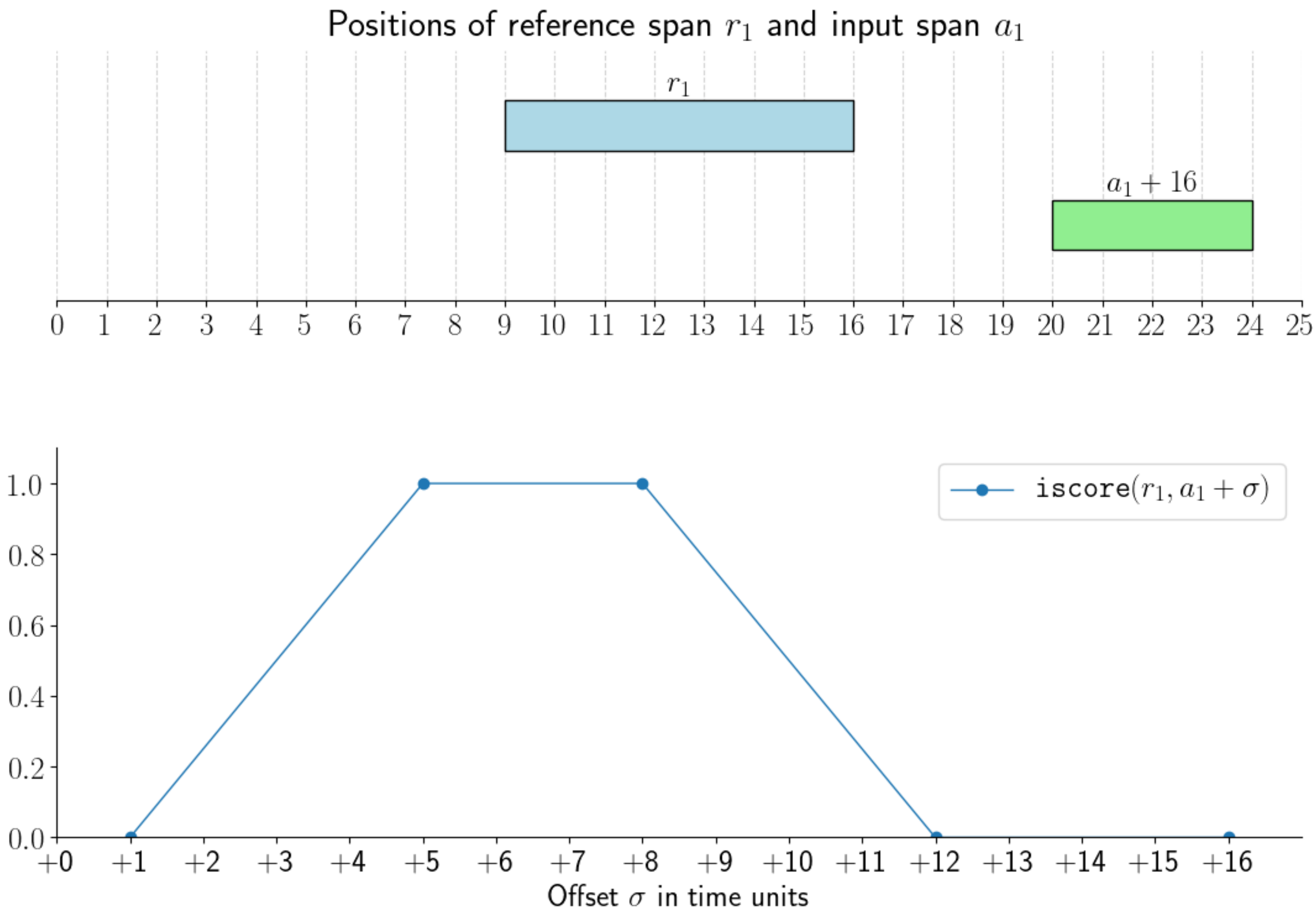

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Scoring for no-split alignments

Given two sequences of spans $r = (r_1, r_2, \ldots, r_K)$ and $a = (a_1, a_2, \ldots, a_N)$, and a weighting function $w : \{1, \ldots, K\} \times \{1, \ldots, N\} \to \mathbb{R}_{>0}$ the `nosplit_score` is defined as

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Exemplary weighting function

$$w(k, n) = \frac{\min(\texttt{length}(r_k), \texttt{length}(a_n))}{\max(\texttt{length}(r_k), \texttt{length}(a_n))}$$

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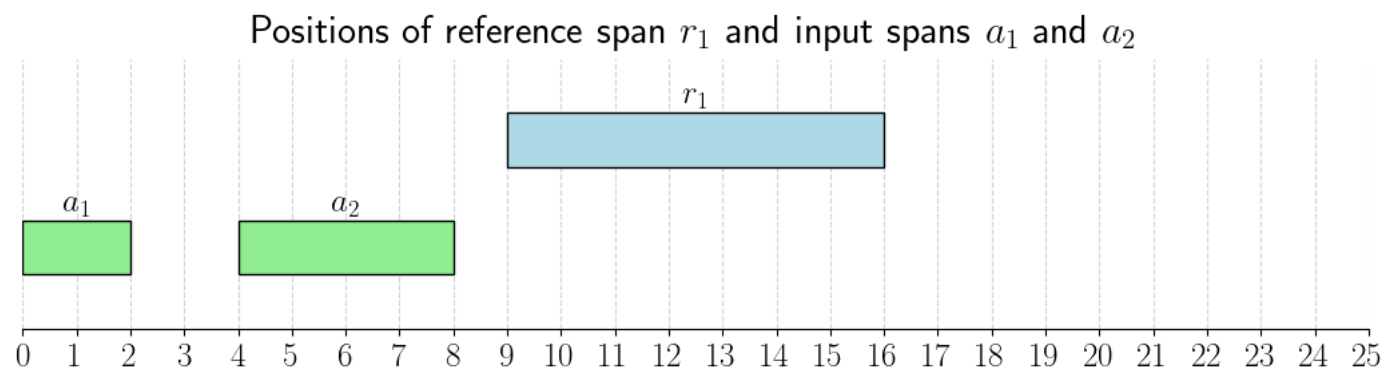

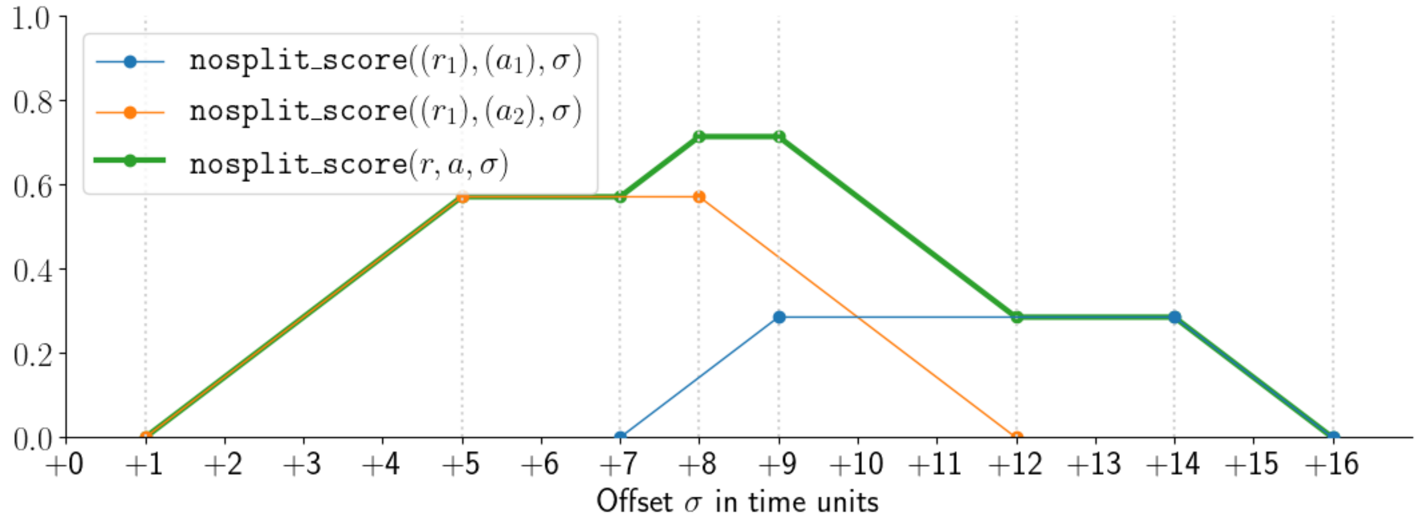

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Finding the optimal no-split offset σ

$$\begin{aligned} K &\approx 1300 \\ N &\approx 1300 \\ T_r = \mathtt{end}(r_K) - \mathtt{start}(r_1) &\approx 8'000'000 \\ T_a = \mathtt{end}(a_N) - \mathtt{start}(a_1) &\approx 8'000'000 \end{aligned}$$

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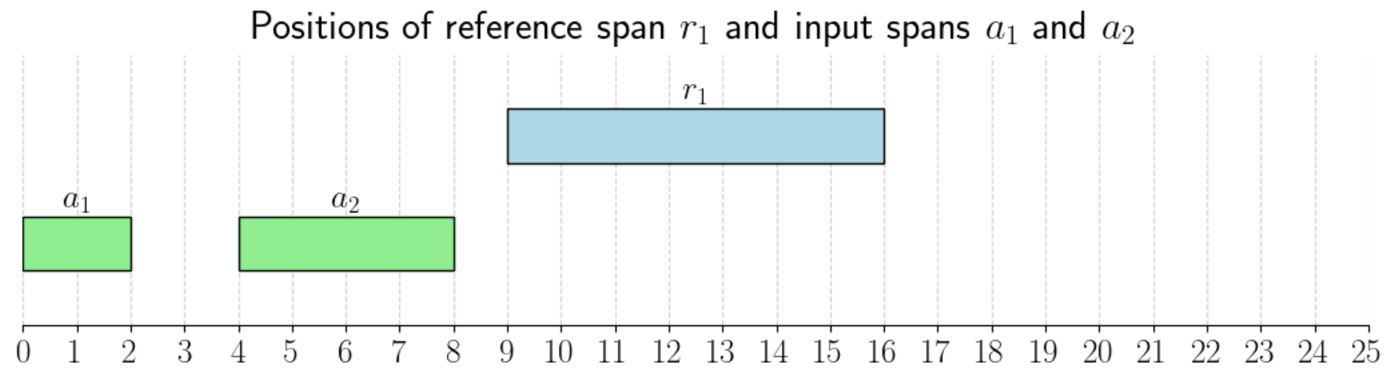

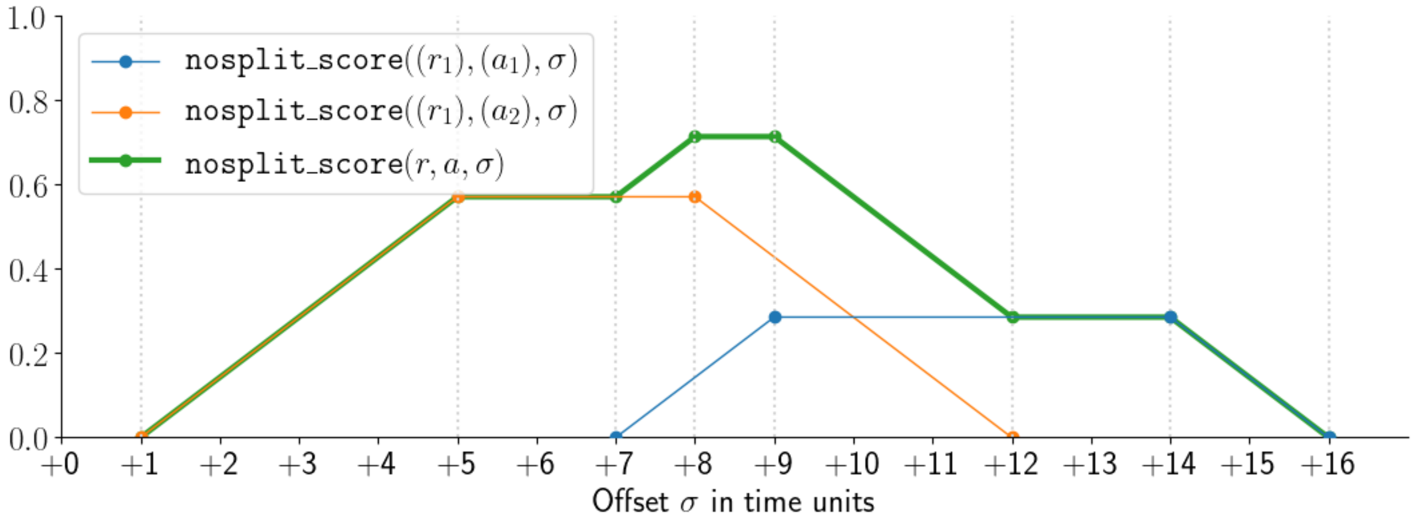

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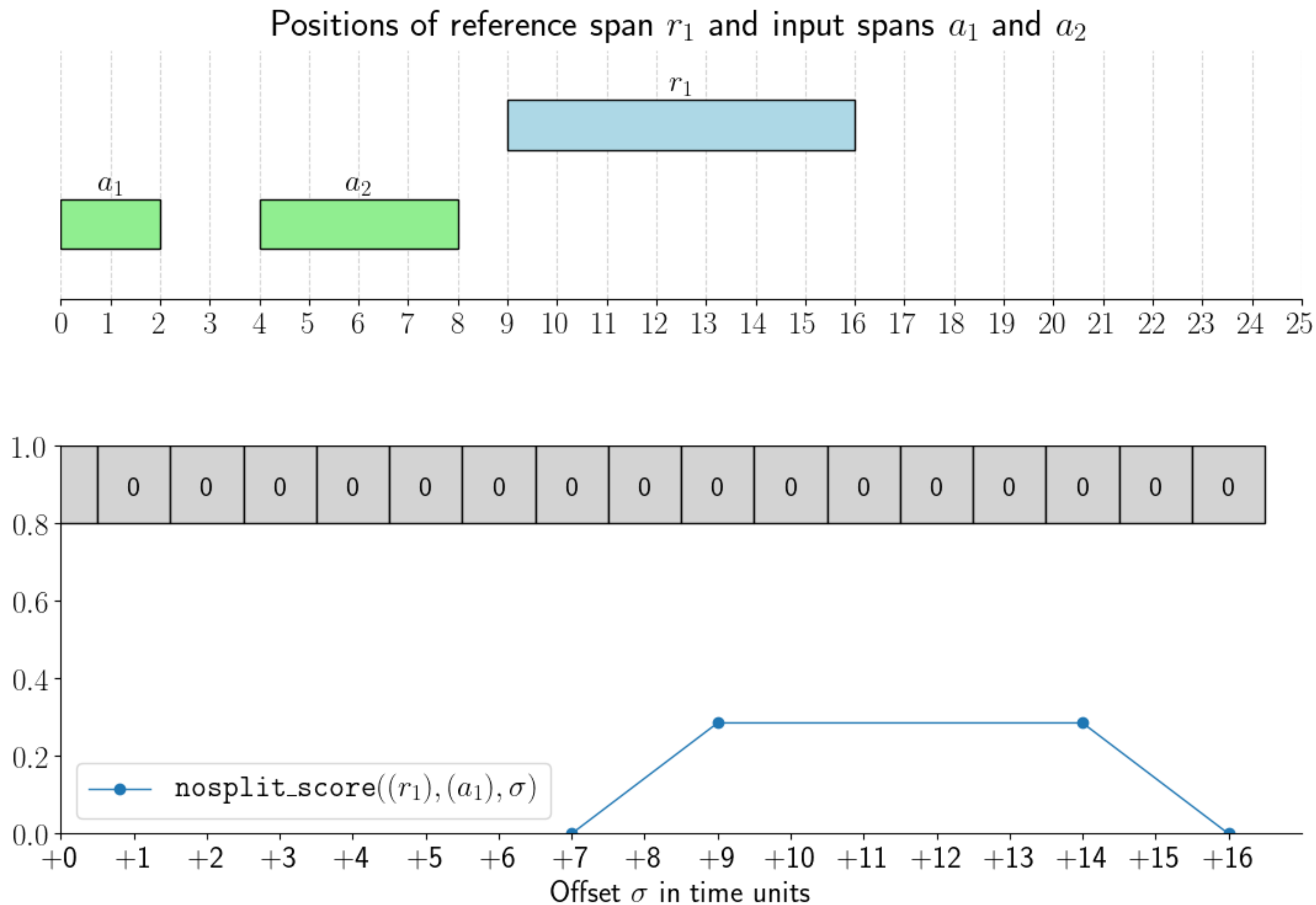

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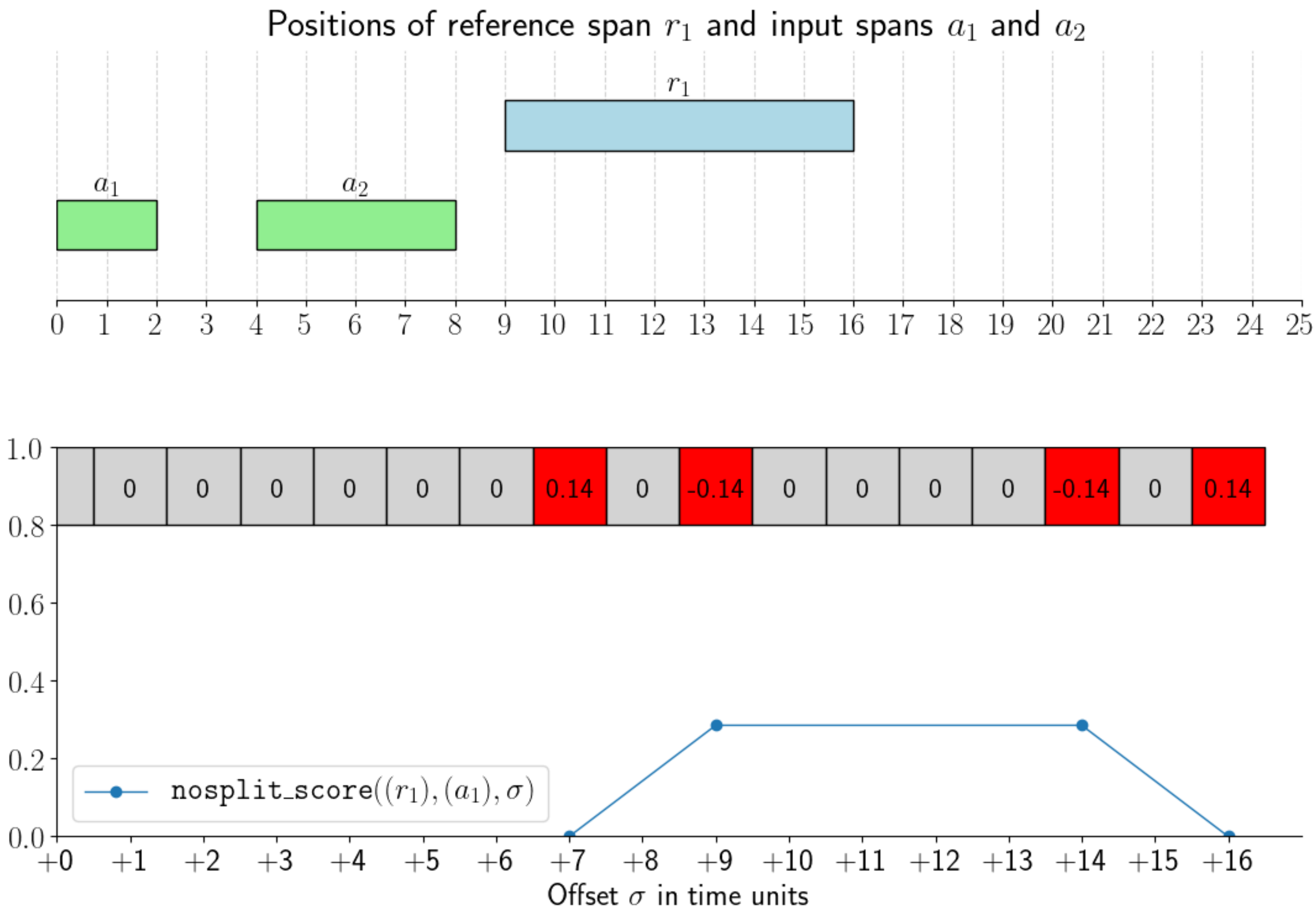

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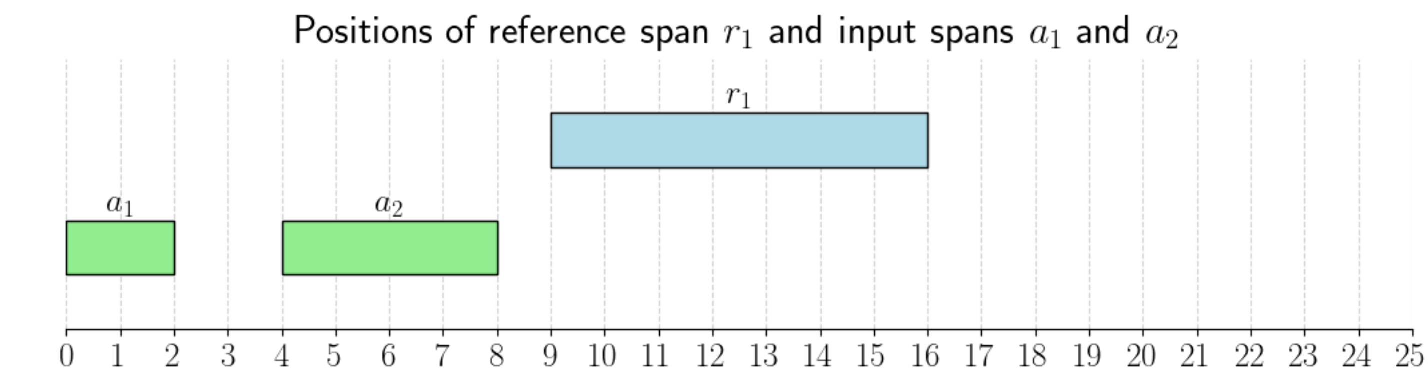

