Quasi-linear Time Computation of the Abelian Periods of a Word

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Abstract. In the last couple of years many research papers have been devoted to Abelian complexity of words. Recently, Constantinescu and Ilie (Bulletin EATCS 89, 167–170, 2006) introduced the notion of *Abelian period*. In this article we present two quadratic brute force algorithms for computing Abelian periods for special cases and a quasi-linear algorithm for computing all the Abelian periods of a word.

Keywords: Abelian period, Abelian repetition, weak repetition, design of algorithms, text algorithms, combinatorics on words

1 Introduction

An integer $p > 0$ is a (classical) period of a word $\boldsymbol{w}$ of length n if $\boldsymbol{w}[i] = \boldsymbol{w}[i+p]$ for any $1 \leqslant i \leqslant n-p$. Classical periods have been extensively studied in combinatorics on words [16] due to their direct applications in data compression and pattern matching.

The Parikh vector of a word $\boldsymbol{w}$ enumerates the cardinality of each letter of the alphabet in $\boldsymbol{w}$. For example, given the alphabet $\Sigma = \{a, b, c\}$, the Parikh vector of the word $\boldsymbol{w} = aaba$ is $(3, 1, 0)$. The reader can refer to [6] for a list of applications of Parikh vectors.

An integer p is an *Abelian period* for a word $\boldsymbol{w}$ over a finite alphabet $\Sigma = \{a_1, a_2, \ldots, a_\sigma\}$ if $\boldsymbol{w}$ can be written as $\boldsymbol{w} = \boldsymbol{u}_0\boldsymbol{u}_1 \cdots \boldsymbol{u}_{k-1}\boldsymbol{u}_k$ where for $0 < i < k$ all the $\boldsymbol{u}_i$'s have the same Parikh vector $\mathcal{P}$ such that $\sum_{i=1}^{\sigma} \mathcal{P}[i] = p$ and the Parikh vectors of $\boldsymbol{u}_0$ and $\boldsymbol{u}_k$ are contained in $\mathcal{P}$ [11]. For example, the word $\boldsymbol{w} = ababbbabb$ can be written as $\boldsymbol{w} = \boldsymbol{u}_0\boldsymbol{u}_1\boldsymbol{u}_2\boldsymbol{u}_3$, with $\boldsymbol{u}_0 = a$, $\boldsymbol{u}_1 = bab$, $\boldsymbol{u}_2 = bba$ and $\boldsymbol{u}_3 = bb$, and 3 is an Abelian period of $\boldsymbol{w}$ with Parikh vector $(1, 2)$ over $\Sigma = \{a, b\}$.

This definition of Abelian period matches that of *weak repetition* (also called *Abelian power*) when $\boldsymbol{u}_0$ and $\boldsymbol{u}_k$ are the empty word and $k > 2$ [12].

In the last couple of years many research papers have been devoted to Abelian complexity [13,1,8,3,14,2,4,20]. Efficient algorithms for Abelian Pattern Matching (also known as Jumbled Pattern Matching) have been designed [10,5,6,17,18,7].

Recently [15] gave algorithms for computing all the Abelian periods of a word of length n in time $O(n^2 \times \sigma)$. This was improved to time $O(n^2)$ in [9].

In this article we present a quasi-linear time algorithm for computing the Abelian periods of a word. In Section 2 we give some basic definitions and notation. Section 3 presents brute force algorithms while Section 4 presents our main contribution. Finally, Section 5 contains conclusions and perspectives.

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2 Notation

Let $\Sigma = \{a_1, a_2, \ldots, a_\sigma\}$ be a finite ordered alphabet of cardinality σ and Σ^* the set of words on alphabet Σ. We denote by $|\boldsymbol{w}|$ the length of the word $\boldsymbol{w}$. We write $\boldsymbol{w}[i]$ for the i-th symbol of $\boldsymbol{w}$ and $\boldsymbol{w}[i\,..\,j]$ for the factor of $\boldsymbol{w}$ from the i-th symbol to the j-th symbol, with $1 \leqslant i \leqslant j \leqslant |\boldsymbol{w}|$. We denote by $|\boldsymbol{w}|_a$ the number of occurrences of the symbol $a \in \Sigma$ in the word $\boldsymbol{w}$.

