

# Notes on Ramey's Lemmas

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In a 1960 paper, George Ramey proved the first two lemmas below; the lemmas suppose we have a finite sequence of numbers meeting certain constraints, and provide the number of cycle shifts that contain all-positive partial sums (Ramey 1960).

These notes expand on the ideas behind these lemmas. The final section of these notes discusses cyclic shifts for finite sequences of independent, uniformly random values; as far as I know, the work in that section is new.

I personally learned of these lemmas in chapter 7 of the book *Concrete Mathematics* (Knuth, Patashnik, and Graham 1998), which explores their applications to generating functions. The presentation of the lemmas here is based on the presentation in *Concrete Mathematics* rather than on Ramey's original paper.

## 1 Exact values for finite integer sequences

**Lemma 1** Suppose  $\sum_{i=1}^n x_i = 1$ , where all  $x_i \in \mathbb{Z}$ . Extend the sequence by letting  $x_{n+p} = x_p$  for  $1 \leq p \leq n$ . Then there is a unique  $j$ ,  $1 \leq j \leq n$ , such that

$$\sum_{i=j}^{j+k-1} x_i > 0; \quad 1 \leq k \leq n.$$

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Intuitively, we can think of such an index  $j$  as a cyclic shift of the sequence that has partial sums that are all positive.

For example, the finite sequence  $\langle x_1, \dots, x_5 \rangle = \langle 3, -2, 4, -1, 1 \rangle$  offers  $j = 5$  as the unique shift providing  $\langle x_5, x_6 = x_1, \dots, x_9 = x_4 \rangle = \langle 1, 3, -2, 4, -5 \rangle$  with partial sums  $\langle 1, 4, 2, 6, 1 \rangle$  that are all positive.

**Definitions** Given a sequence  $\langle x_1, \dots, x_n \rangle$ , it's useful to say that an index  $i \in \{1, \dots, n\}$  is a *positive-sum shift* if and only if the partial sums of

$\langle x_i, \dots, x_n, x_1, \dots, x_{i-1} \rangle$  are all positive. Since these notes focus on finite sequences, we'll implicitly use arbitrary indexes  $x_j, j \in \mathbb{Z}$ , to refer to  $x_k$  with  $k \in \{1, \dots, n\}, k \equiv j \pmod{n}$ .

We'll use the subscript-free letter  $x$  to denote an entire finite sequence  $\langle x_1, \dots, x_n \rangle$ . We'll write  $\sigma(x)$  to indicate the number of indexes of  $x$  that are positive-sum shifts.

We can now concisely state a related result proved by Raney:

**Lemma 2** *Suppose  $\sum_{i=1}^n x_i = \ell$ , where  $x_i \in \mathbb{Z}$  and  $x_i \leq 1$  for all  $i$ . Then  $\sigma(x) = \ell$ ; that is, exactly  $\ell$  indexes in  $\{1, \dots, n\}$  are positive-sum shifts.*

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For example, let  $\langle x_1, \dots, x_8 \rangle = \langle -2, 1, 1, 0, -1, 1, 1, 1 \rangle$ . Then  $\sum x_i = 2$ , and  $x_2, x_6$  are the only positive-sum shifts:

shift	partial sums
$\langle x_2, \dots \rangle = \langle 1, 1, 0, -1, 1, 1, 1, -2 \rangle$	$\langle 1, 2, 2, 1, 2, 3, 4, 2 \rangle$
$\langle x_6, \dots \rangle = \langle 1, 1, 1, -2, 1, 1, 0, -1 \rangle$	$\langle 1, 2, 3, 1, 2, 3, 3, 2 \rangle$

Note that lemma 2 is not a strict generalization of lemma 1 as it adds the condition  $x_i \leq 1$ . This condition is necessary for lemma 2; without it we may have, for example, the one-element sequence  $x = \langle 2 \rangle$  with sum  $\ell = 2$  and  $\sigma(x) = 1$ .

Rather than proving the above two lemmas directly, we'll jump to the general case of real sequences  $x$  and prove strictly more general bounds on  $\sigma(x)$  in that context.

## 2 Bounds for real finite sequences

We start with a general guarantee that  $\sum x_i > 0 \Rightarrow \sigma(x) \geq 1$ . In the context of a sequence  $x$ , it will be useful to write  $s_i$  to denote the  $i^{\text{th}}$  partial sum of  $x$ ; that is,

$$s_i = \sum_{j=1}^i x_j.$$

**Property 3** *Suppose  $\sum_{i=1}^n x_i > 0$ , where  $x_i \in \mathbb{R}$ . Let  $s_i$  denote the  $i^{\text{th}}$  partial sum of  $x$ , and let  $j$  be the largest index in  $\{1, \dots, n\}$  with  $s_j = \min_i s_i$ . Then  $j$  is a positive-sum shift.*

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### **3 Finite sequences with uniformly random values**

Add more content here.

### **References**

Knuth, Donald E., Oren Patashnik, and Ronald L. Graham. 1998. *Concrete Mathematics: A Foundation for Computer Science*. addison-wesley.

Raney, George. 1960. “Functional Composition Patterns and Power Series Reversion.” *Transactions of the American Mathematical Society* 94: 441–51.