

Notes on Raney's Lemmas

Tyler Neylon

251.2015

In a 1960 paper, George Raney 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 (Raney 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 Raney's original paper.

1 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

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

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 ℓ indexes in $\{1, \dots, n\}$ are positive-sum shifts.*

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 Real sequences

In a moment we'll prove 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^{th} partial sum of x ; that is, $s_0 = 0$, and

$$s_i = \sum_{j=1}^i x_j, \quad \text{for } i \geq 1.$$

We can define s_i for $i > n$ using the implicitly periodic sequence characterized by $x_{n+i} = x_i$.

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

Proof Let

$$s'_i = \sum_{k=j}^{j+i-1} x_k$$

denote the i^{th} partial sum of the shifted sequence $\langle x_j, \dots, x_{j+n-1} \rangle$. Then, for $1 \leq i \leq n$,

$$s'_i = s_{j+i-1} - s_{j-1} \begin{cases} > 0 \text{ (by definition of } j) & \text{when } j+i-1 < n \\ = s_n + s_{j+i-1-n} - s_{j-1} \geq s_n > 0 & \text{when } j+i-1 \geq n. \end{cases}$$

□

Now we can assume without loss of generality that any sequence of real numbers $\langle x_1, \dots, x_n \rangle$ with $\sum x_i > 0$ is already shifted so that all its partial sums $s_i > 0$ for $i > 0$. As we'll see in the next property, this assumption allows us to provide a nice general expression for $\sigma(x)$. This expression depends on the set $S(x)$, defined as $\{\min_{j \leq i \leq n} s_i \mid 1 \leq j \leq n\}$ for any finite sequence x with i^{th} partial sum s_i .

Property 4 *Suppose that x is a finite real sequence with i^{th} partial sum s_i , and that $s_i > 0$ for all $i > 0$. Then*

$$\sigma(x) = \#S(x) = \# \left\{ \min_{j \leq i \leq n} s_i \mid 1 \leq j \leq n \right\}. \quad (1)$$

More specifically, an index j with $1 \leq j \leq n$ is a positive-sum shift iff

$$s_{j-1} < s_i \quad \forall i : j \leq i \leq n. \quad (2)$$

Proof We'll start by supposing we have an index j with $1 \leq j \leq n$ and $s_{j-1} < s_i$ for all i with $j \leq i \leq n$; our goal is to show that such a j must be a positive-sum shift. Our approach will be similar to the proof of property 3.

Let s'_i denote the i^{th} partial sum of $\langle x_j, \dots, x_{j+n-1} \rangle$:

$$s'_i = \sum_{k=j}^{j+i-1} x_k.$$

Then

$$s'_i = s_{j+i-1} - s_{j-1} \begin{cases} > 0 & \text{if } j+i-1 \leq n, \\ = s_{j+i-1-n} + s_n - s_{j-1} > 0 & \text{if } j+i-1 > n; \end{cases}$$

the last inequality follows since $s_{j+i-1-n} > 0$ and $s_n > s_{j-1}$.

On the other hand, if $s_{j-1} \geq s_i$ for some i, j with $1 \leq j \leq i \leq n$, then $s'_{i-j+1} = s_i - s_{j-1} \leq 0$, so that j isn't a positive-sum shift. This completes the proof of the last part of the property.

Now let's verify that the set $S = S(x)$ from (1) has size $\sigma(x)$.

Let j_1, \dots, j_k be all the positive-sum shifts with $1 < j_i \leq n$; note that $k = \sigma(x) - 1$ since the trivial shift index 1 has been excluded. Let $T = \{s_{j_1-1}, \dots, s_{j_k-1}, s_n\}$.

Notice that $j = n + 1$ trivially meets condition (2); combine this with the first part of the proof to see that all elements of T meet condition (2). This guarantees that all the elements are unique, so that $|T| = \sigma(x)$. This also means that $T \subset S$. Finally, observe that, for any $s_j \in S$, there's a largest index j' with $1 \leq j' \leq n$ and $s_{j'} = s_j$; this index j' meets condition (2), so that $S \subset T$, confirming that $|S| = |T| = \sigma(x)$. \square

Property 4 lends itself to a nice visual intuition. Consider the example sequence $\langle 2, -1, 2, 2, -3, 2, 1, 1, -1, -2 \rangle$ of length $n = 10$. Below is the line graph of its partial sums, starting with $s_0 = 0$.



Figure 1: *Line graph of the partial sums s_i of the example sequence.*

Imagine an observer standing far to the right of the graph and looking directly to the left so they can only see along a perfectly horizontal line of sight. Below s_n , they can only see the three points s_0 , s_2 , and s_5 . These are exactly the partial sums meeting condition (2), so that they correspond directly to all the positive-sum shifts of x , which have indexes 1, 3, and 6.

This visual intuition — that points visible-from-the-right and below s_n correspond exactly to the positive-sum shifts — extends to any sequence meeting the suppositions of property 4.

It's now possible to prove a simple general upper and lower bound for $\sigma(x)$ in the case that each x_i is an integer. We'll see below that these bounds provide both lemmas 1 and 2 as corollaries.