The *Parikh vector* of a word $\boldsymbol{w}$, denoted by $\mathcal{P}_{\boldsymbol{w}}$, counts the occurrences of each letter of Σ in $\boldsymbol{w}$; that is $\mathcal{P}_{\boldsymbol{w}} = (|\boldsymbol{w}|_{a_1}, \ldots, |\boldsymbol{w}|_{a_\sigma})$. Notice that two words have the same Parikh vector if and only if one word is a permutation of the other.

Given the Parikh vector $\mathcal{P}_{\boldsymbol{w}}$ of a word $\boldsymbol{w}$, we denote by $\mathcal{P}_{\boldsymbol{w}}[i]$ its i-th component and by $|\mathcal{P}_{\boldsymbol{w}}|$ the sum of its components. Thus for $\boldsymbol{w} \in \Sigma^*$ and $1 \leqslant i \leqslant \sigma$, we have $\mathcal{P}_{\boldsymbol{w}}[i] = |\boldsymbol{w}|_{a_i}$ and $|\mathcal{P}_{\boldsymbol{w}}| = \sum_{i=1}^{\sigma} \mathcal{P}_{\boldsymbol{w}}[i] = |\boldsymbol{w}|$.

Finally, given two Parikh vectors $\mathcal{P}, \mathcal{Q}$, we write $\mathcal{P} \subset \mathcal{Q}$ if $\mathcal{P}[i] \leqslant \mathcal{Q}[i]$ for every $1 \leqslant i \leqslant \sigma$ and $|\mathcal{P}| < |\mathcal{Q}|$.

Definition 1 ([11]). *A word $\boldsymbol{w}$ has an Abelian period (h, p) if $\boldsymbol{w} = \boldsymbol{u}_0\boldsymbol{u}_1 \cdots \boldsymbol{u}_{k-1}\boldsymbol{u}_k$ such that:*

- $\mathcal{P}_{\boldsymbol{u}_0} \subset \mathcal{P}_{\boldsymbol{u}_1} = \cdots = \mathcal{P}_{\boldsymbol{u}_{k-1}} \supset \mathcal{P}_{\boldsymbol{u}_k}$,
- $|\mathcal{P}_{\boldsymbol{u}_0}| = h$, $|\mathcal{P}_{\boldsymbol{u}_1}| = p$.

We call $\boldsymbol{u}_0$ and $\boldsymbol{u}_k$ resp. the *head* and the *tail* of the Abelian period. Notice that the length $t = |\boldsymbol{u}_k|$ of the tail is uniquely determined by h, p and $|\boldsymbol{w}|$, namely $t = (|\boldsymbol{w}| - h) \bmod p$.

The following lemma gives a bound on the maximum number of Abelian periods of a word.

Lemma 2 ([15]). *The maximum number of Abelian periods for a word of length n over the alphabet Σ is $\Theta(n^2)$.*

Proof. The word $(a_1a_2 \cdots a_\sigma)^{n/\sigma}$ has Abelian period (h, p) for any $p \equiv 0 \bmod \sigma$ and $h < p$. ☐

A natural order can be defined on the Abelian periods.

Definition 3. *Two distinct Abelian periods (h, p) and (h', p') of a word $\boldsymbol{w}$ are ordered as follows: $(h, p) < (h', p')$ if $p < p'$ or ($p = p'$ and $h < h'$).*

Definition 4 ([9]). *Let $\boldsymbol{w}$ be a word of length n. Then the mapping $pr : \Sigma \to A$, where A is the set of the first σ prime numbers, is defined by:*

$$pr(\sigma_i) = i\text{-th prime number.}$$

The P-signature of $\boldsymbol{w}$ is defined by:

$$P\text{-}signature(\boldsymbol{w}) = \Pi_{i=1}^{n} pr(\boldsymbol{w}[i]).$$

Definition 5 ([9]). *Let $\boldsymbol{w}$ be a word of length n. Then the mapping $s : \Sigma \to B$, where B is the set of the first $\sigma - 1$ powers of $n+1$ and 0, is defined by:*

$$s(\sigma_i) = \begin{cases} 0 & \text{if } i = 1 \\ (n+1)^{i-2} & \text{otherwise.} \end{cases}$$

