Few Matches or Almost Periodicity: Faster Pattern Matching with Mismatches in Compressed Texts

Karl Bringmann, Marvin Künnemann, and Philip Wellnitz

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Pattern Matching with Mismatches

**Pattern Matching**

Given a text $t$ and a pattern $p$, is $p$ a substring of $t$?

```
 t: P A N C A K E
 p:   C A K E
```

Finding CAKE
Pattern Matching with Mismatches

Given a text $t$, a pattern $p$, and an integer $k$, does $t$ have a length-$|p|$ substring with Hamming-distance at most $k$ to $p$?

Finding $\text{ANPAN}$, $k = 2$
Pattern Matching with Mismatches

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**Thm. [Gawrychowski,Uznanski’18]**

Pattern matching with $k$ mismatches on a text of length $n$ and a pattern of length $m$ can be solved in time $\tilde{O}((m + k\sqrt{m}) \cdot n/m)$. 
Pattern Matching with Mismatches

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Matching (conditional) lower bound [GU’18]
What if the text is much larger than the pattern?

**ANPAN**
What if the text is much larger than the pattern?

ANPAN is a Japanese sweet roll most commonly filled with red bean paste. Anpan can also be prepared with other fillings including white beans, green beans, sesame, and chestnut.
What if the text is much larger than the pattern and given in a compressed representation?

ANPAN is a Japanese sweet roll most commonly filled with red bean paste. ANPAN can also be prepared with other fillings including white beans, green beans, sesame, and chestnut.
Grammar Compression

**Straight-Line Program (SLP)**

A Straight-Line Program or SLP $\mathcal{T}$ is a context-free grammar that generates exactly one string $\text{eval}(\mathcal{T})$. 
Grammar Compression

Straight-Line Program (SLP)
An SLP $\mathcal{T}$ is a set of non-terminals $\{T_1, \ldots, T_n\}$ and productions of the form $T_i \rightarrow \sigma$ or $T_i \rightarrow T_\ell T_r$, where $\ell, r < i$.
We write $\text{eval}(\mathcal{T}) = \text{eval}(T_n)$ for the generated string.
Grammar Compression

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$$T_1 \rightarrow A; \ T_2 \rightarrow N; \ T_3 \rightarrow P$$
Grammar Compression

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An SLP $\mathcal{T}$ is a set of non-terminals $\{T_1, \ldots, T_n\}$ and productions of the form $T_i \rightarrow \sigma$ or $T_i \rightarrow T_\ell \, T_r$, where $\ell, r < i$. We write $\text{eval}(\mathcal{T}) = \text{eval}(T_n)$ for the generated string.

- $T_1 \rightarrow A$
- $T_2 \rightarrow N$
- $T_3 \rightarrow P$
- $T_4 \rightarrow T_1 \, T_2$
- $T_5 \rightarrow T_4 \, T_3$

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Grammar Compression

Straight-Line Program (SLP)

An SLP \( \mathcal{T} \) is a set of non-terminals \( \{ T_1, \ldots, T_n \} \) and productions of the form \( T_i \rightarrow \sigma \) or \( T_i \rightarrow T_\ell T_r \), where \( \ell, r < i \).

We write \( \text{eval}(\mathcal{T}) = \text{eval}(T_n) \) for the generated string.

\[
\begin{align*}
T_1 & \rightarrow A; \quad T_2 \rightarrow N; \quad T_3 \rightarrow P \\
T_4 & \rightarrow T_1 T_2; \quad T_5 \rightarrow T_4 T_3 \\
T_6 & \rightarrow T_5 T_4
\end{align*}
\]
Grammar Compression

**Straight-Line Program (SLP)**

An SLP $T$ is a set of non-terminals $\{T_1, \ldots, T_n\}$ and productions of the form $T_i \rightarrow \sigma$ or $T_i \rightarrow T_\ell T_r$, where $\ell, r < i$. We write $\text{eval}(T) = \text{eval}(T_n)$ for the generated string.

$$
T_1 \rightarrow A; \ T_2 \rightarrow N; \ T_3 \rightarrow P \\
T_4 \rightarrow T_1 T_2; \ T_5 \rightarrow T_4 T_3 \\
T_6 \rightarrow T_5 T_4; \ T_7 \rightarrow T_6 T_4
$$
## Known Results

