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Addition Chains Meet Postage Stamps: Reducing the Number of Multiplications

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Abstract

We introduce *stamp chains*. A stamp chain is a finite set of integers that is both an addition chain and an additive 2-basis, i.e., a solution to the postage stamp problem. We provide a simple method for converting known postage stamp solutions of length k into stamp chains of length $k+1$. Using stamp chains, we construct an algorithm that computes $u(x^i)$ for $i = 1, \ldots, n$ in less than $n-1$ multiplications, if u is a function that can be computed at zero cost, and if there exists another zero-cost function v such that $v(a, b) = u(ab)$. This can substantially reduce the computational cost of repeated multiplication, as illustrated by application examples related to matrix multiplication and data clustering using subset convolution. In addition, we report the extremal postage stamp solutions of length $k = 24$.

1 Introduction

An addition chain is an increasing sequence of integers starting from 1, where each subsequent element is a sum of two earlier elements (not necessarily distinct). Addition chains are well known for their use in repeated multiplication to compute x^n. For example, the chain $1, 2, 3, 6, 12, 15$ shows how x^{15} is computed with five multiplications: $xx = x^2$, $x^2x = x^3$, $x^3x^3 = x^6$, $x^6x^6 = x^{12}$, and $x^{12}x^3 = x^{15}$.

If all consecutive powers $x, x^2, \ldots, x^n$ are required, not just the final value, then obviously $n-1$ multiplications are required.

Now suppose that the powers x^i themselves are not of interest, but instead the values $y_i = u(x^i)$, $i = 1, \ldots, n$, are sought for a given function u. Let us also assume that computing u is free of cost (or negligible compared to the cost of multiplication). Let us further assume that given two values a and b, there is a method for computing $v(a, b) := u(ab)$ for free without actually performing the multiplication ab.

If these assumptions hold, then it is not necessary to compute all of the powers $x, x^2, \ldots, x^n$. Instead, a carefully selected subset of these powers is computed; then each y_i is obtained either by applying u to one of the computed powers, or v to a pair of them. For instance, suppose that x^5 and x^7 have been computed but x^{12} has not. Now there are two ways to obtain y_{12}: either multiply $x^{12} = x^5x^7$ and evaluate $y_{12} = u(x^{12})$; or evaluate $y_{12} = v(x^5, x^7)$ avoiding the multiplication. The existence of such a function v is the key assumption underlying our method of reducing the number of multiplications needed.

A straightforward application is found in matrix powers, if from each power we only need a single element $(X^i)_{p,q} =: u(X^i)$. Let X be a large $m \times m$ matrix, and assume that its powers X^i, X^j have been computed. Then the element $(X^{i+j})_{p,q} = \sum_{r=1}^{m} (X^i)_{p,r}(X^j)_{r,q} = v(X^i, X^j)$ can be directly evaluated in $O(m)$ arithmetic operations – essentially for free, compared to the alternative of computing the full matrix product. Another application related to data clustering using subset convolution is given in Section 6.

This setting gives raise to the problem of how to choose a minimal number of powers of x, to be computed via repeated multiplication, such that from them all $y_1, \ldots, y_n$ are obtained through u and v. Superficially, this appears like an addition chain problem; however, for solving it we shall encounter another problem in additive number theory, namely the *postage stamp problem*.

We shall start with some definitions and preliminary observations in the next section. In Section 3 we provide an algorithm for computing $y_1, \ldots, y_n$ with the help of stamp chains, and in Section 4 we present our main result, which shows how stamp chains can be constructed from stamp bases. In Section 5 we show how known properties of stamp bases imply similar properties for stamp chains, and also we report three extremal stamp bases corresponding to $k = 24$. An illustration of the computational benefits and some final remarks are provided in the last two sections of the paper.

2 Definitions

Introductory texts to addition chains are provided by Guy [3, pp. 168–171] and Knuth [4, pp. 398–422]. For information about the postage stamp problem, see Guy [3, pp. 123–127] and Selmer [7].

Notation 1. In the following, k is a positive integer. A_k, B_k and C_k denote sets of k positive integers. Their elements will be indexed in increasing order starting with index 1, thus $A_k = \{a_1 < \ldots < a_k\}$. When $j < k$, the *j-prefix* of A_k is $A_j = \{a_1, \ldots, a_j\}$. As usual in combinatorics, $[c, d]$ denotes the consecutive integers $\{c, c+1, \ldots, d\}$.