The S-signature of $\boldsymbol{w}$ is defined by:

$$S\text{-}signature(\boldsymbol{w}) = \sum_{i=0}^{n} s(\boldsymbol{w}[i]).$$

Observation 1 ([9]) *For a word $\boldsymbol{w}$ of length n the array Pr of n elements is defined by*

$$Pr[i] = \Pi_{j=1}^{i} pr(\boldsymbol{w}[j]),$$

then

$$P\text{-}signature(\boldsymbol{w}[k \mathinner{.\,.} \ell]) = \begin{cases} Pr[\ell]/Pr[k-1] & \text{if } k \neq 0 \\ Pr[\ell] & \text{otherwise.} \end{cases}$$

Observation 2 ([9]) *For a word $\boldsymbol{w}$ of length n the array S of n elements is defined by*

$$S[i] = \sum_{j=1}^{i} s(\boldsymbol{w}[j]),$$

then

$$S\text{-}signature(\boldsymbol{w}[k \mathinner{.\,.} \ell]) = \begin{cases} S[\ell] - S[k-1] & \text{if } k \neq 0 \\ S[\ell] & \text{otherwise.} \end{cases}$$

Example 6. $\boldsymbol{w} =$ `abaab`:

i	1	2	3	4	5
$\boldsymbol{w}[i]$	a	b	a	a	b
$pr(\boldsymbol{w}[i])$	2	3	2	2	3
$Pr[i]$	2	6	12	24	72

$P\text{-}signature(\boldsymbol{w}[3 \mathinner{.\,.} 5]) =$
$P\text{-}signature(\texttt{aab}) =$
$Pr[5]/Pr[2] = 72/6 = 12$

i	1	2	3	4	5
$\boldsymbol{w}[i]$	a	b	a	a	b
$s(i)$	0	1	0	0	1
$S[i]$	0	1	1	1	2

$S\text{-}signature(\boldsymbol{w}[3 \mathinner{.\,.} 5]) =$
$S\text{-}signature(\texttt{aab}) =$
$S[5] - S[2] = 2 - 1 = 1$

3 Brute Force Algorithms

We will first focus on the case where we consider periods without head nor tail.

In the remaining of the article we will write that a word $\boldsymbol{w}$ has Abelian period p whenever it has Abelian period $(0, p)$. When the tail is also empty, for a word $\boldsymbol{w}$ of length n an Abelian period p must divide n. We define:

- $P[i]$ is the set of Abelian periods of $\boldsymbol{w}[1 \mathinner{.\,.} i]$;
- $V[i] = \mathcal{P}(\boldsymbol{w}[1 \mathinner{.\,.} i])$ is the Parikh vector of $\boldsymbol{w}[1 \mathinner{.\,.} i]$.

3.1 Abelian periods with neither head nor tail

In a first step we set $P[i] = \{i\}$ for all the divisors of n. Then we process the positions i of $\boldsymbol{w}$ in ascending order: if $j \in P[i]$ and $\mathcal{P}_{\boldsymbol{w}}[i+1 \mathinner{.\,.} i+j] = \mathcal{P}_{\boldsymbol{w}}[1 \mathinner{.\,.} j]$, then we add j to $P[i+j]$. This test can be done in $O(\sigma)$ time by precomputing the Parikh vectors of all the prefixes of $\boldsymbol{w}$ or in constant time using signatures. At the end of the process $P[n]$ contains all the Abelian periods of $\boldsymbol{w}$ with neither head nor tail (see algorithm in Figure 1).

```
AbelianPeriodsNoHeadNoTail(w, n)
 1  V[i] ← P(w[1..i]), ∀ 1 ≤ i ≤ n
 2  P[i] ← ∅, ∀ 1 ≤ i ≤ n
 3  for i ← 1 to n/2 do
 4     if n mod i = 0 then
 5        P[i] ← {i}
 6  for i ← 1 to n − 1 do
 7     for j ∈ P[i] do
 8        if V[i + j] − V[i] = V[j] then
 9           P[i + j] ← P[i + j] ∪ {j}
10  return P[n]
```