<table>
<thead>
<tr>
<th>Problem</th>
<th>uncompressed</th>
<th>LZW/LZ78 text</th>
<th>SLP text</th>
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<tbody>
<tr>
<td>n = Ω(√N)</td>
<td>n = Ω(log N)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pattern</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matching</td>
<td>O(N + m)</td>
<td>O(n + m) ★</td>
<td>Ĝ(n + m) ★ ★</td>
</tr>
<tr>
<td></td>
<td>[KMP'77]</td>
<td>[G'12]</td>
<td>[J'15]</td>
</tr>
<tr>
<td>PM with k</td>
<td>Ĝ(N/m (m + k√m))</td>
<td>O(n√mk²)</td>
<td>Ĝ(nmpoly(k))</td>
</tr>
<tr>
<td>Mismatches</td>
<td>[GU'18]</td>
<td>[GS'13]</td>
<td>[T'14, BLRS'15]</td>
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N: length of uncompressed text  
$n$: length of compressed text  
$k$: number of mismatches  

m: length of pattern  
★: allows compressed pattern

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<td>PM with (k) Mismatches</td>
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Improvement obtained via new structural insight in solution structure
Solution Structure of Pattern Matching

Fact (Folklore)

Let text $t$ and pattern $p$, $|t| \leq \frac{3}{2}|p|$, be given such that there are $\geq 2$ matches of $p$ in $t$ that together match $t$ completely. Then, both $p$ and $t$ are periodic with some period $x$ and every match of $p$ in $t$ starts at a position $1 + i \cdot |x|$. 
Solution Structure of Pattern Matching

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![Diagram](image)
Solution Structure of Pattern Matching

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![Diagram of text $t$ and pattern $p$ matching](image)
Solution Structure of Pattern Matching

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![Diagram of text and pattern](image_url)
What is the solution structure of Pattern Matching with Mismatches?
Solution Structure of Pattern Matching with Mismatches

If there are at least 2 $k$-matches of $p$ in $t$, then $p$ and $t$ are periodic and every $k$-match of $p$ starts at a position $1 + i|x|$?
Solution Structure of Pattern Matching with Mismatches

If there are at least two \( k \)-matches of \( p \) in \( t \), then \( p \) and \( t \) are periodic and every \( k \)-match of \( p \) starts at a position \( 1 + i|\chi| \)?
Solution Structure of Pattern Matching with Mismatches

If there are at least two $k$-matches of $p$ in $t$, then $p$ and $t$ are periodic and every $k$-match of $p$ starts at a position $1 + i|x|$?

- $p$ and $t$ not periodic, but $2k$ $k$-matches of $p$ in $t$
Solution Structure of Pattern Matching with Mismatches

If there are at least two $\Omega(\text{poly}(k))$ $k$-matches of $p$ in $t$, then $p$ and $t$ are periodic and every $k$-match of $p$ starts at a position $1 + i|x|$?

**Insight 1**

Periodicity only if number of $k$-matches of $p$ in $t$ is $\Omega(\text{poly}(k))$
Solution Structure of Pattern Matching with Mismatches

If there are at least $\Omega(\text{poly}(k))$ $k$-matches of $p$ in $t$, then $p$ and $t$ are periodic and every $k$-match of $p$ starts at a position $1 + i|x|$?

\[ t \quad A \quad A \quad \cdots \quad A \quad A \quad A \quad A \quad A \quad A \quad A \quad \cdots \quad A \quad A \]

\[ p \quad A \quad A \quad \cdots \quad A \quad A \quad A \quad A \quad A \quad A \quad A \]

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Solution Structure of Pattern Matching with Mismatches

If there are at least $\Omega(poly(k))$ $k$-matches of $p$ in $t$, then $p$ and $t$ are periodic and every $k$-match of $p$ starts at a position $1 + i|x|$?
Solution Structure of Pattern Matching with Mismatches

If there are at least $\Omega(\text{poly}(k))$ $k$-matches of $p$ in $t$, then $p$ and $t$ are periodic and every $k$-match of $p$ starts at a position $1 + i|\chi|$?

- $O(m)$ $k$-matches of $p$ in $t$, but $p$ and $t$ not perfectly periodic
Solution Structure of Pattern Matching with Mismatches

If there are at least $\Omega(\text{poly}(k))$ $k$-matches of $p$ in $t$, then $p$ and $t$ are periodic up to $O(k)$ mismatches and every $k$-match of $p$ starts at a position $1 + i|x|$?

**Insight 2**

Periodicity only up to $O(k)$ mismatches
Solution Structure of Pattern Matching with Mismatches

If there are at least $\Omega(poly(k))$ $k$-matches of $p$ in $t$, then $p$ and $t$ are periodic up to $O(k)$ mismatches and every $k$-match of $p$ starts at a position $1 + i|x|$?
Main Result

Theorem (Structural Insight)

For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$, or

- $t'$: shortest substring of $t$ such that any $k$-match of $p$ in $t$ is also a $k$-match in $t'$. Both $t'$ and $p$ have HD $O(k)$ to the same periodic string $x$ and all $k$-matches of $p$ in $t'$ start at a position $1 + i \cdot |x|$. 
Main Result