Definition 2. An integer c is *generated* by A_k, if $c = a_i$ or $c = a_h + a_i$ for some indices $1 \le h, i \le k$. (Note that $h = i$ is allowed.)

Definition 3. A_k is an *addition chain* if $a_1 = 1$, and for $j = 2, \ldots, k$, the element a_j is generated by A_{j-1}.

Remark 4. In addition chain literature it is customary to start indexing from $a_0 = 1$, and not to count this zeroth element in the length of the chain (thus $a_0, \ldots, a_k$ is customarily defined to have length k). We have here departed from this notation in order to ensure compatibility with the established notation for postage stamps. For the same reason we have used a set notation, instead of the more usual tuple notation.

Definition 5. A_k is a *stamp basis* for n, if every integer in $[1, n]$ is generated by A_k. The *range* of A_k, denoted by $n(A_k)$, is the largest n such that A_k generates $[1, n]$. The elements of a stamp basis are called *stamps*.

Remark 6. In a stamp basis a_1 must be 1, since otherwise 1 is not generated.

Definition 7. The *range* of k, denoted by $n(k)$, is the largest range attained by stamp bases of length k. An *extremal stamp basis* is one that attains this maximum.

A stamp basis may be interpreted as a set of k postage stamp denominations, such that any integral postage fare up to n can be paid by attaching at most 2 stamps on an envelope. The problem of finding optimal bases is known as the *postage stamp problem*. A stamp basis is also known in the literature as an *additive 2-basis*. More generally, if h stamps are allowed on the envelope, the set of stamp denominations is called an *h-basis* and the largest n attained is called the *h-range*. In this work we consider exclusively the case $h = 2$.

Definition 8. A *stamp chain* for n is a set of integers that is both an addition chain, and a stamp basis for n.

Definition 9. The maximum range among k-length stamp chains is denoted by $\overline{n}(k)$. An *extremal stamp chain* (of length k) is one that attains this maximum.

Example 10. $A_5 = \{1, 2, 4, 8, 16\}$ is an addition chain, and in fact a minimal-length addition chain ending at 16. It is not a particularly good postage stamp basis: its range is only 6, since it does not generate 7.

Example 11. $B_5 = \{1, 3, 5, 7, 8\}$ is an extremal stamp basis of length 5, and has range $n(B_5) = 16$. However, it is not an addition chain, since for example 5 is not generated by the prefix $\{1, 3\}$.

Example 12. $C_5 = \{1, 2, 4, 6, 7\}$ is a stamp chain of length 5, and has range $n(C_5) = 14$. As a stamp chain, it is extremal: no stamp chain of length 5 has range greater than 14. The proof of this extremality follows from theorems that will be established in Section 4.

Remark 13. Since any stamp chain is also a stamp basis, it follows that $\overline{n}(k) \le n(k)$. The inequality may be strict, as seen in the previous two examples.

3 Multiplication algorithm

We now return to the task outlined in the introduction. Given an initial value x, a positive integer n, an associative binary operation (multiplication), and the zero-cost functions u and v such that $v(a, b) = u(ab)$, the task is to compute $y_1, \ldots, y_n$, where $y_i = u(x^i)$.

The straightforward method computes all powers $x^2, \ldots, x^n$ and uses $n-1$ multiplications. To improve upon this, let $k < n$, and let us perform $k - 1$ multiplications with results x^{a_j}, where $j = 2, \ldots, k$. Without loss of generality, we may assume that the exponents a_j are distinct and in increasing order, otherwise some multiplications could be eliminated or rearranged. The set $A_k = \{a_1 < \ldots < a_k\}$, with $a_1 = 1$, will be called a *multiplication plan*.

We now have two requirements for the choice of the multiplication plan A_k:

1. A_k must be an addition chain. This ensures that for each $j = 2, \ldots, k$, the exponent a_j equals $a_h + a_i$ for some $1 \le h, i < j$, and thus x^{a_j} can be computed with one multiplication as $(x^{a_h})(x^{a_i})$.