Figure 1. Compute the Abelian periods with no head and no tail of a word $\boldsymbol{w}$ of length n

```
AbelianPeriodsNoHeadWithTail(w, n)
 1  V[i] ← P(w[1..i]), ∀ 1 ⩽ i ⩽ n
 2  P[i] ← {i}, ∀ 1 ⩽ i ⩽ n/2
 3  P[i] ← ∅, ∀ n/2 < i ⩽ n
 4  for i ← 1 to n − 1 do
 5     for j ∈ P[i] do
 6        if i + j > n then
 7           if V[n] − V[i + 1] ≤ V[j] then
 8              P[n] ← P[n] ∪ {j}
 9        else if V[i + j] − V[i] = V[j] then
10              P[i + j] ← P[i + j] ∪ {j}
11  return P[n]
```

Figure 2. Compute the Abelian periods without head and with a possibly non-empty tail of a word $\boldsymbol{w}$ of length n

Example 7. $\boldsymbol{w}$ = abaababbbabaabbabbaaabbababbaa:

i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
$\boldsymbol{w}[i]$	a	b	a	a	b	a	b	b	b	a	b	a	a	b	b	a	b	b	a	a	a	b	b	a	b	a	b	b	a	a
P	{1}	{2}	{3}		{5}	{6}				{10}					{15}					{10}										{10}
						{3}																								

Theorem 8. *The algorithm **AbelianPeriodsNoHeadNoTail** computes all the Abelian periods with neither head nor tail of a word $\boldsymbol{w}$ of length n in time $O(n^2 \times \sigma)$ if the test in line 8 is performed by comparing Parikh vectors and in time $O(n^2)$ if the test in line 8 is performed by using S-signatures or P-signatures.*

3.2 Abelian periods without head with tail

Now we consider Abelian periods without head and with a possibly non-empty tail. We adapt the previous algorithm by setting $P[i] = \{i\}$ for $1 \leqslant i \leqslant n/2$ (see algorithm Figure 2).

Theorem 9. *The algorithm **AbelianPeriodsNoHeadWithTail** computes all the Abelian periods without head and with tail of a word $\boldsymbol{w}$ of length n in time $O(n^2 \times \sigma)$ if the tests in lines 7 and 1 are performed by comparing Parikh vectors and in time $O(n^2)$ if the test in lines 7 and 1 are performed by using S-signatures or P-signatures.*

4 Quasi-Linear Time Computation of Abelian Periods with neither Head nor Tail

In a linear-time preprocessing phase we compute $\mathcal{P}_{\boldsymbol{w}}[j]$, $j = 1, 2, \ldots, \sigma$, the components of the Parikh vector of the word $\boldsymbol{w}$. Also we compute

$$g = \gcd(\mathcal{P}_{\boldsymbol{w}}[1], \mathcal{P}_{\boldsymbol{w}}[2], \ldots, \mathcal{P}_{\boldsymbol{w}}[\sigma])$$

and $q = n/g$. Without loss of generality we suppose $\sigma \geq 2$ and $g > 1$. In $O(\sqrt{g})$ time we compute a stack D of all divisors $1 \leq d \leq g$ of g in ascending order.

Definition 10. *The word $\boldsymbol{w}$ is an **Abelian repetition** of **period** p and **exponent** e if $p \mid n$ and each of the e substrings*

$$\boldsymbol{w}[1\,..\,p], \boldsymbol{w}[p+1\,..\,2p], \ldots, \boldsymbol{w}[n-p+1\,..\,n]$$

contains $(p \times \mathcal{P}_{\boldsymbol{w}}[j])/n = \mathcal{P}_{\boldsymbol{w}}[j]/e$ occurrences of the letter $\sigma_j \in \Sigma$ for any j.