Theorem (Structural Insight)

For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

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Main Result, Proof Overview

**Theorem (Structural Insight)**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

- The number of $k$-matches of $p$ in $t$ is at most $1000k^2$, or
- Both $t'$ and $p$ have HD $< 20k$ to a periodic $x$; all $k$-matches start at position $1 + i \cdot |x|$.
Main Result, Proof Overview

**Theorem (Structural Insight)**

For pattern \( p \) and text \( t \), \( |t| \leq 2|p| \), at least one of the following holds:

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Consider \( t' \): shortest substring of \( t \) that contains all \( k \)-matches
Main Result, Proof Overview

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- Both $t'$ and $p$ have $\text{HD} < 20k$ to a periodic $x$; all $k$-matches start at position $1 + i \cdot |x|$.

- Split $p$ into $16k$ parts $p_i$ of equal length
Main Result, Proof Overview

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For pattern \( p \) and text \( t \), \( |t| \leq 2|p| \), at least one of the following holds:
- The number of \( k \)-matches of \( p \) in \( t \) is at most \( 1000k^2 \), or
- Both \( t' \) and \( p \) have HD < 20\( k \) to a periodic \( x \); all \( k \)-matches start at position \( 1 + i \cdot |x| \).

- Fix a \( p_i \)
Main Result, Proof Overview

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For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

- The number of $k$-matches of $p$ in $t$ is at most $1000k^2$, or
- Both $t'$ and $p$ have $\text{HD} < 20k$ to a periodic $x$; all $k$-matches start at position $1 + i \cdot |x|$.

- Consider prefix $x_i$ of $p_i$ that is also a period of $p_i$
Main Result, Proof Overview

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For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

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- Both $t'$ and $p$ have HD $< 20k$ to a periodic $x$; all $k$-matches start at position $1 + i \cdot |x|$.

- Find first $3k$ mismatches between $p$ and $x_i^*$ before and after $p_i$
Main Result, Proof Overview

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For pattern \( p \) and text \( t \), \( |t| \leq 2|p| \), at least one of the following holds:

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\[ p \]
\[ t' \]
\[ x_i^* \]
\[ \begin{array}{cccccccc}
  x_i & x_i & x_i & x_i & x_i & x_i & x_i & x_i \\
\end{array} \]

\[ < 6k \text{ mism.} \]
Main Result, Proof Overview

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**Insight**

Any $k$-match of $p$ in $t'$ must match at least one $p_i$'s exactly.
Main Result, Proof Overview

Theorem (Structural Insight)

For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

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- Fix a $p_i$
Main Result, Proof Overview

Theorem (Structural Insight)

For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

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- Both $t'$ and $p$ have $\text{HD} < 20k$ to a periodic $x$; all $k$-matches start at position $1 + i \cdot |x|$.

- Fix a $p_i$; count $k$-matches where $p_i$ is matched exactly
Main Result, Proof Overview

**Theorem (Structural Insight)**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

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Consider occurrences of $x_i$ in $t'$.
Main Result, Proof Overview

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---

**Problem**

Up to $O(m)$ exact matches of $x_i$ in $t'$.
Main Result, Proof Overview

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Consider power stretches of $x_i$ in $t'$ of length $\geq |p_i|$.
Main Result, Proof Overview

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- Consider **power stretches** of $x_i$ in $t'$ of length $\geq |p_i|$,
  - $\leadsto$ at most $150k$ different power stretches.
Main Result, Proof Overview

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- Fix a power stretch $t_j$ of $x_i$ in $t'$.
Main Result, Proof Overview

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- Fix a power stretch \( t_j \) of \( x_i \) in \( t' \).
Main Result, Proof Overview

**Theorem (Structural Insight)**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

- The number of $k$-matches of $p$ in $t$ is at most $1000k^2$, or
- Both $t'$ and $p$ have HD $< 20k$ to a periodic $x$; all $k$-matches start at position $1 + i \cdot |x|$.

**Insight**

Must align at least one mismatch.
Main Result, Proof Overview

Theorem (Structural Insight)

For pattern \( p \) and text \( t \), \(|t| \leq 2|p|\), at least one of the following holds:

- **The number of \( k \)-matches of \( p \) in \( t \) is at most \( 1000k^2 \), or**
- Both \( t' \) and \( p \) have HD < 20k to a periodic \( x \); all \( k \)-matches start at position \( 1 + i \cdot |x| \).

\[
\begin{align*}
\text{Insight} \\
\text{At most } O(k^4) \text{ matches: } O(k) \text{ parts in } p, O(k) \text{ stretches, } O(k^2) \text{ matches per combination.}
\end{align*}
\]
Main Result

**Theorem (Structural Insight) ✔**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, at least one of the following holds:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$, or

- $t'$: shortest substring of $t$ such that any $k$-match of $p$ in $t$ is also a $k$-match in $t'$
  
  Both $t'$ and $p$ have Hamming distance $O(k)$ to the same periodic string $x$ and all $k$-matches of $p$ in $t'$ start at a position $1 + i \cdot |x|$. 
Faster Algorithm

**Theorem (Algorithm)**

Pattern matching with $k$ mismatches on a text $t$ given by an SLP of size $n$ and a pattern $p$ of length $m$ can be solved in time $O(n k^3 (k \log k + \log m) + k m)$.