2. A_k must be a stamp basis. This ensures that for each integer $c \in [1, n]$, either $c = a_i$ or $c = a_h + a_i$ for some h, i, and thus y_c can be computed at zero cost, either as $u(x^{a_i})$ or as $v(x^{a_h}, x^{a_i})$.

Combining the requirements, we observe that a multiplication plan has to be a stamp chain for n. Conversely, given a k-length stamp chain for n, the following algorithm computes $y_1, \ldots, y_n$ using $k-1$ multiplications. The first phase performs $k-1$ multiplications and the second phase performs none, since it does only zero-cost evaluations of u and v.

Algorithm A
Phase 1. For each $j = 2, \ldots, k$, find $h, i < j$ such that $a_h + a_i = a_j$. This is possible because A_k is an addition chain. Compute $x^{a_j} = (x^{a_h})(x^{a_i})$.
Phase 2. For each integer $c \in [1, n]$, either c is a stamp, or there are two stamps a_h, a_i such that $c = a_h + a_i$. In the first case, compute $y_c = u(x^c)$. In the second case compute $y_c = v(x^{a_h}, x^{a_i})$.

Example 14. If $y_1, \ldots, y_{14}$ are sought, the multiplication plan has to be a stamp chain with a range at least 14. In the previous section we mentioned that $C_5 = \{1, 2, 4, 6, 7\}$ is a stamp chain for 14. Using this stamp chain, Algorithm A will compute $y_1, \ldots, y_{14}$ in $5 - 1 = 4$ multiplications as follows:

1. Compute $xx = x^2$, $x^2x^2 = x^4$, $x^2x^4 = x^6$, and $x^6x = x^7$.

2. Compute $y_1 = u(x), y_2 = u(x^2), y_3 = v(x, x^2), \ldots, y_{14} = v(x^7, x^7)$.

4 Constructing stamp chains

If A_k is a stamp chain for n, then Algorithm A computes the values $y_1, \ldots, y_n$ using $k - 1$ multiplications. In order to minimize the number of multiplications, we would like to find a stamp chain as short as possible, with a range at least n. Ideally, we wish to identify an extremal stamp chain, since an extremal stamp chain attains the maximum range for any given length k.

It may not be immediately clear how a stamp chain of a given length could be found, other than by constructing stamp bases and checking whether they also happen to be addition chains; or vice versa. However, in this section we shall introduce a direct method for converting any admissible stamp basis into a stamp chain.

Definition 15. A stamp basis A_k is *admissible* if it generates all integers in $[1, a_k]$.

Remark 16. If A_k is admissible, and $1 < c < a_j$, then c is generated by A_{j-1}.

The following lemma is an already established result for stamp bases [1].

Lemma 17. *An extremal stamp basis is admissible.*

A similar property holds for stamp chains.

Lemma 18. *An extremal stamp chain is admissible.*

Proof. Let A_k be a non-admissible stamp chain, and let $c = n(A_k)+1$, that is, c is the smallest positive integer not generated by A_k. It follows that $c-1$ is generated by A_k, and also that $c-1 \notin A_k$ (otherwise $c = 1+(c-1)$ would be generated). Let then $B_k = A_{k-1} \cup \{c-1\}$. Now B_k is a stamp basis that generates all integers in $[1, c]$, in particular it generates $c = 1+(c-1)$. Thus $n(B_k) > n(A_k)$. Furthermore, since $c-1$ is generated by A_k but not an element of it, it follows that $c-1 = a_h + a_i = b_h + b_i$ for some indices h, i. Thus B_k is also an addition chain.

Since B_k is a stamp chain with $n(B_k) > n(A_k)$, it follows that A_k is not extremal. $\square$

Thus, in order to maximize the range of a stamp basis (stamp chain), it is sufficient to consider only the admissible stamp bases (stamp chains).

Notation 19. If $A_k = \{a_1, \ldots, a_k\}$ is a set of integers and s is an integer, then $A_k + s := \{a_1 + s, \ldots, a_k + s\}$.