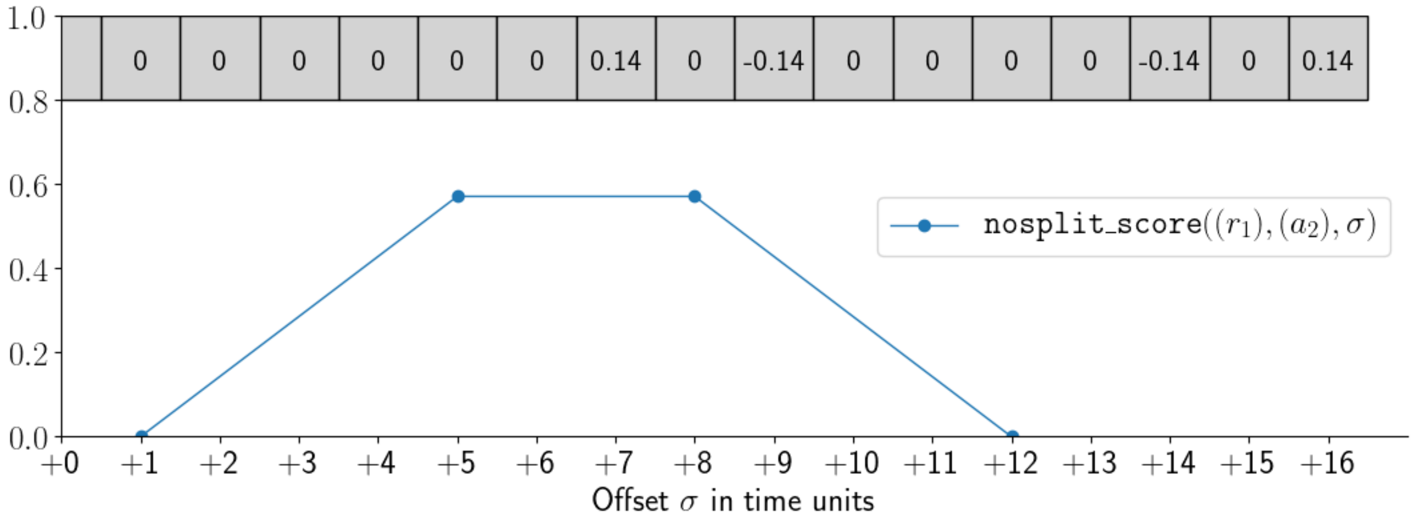

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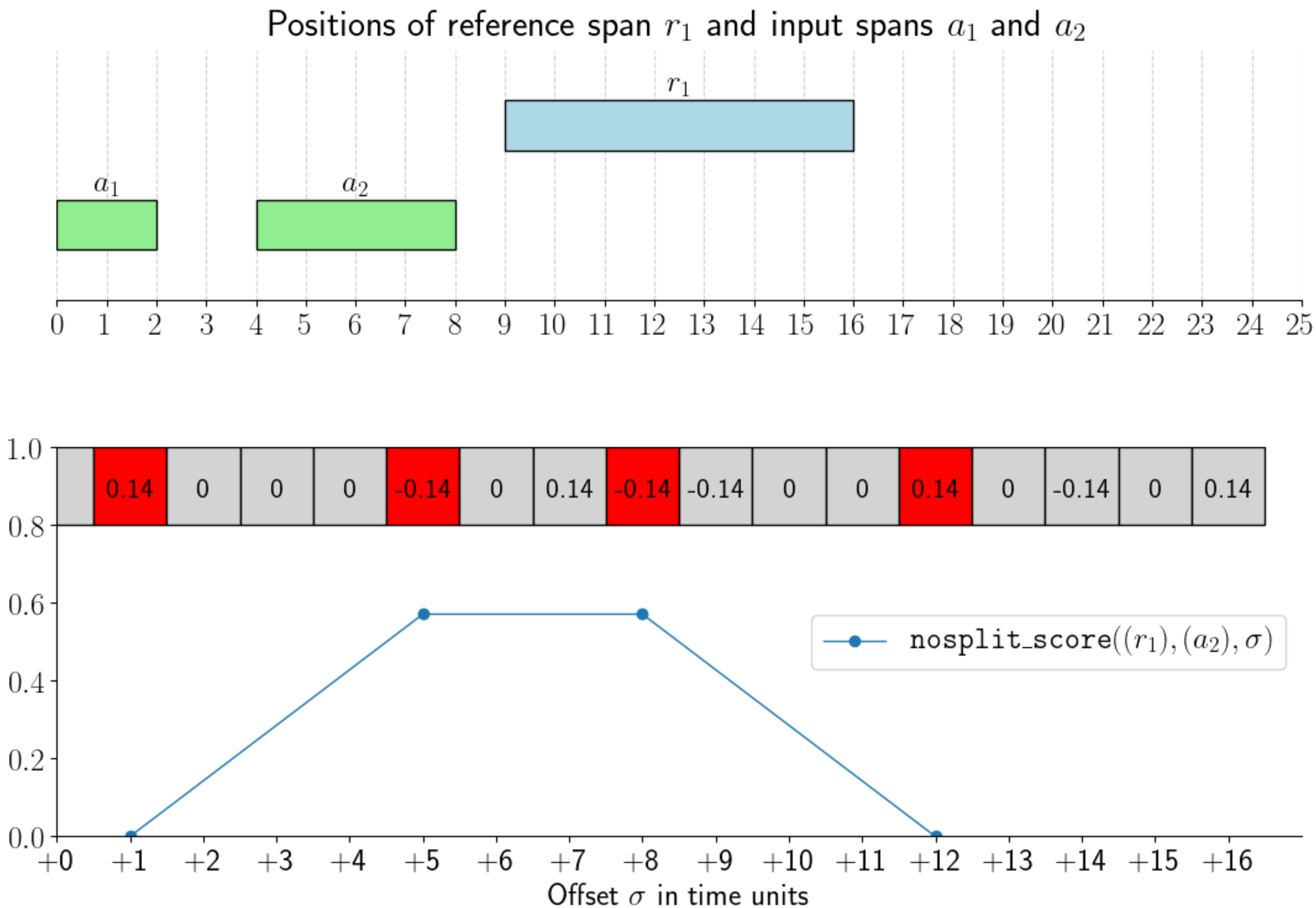

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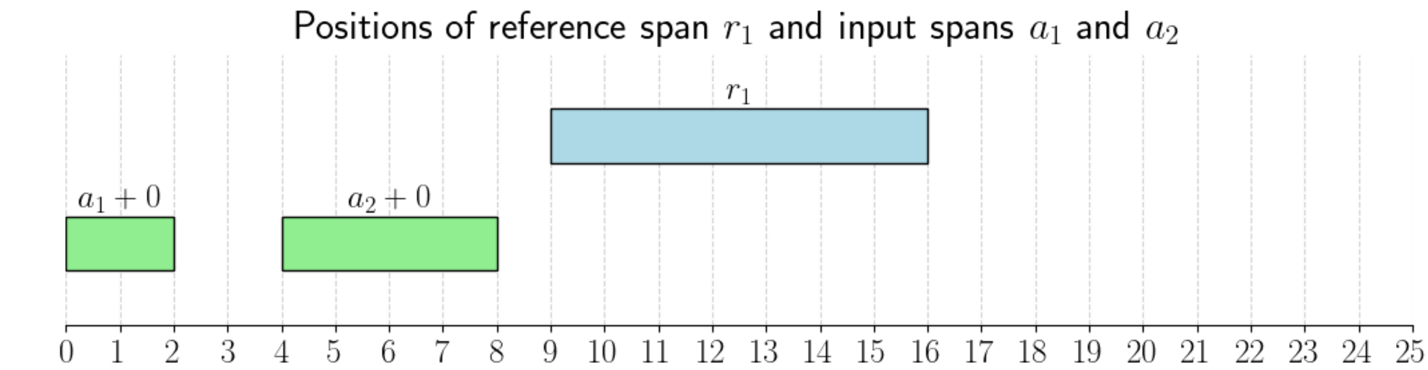

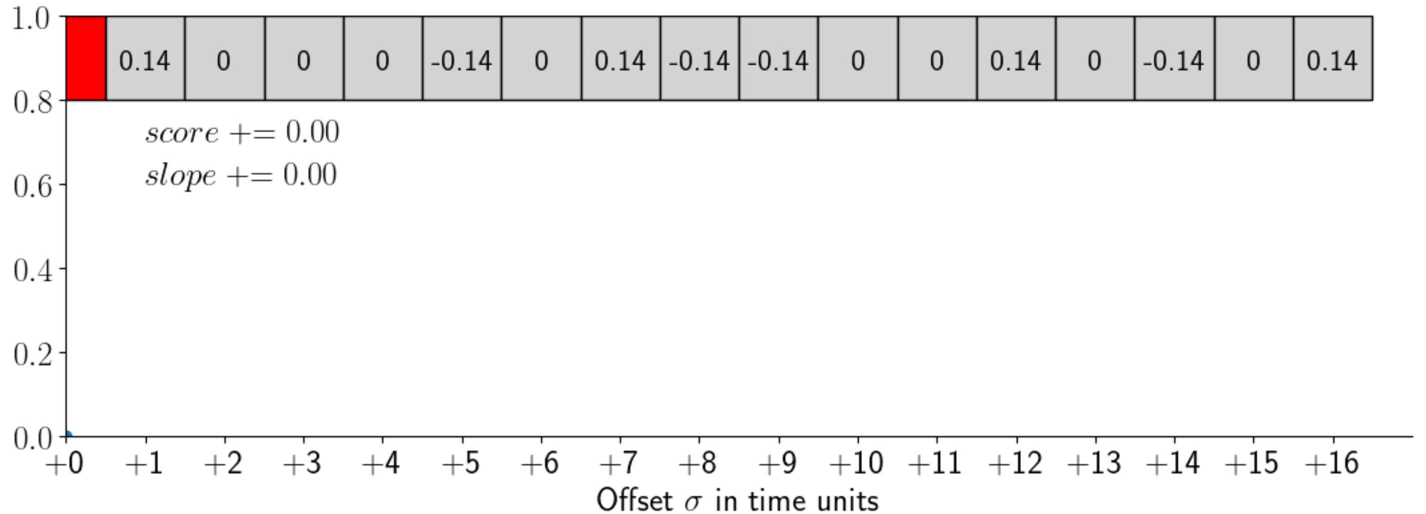

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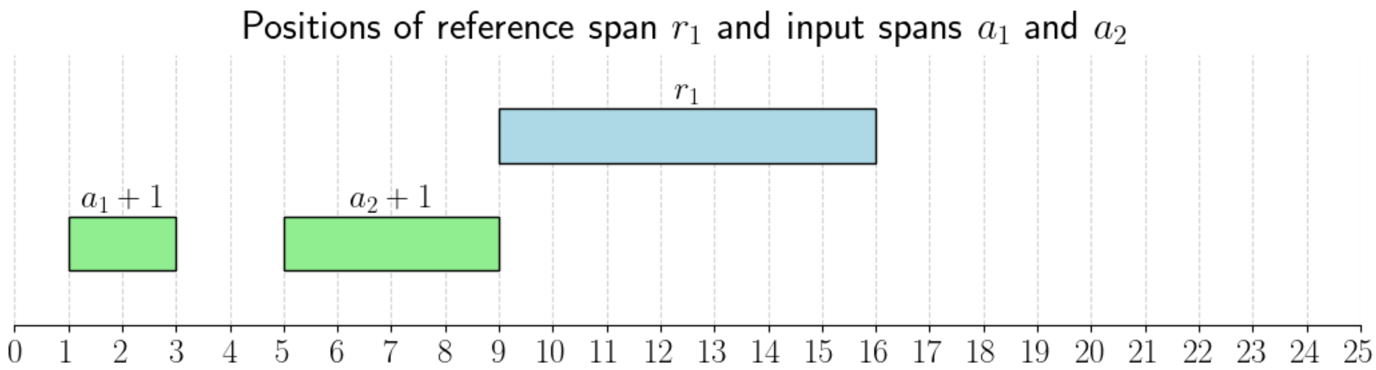

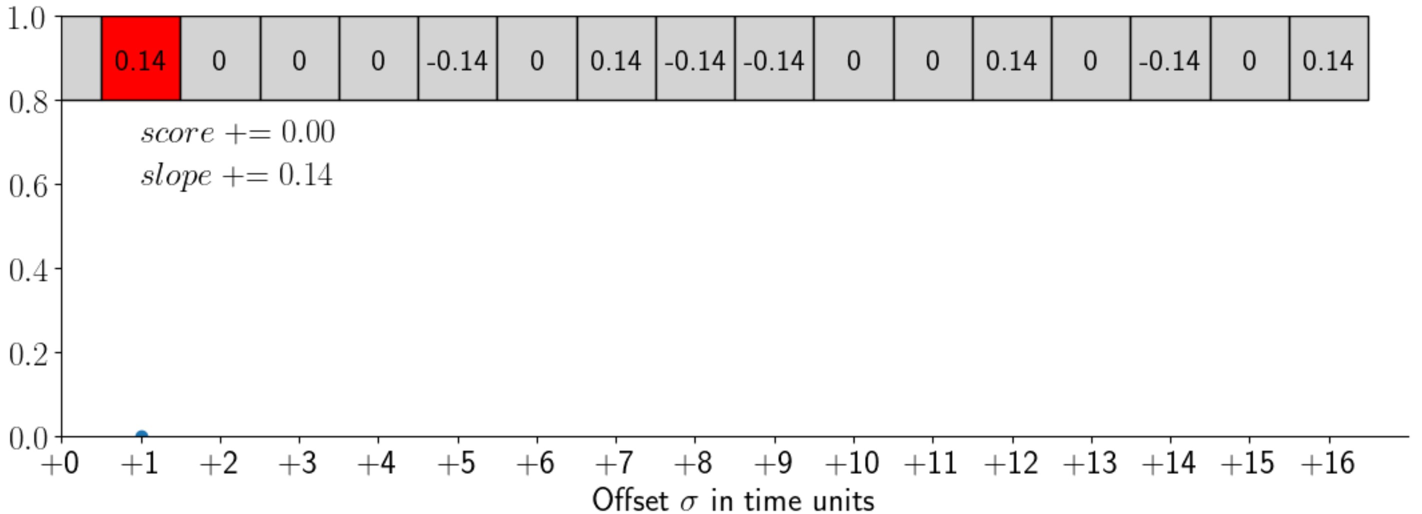

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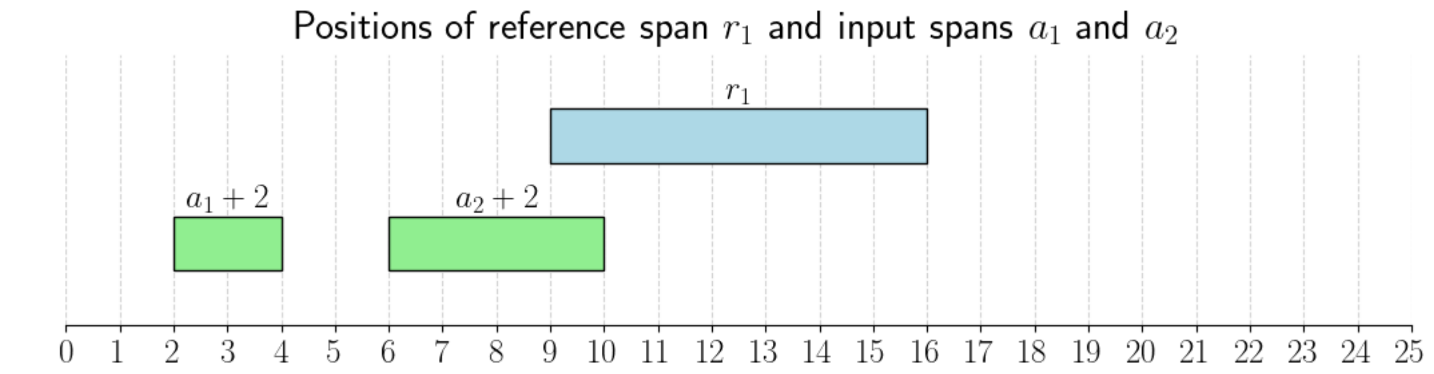

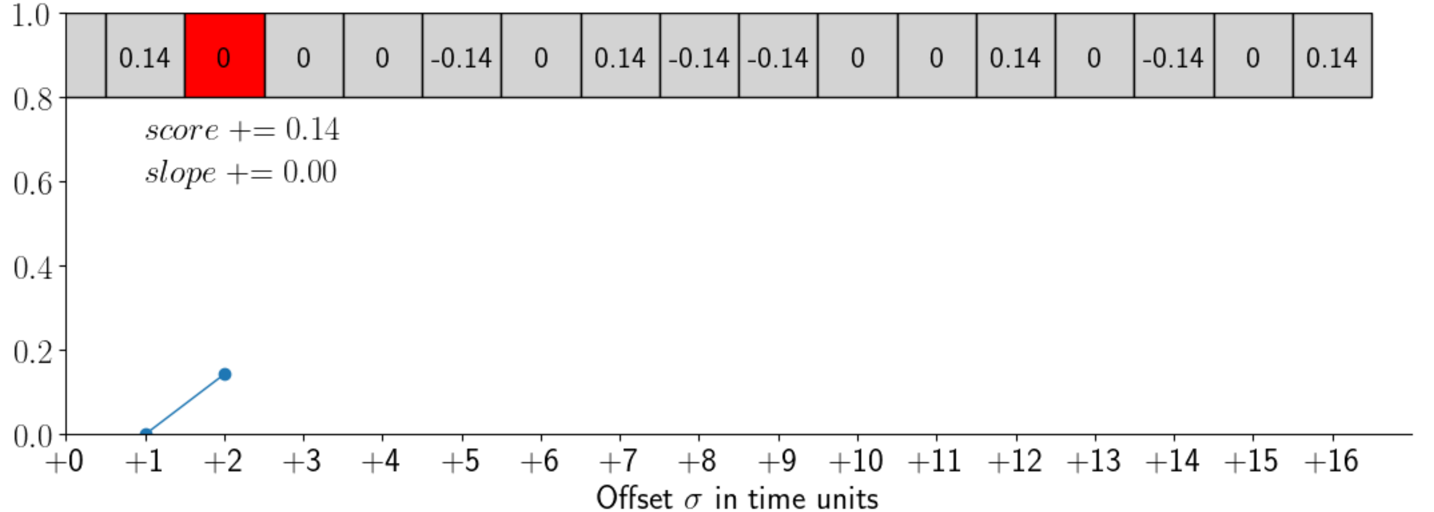

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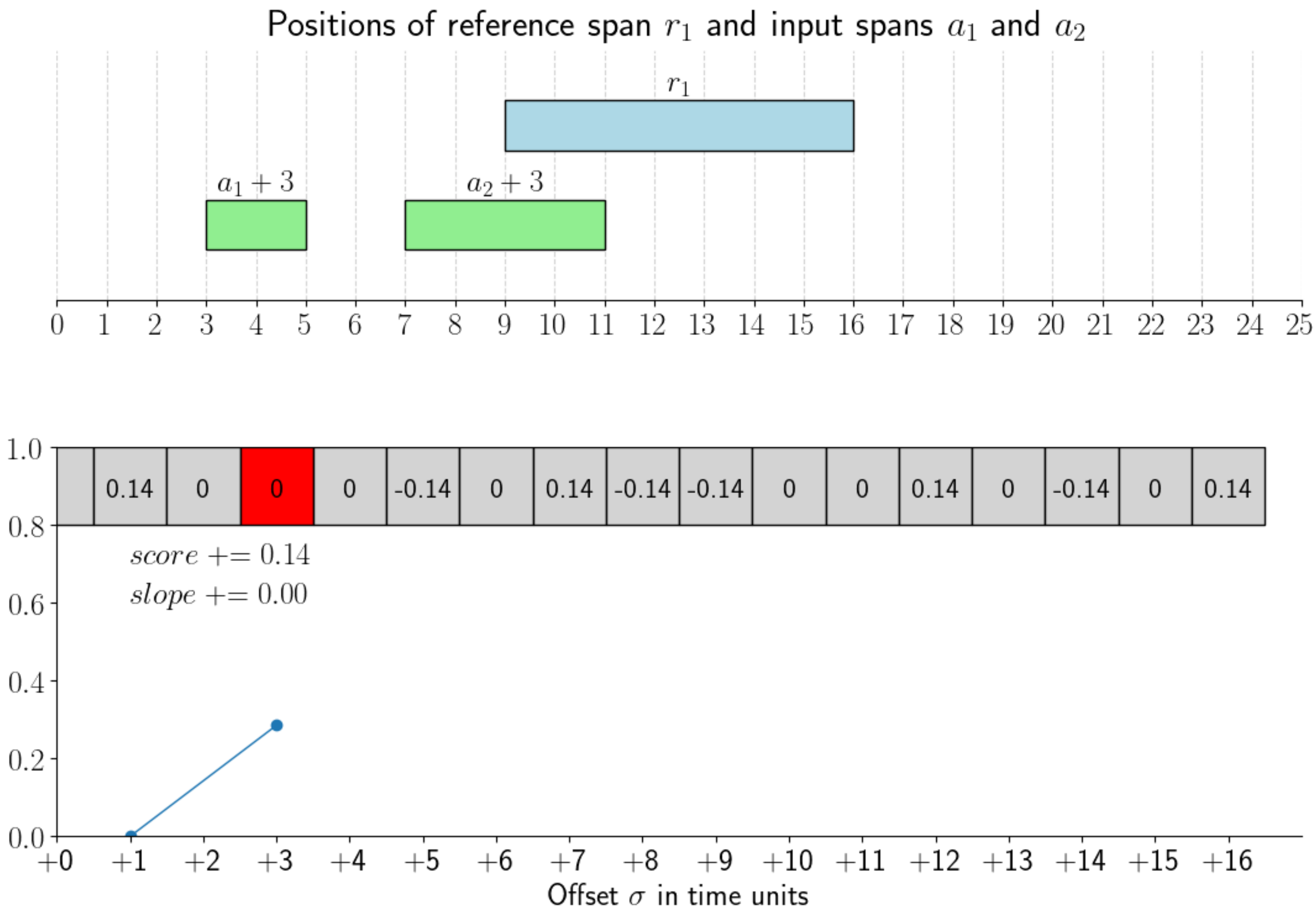

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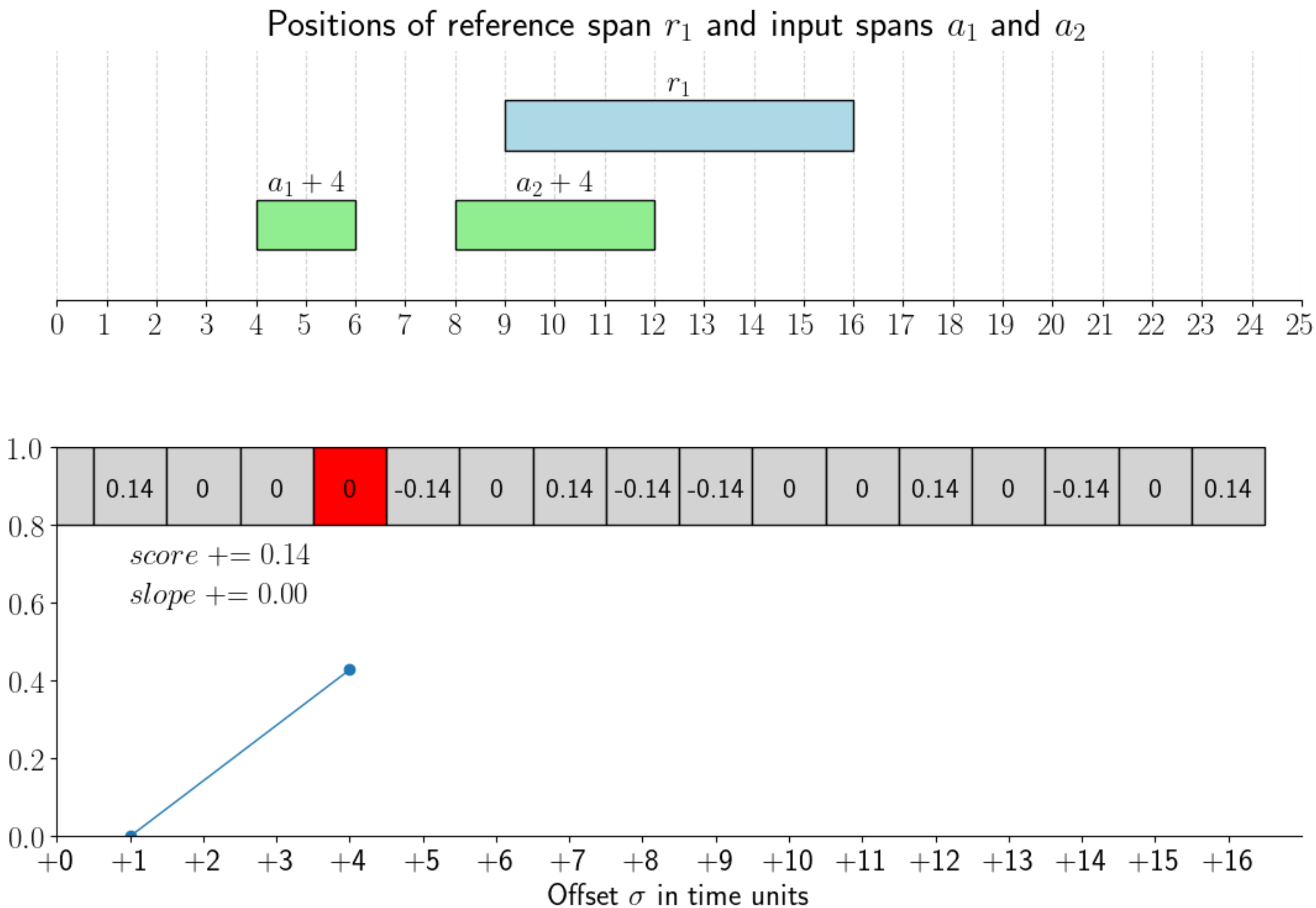