- Implementation of structural insight
- Use pattern-compressed string framework of [Gawrychowski, Straszak’13]
- Need e.g. tools for finding first $O(k)$ mismatches to a periodic string or finding all power stretches of a given string in a pc-string
Faster Algorithm

**Theorem (Algorithm)**

Pattern matching with \( k \) mismatches on a text \( t \) given by an SLP of size \( n \) and a pattern \( p \) of length \( m \) can be solved in time \( O(nk^3(k \log k + \log m) + km) \).

- Implementation of structural insight
  - Use pattern-compressed string framework of [Gawrychowski, Straszak’13]
  - Need e.g. tools for finding first \( O(k) \) mismatches to a periodic string or finding all power stretches of a given string in a pc-string
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- Implementation of structural insight
- Use pattern-compressed string framework of [Gawrychowski, Straszak’13]
- Need e.g. tools for finding first \( O(k) \) mismatches to a periodic string or finding all power stretches of a given string in a pc-string
Theorem (Algorithm) ✓

Pattern matching with $k$ mismatches on a text $t$ given by an SLP of size $n$ and a pattern $p$ of length $m$ can be solved in time $O(n k^3 (k \log k + \log m) + k m)$. 

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Faster Pattern Matching with Mismatches in Compressed Texts
Open Problems
Open Problems

- Improve insight to $O(k)$ mismatches in the aperiodic case

**Theorem (Structural Insight)**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, it holds at least one of:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$, or

- $t'$: shortest substring of $t$ such that any $k$-match of $p$ in $t$ is also a $k$-match in $t'$
  - Both $t'$ and $p$ have Hamming distance $O(k)$ to the same periodic string $x$
  - and all $k$-matches of $p$ in $t'$ start at a position $1 + i \cdot |x|$.
Open Problems

- Improve insight to $O(k)$ mismatches in the aperiodic case
- Improve dependence on $k$ in the algorithm

**Theorem (Algorithm)**
Pattern matching with $k$ mismatches on a text $t$ given by an SLP of size $n$ and a pattern $p$ of length $m$ can be solved in time $O(n k^3 (k \log k + \log m) + k m)$. 
Open Problems

- Improve insight to $O(k)$ mismatches in the aperiodic case
- Improve dependence on $k$ in the algorithm
- Fully-compressed setting ($p$ also given as an SLP)
Open Problems

- Improve insight to $O(k)$ mismatches in the aperiodic case
- Improve dependence on $k$ in the algorithm
- Fully-compressed setting ($p$ also given as an SLP)
- Pattern Matching with Errors (Edit distance instead of Hamming distance)
Solution Structure of Pattern Matching with Mismatches

\[ t = A \cdots A A A \cdots A A A \cdots A A \]

\[ p = A \cdots A A \cdots A A \cdots A \]

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Solution Structure of Pattern Matching with Mismatches

\[
\begin{align*}
\text{t} & \quad A^{2m/3-1} \quad A^{2m/3-1} \quad A^{2m/3} \\
 & \quad \underbrace{A \cdots A}_{A^{2m/3-1}} \quad B \quad A \cdots A \quad B \quad A \cdots A \\
\text{p} & \quad A^{(m-k-1)/2} \quad \underbrace{B^{k+1} A^{(m-k-1)/2}}_{A^{2m/3-1}} \\
\end{align*}
\]

B at \(2m/3, 4m/3\) in \(t\) and the middle \(k+1\) positions in \(p\)
Solution Structure of Pattern Matching with Mismatches

- All matches start at the union of two intervals.
Solution Structure of Pattern Matching with Mismatches

\[ t = A^{2m/3-1}A A^{2m/3-1}A \]

\[ B \text{ at } 2m/3, 4m/3 \text{ in } t \text{ and the middle } k + 1 \text{ positions in } p \]

\[ p = A \cdots A B \cdots B A \cdots A \]

\[ A^{(m-k-1)/2} B^{k+1} A^{(m-k-1)/2} \]

Insight 3

Arithmetic progression only approximates all matches
Main Result

**Theorem (Structural Insight)**

Given strings $p$ of length $m$ and $t$ of length at most $2m$, at least one of the following holds:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$.
- $t'$: shortest substring of $t$ such that any $k$-match of $p$ in $t$ is also a $k$-match in $t'$
  
  There is a substring $x$ of $p$, with $|x| = O(m/k)$, such that
  
  $\delta_H(p, x^*[1, m]) \leq O(k)$ and $\delta_H(t', x^*[1, |t'|]) \leq O(k)$.