Lemma 20. *If A_k is a stamp basis for n, then $B_{k+1} = \{1\} \cup (A_k + 1)$ is a stamp basis for $n+2$.*

Proof. Let $c \in [1, n+2]$ be arbitrary. If $c \leq 2$, then B_{k+1} generates it either as $b_1 = 1$, or as $b_1 + b_1 = 1 + 1 = 2$. If $c \geq 3$, let $c' = c-2$. Since $c' \in [1, n]$, there is either one stamp $a_h = c'$ or two stamps $a_h + a_i = c'$. In the first case, $b_1 + b_{h+1} = 1 + (a_h + 1) = c' + 2 = c$. In the second case, $b_{h+1} + b_{i+1} = (1 + a_h) + (1 + a_i) = c' + 2 = c$. This proves that B_{k+1} generates $[1, n+2]$. $\square$

Note that the previous lemma gives only a lower bound for the range of the new basis (consider $A_2 = \{1, 4\}$, which has $n(A_2) = 2$ but $n(B_3) = n(\{1, 2, 5\}) = 7 > 2+2$). However, for *admissible* bases we have a stronger result in the following theorem.

Theorem 21. *If A_k is an admissible stamp basis with range n, then $B_{k+1} = \{1\} \cup (A_k + 1)$ is an admissible stamp chain with range $n + 2$.*

Proof. By Lemma 20, B_{k+1} is a stamp basis for $n + 2$. Because A_k is admissible, $n \geq a_k$, thus $n + 2 \geq a_k + 1 = b_{k+1}$, and B_{k+1} is admissible.

To prove that B_{k+1} is also an addition chain, note first that by construction $b_1 = 1$. Clearly $b_2 = 2 = b_1 + b_1$ is generated by the prefix B_1. Let then $3 \leq j \leq k + 1$. Since A_k is admissible, A_{j-2} generates $a_{j-1} - 1$, and by Lemma 20 the prefix $B_{j-1} = \{1\} \cup (A_{j-2} + 1)$ generates $a_{j-1} + 1 = b_j$.

Finally, let us prove that $n(B_{k+1})$ does not exceed $n + 2$, in particular, that B_{k+1} does not generate $n + 3$. Since A_k is admissible, $a_k \leq n$, thus $b_{k+1} \leq n + 1$. Thus $n + 3 \notin B_{k+1}$. Suppose then $n + 3 = b_h + b_i$. This would imply that $b_h, b_i > 1$, and then $a_{h-1} + a_{i-1} = n + 1$, contradicting the assumption that $n(A_k) = n$. □

While the construction in Theorem 21 has the consequence of extending the range of the stamp basis by 2, this is not the main reason for the construction. For our purposes the crucial consequence of Theorem 21 is that the new basis B_{k+1} is guaranteed to be an addition chain, even if A_k is not. This ensures that B_{k+1} can be used as a multiplication plan in Algorithm A.

Example 22. $A_5 = \{1, 3, 5, 7, 8\}$ is an admissible stamp basis for $n = 16$, but it is not an addition chain. However, by Theorem 21, $B_6 = \{1\} \cup (A_5 + 1) = \{1, 2, 4, 6, 8, 9\}$ is an admissible stamp chain for $n = 18$.

Theorem 21 shows how to construct a stamp chain of length k from any admissible stamp basis of length $k-1$. Conversely, we shall prove that this construction produces *all* admissible stamp chains of length $k > 1$. For length $k = 1$, the only stamp chain is $B_1 = \{1\}$.

Theorem 23. *If $k > 1$ and B_k is an admissible stamp chain with range n, then $A_{k-1} = \{b_2 - 1, \ldots, b_k - 1\}$ is an admissible stamp basis with range $n - 2$.*

Proof. We will first prove that A_{k-1} generates all integers in $[1, n - 2]$. Since by assumption B_k is an addition chain, its smallest two elements must be 1 and 2. Thus $a_1 = b_2 - 1 = 1$, and A_{k-1} generates 1 and 2.

Let $c \in [3, n - 2]$ be arbitrary, and let $c' = c + 2$. Since B_k is a stamp basis, c' is generated either by one stamp $b_j = c'$ or by two stamps $b_h + b_i = c'$. But in the first case, $c' = b_j = b_h + b_i$ for some $h, i < j$, because B_k is an addition chain. Thus in either case we have $c' = b_h + b_i$ for some h, i. Without loss of generality we may assume $h \geq i$. Now consider separately the possibilities $i = 1$ and $i > 1$.