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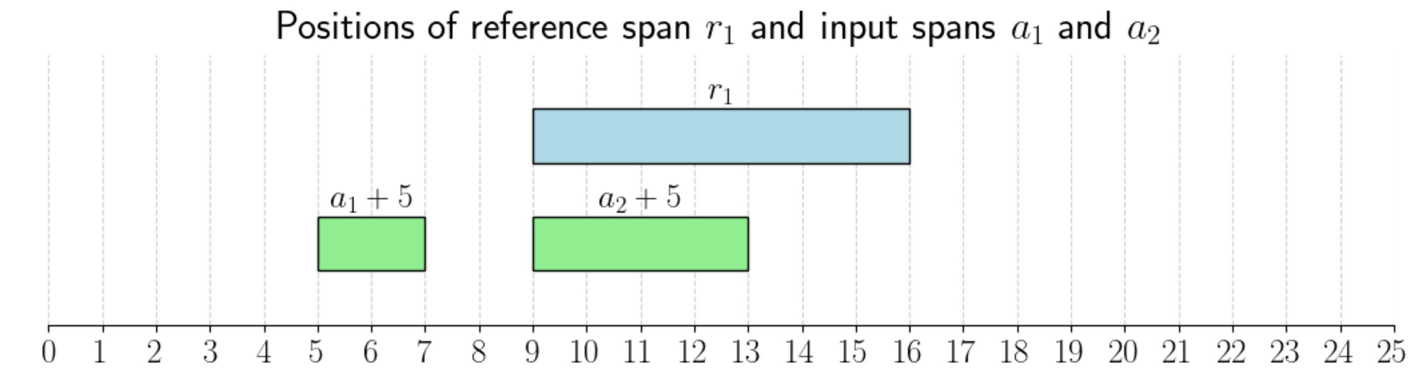

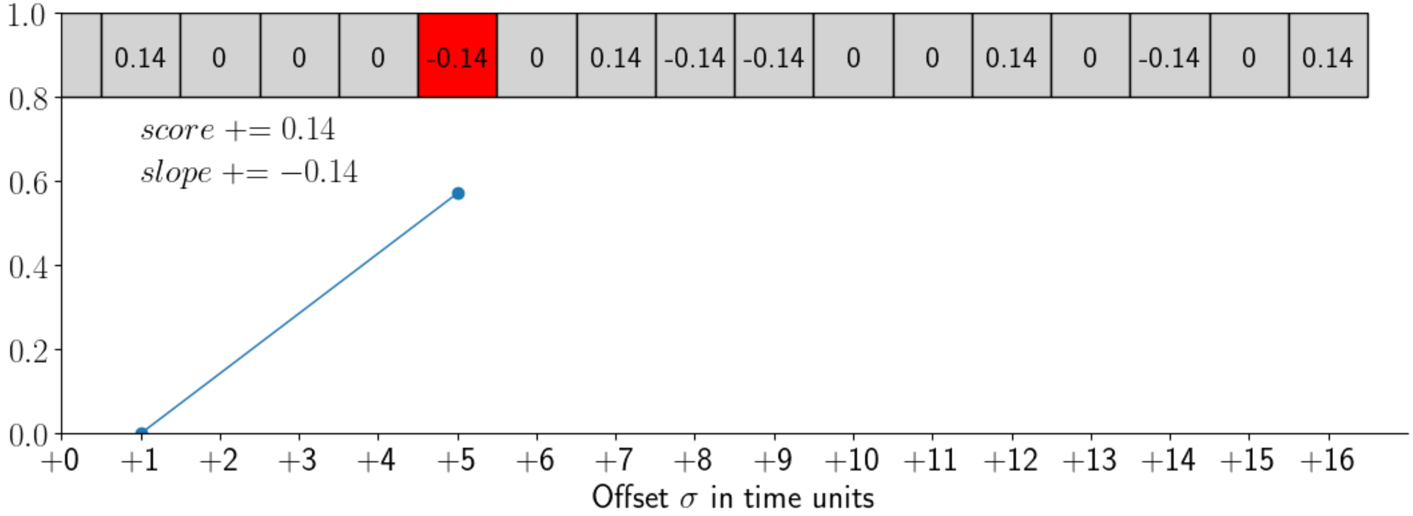

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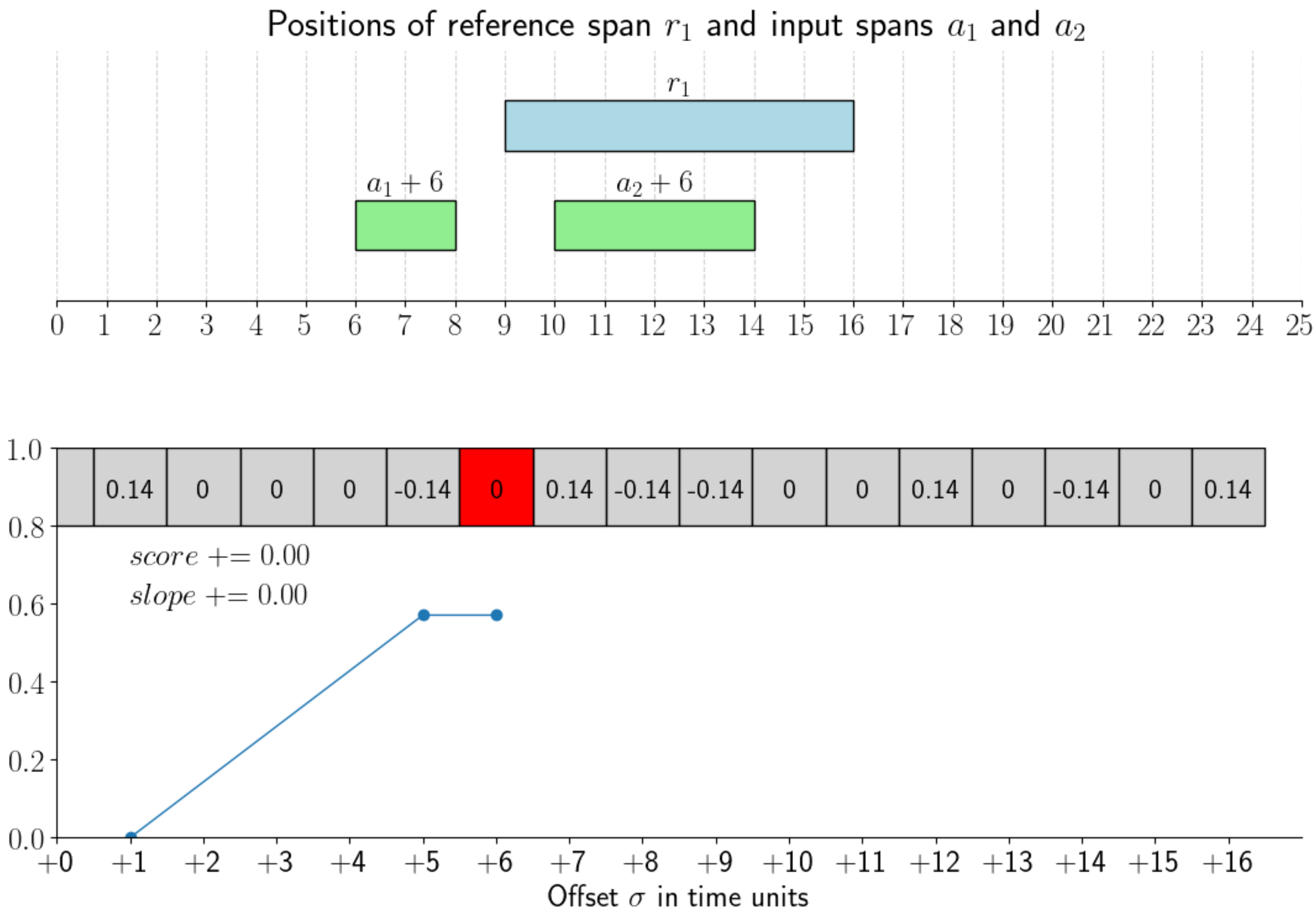

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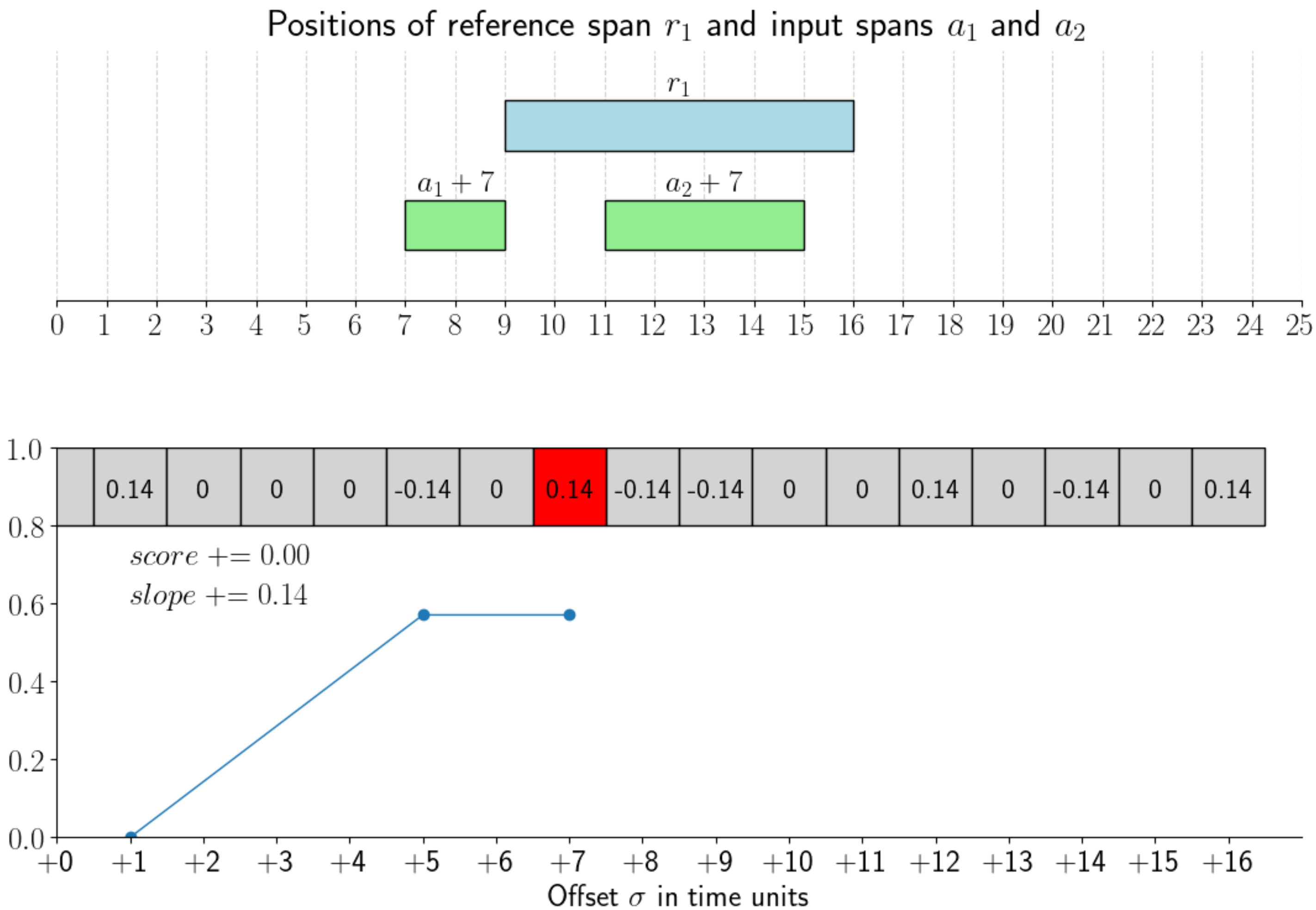

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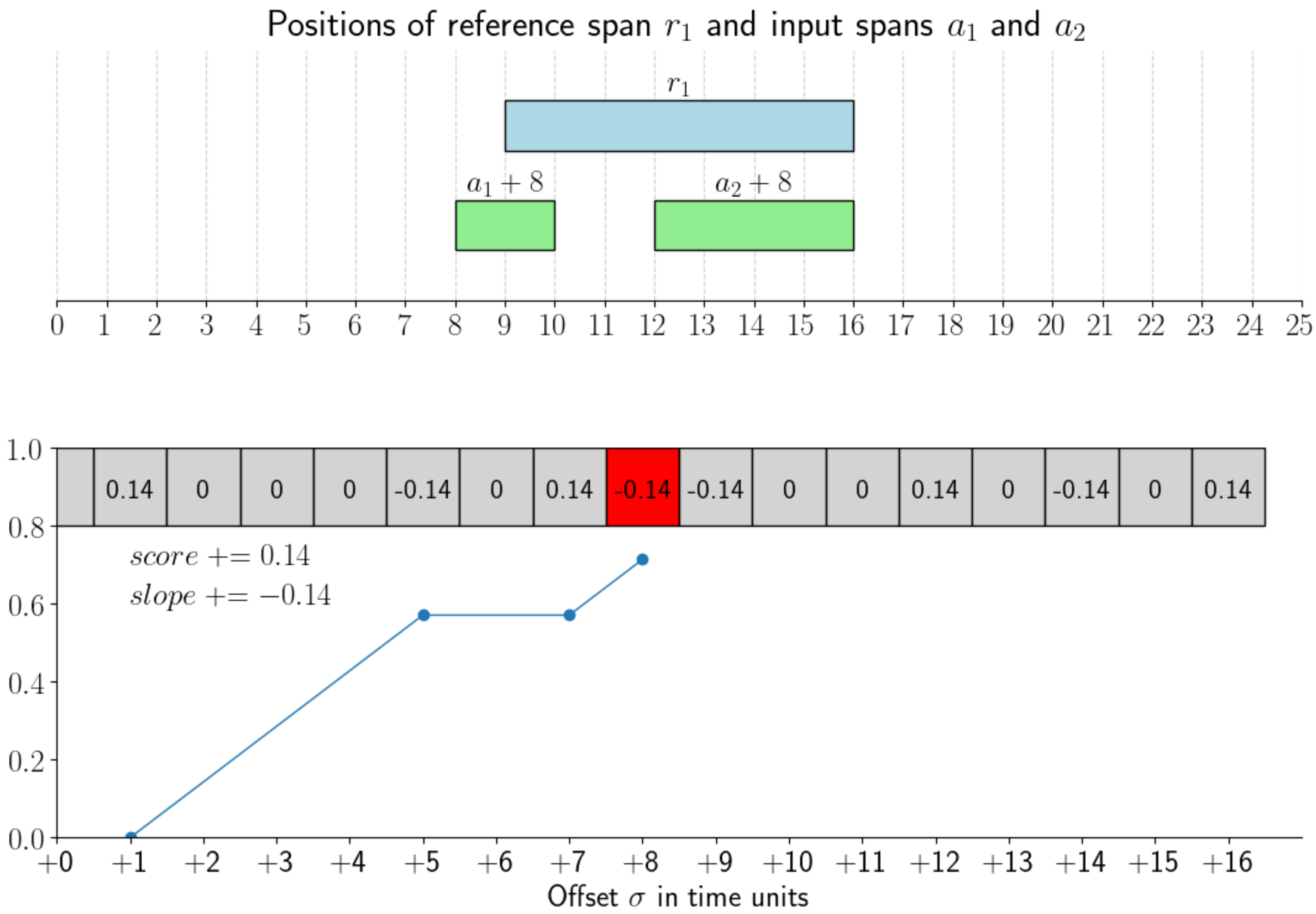

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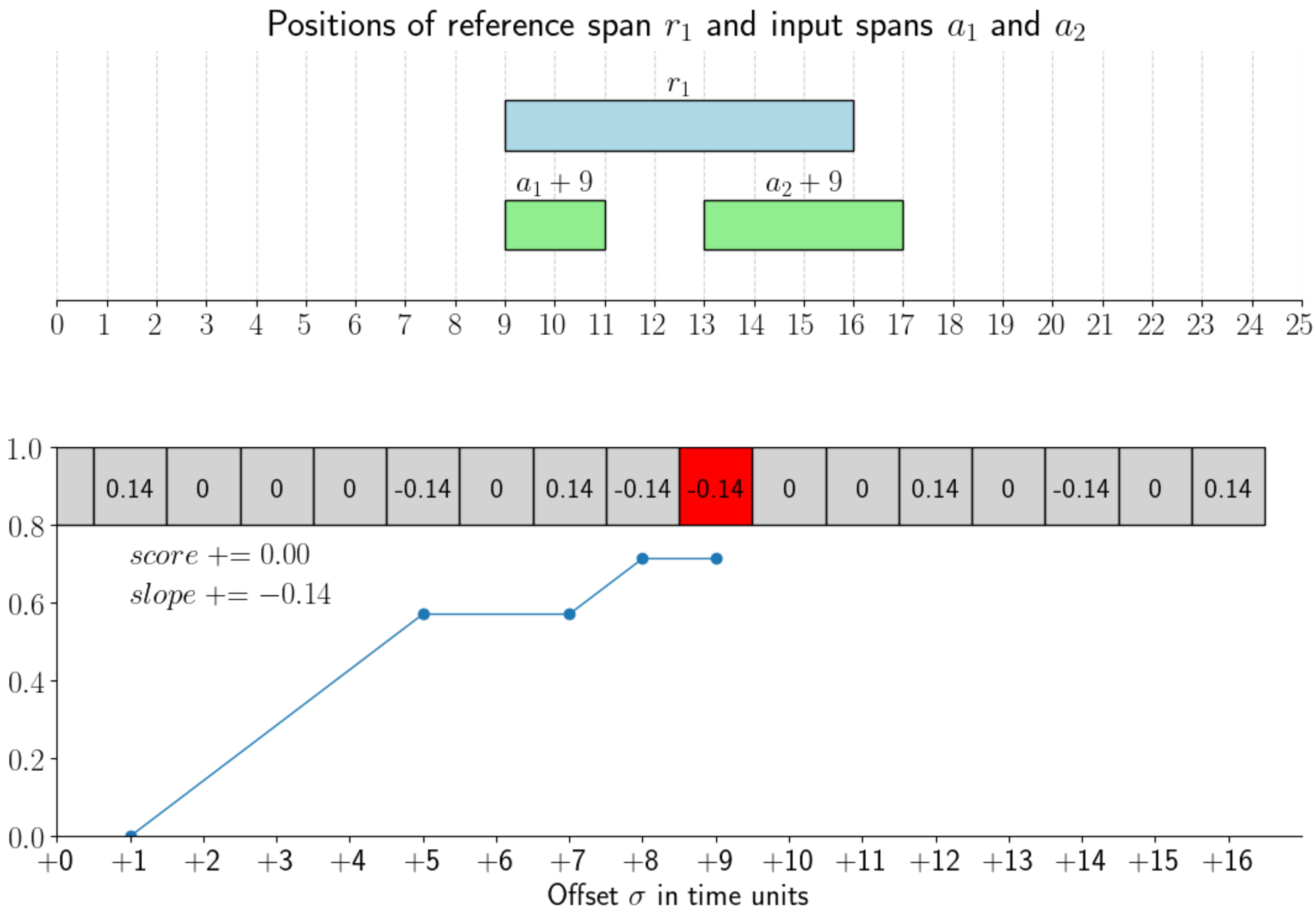

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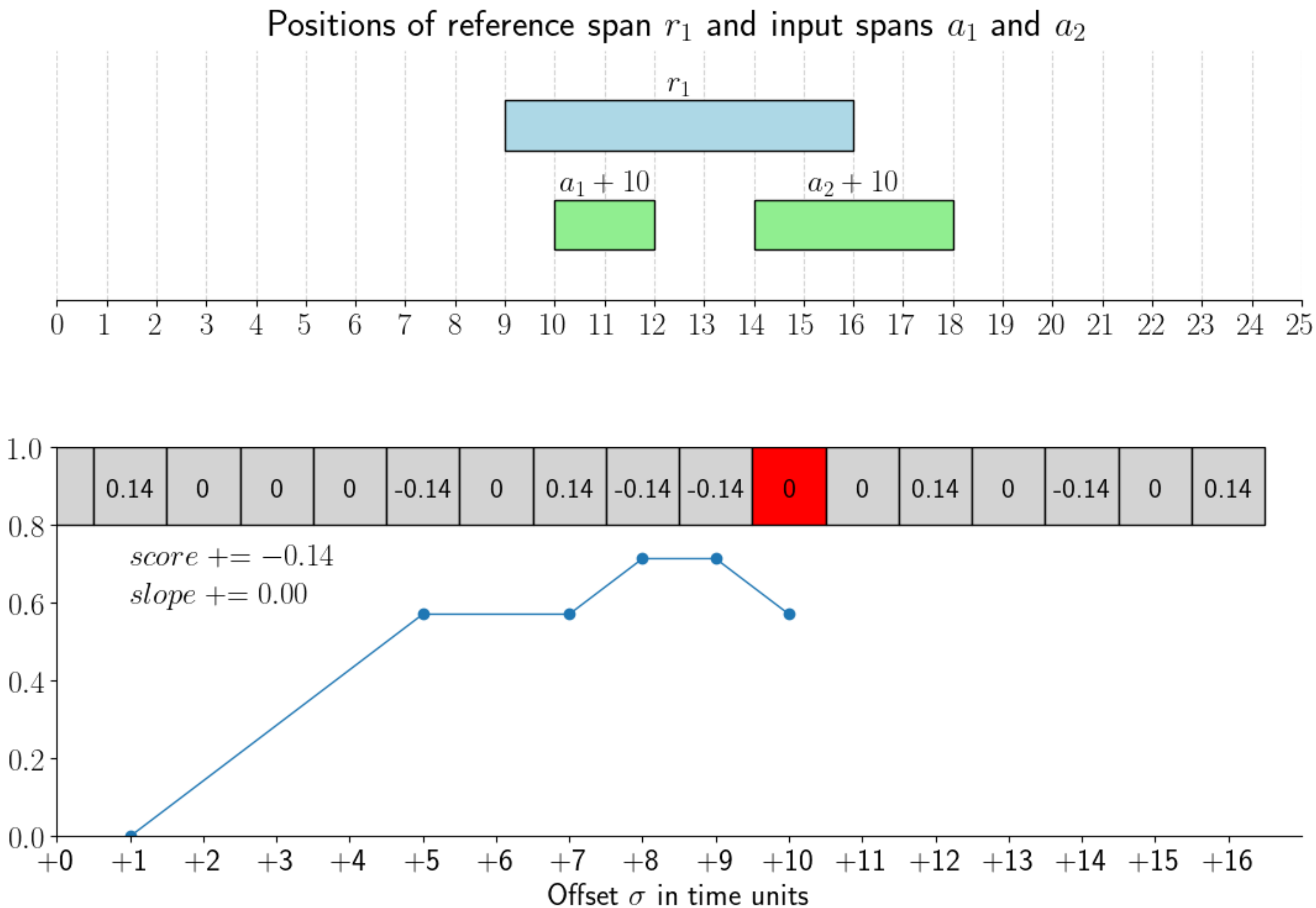

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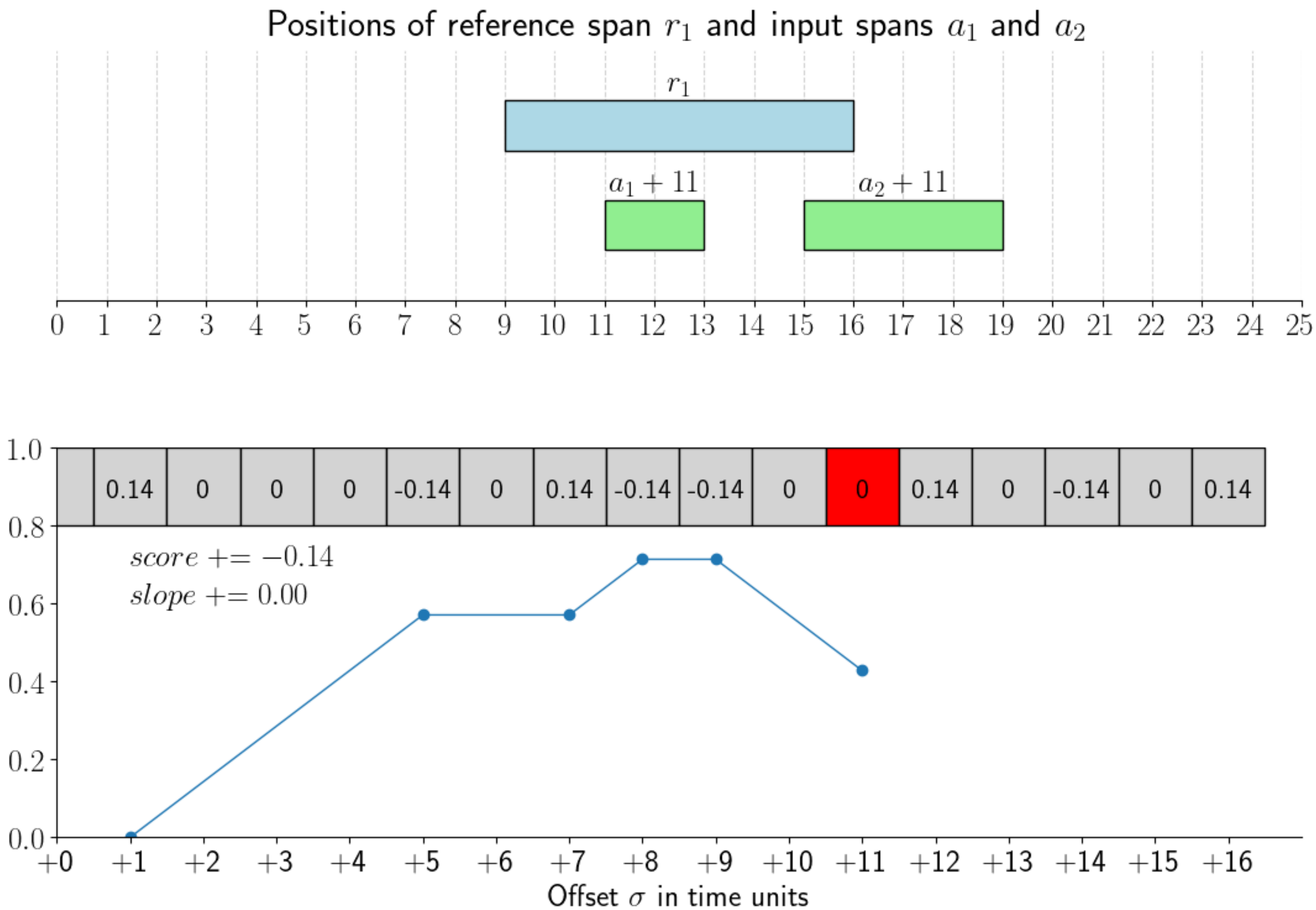