  Moreover, any $k$-match of $p$ in $t'$ starts at a position of the form $1 + i \cdot |x|$ with $0 \leq i \leq (|t'| - |p|)/|x|$ (but not every starting position $1 + i \cdot |x|$ necessarily yields a $k$-match).
Main Result

**Theorem (Structural Insight)**

Given strings $p$ of length $m$ and $t$ of length at most $2m$, at least one of the following holds:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$.
- $t'$: shortest substring of $t$ such that any $k$-match of $p$ in $t$ is also a $k$-match in $t'$
  
  There is a substring $x$ of $p$, with $|x| = O(m/k)$, such that $\delta_H(p, x^[1, m]) \leq O(k)$ and $\delta_H(t', x^[1, |t'|]) \leq O(k)$.

Moreover, any $k$-match of $p$ in $t'$ starts at a position of the form $1 + i \cdot |x|$ with $0 \leq i \leq (|t'| - |p|)/|x|$ (but not every starting position $1 + i \cdot |x|$ necessarily yields a $k$-match).
Main Result

**Theorem (Structural Insight)**

Given strings $p$ of length $m$ and $t$ of length at most $2m$, at least one of the following holds:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$.
- $t'$: shortest substring of $t$ such that any $k$-match of $p$ in $t$ is also a $k$-match in $t'$

There is a substring $x$ of $p$, with $|x| = O(m/k)$, such that

$$\delta_H(p, x^*[1, m]) \leq O(k)$$

and

$$\delta_H(t', x^*[1, |t'|]) \leq O(k).$$

Moreover, any $k$-match of $p$ in $t'$ starts at a position of the form $1 + i \cdot |x|$ with $0 \leq i \leq (|t'| - |p|)/|x|$ (but not every starting position $1 + i \cdot |x|$ necessarily yields a $k$-match).

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Main Result

**Theorem (Structural Insight)**

Given strings \( p \) of length \( m \) and \( t \) of length at most \( 2m \), at least one of the following holds:

- The number of \( k \)-matches of \( p \) in \( t \) is at most \( O(k^2) \).
- \( t' \): shortest substring of \( t \) such that any \( k \)-match of \( p \) in \( t \) is also a \( k \)-match in \( t' \)

There is a substring \( x \) of \( p \), with \( |x| = O(m/k) \), such that

\[
\delta_H(p, x^*[1, m]) \leq O(k) \quad \text{and} \quad \delta_H(t', x^*[1, |t'|]) \leq O(k).
\]

Moreover, any \( k \)-match of \( p \) in \( t' \) starts at a position of the form \( 1 + i \cdot |x| \) with \( 0 \leq i \leq (|t'| - |p|)/|x| \) (but not every starting position \( 1 + i \cdot |x| \) necessarily yields a \( k \)-match).
Main Result

**Theorem (Structural Insight)**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, it holds at least one of:
- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$, and
- Both $t$ and $p$ have HD $O(k)$ to the same periodic string.
Main Result

**Theorem (Structural Insight)**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, it holds at least one of:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$, and
- Both $t$ and $p$ have HD $O(k)$ to the same periodic string.

Finding ANPAN, $k = 2$

non-periodic case

Finding PANPAN, $k = 2$

periodic case
Main Result

**Theorem (Structural Insight)**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, it holds at least one of:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$, and
- Both $t$ and $p$ have HD $O(k)$ to the same periodic string.

**Finding ANPAN**, $k = 2$

non-periodic case

**Finding PANPAN**, $k = 2$

periodic case
Main Result

**Theorem (Structural Insight)**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, it holds at least one of:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$, and
- Both $t$ and $p$ have HD $O(k)$ to the same periodic string.

Finding **ANPAN**, $k = 2$

non-periodic case

Finding **PANPAN**, $k = 2$

periodic case
Main Result

**Theorem (Structural Insight)**

For pattern $p$ and text $t$, $|t| \leq 2|p|$, it holds at least one of:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$, and
- Both $t$ and $p$ have HD $O(k)$ to the same periodic string.

**Finding ANPAN, $k = 2$**

- Non-periodic case

**Finding PANPAN, $k = 2$**

- Periodic case
Theorem (Structural Insight)

For pattern $p$ and text $t$, $|t| \leq 2|p|$, it holds at least one of:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$, and
- Both $t$ and $p$ have HD $O(k)$ to the same periodic string.
Main Result, Proof Overview

**Theorem (Structural Insight)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, then both $t$ and $p$ have a HD $< 20k$ to the same periodic string.
Main Result, Proof Overview

**Theorem (Structural Insight)**
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, then both $t$ and $p$ have a HD < $20k$ to the same periodic string.