If $i = 1$, then $b_i = 1$, and $c = c' - 2 = b_h + b_i - 2 = b_h - 1 = a_{h-1}$ is generated by a single stamp a_{h-1}. Note that we have necessarily $h > 1$, so a_{h-1} indeed exists. This is because we have assumed that $c \geq 3$, and consequently $b_h + b_i = c' \geq 5$ implying that $b_h \geq 4$.

If $i > 1$, then $b_i > 1$, and $c = c' - 2 = b_h + b_i - 2 = (b_h - 1) + (b_i - 1) = a_{h-1} + a_{i-1}$, so c is generated by the two stamps a_{h-1} and a_{i-1}. Note that, by assumption, $h \geq i > 1$, so the stamps a_{h-1} and a_{i-1} indeed exist.

We have now proven that any $c \in [1, n-2]$ is generated by either one or two stamps from A_{k-1}. In other words, A_{k-1} is a stamp basis with range at least $n-2$.

Since by assumption $n(B_k) = n$ exactly, it follows that B_k does not generate $n+1$. From this it follows that $b_k < n$, thus $a_{k-1} < n-1$. Hence A_{k-1} does not generate $n-1$, and the range is $n(A_{k-1}) = n-2$ exactly.

Finally, since $n(A_{k-1}) = n-2 > b_k - 2 = a_{k-1} - 1$, it follows that A_{k-1} is admissible. $\square$

By Theorems 21 and 23, admissible stamp bases of length k and range n are in one-to-one correspondence with admissible stamp chains of length $k+1$ and range $n+2$. Since extremal stamp bases and extremal stamp chains are always admissible, we have the following corollaries for all $k > 1$.

Corollary 24. *B_k is an extremal stamp chain if and only if $B_k = \{1\} \cup (A_{k-1} + 1)$, where A_{k-1} is an extremal stamp basis. Then also their ranges are related as $n(B_k) = n(A_{k-1}) + 2$.*

Corollary 25. $\overline{n}(k) = n(k-1) + 2$.

5 Some properties of stamp chains

Known properties of (extremal) stamp bases carry over naturally to (extremal) stamp chains. For example, some asymptotic lower and upper bounds for $n(k)$ are known [3]:

$$\frac{2}{7}k^2 + O(k) \le n(k) \le 0.4802k^2 + O(k).$$

Since $\overline{n}(k) = n(k-1) + 2$ by Corollary 25, it follows that also

$$\frac{2}{7}k^2 + O(k) \le \overline{n}(k) \le 0.4802k^2 + O(k).$$

This means that for large n, roughly $\sqrt{(7/2)n}$ multiplications are sufficient to compute $y_1, \ldots, y_n$ through Algorithm A.

1	3	4	6	10	13	15	21	29	37	45	53	61	69	77	85	91	93	96	100	102	103	105	106	*
1	3	4	6	10	13	15	21	29	37	45	53	61	69	77	85	93	97	99	102	103	104	106	108	
1	3	4	6	10	13	15	21	29	37	45	53	61	69	77	85	93	97	99	102	103	106	108	112	

Table 1: The extremal bases of length 24. The basis marked with * is symmetric.

All extremal stamp bases of lengths $k = 1, \ldots, 23$ are previously known. Challis and Robinson list them for $k = 3, \ldots, 22$ [2, pp. 7–8], and for $k = 23$ in an addendum. We have computed the extremal stamp bases of length $k = 24$, using an exhaustive search based on the algorithm described by Challis [1]. The search took 606 CPU days on parallel 2.6 GHz AMD Opteron processors. The new extremal bases have range 212, and are shown in Table 1.

Note that the symmetric basis appears already in Mossige's list of symmetric bases [6], but until now it was not known to be extremal.

Extremal stamp chains of lengths $k = 2, \ldots, 25$ can be constructed from known extremal stamp bases by Corollary 24. Since $\overline{n}(25) = n(24) + 2 = 214$, these chains provide the minimum-length multiplication plans for computing $y_1, \ldots, y_n$ for $n \leq 214$.

k	$n(k)$	stamp basis	k	$\overline{n}(k)$	stamp chain
1	2	1	2	4	1 2
2	4	1 3	3	6	1 2 4
3	8	1 3 4	4	10	1 2 4 5
4	12	1 3 5 6	5	14	1 2 4 6 7
5	16	1 3 5 7 8	6	18	1 2 4 6 8 9
6	20	1 2 5 8 9 10	7	22	1 2 3 6 9 10 11
7	26	1 2 5 8 11 12 13	8	28	1 2 3 6 9 12 13 14
8	32	1 2 5 8 11 14 15 16	9	34	1 2 3 6 9 12 15 16 17