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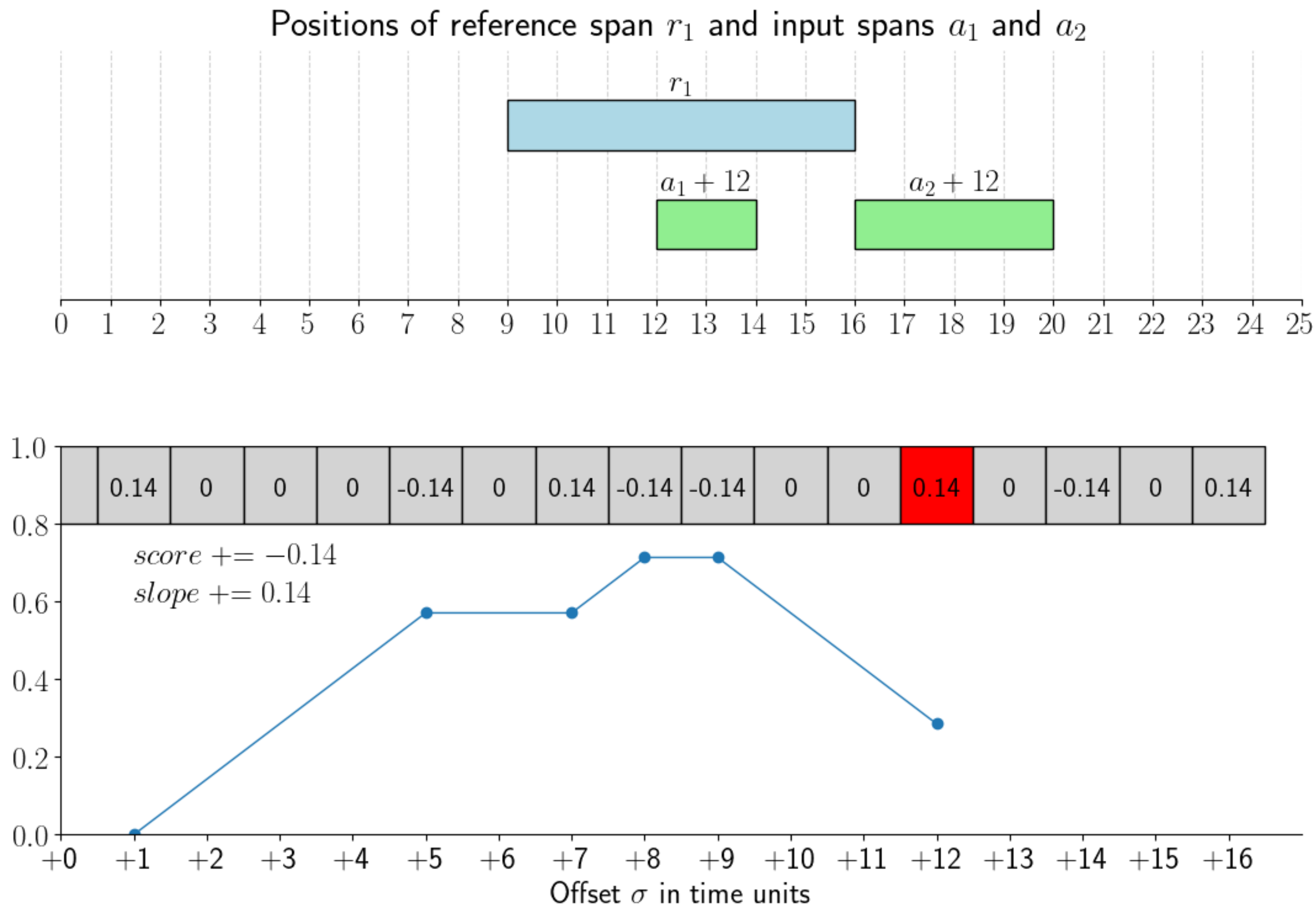

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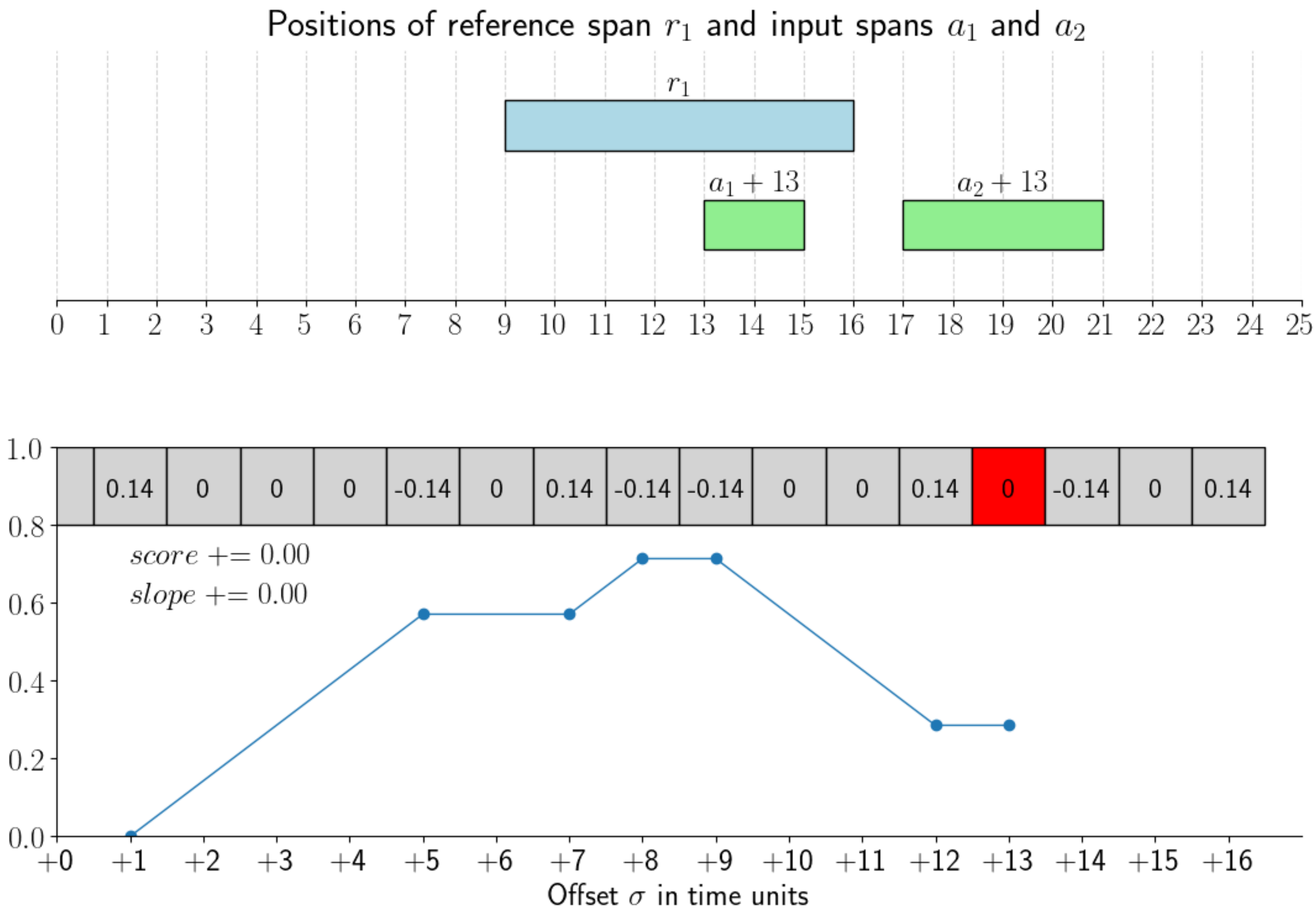

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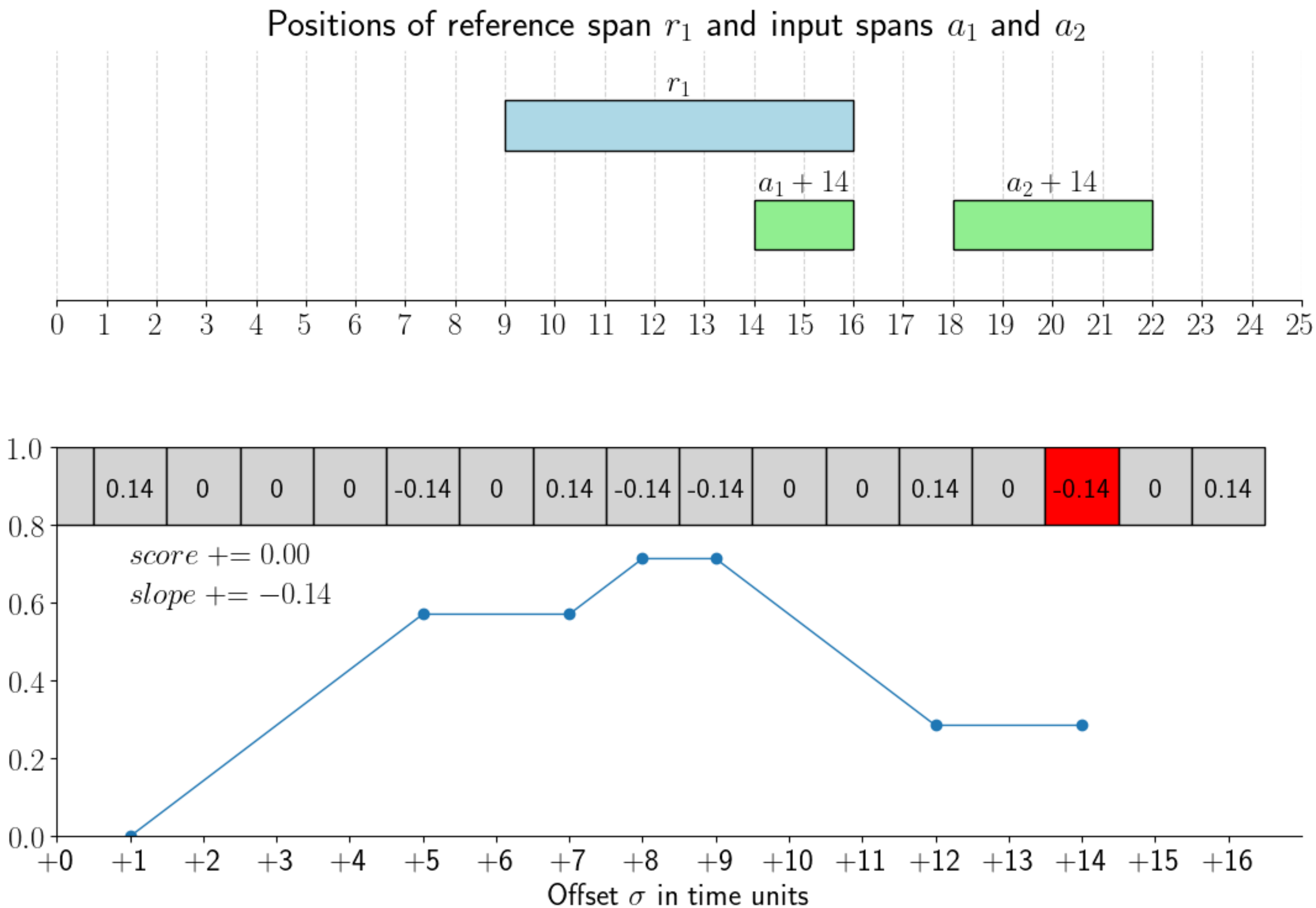

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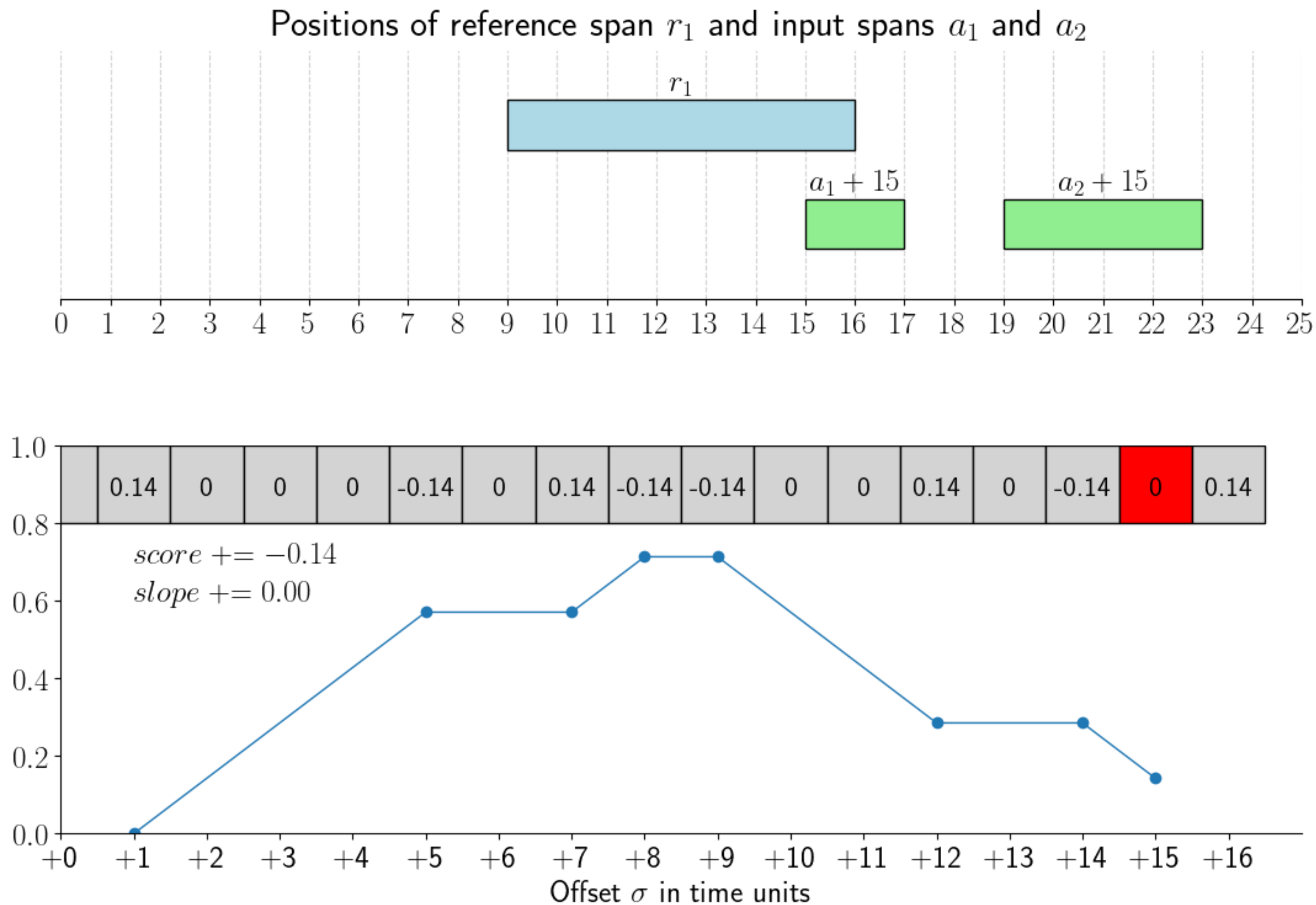

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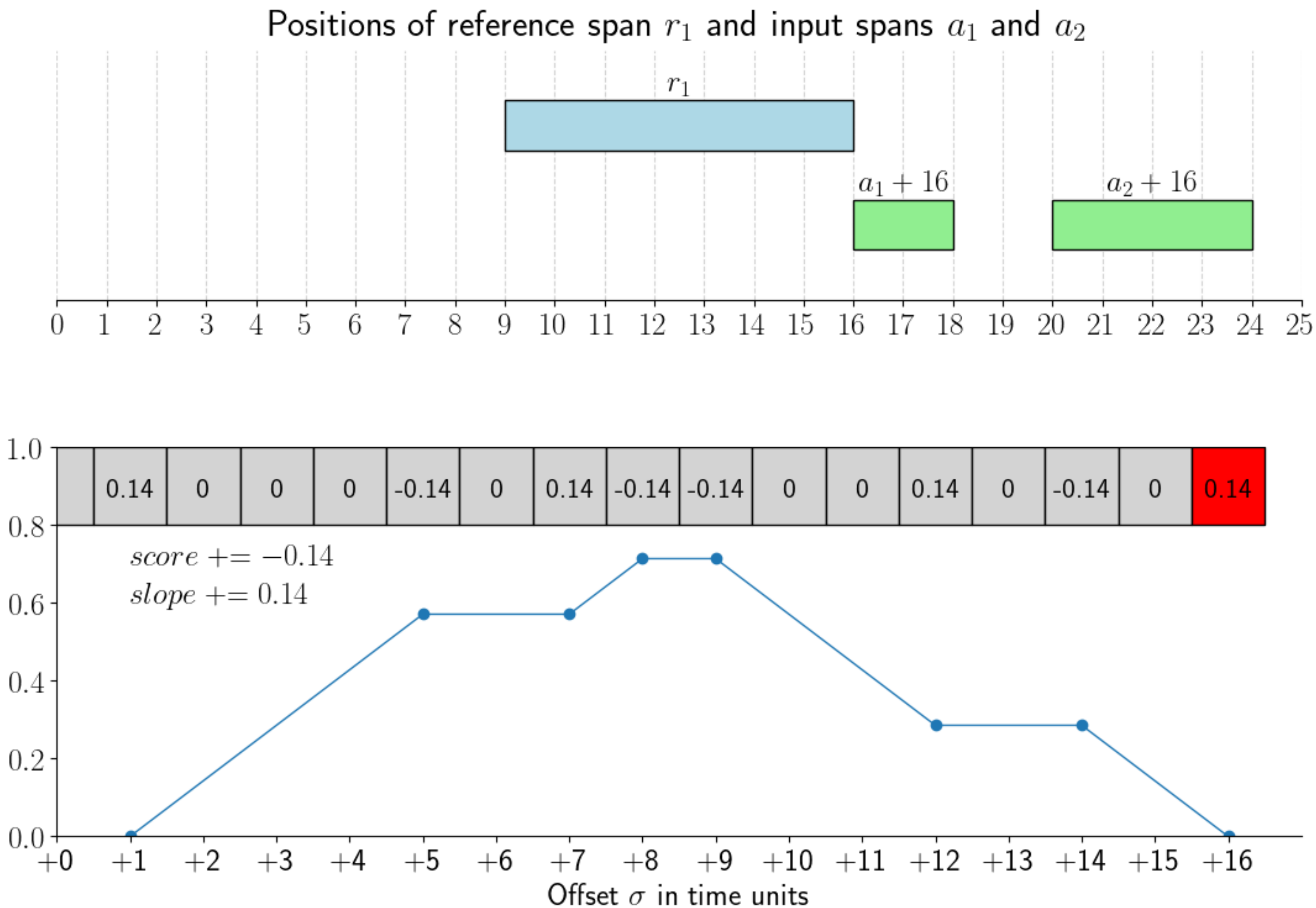

Optimal no-split alignment

Analysis of the slope tracking algorithm

- $4KN$ "insertions"
- $T_r + T_a$ iterations

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Hybrid: Switch depending on the ratio $\frac{4KN}{T_r + T_a}$!

Optimal split alignment

Split alignment σ

Given the input span sequence $a = (a_1, \ldots, a_N)$, a *split alignment* is a sequence of offsets $\sigma = (\sigma_1, \ldots, \sigma_N)$ which does not reorder the input sequence:

Optimal split alignment

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$$\begin{gathered}
\mathtt{end}(a_1 + \sigma_1) \leq \mathtt{start}(a_2 + \sigma_2) \\
\mathtt{end}(a_2 + \sigma_2) \leq \mathtt{start}(a_3 + \sigma_3) \\
\vdots \\
\mathtt{end}(a_{N-1} + \sigma_{N-1}) \leq \mathtt{start}(a_N + \sigma_N)
\end{gathered}$$

Optimal split alignment

Number of splits in σ

The *number of splits* of the alignment, $\texttt{splits}(\sigma)$ is defined as

$$\texttt{splits}(\sigma) = \sum_{n=1}^{N-1} \begin{cases} 1 & \text{if } \sigma_n \neq \sigma_{n+1} \\ 0 & \text{if } \sigma_n = \sigma_{n+1} \end{cases}$$

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Scoring for split alignments

Given two sequences of spans $r = (r_1, r_2, \ldots, r_K)$ and $a = (a_1, a_2, \ldots, a_N)$, a weighting function w and the split penalty p, the $\texttt{score}$ of an alignment $\sigma = (\sigma_1, \ldots, \sigma_N)$ is defined as

$$\texttt{score}(r, a, \sigma, p, w) = \sum_{n=1}^{N} \sum_{k=1}^{K} \texttt{iscore}(r_k, a_n + \sigma_n) \cdot w(k, n) - \texttt{splits}(\sigma) \cdot p$$

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Optimal split alignment

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- Enumerating all splits: $O(2^N) \approx 10^{370}$ years
- Can we do it in under 5 minutes? Yes!