Main Steps:
- At least $1000k^2$ $k$-matches of $p$ in $t$ and $p$ has a HD < $6k$ to a specific periodic string $x \in x(p)$
  \[ \implies t \text{ has a Hamming Distance } < 20k \text{ to } x \]
- $p$ has HD $\geq 6k$ to any specific periodic string $x \in x(p)$
  \[ \implies \text{Less than } 1000k^2 \text{ $k$-matches of } p \text{ in } t \]
Main Result, Proof Overview

**Theorem (Structural Insight)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, then both $t$ and $p$ have a HD $< 20k$ to the same periodic string.

Main Steps:

- **At least $1000k^2$ $k$-matches of $p$ in $t$ and $p$ has a HD $< 6k$ to a specific periodic string $x \in x(p)$**
  \[ \implies t \text{ has a Hamming Distance} < 20k \text{ to } x \]

- **$p$ has HD $\geq 6k$ to any specific periodic string $x \in x(p)$**
  \[ \implies \text{Less than } 1000k^2 \text{ $k$-matches of } p \text{ in } t \]
Main Result, Proof Overview

Lemma (Step 1)

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to a periodic string $x \in x(p)$, then $t$ has HD $< 20k$ to $x$. 

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Main Result, Proof Overview

**Lemma (Step 1)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$.

If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to a periodic string $x \in x(p)$, then $t$ has HD $< 20k$ to $x$. 

$t$

$p$
Main Result, Proof Overview

Lemma (Step 1)

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to a periodic string $x \in x(p)$, then $t$ has HD $< 20k$ to $x$.

- Split $p$ into $16k$ parts $p_i$ of equal length
Main Result, Proof Overview

Lemma (Step 1)

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to a periodic string $x \in x(p)$, then $t$ has HD $< 20k$ to $x$.

- Split $p$ into $16k$ parts $p_i$ of equal length
Main Result, Proof Overview

**Lemma (Step 1)**
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to a periodic string $x \in x(p)$, then $t$ has HD $< 20k$ to $x$.

- Fix a $p_i$
Main Result, Proof Overview

**Lemma (Step 1)**
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to a periodic string $x \in x(p)$, then $t$ has HD $< 20k$ to $x$.

- Consider prefix $x_i$ of $p_i$ that is also a period of $p_i$
Main Result, Proof Overview

Lemma (Step 1)

Fix a pattern \( p \) of length \( m \) and a text \( t \) of length at most \( 2m \).
If the number of \( k \)-matches of \( p \) in \( t \) is at least \( 1000k^2 \), and \( p \) has HD < 6\( k \) to a periodic string \( x \in x(p) \), then \( t \) has HD < 20\( k \) to \( x \).

\[
\begin{align*}
x_i^* & \quad x_i \quad x_i \quad x_i \quad x_i \quad x_i \quad x_i \quad x_i \quad x_i \quad x_i \quad x_i \\
p & \quad x_i \quad x_i \\
\end{align*}
\]

- Find first 3\( k \) mismatches between \( p \) and \( x_i^* \) before and after \( p_i \)
Main Result, Proof Overview

**Lemma (Step 1)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has $\text{HD} < 6k$ to a periodic string $x \in x(p)$, then $t$ has $\text{HD} < 20k$ to $x$.

- Find first $3k$ mismatches between $p$ and $x_i^*$ before and after $p_i$
Main Result, Proof Overview

**Lemma (Step 1)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to some $x_i^*, 1 \leq i \leq 16k$, then $t$ has HD $< 20k$ to $x_i^*$.
Main Result, Proof Overview

**Lemma (Step 1)**
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to some $x_i^*$, $1 \leq i \leq 16k$, then $t$ has HD $< 20k$ to $x_i^*$.

**Claim (Proof omitted)**
If there are at least $2 + 16k$ $k$-matches of $p$ in $t$, all starting positions of $k$-matches differ by (integer) multiples of $|x_i|$. 

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Main Result, Proof Overview

**Lemma (Step 1)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to some $x_i^*, 1 \leq i \leq 16k$, then all starting positions of $k$-matches differ by multiples of $|x_i|$ and $t$ has HD $< 20k$ to $x_i^*$. 
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to some $x_i^*, 1 \leq i \leq 16k$, then all starting positions of $k$-matches differ by multiples of $|x_i|$ and $t$ has HD $< 20k$ to $x_i^*$. 
Main Result, Proof Overview

**Lemma (Step 1)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to some $x_i^*, 1 \leq i \leq 16k$, then all starting positions of $k$-matches differ by multiples of $|x_i|$ and $t$ has HD $< 20k$ to $x_i^*$. 