Table 2: Some extremal stamp bases for $k \leq 8$, and the corresponding extremal stamp chains for $k \leq 9$.

k	$\overline{n}(k)$	k	$\overline{n}(k)$	k	$\overline{n}(k)$
1	2	11	48	21	154
2	4	12	56	22	166
3	6	13	66	23	182
4	10	14	74	24	198
5	14	15	82	25	214
6	18	16	94		
7	22	17	106		
8	28	18	118		
9	34	19	130		
10	42	20	142		

Table 3: Known values of $\overline{n}$.

The connection between stamp bases and stamp chains is illustrated in Table 2, which contains one extremal stamp basis for each $k = 1, \ldots, 8$, and the corresponding extremal stamp chain constructed by Corollary 24. In Table 3 we list all known values of $\overline{n}(k)$. They were computed by applying Corollary 25 to the ranges of previously known extremal stamp bases (see [2] and A001212 in [8]) of our new $k = 24$ stamp bases. A listing of known extremal stamp bases and extremal stamp chains can be found in Tables 4 and 5 at the end of this article.

Several authors have observed that many extremal stamp bases (but not all) are symmetric in the sense that $a_i + a_{k-i} = a_k$ for all $i = 1, \ldots, k-1$. The corresponding extremal stamp chains are then, by construction, symmetric in the sense that $a_i + a_{k+1-i} = a_1 + a_k$ for all $i = 1, \ldots, k$. Symmetric stamp bases up to $k = 30$ are reported by Mossige [6].

If a stamp chain is needed for n so large that no extremal stamp basis is currently known for $n-2$, one can instead take any admissible stamp basis and convert it into an admissible stamp chain using Theorem 21. Very good admissible stamp bases (although not necessarily extremal) for up to $k = 82$ and $n = 2100$ are listed by Challis and Robinson [2, p. 6].

6 An application to subset convolution

The multiplication in Algorithm A may in general be any associative binary operation. In the introduction a simple example related to matrix multiplication was mentioned. Here, we consider a more detailed application to a data clustering problem.

In previous work [5], we have considered a class of Bayesian probability models where N items of data belong to c clusters, such that c is an unknown integer in the range $1, \ldots, n$, and $n \leq N$. The exact posterior distribution for c is computed using an algorithm whose time requirement is exponential in N. The algorithm first computes a likelihood function f for each possible cluster, that is, for each subset of $\{1, \ldots, N\}$. This computation takes time $O(2^N)$, and its result is a table of 2^N numbers.

The next, and the most time-consuming step of the algorithm is to compute successively the values of $f_2 = f * f, f_3 = f_2 * f, \ldots, f_n = f_{n-1} * f$, where $*$ is an operation called subset convolution. Subset convolution takes as its input two functions, each represented by a table of 2^N numbers, and computes another such function. The operation is associative, so for the current purposes it is a multiplication. A single subset convolution takes either $O(3^N)$ or $O(2^N N^2)$ time, depending on the algorithm used.

However, to obtain the posterior probability for c, the full tables $f_1, \ldots, f_n$ are actually not needed. Instead, we only need the last element from each table, corresponding to $f_c(U)$, where $U = \{1, \ldots, N\}$ is the set of all data items. Thus, it is necessary to compute the values of $y_c = u(f_c) := f_c(U)$, for $c = 1, \ldots, n$. Furthermore, if f_a and f_b have been fully computed, and $c = a + b$, then the single value $f_c(U) = (f_a * f_b)(U)$ can be computed in only $O(2^N)$ time. Hence, computing $v(f_a, f_b) := u(f_a * f_b)$ is also fast, compared to performing the full subset convolution $f_a * f_b$.

Since u and v are much faster to compute than $*$, our aim is to find a minimal set of values of c, for which the full subset convolution f_c is computed, since for these values, $y_c = u(f_c(U))$ then refers to only a table lookup. For other $c \in [1, \ldots, n]$, the quantity y_c is computed as $v(f_i, f_j)$, where f_i and f_j have been computed in full. The end result is that $y_1, \ldots, y_n$ are obtained with only $k-1$ subset convolutions, where k is the length of a stamp chain for n. In comparison, the straightforward algorithm performs $n-1$ subset convolutions.