Optimal split alignment

Recursion form

$$t_n(\sigma'_n) = \max_{\substack{(\sigma_1,\ldots,\sigma_n) \\ \text{where } \sigma_n = \sigma'_n}} \mathtt{score}(r, (a_1, \ldots, a_n), (\sigma_1, \ldots, \sigma_n))$$

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$$s_n(\sigma'_n) = \max_{\substack{(\sigma_1,\ldots,\sigma_{n-1}) \text{ where} \\ \sigma_{n-1} + \texttt{end}(a_{n-1}) \leq \sigma'_n + \texttt{start}(a_n)}} \texttt{score}(r, (a_1, \ldots, a_{n-1}), (\sigma_1, \ldots, \sigma_{n-1}))$$

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$$s_n(\sigma'_n) = \max_{\substack{(\sigma_1,\ldots,\sigma_{n-1}) \text{ where} \\ \sigma_{n-1} \leq \sigma'_n + \texttt{start}(a_n) - \texttt{end}(a_{n-1})}} \texttt{score}(r, (a_1, \ldots, a_{n-1}), (\sigma_1, \ldots, \sigma_{n-1}))$$

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Optimal split alignment

Recursion formula

$$t_n(\sigma'_n) = \texttt{score}(r, (a_n), \sigma'_n) + \max \begin{cases} t_{n-1}(\sigma'_n) \\ s_n(\sigma'_n) - p \end{cases}$$

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Culmulative recursion formula

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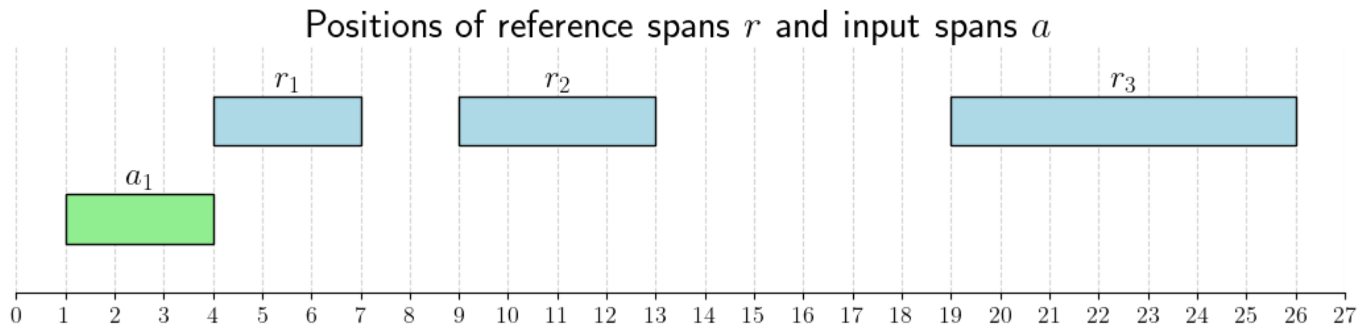

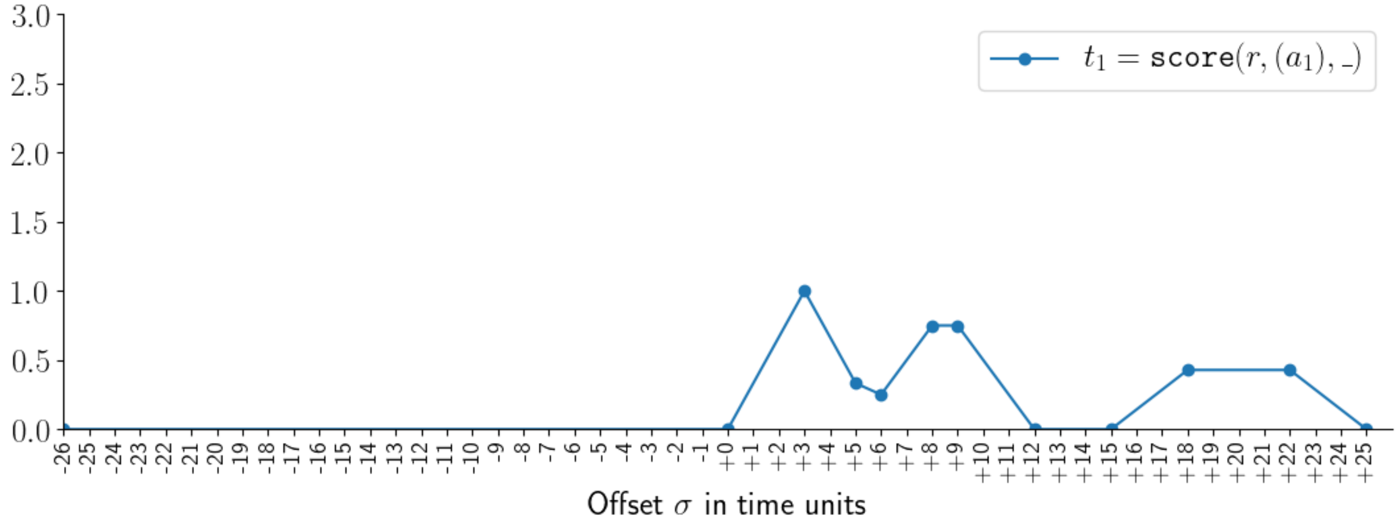

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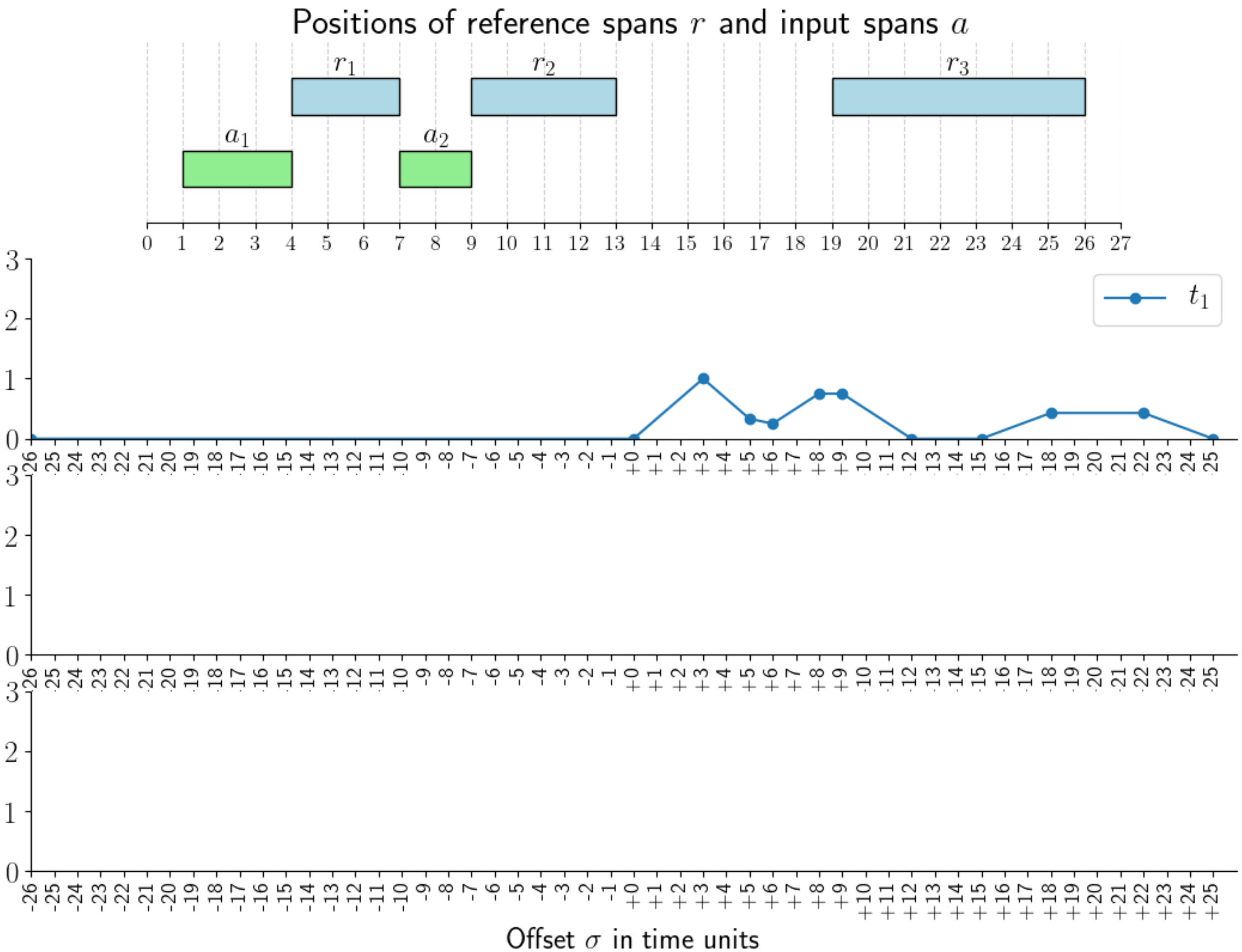

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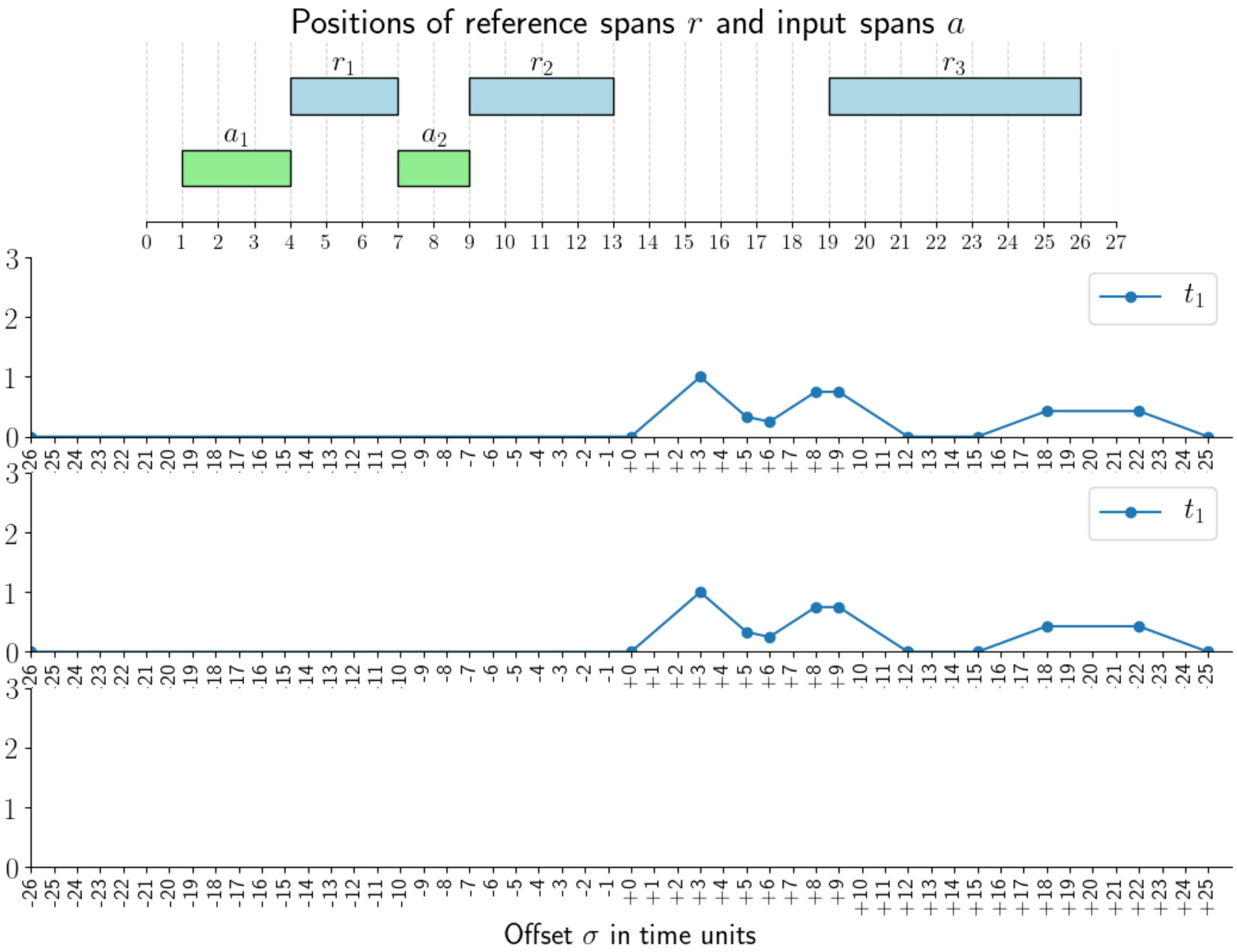

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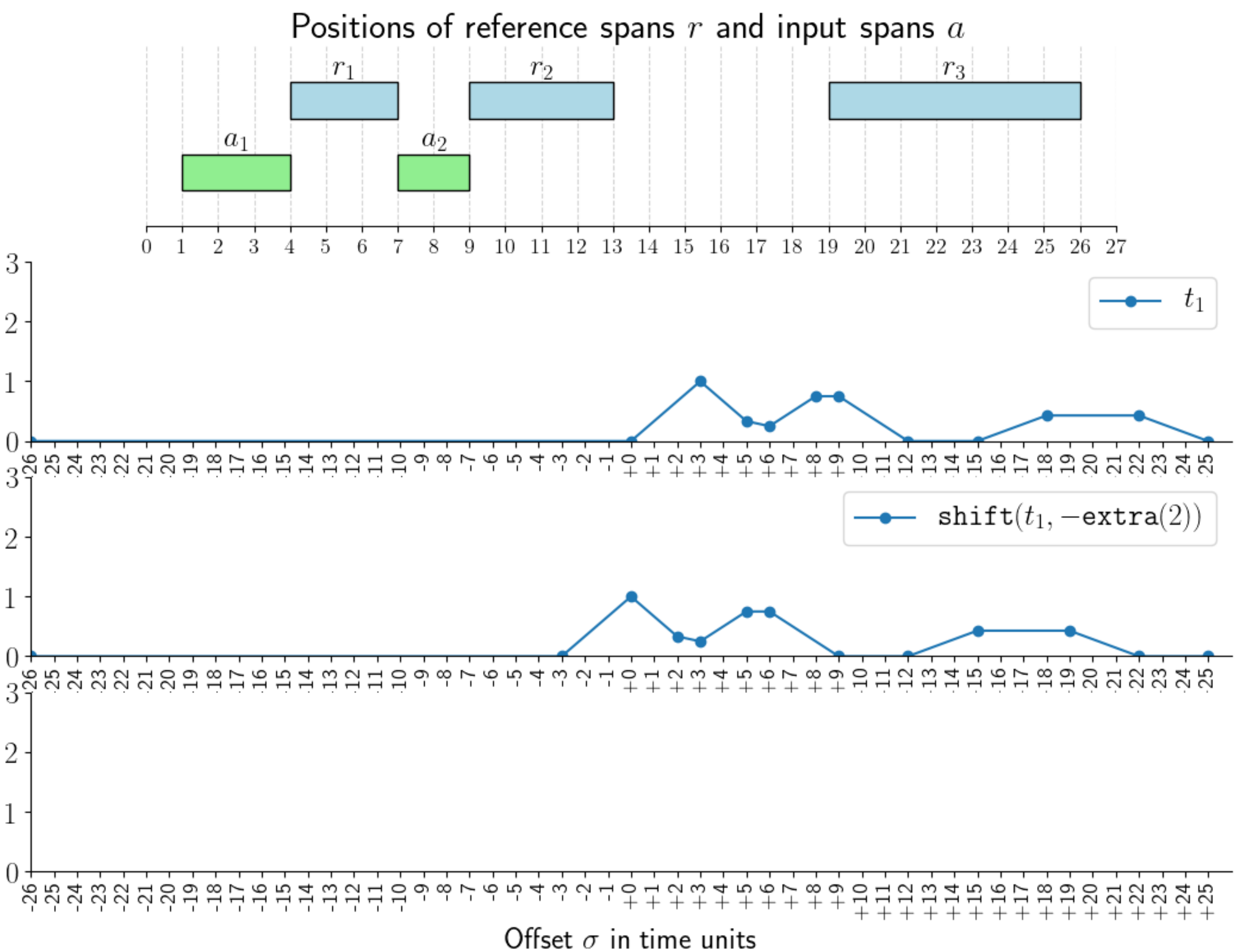

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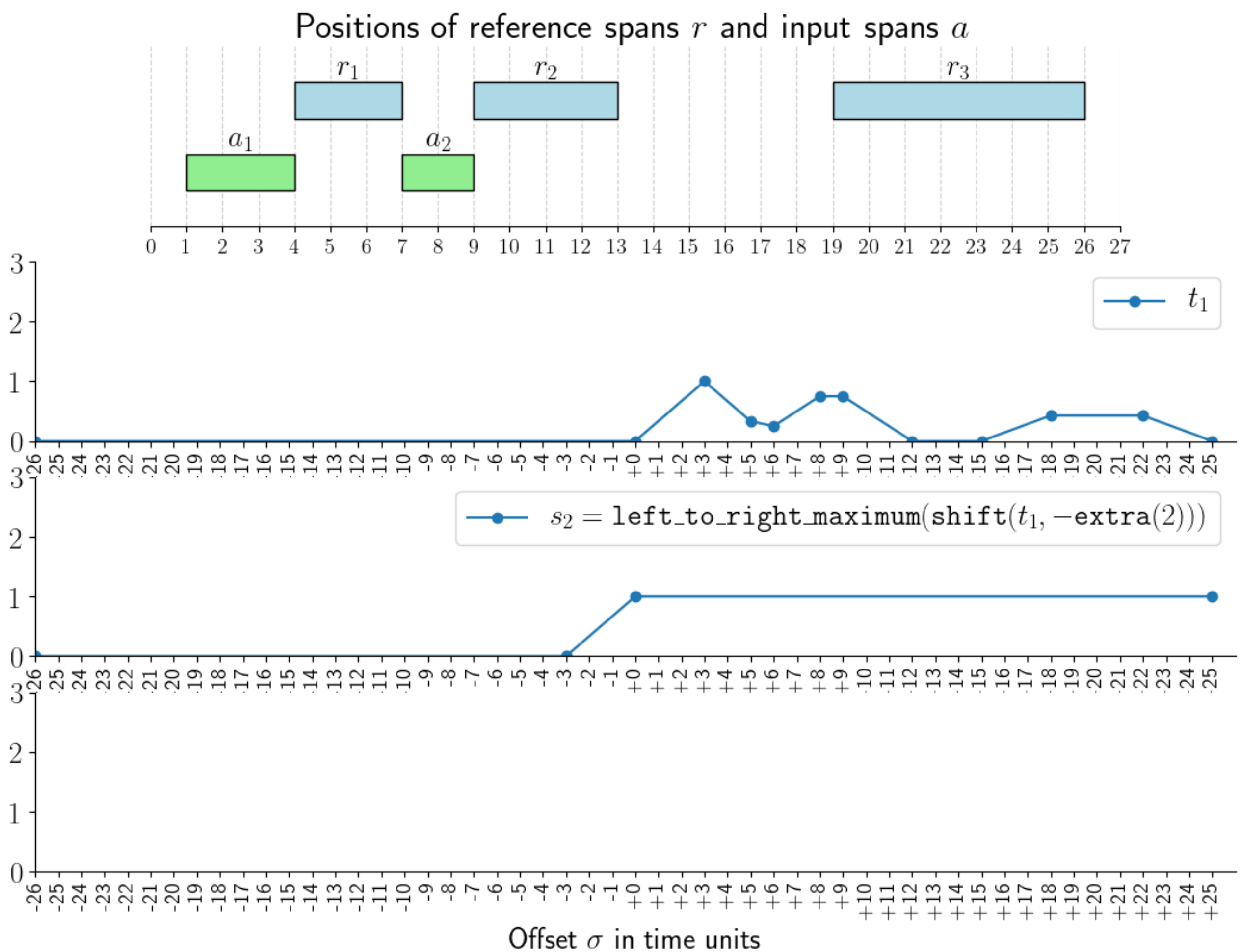

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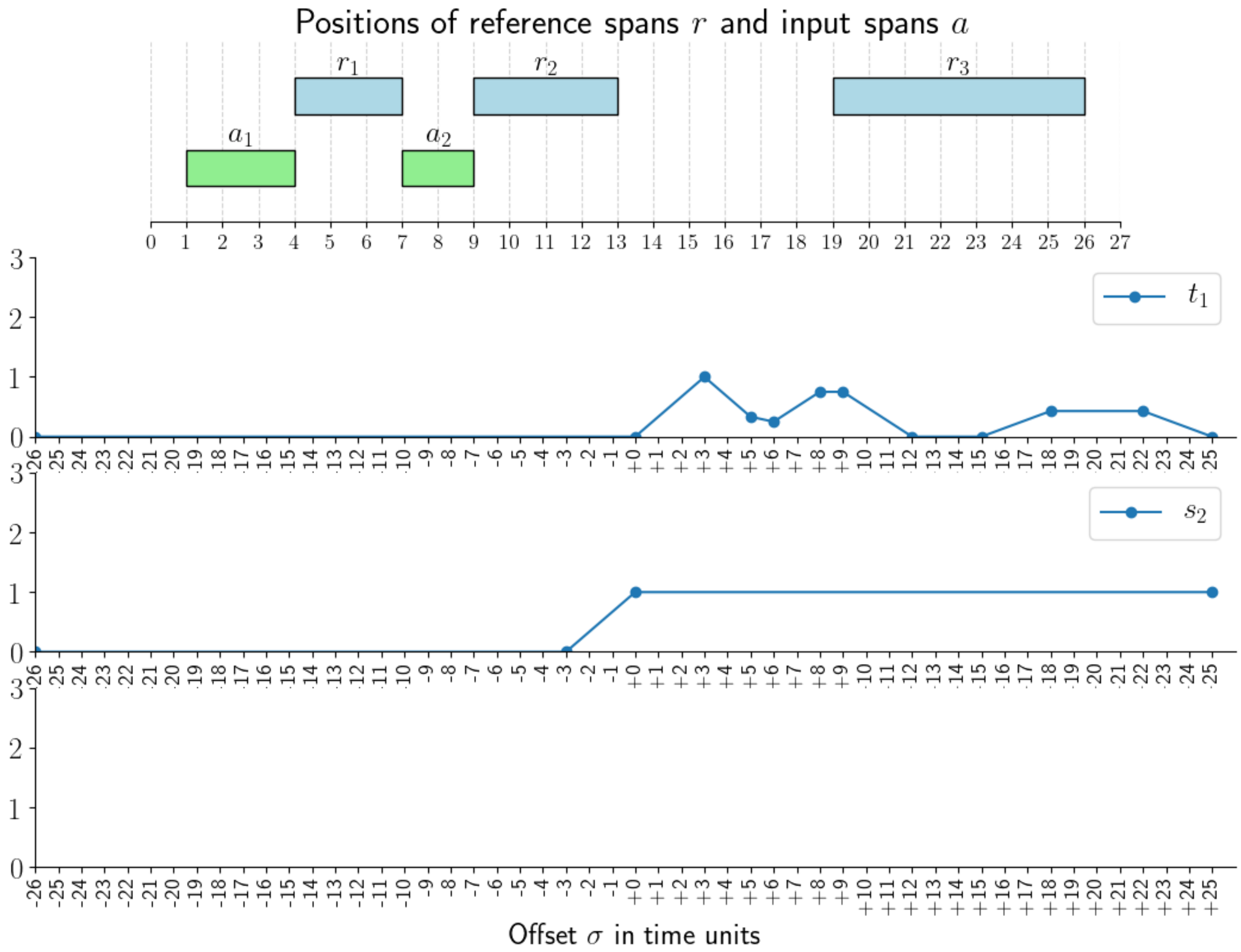

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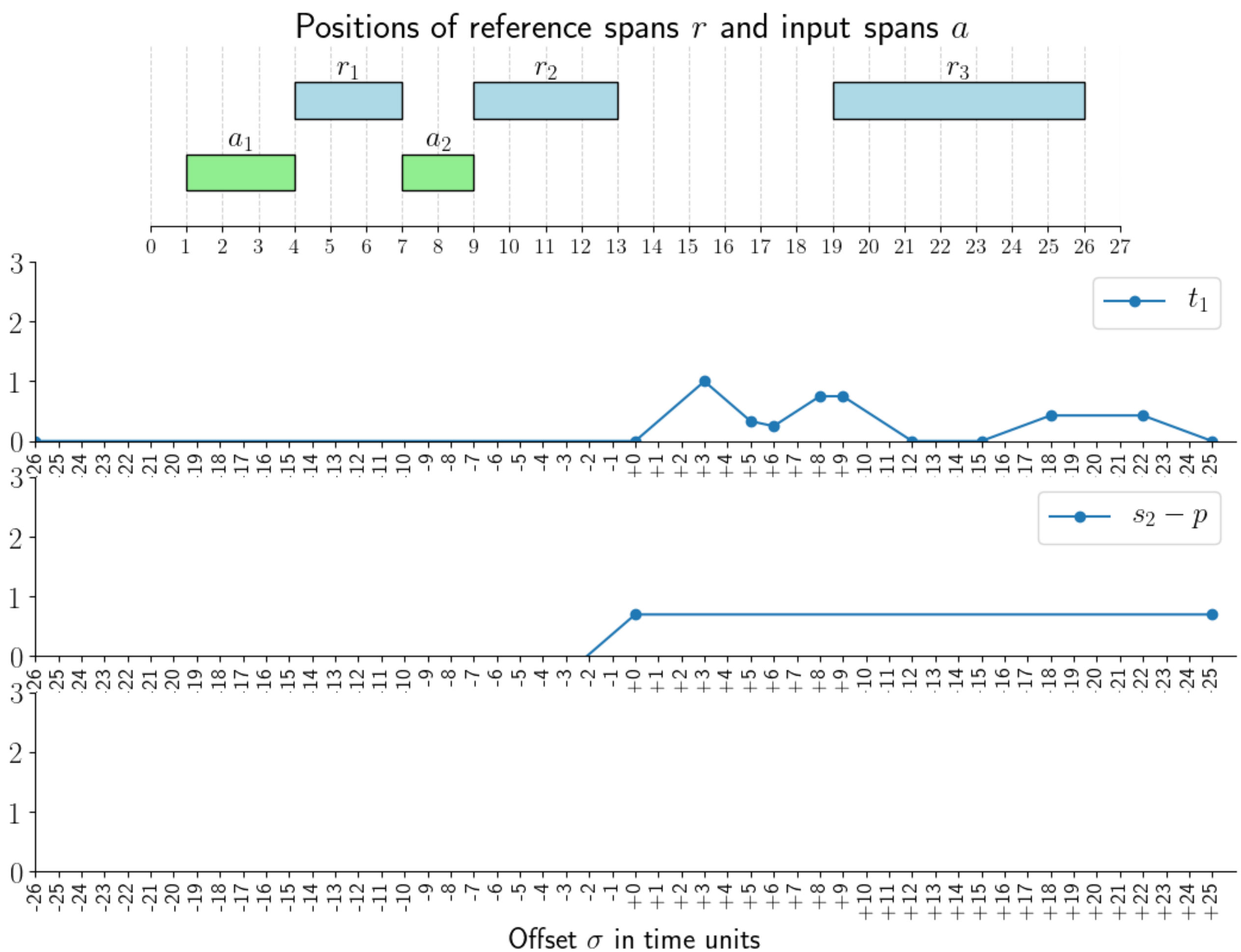