In other words, an Abelian repetition of period p and exponent e is the concatenation of e strings all having the same Parikh vector $\mathcal{P}$ of length p.

Observation 3 *The only possible Abelian periods p of $\boldsymbol{w}$ are of the form $p = d \times q$, where d is an entry in D. Thus the smallest period is $d \times q$, where d is the least such entry.(Note that the last element of D is g.)*

Definition 11 (Segment). *A factor $\boldsymbol{w}[i\,..\,j]$ is a **segment** of $\boldsymbol{w}$ if:*

1. *$i = k \times q + 1$ with $k \geqslant 0$;*
2. *$j - i + 1 = t \times q$ with $t \geqslant 1$;*
3. *$\mathcal{P}_{\boldsymbol{w}[i..j]}[k]/(j - i + 1) = \mathcal{P}_{\boldsymbol{w}}[k]/|\boldsymbol{w}|$ for every letter $\sigma_k \in \Sigma$;*
4. *there does not exist a $j' < j$ such that $j' - i + 1 = t' \times q$ and $\mathcal{P}_{\boldsymbol{w}[i..j']}[k]/(j' - i + 1) = \mathcal{P}_{\boldsymbol{w}}[k]/|\boldsymbol{w}|$ for every letter $\sigma_k \in \Sigma$.*

In other words segments:

- start at positions multiples of q plus one;
- are non-empty and of length multiple of q;
- have the same proportion of every letter as the whole word $\boldsymbol{w}$;
- are of minimal length.

Since we suppose that $\boldsymbol{w}$ has Abelian period $p \in 1\,..\,n/2$, it follows that either $\boldsymbol{w}$ itself is a segment or else consists of a concatenation of segments. Note that a segment is a minimum-length substring of Abelian period p.

Lemma 12. *The word $\boldsymbol{w}$ has Abelian period $d \times q$ if and only if for every $k = 0, 1, \ldots, n/(d \times q) - 1$, $k \times d \times q + 1$ is the starting position of a segment of $\boldsymbol{w}$.*

We begin by computing the segments of $\boldsymbol{w}$ (see Figure 3), making use of the precomputed values q and $\mathcal{P}_{\boldsymbol{w}}$. We compute a Boolean array L of n elements: for $1 \leqslant i \leqslant n$, $L[i] = 1$ iff i is the starting position of a segment, $L[i] = 0$ otherwise.

Observation 4 *If p is an Abelian period of $\boldsymbol{w}$ with neither head nor tail and T is the length of the longest segment of $\boldsymbol{w}$ divided by q, then $p \geqslant T$.*

```
ComputesSegments(w, n, q, P_w)
(i, T) ← (1, 0)
L ← 0^n
while i ⩽ n do
   ▷ Start a new segment
   (i_0, j, t, count) ← (i, 0, 0, 0^σ)
   while j ⩽ σ do
      ▷ See if t partitions of length q form a segment
      t ← t + 1
      for k ← 1 to q do
         j ← w[i]
         count[j] ← count[j] + 1
         i ← i + 1
      ▷ Check counts of letters 1 . . j from position i_0
      j ← 1
      t' ← t × q
      while j ⩽ σ and count[j] = (t' × P_w[j])/n do
         j ← j + 1
   ▷ Update the array L and the maximum segment length T
   L[i_0] ← 1
   T ← max{T, t}
return (L, T)
```

Figure 3. Compute a Boolean array L of the starting positions of the segments of $\boldsymbol{w}$ ordered from left to right, also the maximum number T of factors of length q in any segment

The procedure that computes L visits each position i in $\boldsymbol{w}$ once, and corresponding to each i performs constant-time processing: the internal **while** loop updates j at most σ times corresponding to each partition of length $q \geqslant \sigma$.

Proposition 13. *The algorithm* ComputesSegments$(\boldsymbol{w}, n, q, \mathcal{P}_{\boldsymbol{w}})$ *computes the segments of a word* $\boldsymbol{w}$ *of length* n *on an alphabet of size* σ *in time* $O(n)$.