To provide a concrete example, for $N = 20$ and $n = 20$ straightforward multiplication performs $n - 1 = 19$ subset convolutions to compute $f_2, \ldots, f_{20}$, which takes approximately 7 minutes of CPU time on a 2.4 GHz AMD Opteron processor. However, from Table 2 we find an extremal stamp chain

$$B_7 = \{1, 2, 3, 6, 9, 10, 11\},$$

which has range $22 \geq n$. Using this chain and Algorithm A, only 6 subset convolutions are required:

$$\begin{aligned}
f_2 &= f * f \\
f_3 &= f_2 * f \\
f_6 &= f_3 * f_3 \\
f_9 &= f_6 * f_3 \\
f_{10} &= f_9 * f \\
f_{11} &= f_{10} * f
\end{aligned}$$

Consequently, the posterior distribution for c is obtained in about one third (6/19) of the time required by the straightforward algorithm.

7 Discussion

The existing bodies of literature on both addition chains and on postage stamps are substantial. However, this far they seem to be almost completely disjoint. We have here explored the connection between these two concepts, and presented a theorem establishing a relationship between addition chains and stamp bases. The theorem provides a way to construct an optimal procedure to perform certain multiplicative computational operations, illustrated by an application to data clustering using subset convolution. As a future research topic, it would be interesting to explore possible other useful connections between addition chains and the postage stamp problem.

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k	$n(k)$	stamp basis
1	2	1
2	4	1 3
3	8	1 3 4
4	12	1 3 5 6
5	16	1 3 5 7 8
6	20	1 3 5 7 9 10
6	20	1 2 5 8 9 10
6	20	1 3 4 8 9 11
6	20	1 3 5 6 13 14
6	20	1 3 4 9 11 16
7	26	1 3 4 9 10 12 13
7	26	1 2 5 8 11 12 13
7	26	1 3 5 7 8 17 18
8	32	1 2 5 8 11 14 15 16
8	32	1 3 5 7 9 10 21 22
9	40	1 3 4 9 11 16 17 19 20
10	46	1 2 3 7 11 15 19 21 22 24
10	46	1 2 5 7 11 15 19 21 22 24
11	54	1 3 5 6 13 14 21 22 24 26 27
11	54	1 3 4 9 11 16 18 23 24 26 27
11	54	1 2 3 7 11 15 19 23 25 26 28
11	54	1 2 5 7 11 15 19 23 25 26 28
12	64	1 3 4 9 11 16 21 23 28 29 31 32
13	72	1 3 4 9 11 16 20 25 27 32 33 35 36
14	80	1 3 4 5 8 14 20 26 32 35 36 37 39 40
14	80	1 3 4 9 10 15 16 21 22 24 25 51 53 55
14	80	1 2 5 8 11 14 17 20 23 24 25 51 53 55
15	92	1 3 4 5 8 14 20 26 32 38 41 42 43 45 46
16	104	1 3 4 5 8 14 20 26 32 38 44 47 48 49 51 52
17	116	1 3 4 5 8 14 20 26 32 38 44 50 53 54 55 57 58
18	128	1 3 4 5 8 14 20 26 32 38 44 50 56 59 60 61 63 64
19	140	1 3 4 5 8 14 20 26 32 38 44 50 56 62 65 66 67 69 70
20	152	1 3 4 5 8 14 20 26 32 38 44 50 56 62 68 71 72 73 75 76
21	164	1 3 4 6 10 13 15 21 29 37 45 53 61 67 69 72 76 78 79 81 82
21	164	1 3 4 5 8 14 20 26 32 38 44 50 56 62 68 74 77 78 79 81 82
21	164	1 3 4 6 10 13 15 21 29 37 45 53 61 69 73 75 78 79 80 82 84
21	164	1 3 4 6 10 13 15 21 29 37 45 53 61 69 73 75 78 79 82 84 88
22	180	1 3 4 6 10 13 15 21 29 37 45 53 61 69 75 77 80 84 86 87 89 90
22	180	1 3 4 6 10 13 15 21 29 37 45 53 61 69 77 81 83 86 87 88 90 92
22	180	1 3 4 6 10 13 15 21 29 37 45 53 61 69 77 81 83 86 87 90 92 96
23	196	1 3 4 6 10 13 15 21 29 37 45 53 61 69 77 83 85 88 92 94 95 97 98
23	196	1 3 4 6 10 13 15 21 29 37 45 53 61 69 77 85 89 91 94 95 96 98 100
23	196	1 3 4 6 10 13 15 21 29 37 45 53 61 69 77 85 89 91 94 95 98 100 104
24	212	1 3 4 6 10 13 15 21 29 37 45 53 61 69 77 85 91 93 96 100 102 103 105 106
24	212	1 3 4 6 10 13 15 21 29 37 45 53 61 69 77 85 93 97 99 102 103 104 106 108
24	212	1 3 4 6 10 13 15 21 29 37 45 53 61 69 77 85 93 97 99 102 103 106 108 112