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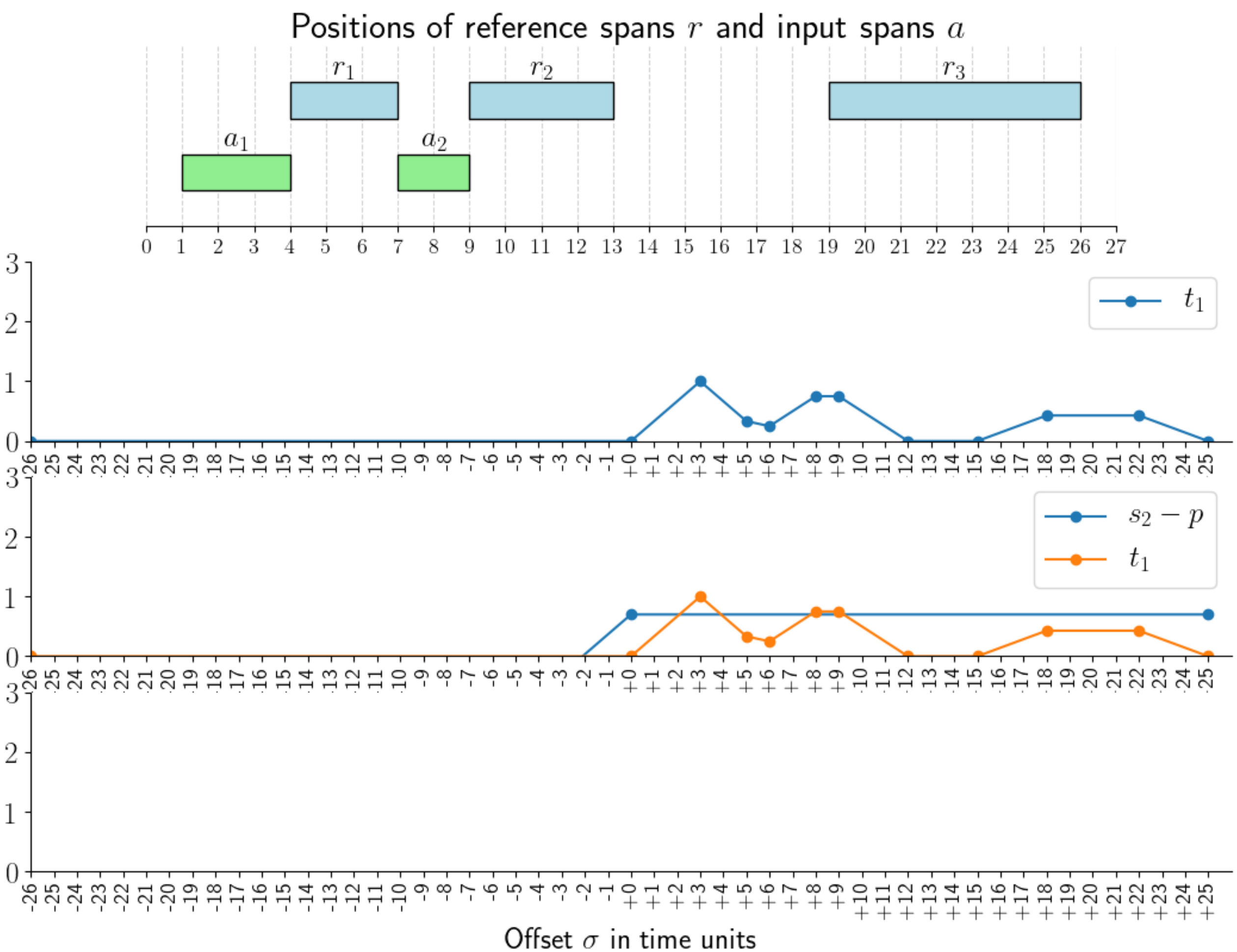

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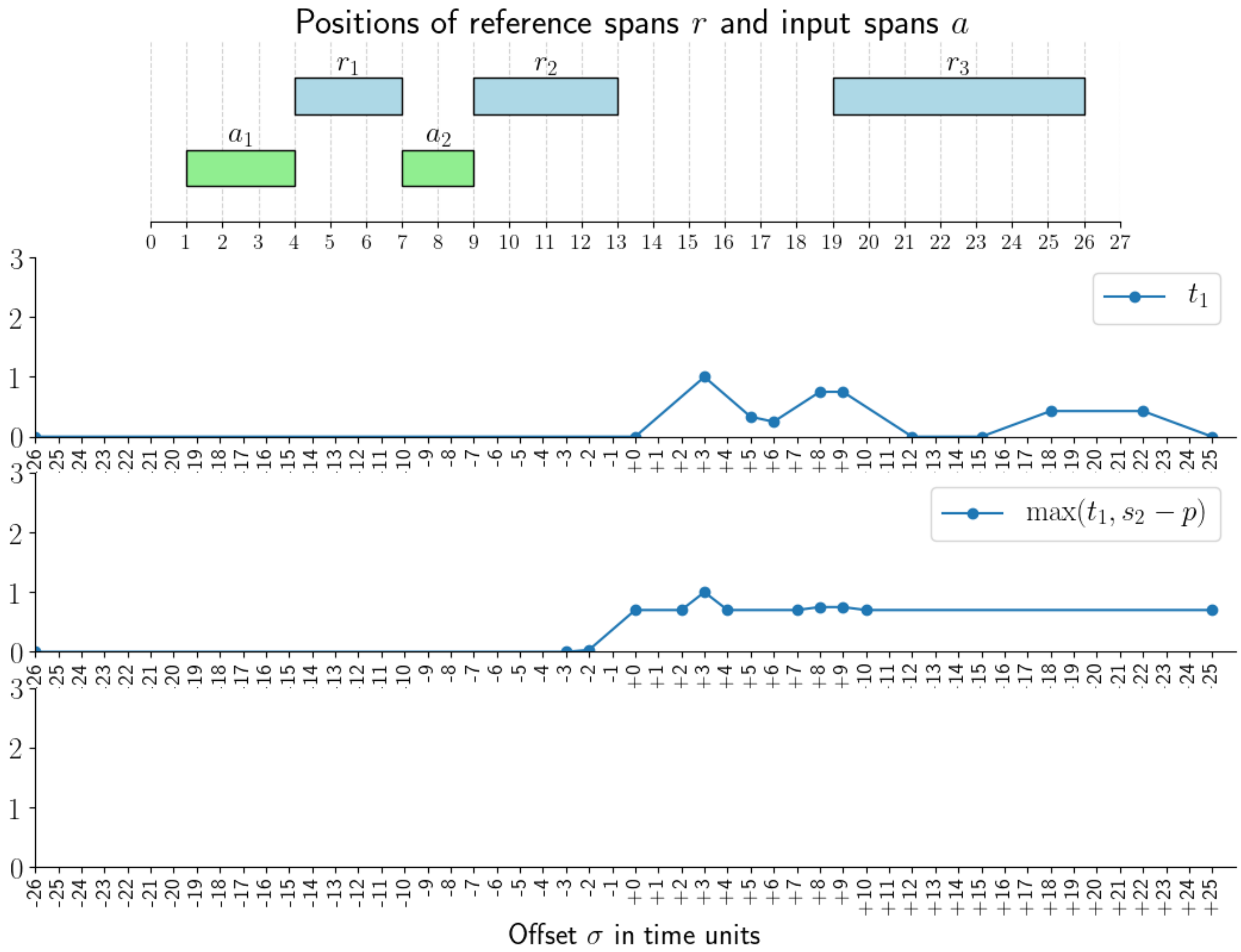

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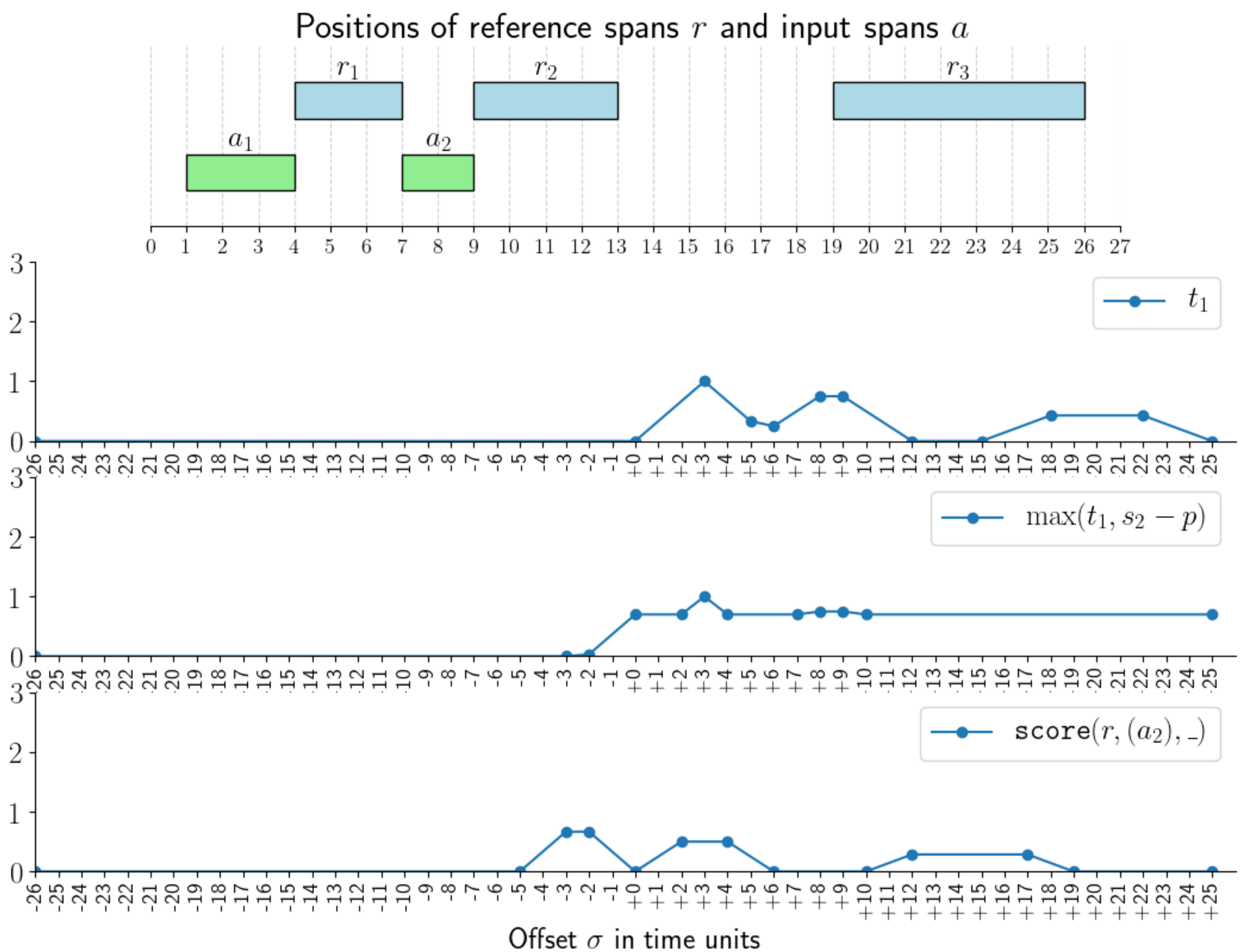

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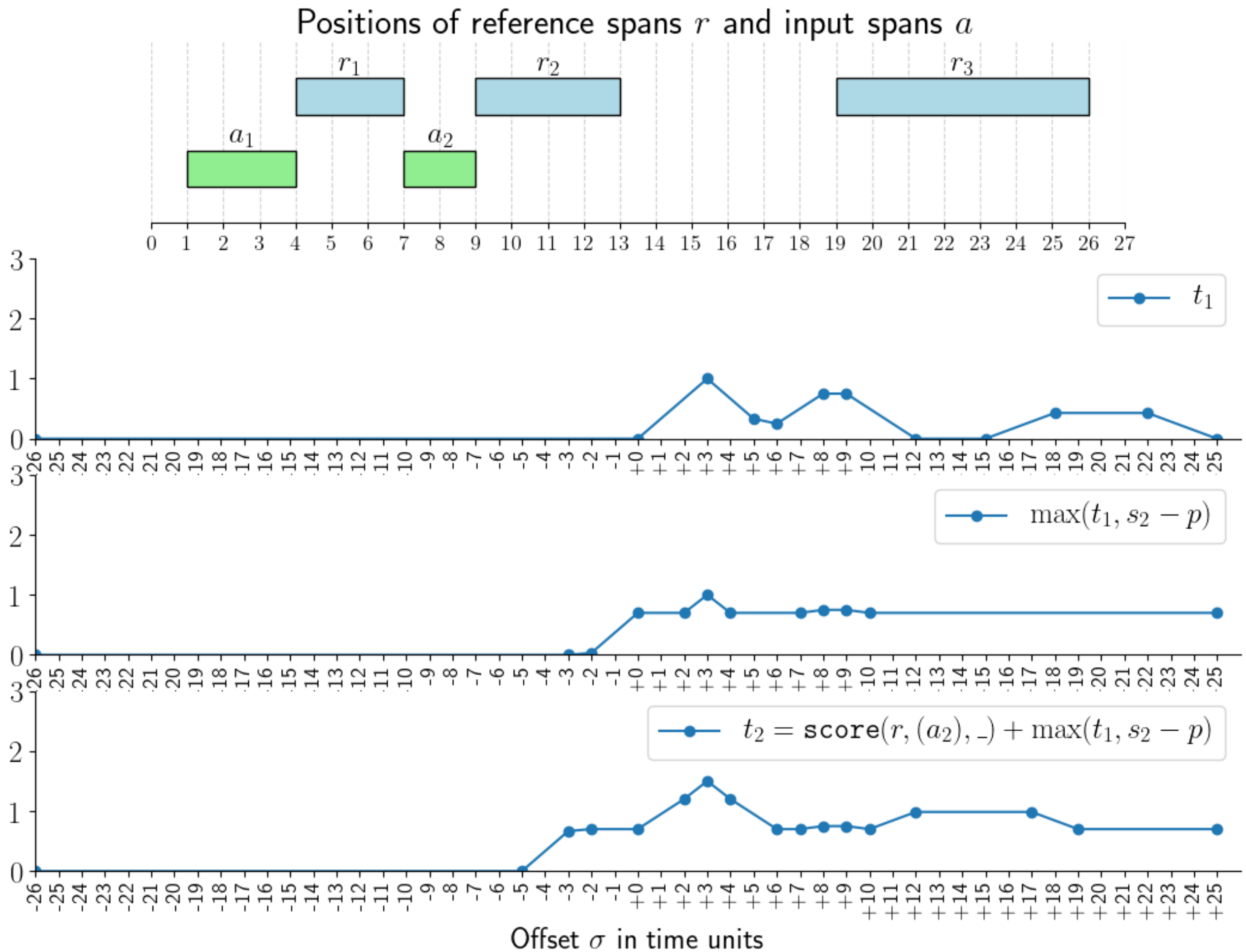

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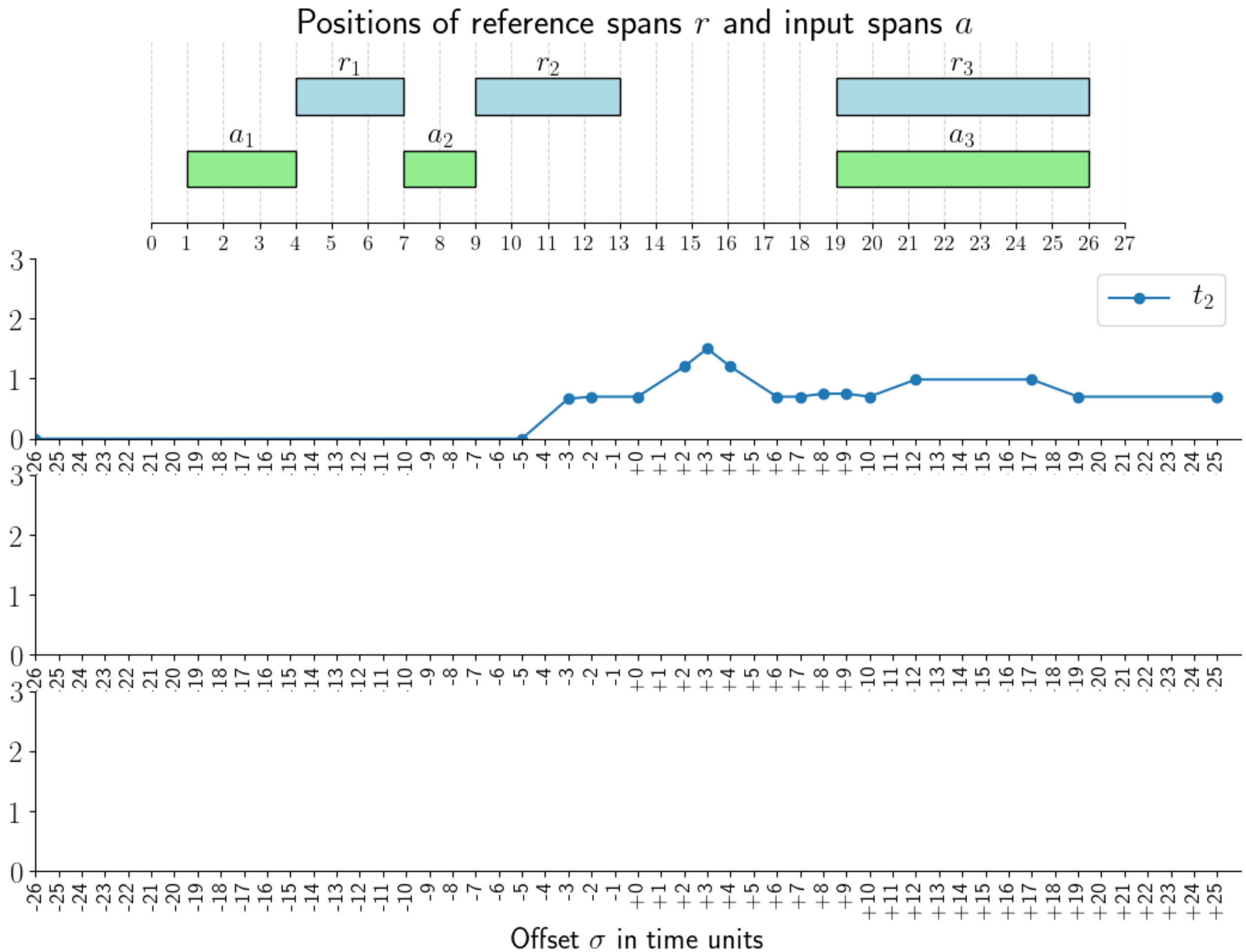

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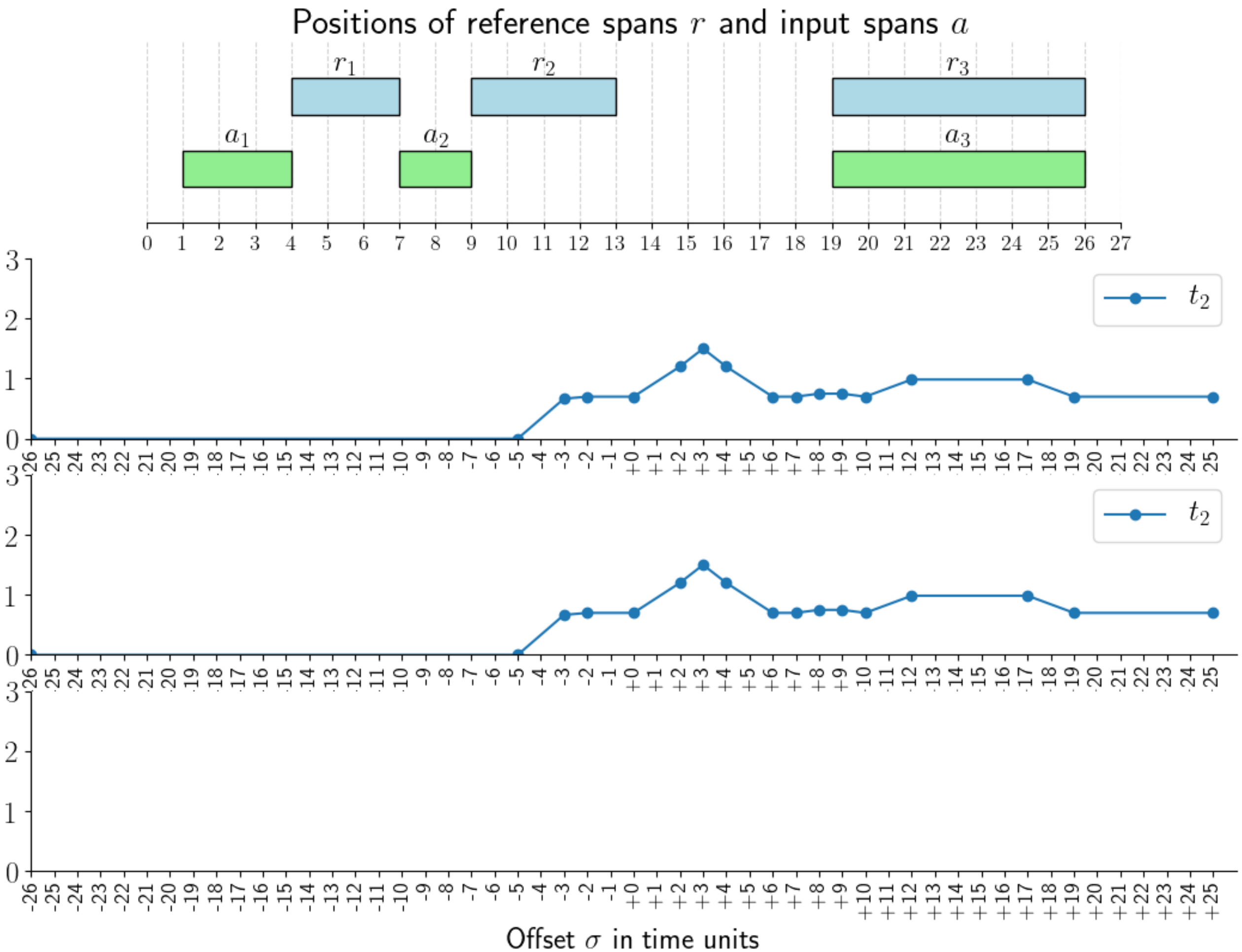