---

$t$

$x_i^*$

$p$

---

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Faster Pattern Matching with Mismatches in Compressed Texts
Main Result, Proof Overview

**Lemma (Step 1)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to some $x_i^*$, $1 \leq i \leq 16k$, then all starting positions of $k$-matches differ by multiples of $|x_i|$ and $t$ has HD $< 20k$ to $x_i^*$.
Main Result, Proof Overview

** Lemma (Step 1) **

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has $HD < 6k$ to some $x_i^*$, $1 \leq i \leq 16k$, then all starting positions of $k$-matches differ by multiples of $|x_i|$ and $t$ has $HD < 20k$ to $x_i^*$. 

![Diagram showing the relationship between pattern $p$, text $t$, and $x_i^*$, highlighting the conditions for the lemma to hold.](image-url)
Main Result, Proof Overview

**Lemma (Step 1)**
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the number of $k$-matches of $p$ in $t$ is at least $1000k^2$, and $p$ has HD $< 6k$ to some $x_i^*$, $1 \leq i \leq 16k$, then all starting positions of $k$-matches differ by multiples of $|x_i|$ and $t$ has HD $< 20k$ to $x_i^*$.

**Lemma (Step 2)**
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the pattern $p$ has a HD $\geq 6k$ to all strings $x_i^*$, $1 \leq i \leq 16k$, then there are less than $1000k^2$ $k$-matches of $p$ in $t$. 
Main Result, Proof Overview

Lemma (Step 2)
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the pattern $p$ has a HD $\geq 6k$ to all strings $x_{i^*}$, $1 \leq i \leq 16k$, then there are less than $1000k^2$ $k$-matches of $p$ in $t$. 
Main Result, Proof Overview

**Lemma (Step 2)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$.
If the pattern $p$ has a HD $\geq 6k$ to all strings $x_i^*$, $1 \leq i \leq 16k$, then there are less than $1000k^2$ $k$-matches of $p$ in $t$.

- Recall: Split $p$ into $16k$ parts $p_i$ of equal length.

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Main Result, Proof Overview

**Lemma (Step 2)**
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$.
If the pattern $p$ has a HD $\geq 6k$ to all strings $x_i^*$, $1 \leq i \leq 16k$, then there are less than $1000k^2$ $k$-matches of $p$ in $t$.

**Insight**
Any $k$-match of $p$ in $t$ must match at least $15k$ $p_i$'s **exactly**.
Main Result, Proof Overview

**Lemma (Step 2)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the pattern $p$ has a HD $\geq 6k$ to all strings $x_i^*, 1 \leq i \leq 16k$, then there are less than $1000k^2 k$-matches of $p$ in $t$.

- Fix a $p_i$
Main Result, Proof Overview

**Lemma (Step 2)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the pattern $p$ has a HD $\geq 6k$ to all strings $x_i^*$, $1 \leq i \leq 16k$, then there are less than $1000k^2$ $k$-matches of $p$ in $t$.

- Fix a $p_i$; count $k$-matches where $p_i$ is matched exactly

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Faster Pattern Matching with Mismatches in Compressed Texts
Main Result, Proof Overview

**Lemma (Step 2)**
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$.
If the pattern $p$ has a HD $\geq 6k$ to all strings $x_i^*$, $1 \leq i \leq 16k$, then there are less than $1000k^2$ $k$-matches of $p$ in $t$.

- Search for $x_i$ in $t$
Main Result, Proof Overview

**Lemma (Step 2)**
Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the pattern $p$ has a HD $\geq 6k$ to all strings $x_i^*, 1 \leq i \leq 16k$, then there are less than $1000k^2$ $k$-matches of $p$ in $t$.

Problem
Up to $O(m)$ exact matches of $x_i$ in $t$. 
Main Result, Proof Overview

**Lemma (Step 2)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$.
If the pattern $p$ has a HD $\geq 6k$ to all strings $x_i^*, 1 \leq i \leq 16k$, then there are less than $1000k^2$ $k$-matches of $p$ in $t$. 

- Search for **power stretches** of $x_i$ in $t$ of length $\geq |p_i|$
Main Result, Proof Overview

**Lemma (Step 2)**

Fix a pattern \( p \) of length \( m \) and a text \( t \) of length at most \( 2m \).
If the pattern \( p \) has a HD \( \geq 6k \) to all strings \( x_i^*, 1 \leq i \leq 16k \), then there are less than \( 1000k^2 \) \( k \)-matches of \( p \) in \( t \).

\[
\begin{array}{ccccccc}
\[ \text{t} \] & x_i & x_i & x_i & x_i & x_i & x_i \\
\end{array}
\]

Only \( \leq 150k \) different power stretches of \( x_i \) in \( t \).
Main Result, Proof Overview

**Lemma (Step 2)**

Fix a pattern $p$ of length $m$ and a text $t$ of length at most $2m$. If the pattern $p$ has a HD $\geq 6k$ to all strings $x_i^*, 1 \leq i \leq 16$, then there are less than $1000k^2$ $k$-matches of $p$ in $t$.