Table 4: Extremal stamp bases for $k = 1, \ldots, 24$ and their ranges.

k	$\overline{n}(k)$	stamp chain
2	4	1 2
3	6	1 2 4
4	10	1 2 4 5
5	14	1 2 4 6 7
6	18	1 2 4 6 8 9
7	22	1 2 4 6 8 10 11
7	22	1 2 3 6 9 10 11
7	22	1 2 4 5 9 10 12
7	22	1 2 4 6 7 14 15
7	22	1 2 4 5 10 12 17
8	28	1 2 4 5 10 11 13 14
8	28	1 2 3 6 9 12 13 14
8	28	1 2 4 6 8 9 18 19
9	34	1 2 3 6 9 12 15 16 17
9	34	1 2 4 6 8 10 11 22 23
10	42	1 2 4 5 10 12 17 18 20 21
11	48	1 2 3 4 8 12 16 20 22 23 25
11	48	1 2 3 6 8 12 16 20 22 23 25
12	56	1 2 4 6 7 14 15 22 23 25 27 28
12	56	1 2 4 5 10 12 17 19 24 25 27 28
12	56	1 2 3 4 8 12 16 20 24 26 27 29
12	56	1 2 3 6 8 12 16 20 24 26 27 29
13	66	1 2 4 5 10 12 17 22 24 29 30 32 33
14	74	1 2 4 5 10 12 17 21 26 28 33 34 36 37
15	82	1 2 4 5 6 9 15 21 27 33 36 37 38 40 41
15	82	1 2 4 5 10 11 16 17 22 23 25 26 52 54 56
15	82	1 2 3 6 9 12 15 18 21 24 25 26 52 54 56
16	94	1 2 4 5 6 9 15 21 27 33 39 42 43 44 46 47
17	106	1 2 4 5 6 9 15 21 27 33 39 45 48 49 50 52 53
18	118	1 2 4 5 6 9 15 21 27 33 39 45 51 54 55 56 58 59
19	130	1 2 4 5 6 9 15 21 27 33 39 45 51 57 60 61 62 64 65
20	142	1 2 4 5 6 9 15 21 27 33 39 45 51 57 63 66 67 68 70 71
21	154	1 2 4 5 6 9 15 21 27 33 39 45 51 57 63 69 72 73 74 76 77
22	166	1 2 4 5 7 11 14 16 22 30 38 46 54 62 68 70 73 77 79 80 82 83
22	166	1 2 4 5 6 9 15 21 27 33 39 45 51 57 63 69 75 78 79 80 82 83
22	166	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 74 76 79 80 81 83 85
22	166	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 74 76 79 80 83 85 89
23	182	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 76 78 81 85 87 88 90 91
23	182	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 78 82 84 87 88 89 91 93
23	182	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 78 82 84 87 88 91 93 97
24	198	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 78 84 86 89 93 95 96 98 99
24	198	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 78 86 90 92 95 96 97 99 101
24	198	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 78 86 90 92 95 96 99 101 105
25	214	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 78 86 92 94 97 101 103 104 106 107
25	214	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 78 86 94 98 100 103 104 105 107 109
25	214	1 2 4 5 7 11 14 16 22 30 38 46 54 62 70 78 86 94 98 100 103 104 107 109 113

Table 5: Extremal stamp chains for $k = 2, \ldots, 25$ and their ranges.

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