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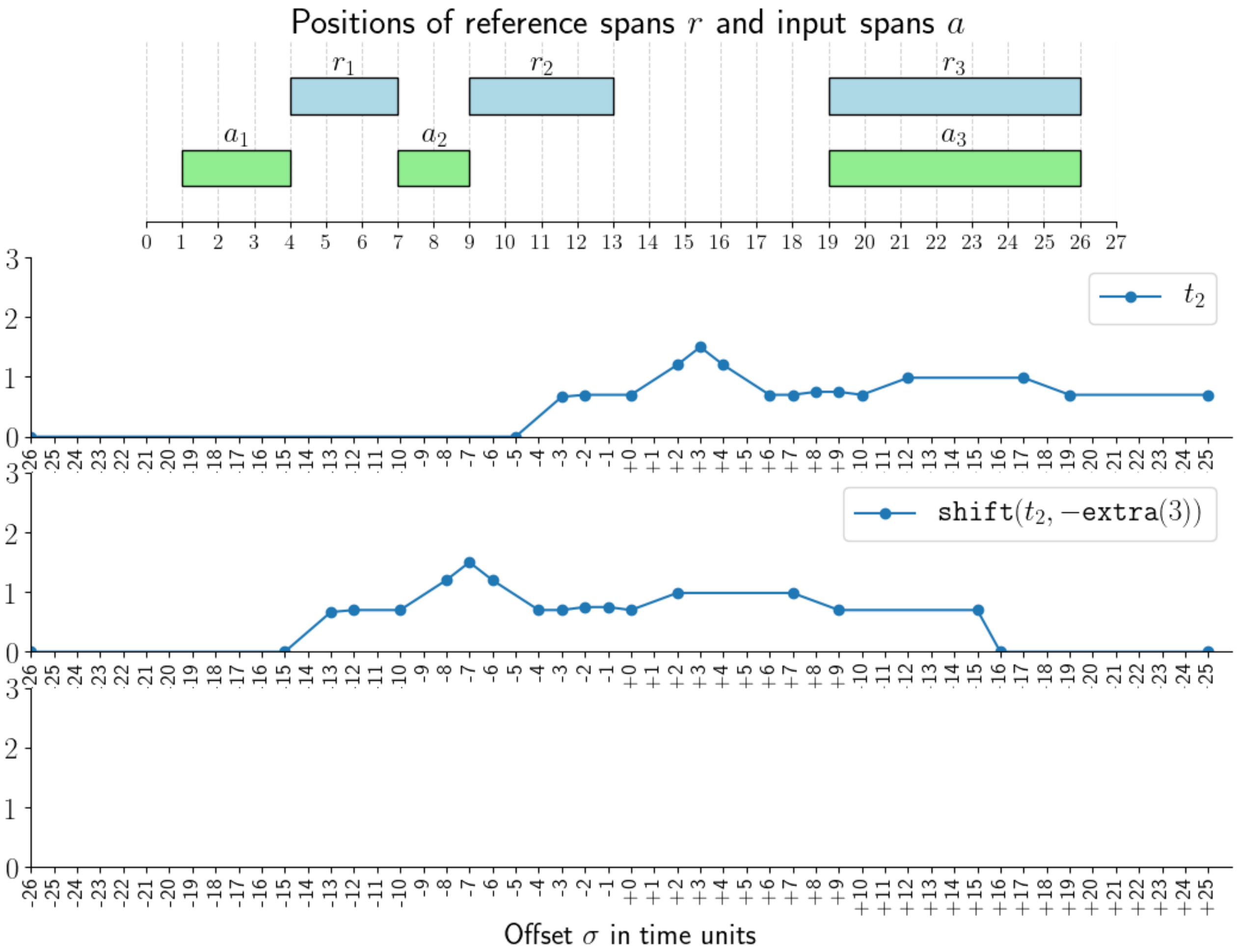

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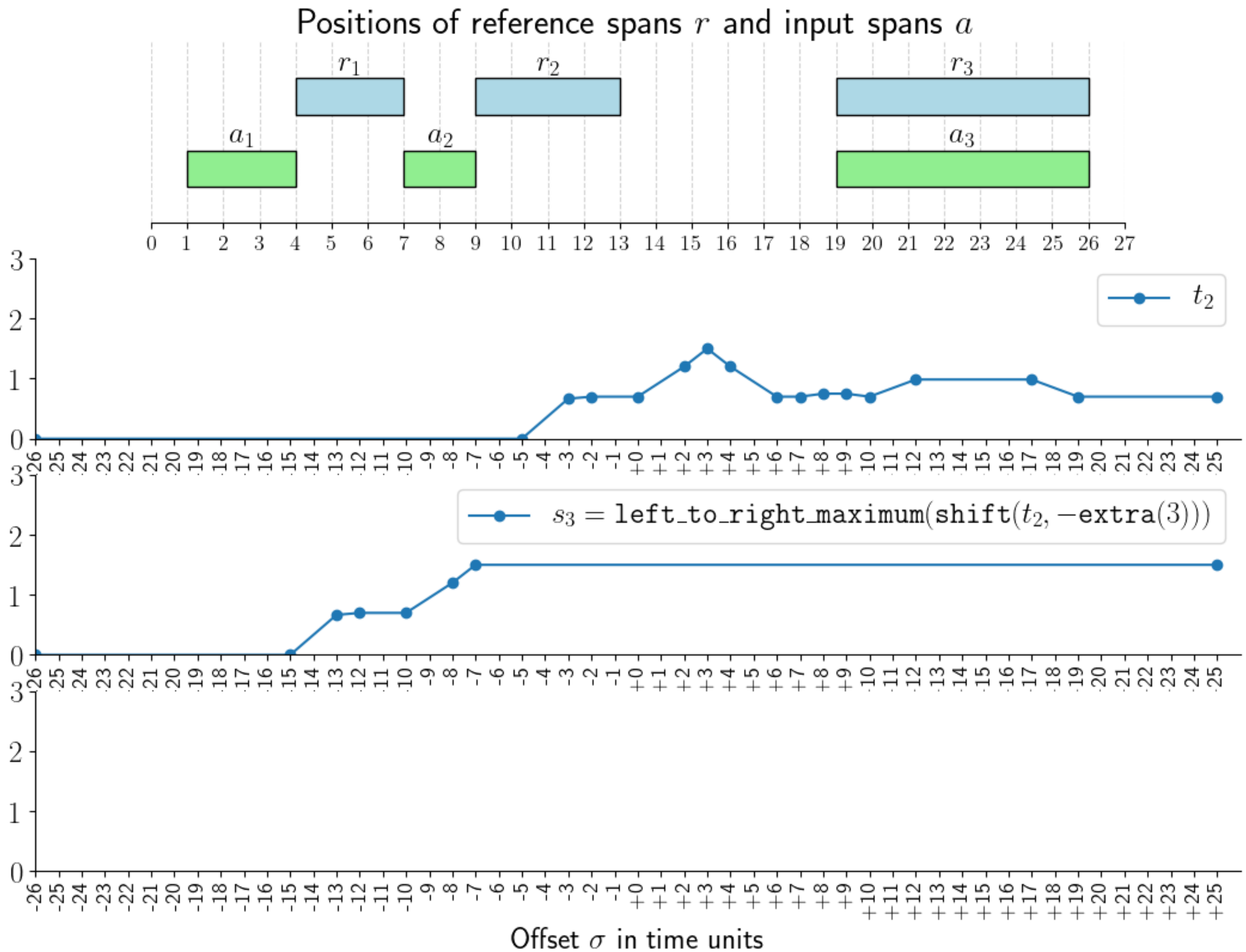

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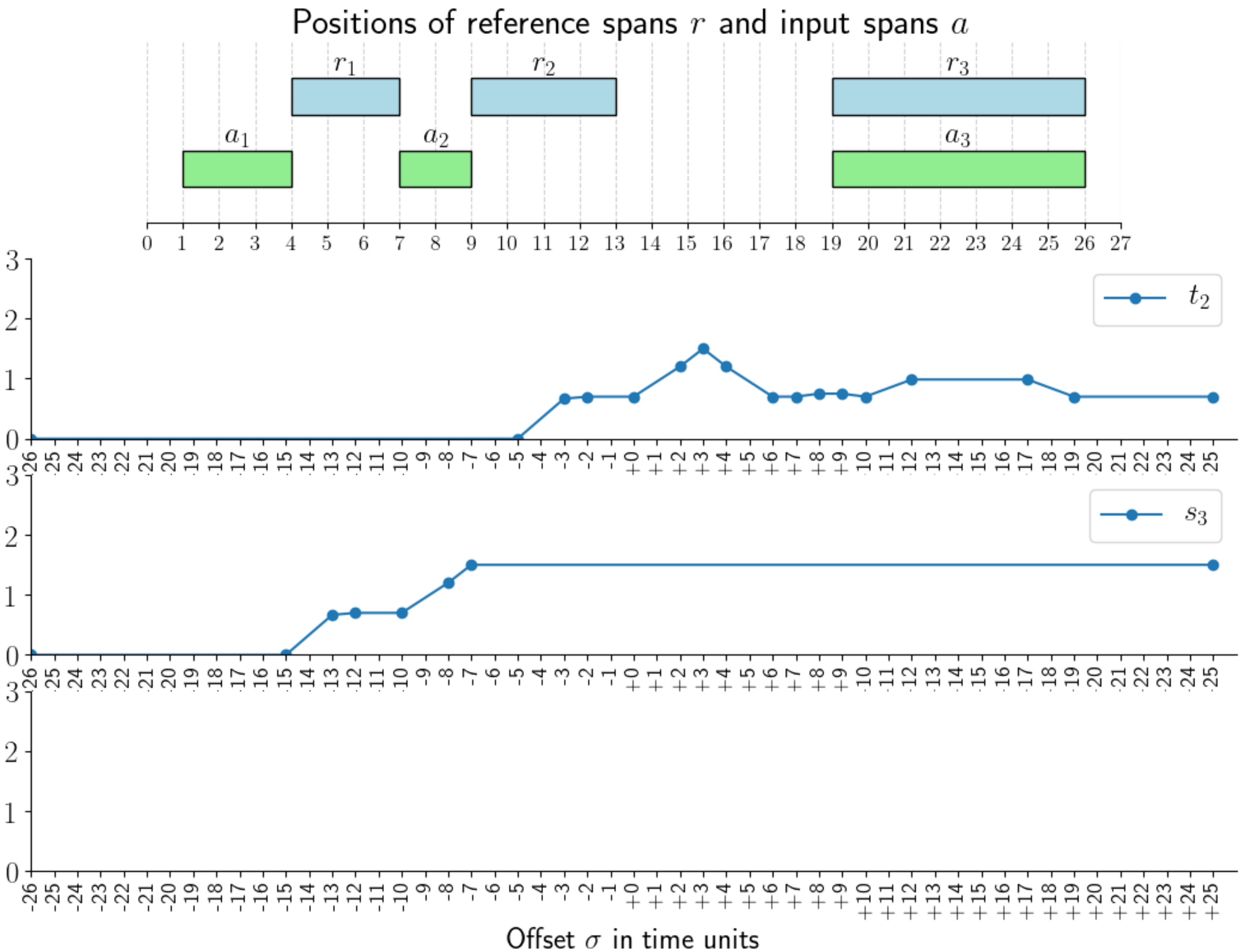

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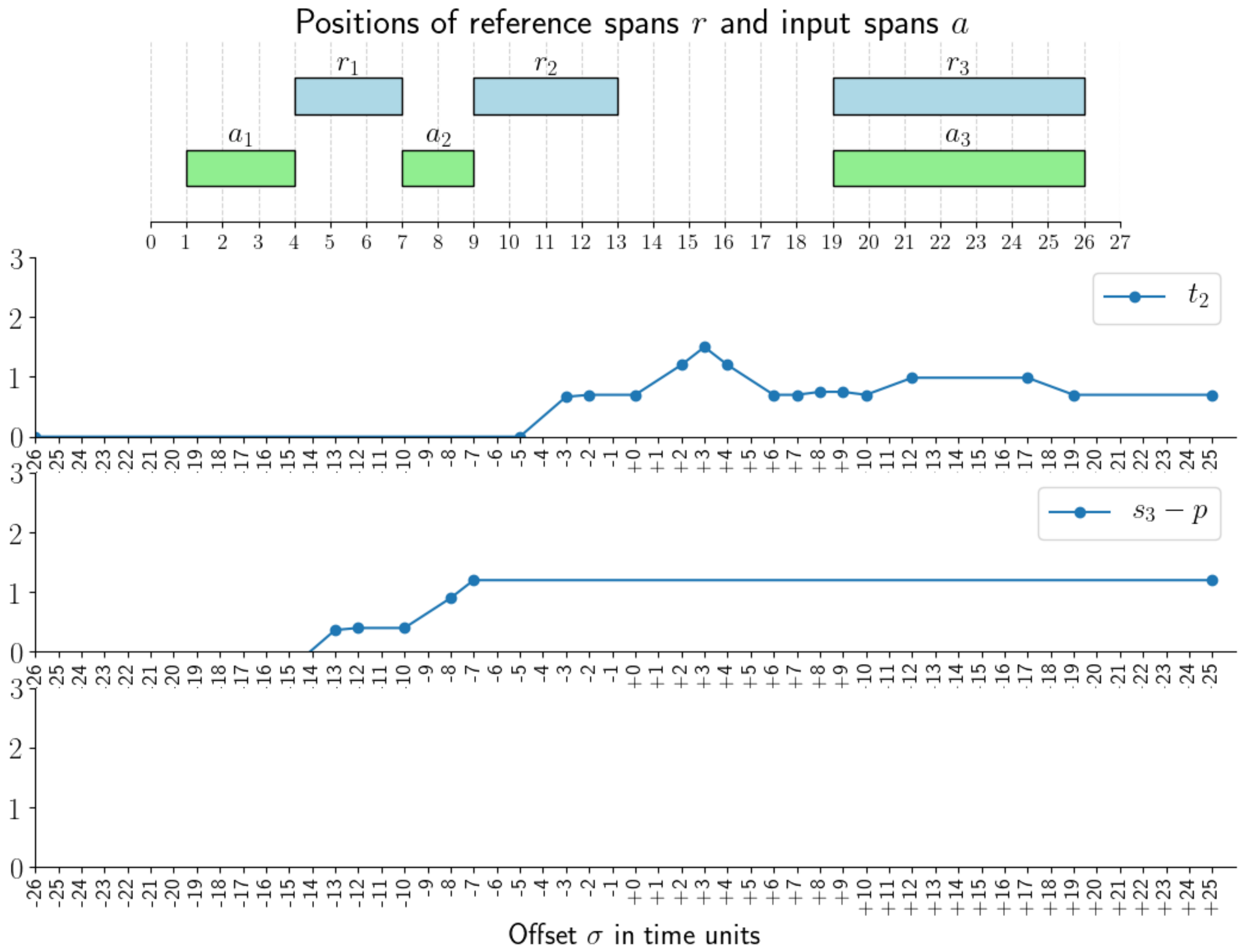
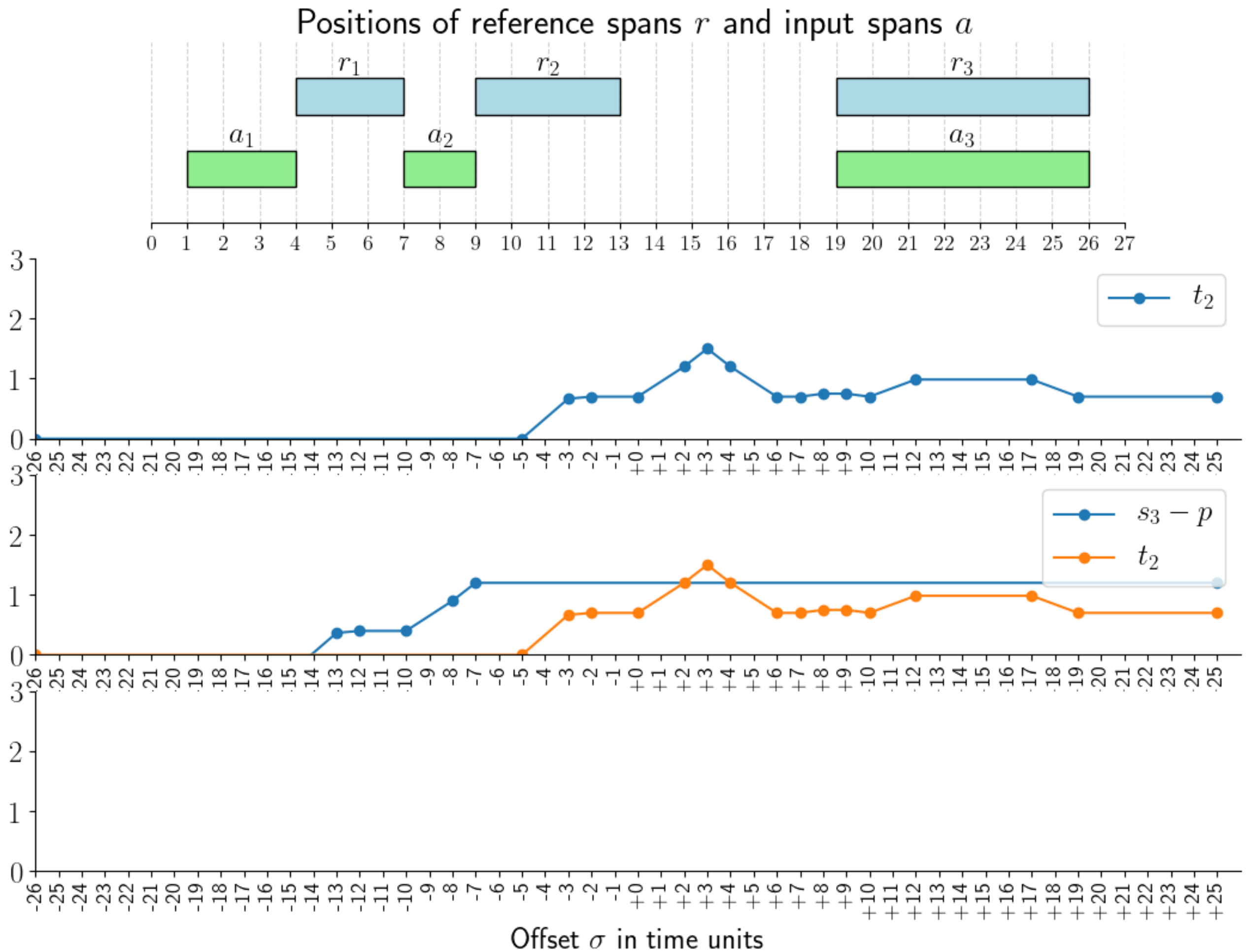


Optimal split alignment



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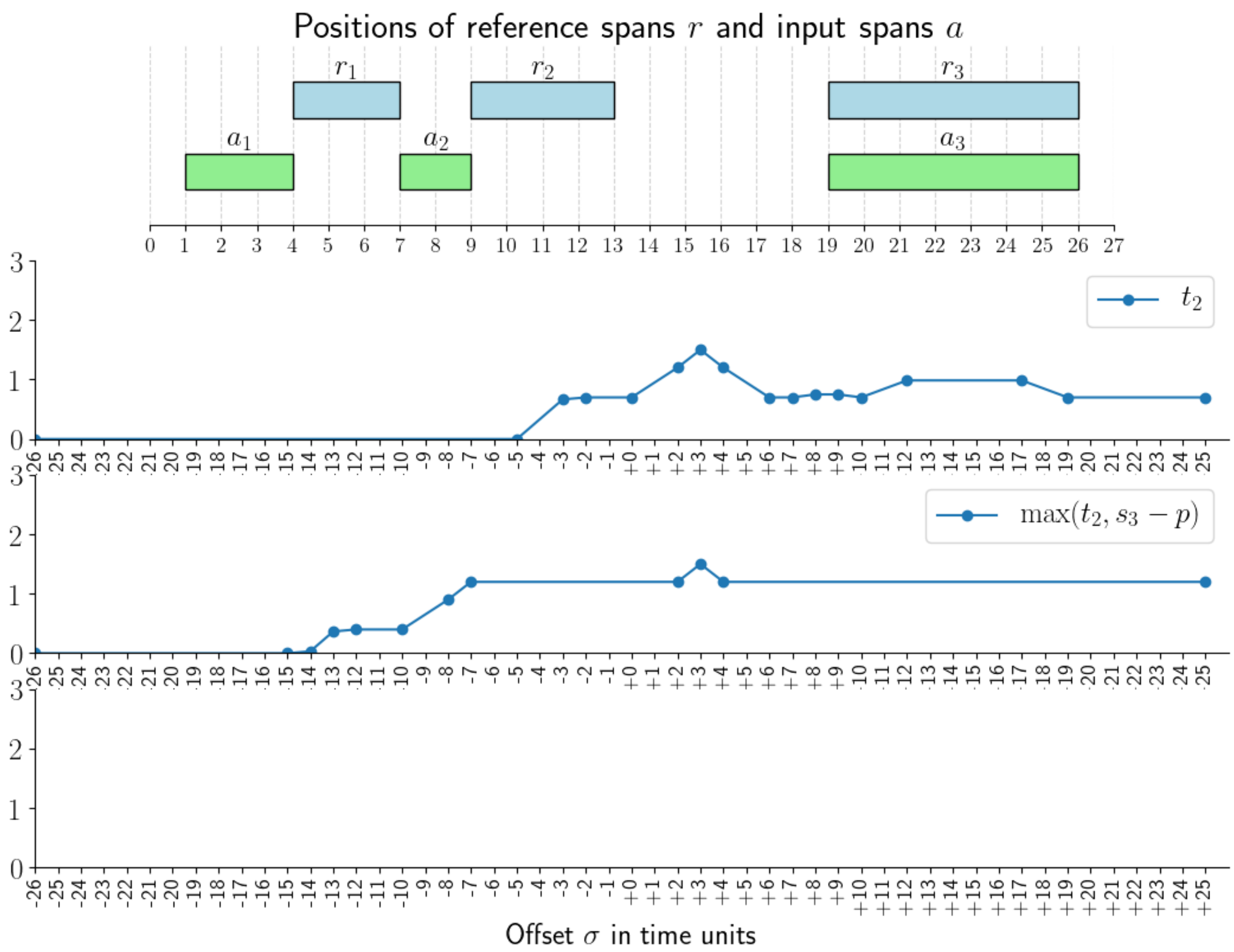