Example 14. $\boldsymbol{w} = \texttt{abaababbbabaabbabbaaabbababbaa}$: $n = 30$, $\mathcal{P}_{\boldsymbol{w}} = (15, 15)$

i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
$\boldsymbol{w}[i]$	a	b	a	a	b	a	b	b	b	a	b	a	a	b	b	a	b	b	a	a	a	b	b	a	b	a	b	b	a	a
$L[i]$	1	0	1	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	0	0	1	0	1	0	1	0	1	0	0	0
T	0	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

$\boldsymbol{w}$ is thus a concatenation of segments: $\boldsymbol{w} = \texttt{ab} \cdot \texttt{aababb} \cdot \texttt{ba} \cdot \texttt{ba} \cdot \texttt{ab} \cdot \texttt{ba} \cdot \texttt{bbaa} \cdot \texttt{ab} \cdot \texttt{ba} \cdot \texttt{ba} \cdot \texttt{bbaa}$ and $T = 3$.

The procedure, given in Figure 4, scans all the multiples of the divisors $d \in D$, their number is equal to the sum of the divisors of g which is in $O(n \log\log n)$ [19].

In practice, the case where $d = 1$ is treated in lines 5 and 7. If $T = 1$, it means that w can be segmented into factors of length q: q is then an Abelian period of w. The case where $d = g$ is treated outside the main loop, at the end of the algorithm: it corresponds to the trivial case where the Abelian period is n.

Example 15. $\boldsymbol{w} = \texttt{abaababbbabaabbabbaaabbababbaa}$: $n = 30$, $\mathcal{P}_{\boldsymbol{w}}[1] = \mathcal{P}_{\boldsymbol{w}}[2] = 15$, $g = 15$, $q = 2$, $D = (1, 3, 5, 15)$ and $T = 3$. Since $T \neq 1$, q is not an Abelian period: case $d = 1$ is done. When $d = 3$, $p = 7$ and 7 is not a starting position of a segment. When $d = 5$, $p = 11$ and 11 is a starting position of a segment then $p = 21$

```
ComputesPeriod(w, n)
Compute P_w, g, D
q ← n/g
(L, T) ← ComputesSegments(w, n, q, P_w)
R ← ∅
▷ Deal quickly with easy cases
if T = 1 then
    R ← R ∪ {q}
    d ← Pop(D)
▷ Fast forward in D past impossible cases
repeat
    d ← Pop(D)
until d ⩾ T
while d < g do
    p ← d × q + 1
    ▷ Test if all multiples of p are starting positions of segments
    while p < n do
        if L[p] = 1 then
            p ← p + d × q
        else break
    if p ⩾ n then
        R ← R ∪ {d × q}
    d ← Pop(D)
if q ≠ n then
    R ← R ∪ {n}
return R
```

Figure 4. In ascending order of divisors d of g, use the array L to determine whether or not $\boldsymbol{w}$ is an Abelian repetition of period $d \times q$

and 21 is a starting position of a segment: 10 is an Abelian period. The case where $d = 15$ is trivial since it corresponds to Abelian period n. Thus the algorithm returns $\{10, 30\}$. In the worst case the algorithm could have scanned all the multiples of 3 (they are 5) and all the multiples of 5 (they are 3) less than or equal to 15.

Theorem 16. *The algorithm* ComputesPeriod$(\boldsymbol{w}, n)$ *computes all the Abelian periods of* $\boldsymbol{w}$ *in time* $O(n \log \log n)$.

5 Conclusions and perspectives

In this article we gave brute force algorithms for computing Abelian periods for a word $\boldsymbol{w}$ of length n in the two following cases: no head, no tail and no head with tail. These algorithms run in time $O(n^2)$ but is this complexity tight? We also present a quasi-linear time algorithm for computing all the Abelian periods of a word in the case no head, no tail. Does an algorithm of the same complexity exist for a word $\boldsymbol{w}$ of length at most $n + q - 1$ containing a substring of length n that is an Abelian repetition with neither head nor tail of some period $dq \leq n$?

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