- Fix a power stretch $t_j$ of $x_i$ in $t$. 
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![Diagram](image-url)
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\[ p \]

\[ x_i x_i \]

\[ t \]

\[ x_i x_i x_i x_i \]

\[ x_i^* \]

\[ x_i x_i x_i x_i x_i x_i x_i x_i x_i x_i x_i x_i x_i x_i x_i x_i \]

\[ p_i \geq 3k \text{ mism.} \]
Main Result, Proof Overview

$$t$$

$$x_i^*$$

$$p$$

$$(x_i x_j x_i x_j x_i x_j x_i x_j x_i)$$

$$t_j$$

$$\geq 2k \text{ mism.}$$

$$p_i$$

$$\geq 3k \text{ mism.}$$

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Faster Pattern Matching with Mismatches in Compressed Texts
Main Result, Proof Overview

\[ t_j \geq 2k \text{ mism.} \]

\[ x_i^* \]

\[ p_i \geq 3k \text{ mism.} \]

Insight
Must align at least \( k \) mismatches.
Main Result, Proof Overview

\[ \begin{align*}
& t_j \geq 2k \text{ mism.} \\
& x_i^* \geq 2k \text{ mism.} \\
& p_i \geq 3k \text{ mism.}
\end{align*} \]

**Insight**

At most \( O(k^4) \) matches: \( O(k) \) parts in \( p \), \( O(k) \) stretches, \( O(k^2) \) matches per combination.
Main Result, Proof Overview

<table>
<thead>
<tr>
<th>Lemma (Step 1)</th>
<th>✓</th>
</tr>
</thead>
<tbody>
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Main Result, Proof Overview

**Theorem (Structural Insight)**

Given strings $p$ of length $m$ and $t$ of length at most $2m$, at least one of the following holds:

- The number of $k$-matches of $p$ in $t$ is at most $O(k^2)$.
- $t'$: shortest substring of $t$ such that any $k$-match of $p$ in $t$ is also a $k$-match in $t'$
  There is a substring $x$ of $p$, with $|x| = O(m/k)$, such that $\delta_H(p, x^*[1, m]) \leq O(k)$ and $\delta_H(t', x^*[1, |t'|]) \leq O(k)$.
  Moreover, any $k$-match of $p$ in $t'$ starts at a position of the form $1 + i \cdot |x|$ with $0 \leq i \leq (|t'| - |p|)/|x|$ (but not every starting position $1 + i \cdot |x|$ necessarily yields a $k$-match).
Faster Algorithm for Pattern-Compressed Strings

Pattern-Compressed String [GS’13]

Let $p$ be a string of length $m$. We call a string $f = v_1 \ldots v_q, \sum_{i=1}^{q} |v_i| \leq 2m$ a $p$-pattern-compressed string (pc-string) if every $v_i$ is a substring of $p$. We call the $v_i$’s factors of $f$. 
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SLP Instance $I$

$T = T_1, \ldots, T_n$

$k, p$ of length $m$

O($n (\log m + T(m, k)) + km$)

T($m, k$) algorithm

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![Diagram showing SLP instances and PC-String instances with O(k^3(k \log k + \log m)) algorithm.]
Faster Algorithm for Pattern-Compressed Strings

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---

**SLP Instance \( I \)**

\[
\begin{align*}
& \text{SLP } \mathcal{T} = T_1, \ldots, T_n \\
& k, p \text{ of length } m \\
& O(n k^3 (k \log k + \log m) + k m)
\end{align*}
\]

**PC-String, inst. \( J_1 \)**

\[
\begin{align*}
& k, p, f_1 \text{ with } O(k) \text{ factors} \\
& O(k^3(k \log k + \log m)) \text{ algorithm}
\end{align*}
\]

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**Theorem (Algorithm for pc-strings)**

Pattern matching with $k$ mismatches on a pattern $p$ of length $m$ and a $p$-pc-string $f$ of size $O(k)$ representing at most $2m$ characters, can be solved in time $O(k^3(k \log k + \log m))$.

(With $O(km)$ preprocessing on $p$.)

- Implementation of structural insight
- Need e.g. tools for finding first $O(k)$ mismatches to a periodic string or finding all power stretches of a given string in a pc-string
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