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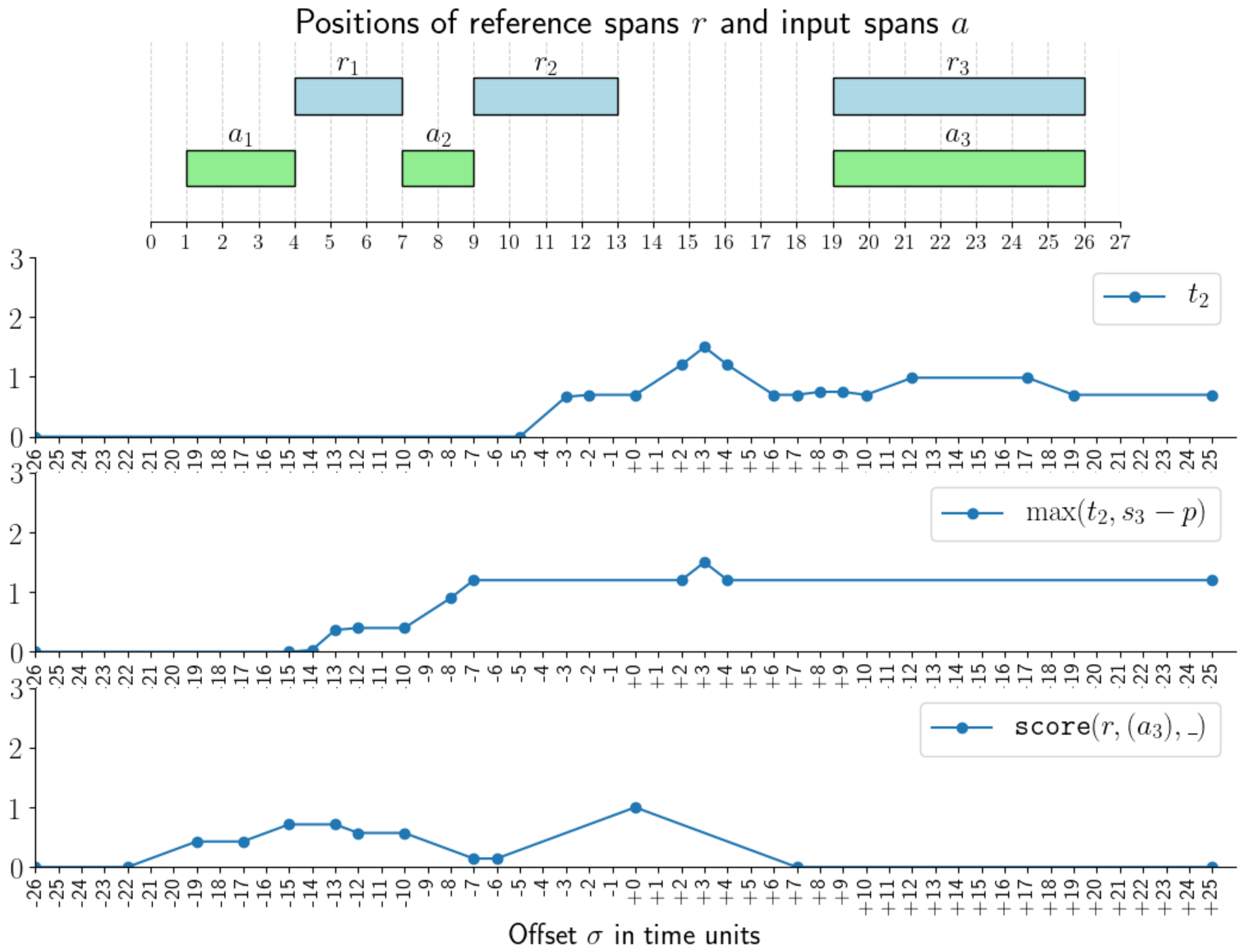
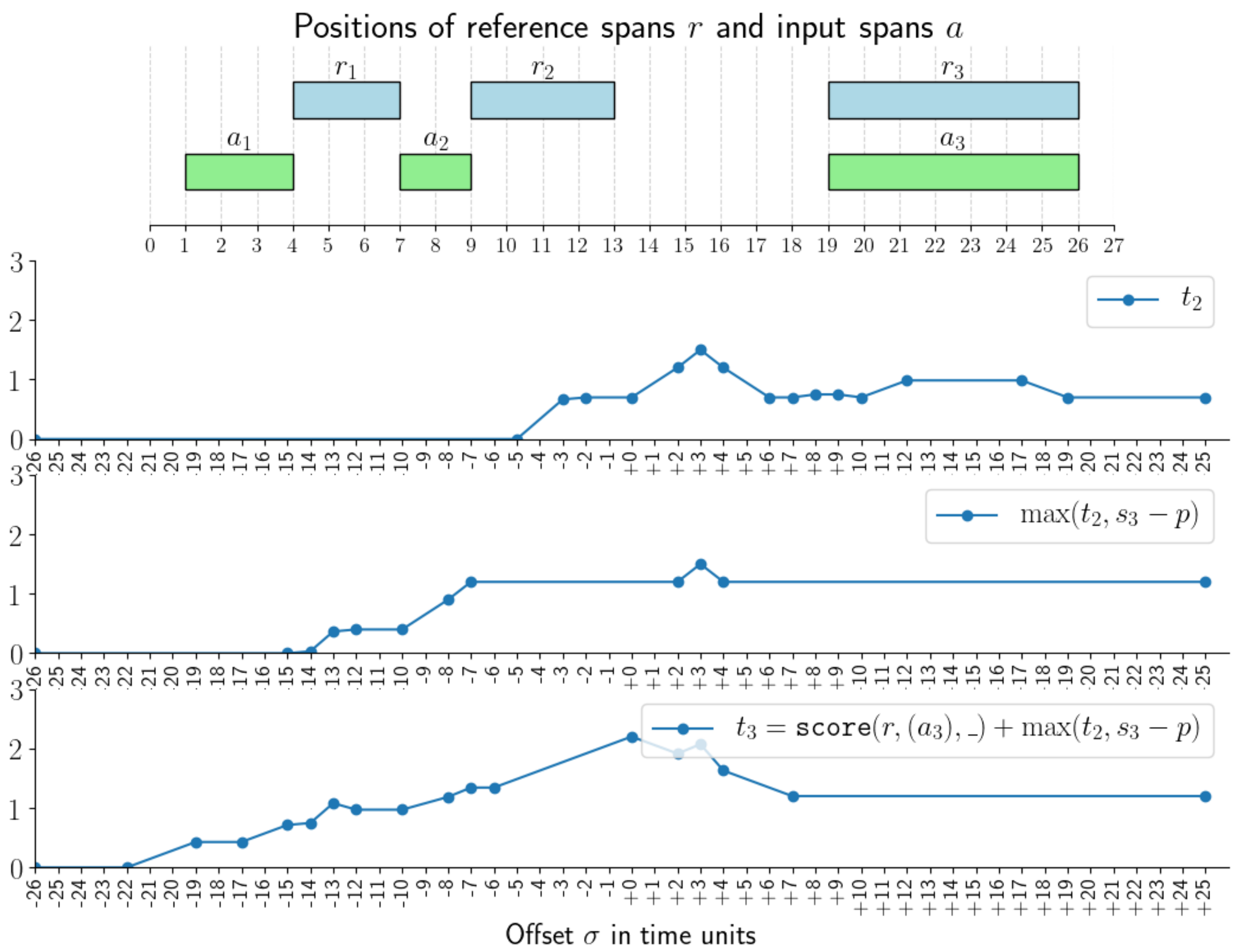


Optimal split alignment



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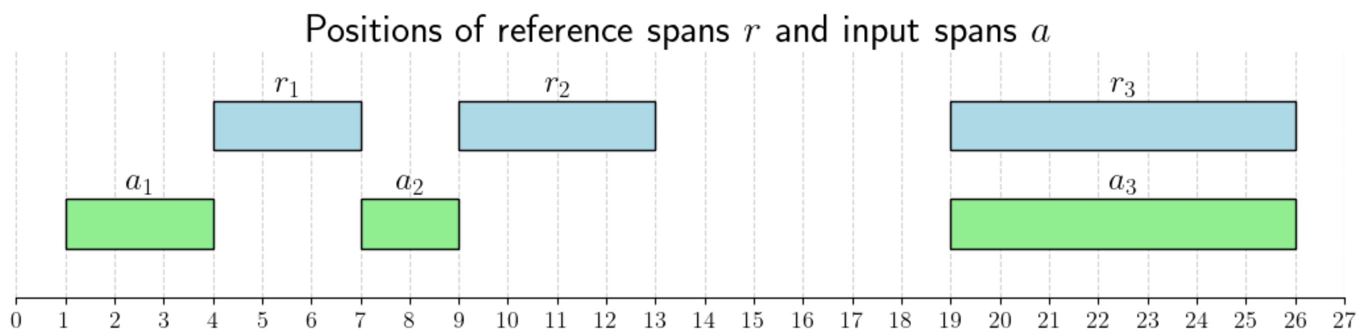
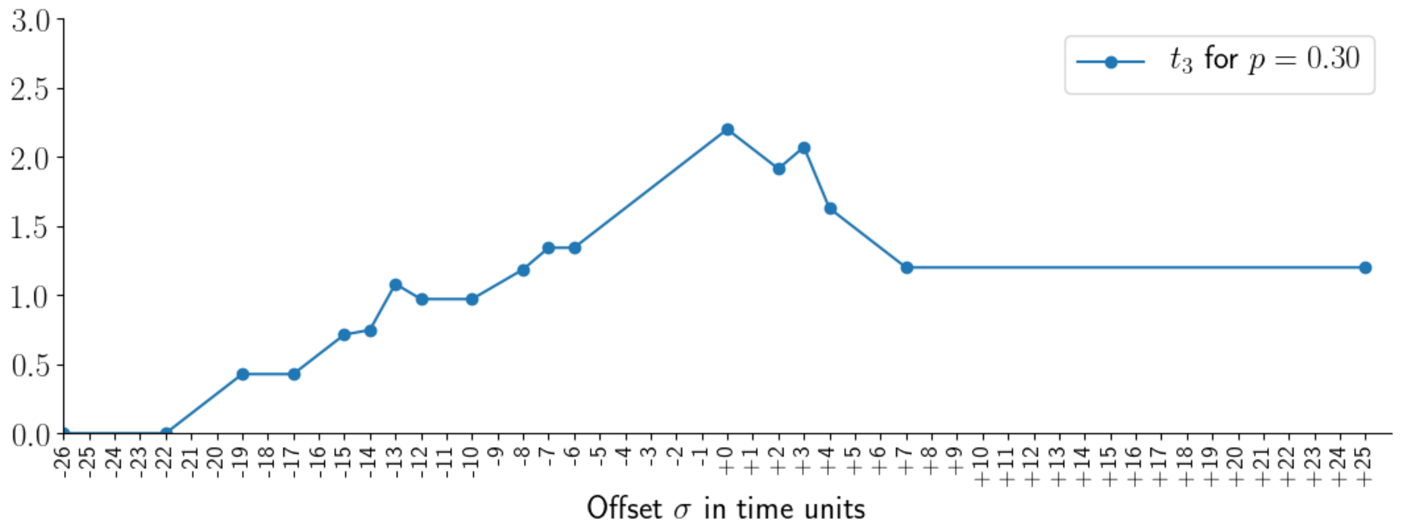
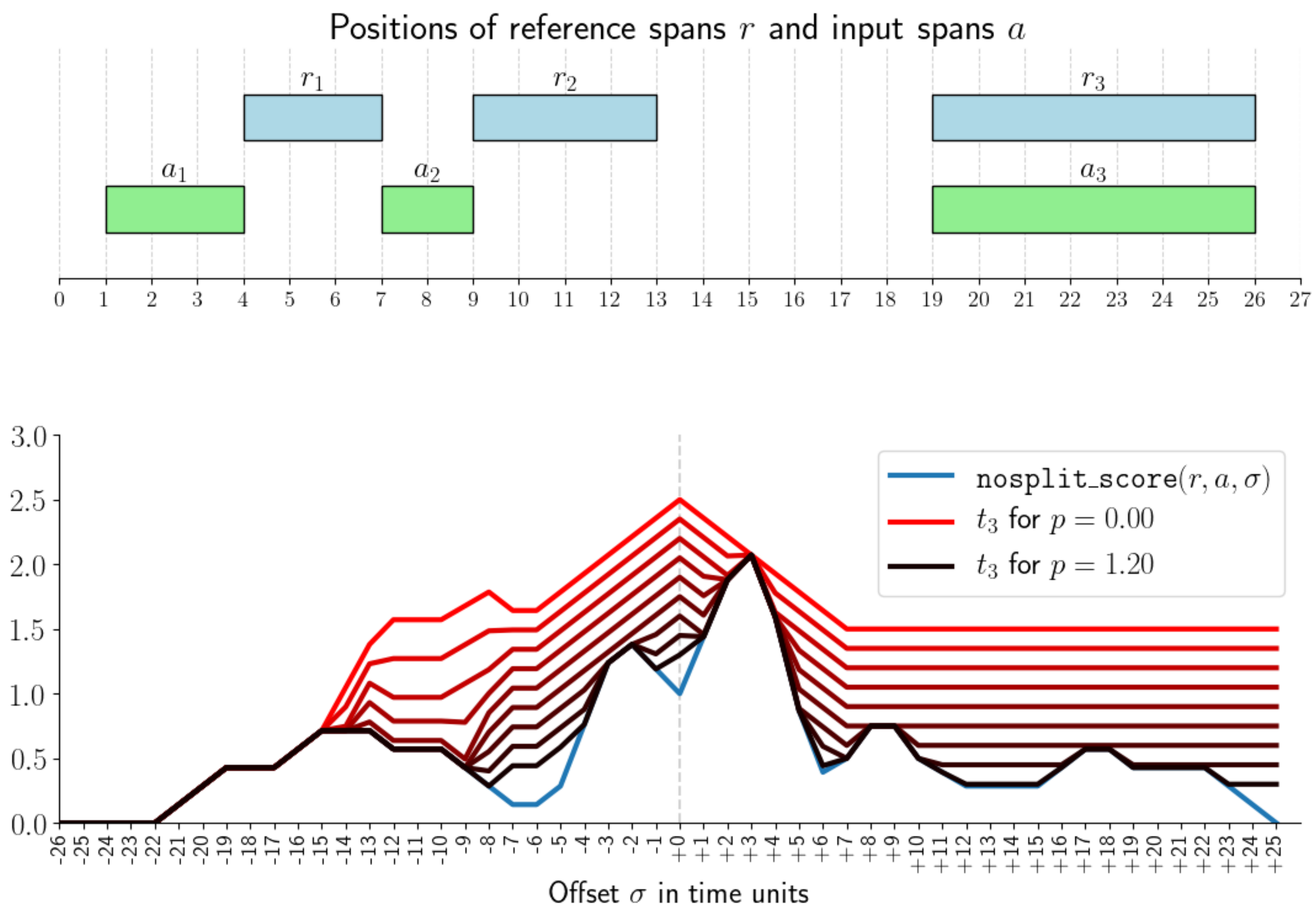




Optimal split alignment



Optimal split alignment

Extracting optimal split alignment $\sigma^* = (\sigma_1^*, \ldots, \sigma_N^*)$

- maximum of t_N occurs for σ_N^*
- recursion formula selects σ_{n-1}^* depending on σ_n^*

Optimal split alignment

Analysis

- runtime complexity: $O(N \cdot (T_r + T_a))$

Optimal split alignment

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Optimal split alignment

Analysis

- runtime complexity: $O(N \cdot (T_r + T_a)) \approx 3$ min
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Optimal split alignment

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Algorithm useless?

Optimal split alignment

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Optimal split alignment

Analysis

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- space complexity: $O(N \cdot (T_r + T_a)) \approx 53.6\text{GB}$ for $\sigma_n \to \sigma_{n-1}$ table

Algorithm useless?

- Merge segments with maximum error $\epsilon \approx 3$ seconds
- save $\sigma_n \to \sigma_{n-1}$ in linear segments: $< 150\text{MB}$ for 118 subtitles

Framerate correction

Assumption: Framerates can only differ by a few common fractions.

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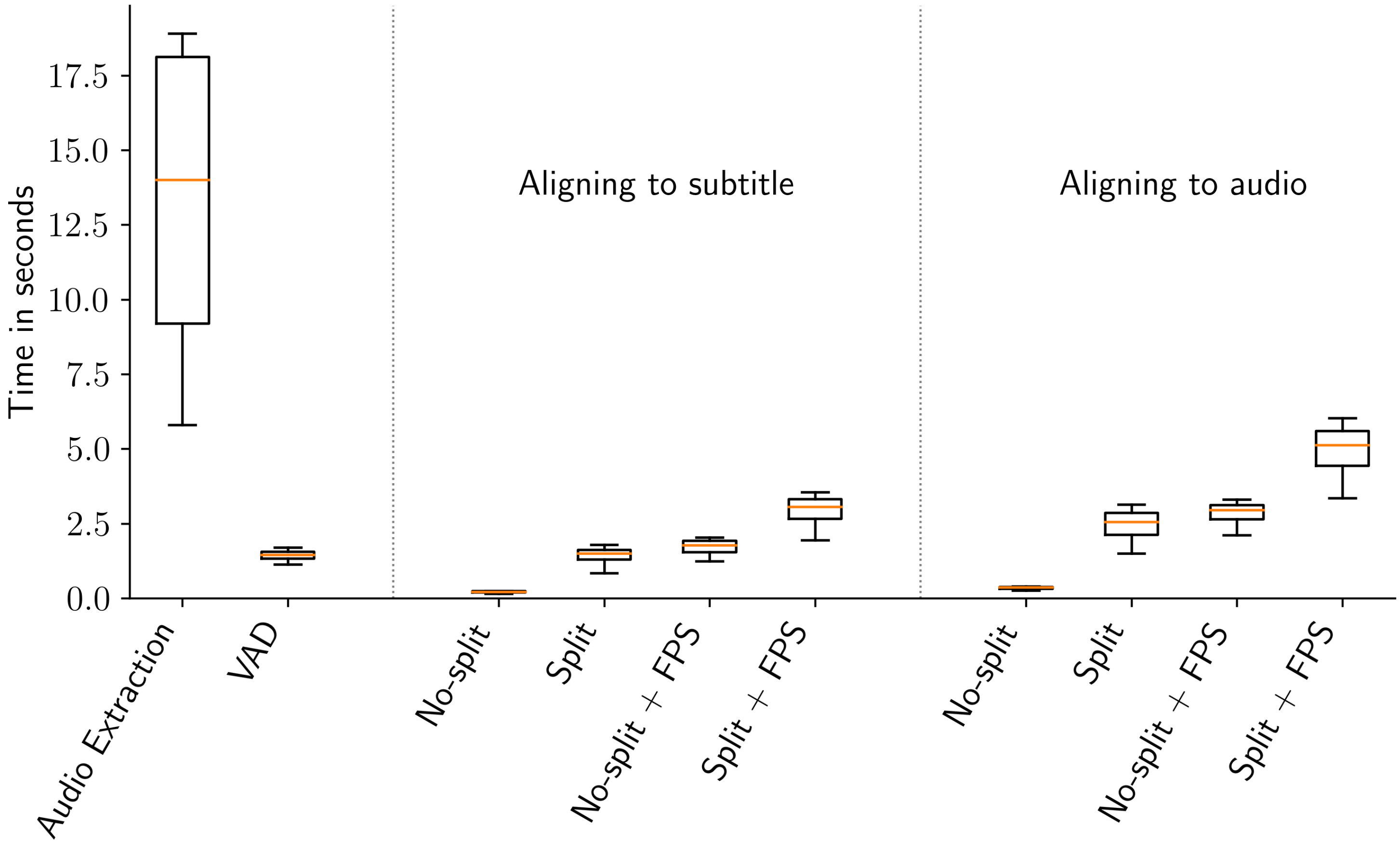
Compare no-split score of all subtitles scaled with the 7 ratios.

- 27 out of 118 subtitles: framerate difference All corrected!
- 91 out of 118 subtitle: no framerate difference 3 wrong guesses!

Performance comparison

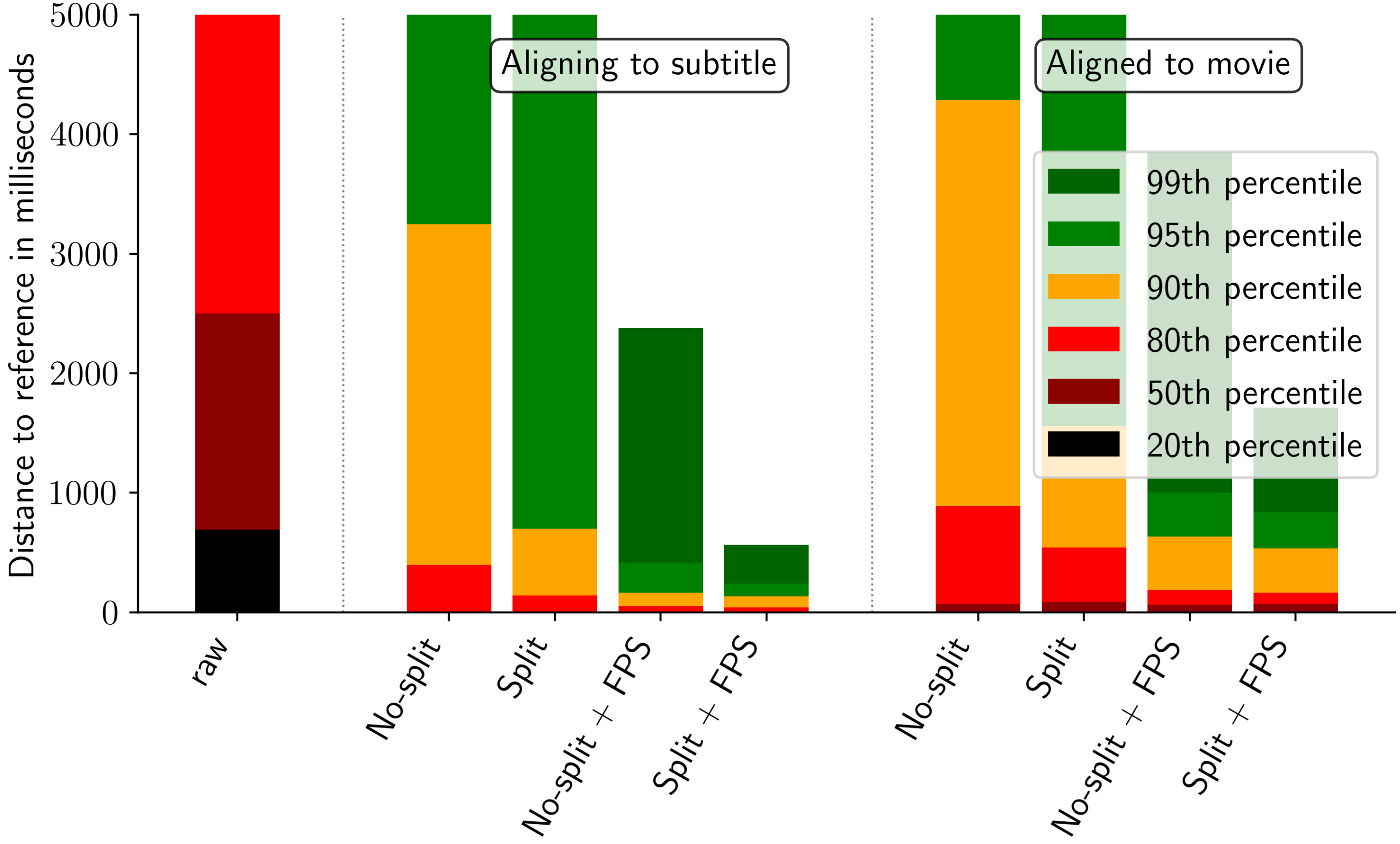


Results

Test Database

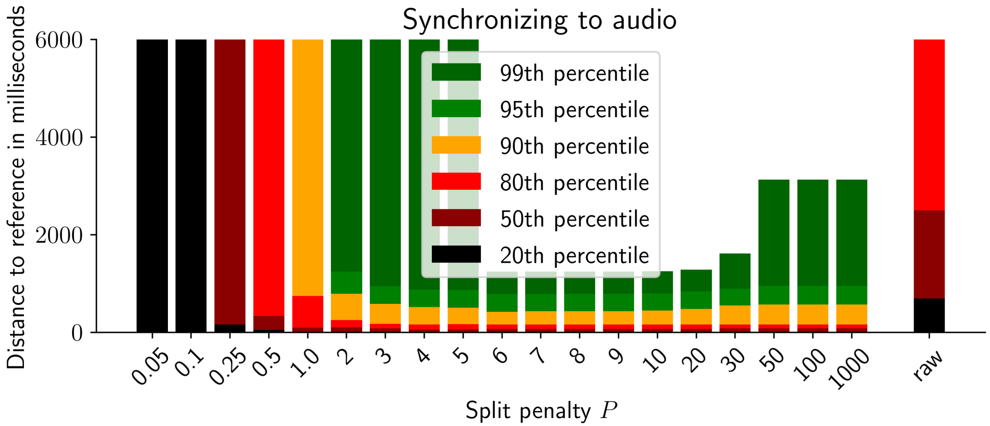
- 29 movies + 29 "reference subtitles"
- 118 input subtitles
- compare alignment against reference subtitle

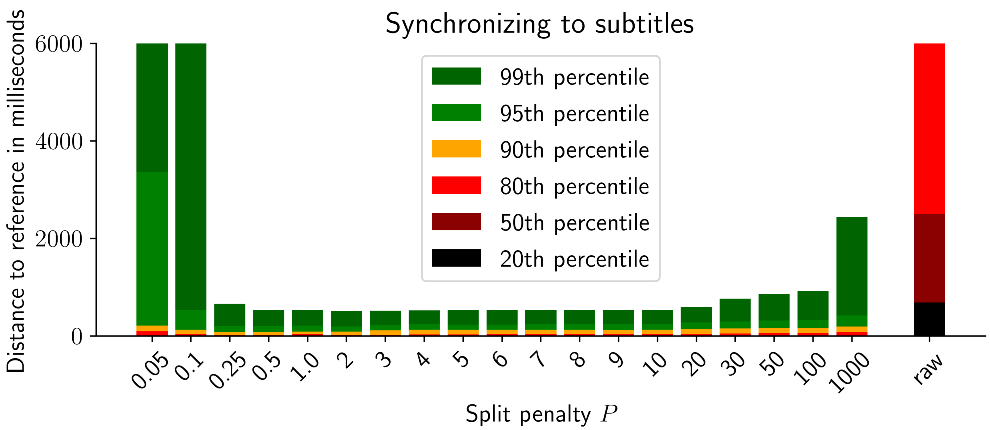
Alignment algorithms comparison



Results

Split penalties





Results

Alignment Classification

A "good subtitle" is defined here as

- less than 25% of lines having a distance of at most 300ms
- less than 70% of lines having a distance of at most 500ms
- less than 95% of lines having a distance of at most 1000ms
- less than 99% of lines having a distance of at most 1300ms

Results

Alignment Classification