Property 5 *Suppose we have a finite integer sequence $x = \langle x_1, \dots, x_n \rangle$ with $s_n > 0$. Let $m = \max_i x_i$. Then*

$$\lceil s_n/m \rceil \leq \sigma(x) \leq s_n.$$

Proof idea Here is the informal intuition behind the proof: We'll start by noticing that, for sum-positive x , $S(x) \subset (0, s_n]$; this is the basis used for the upper bound. The lower bound is based on the idea that each jump upwards from one $s_i \in S(x)$ to the next $s_j \in S(x)$ is limited by distance m . The smallest element in $S(x)$ can be at most m above $s_0 = 0$, and the largest is necessarily s_n , so that there must be at least s_n/m elements between the extremes.

Proof Notice that we can work with any cyclic shift x' of x without changing s_n or m . Thus, using property 3, we can assume without loss of generality that $s_i > 0$ for $i > 0$.

Next, we can bound the elements of $S(x)$ via

$$0 < \min_{j \leq i \leq n} s_i \leq s_n$$

for all j with $1 \leq j \leq n$. So all elements of $S(x)$ are in the range $(0, s_n]$, and are integers. Hence $\#S(x) \leq s_n$, completing the proof of the upper bound.

Toward the lower bound, let's suppose that $S(x) = \{s_{j_1}, \dots, s_{j_k}\}$ with each s_{j_i} meeting condition (2) and $0 < s_{j_i} < s_{j_{i+1}}$. We know such s_{j_i} exist as they are simply those partial sums in $s_{j_i} \in S(x)$ chosen so that $j_i = \max_{1 \leq k \leq n} \{k : s_k = s_{j_i}\}$.

By our definition of s_{j_i} , we have

$$s_{j_i} = \min_{j_i \leq k \leq n} s_k \text{ and } s_{j_{i+1}} = \min_{j_{i+1} \leq k \leq n} s_k.$$

This means that

$$s_{j_{i+1}} - s_{j_i} = \min_{j_{i+1} \leq k \leq n} s_k - s_{j_i} \leq s_{j_{i+1}} - s_{j_i} \leq m.$$

Note that $s_{j_k} = s_n$ so that $s_n - s_{j_{k-1}} \leq m \Rightarrow s_{j_{k-1}} \geq s_n - m$. This can be extended to see that $s_{j_{k-2}} \geq s_n - 2m$, and in general that

$$s_{j_{k-p}} \geq s_n - pm.$$

Our definition of m gives us that $s_{j_1} \leq m$, so $m \geq s_{j_1} \geq s_n - (k-1)m$, from which we can derive that

$$1 \geq s_n/m - (k-1) \Rightarrow k \geq s_n/m \Rightarrow k \geq \lceil s_n/m \rceil;$$

the last inequality uses the fact that $k = \sigma(x)$ is an integer. This completes the proof. \square

The Contraction Perspective

Next we'll consider a contraction operation that may shorten a sequence x while preserving $\sigma(x)$.

Call a sequence $x = \langle x_1, \dots, x_n \rangle$ *sum-positive* iff $s_i > 0$ when $i > 0$. We'll say that a sequence $x' = \langle x'_1, \dots, x'_{n-1} \rangle$ is a *contraction* of the length- n sum-positive sequence x iff there is some index j so that $x_{j+1} \leq 0$ and, for $1 \leq i \leq n-1$,

$$x'_i = \begin{cases} x_i & \text{if } i < j, \\ x_i + x_{i+1} & \text{if } i = j, \text{ and} \\ x_{i+1} & \text{if } i > j. \end{cases}$$

For example. $x' = \langle 2, -1, 2 \rangle$ is a contraction of $x = \langle 3, -1, -1, 2 \rangle$ since the sequences are same except for the replacement of x_1, x_2 by their sum as x'_1 , and $x_2 = -1 \leq 0$. The alternative sequence $x'' = \langle 3, -1, 1 \rangle$ is *not* a contraction as it replaces x_3, x_4 with their sum x'_3 , but $x_4 = 2 > 0$.

Property 6 *If x' is a contraction of x , then x' is sum-positive and $\sigma(x') = \sigma(x)$.*

Proof Let j be the contracted index, so that $x'_j = x_j + x_{j+1}$ and $x_{j+1} \leq 0$.

Let s'_i denote the i^{th} partial sum of x' . Then

$$s'_i = \begin{cases} s_i & \text{if } 0 \leq i < j \\ s_{i+1} & \text{if } j \leq i \leq n-1. \end{cases}$$

So $s'_i > 0$ for $0 < i \leq n-1$, making x' sum-positive.

Since $x_{j+1} \leq 0$, $s_{j+1} \leq s_j$. This means that

$$\min_{k \leq i \leq n} s_i = \min_{k \leq i \leq n, i \neq j} s_i, \text{ and } \min_{k \leq i \leq n} s'_i = \begin{cases} \min_{k \leq i \leq n} s_i & \text{if } k < j, \text{ and} \\ \min_{k+1 \leq i \leq n} s_i & \text{if } k \geq j, \end{cases}$$

for all k with $1 \leq k \leq n$. This last equality ensures that $S(x) = S(x')$, so that $\sigma(x) = \sigma(x')$ using property 4. This completes the proof. \square

As long as a sum-positive sequence x has any element $x_i \leq 0$, we can apply a contraction to it to arrive at a shorter sequence. Thus, we can always apply a series of contractions to arrive at a sum-positive, length- k sequence x' with all elements $x'_i > 0$. All shifts of this x' are positive-sum shifts, so that $\sigma(x') = k$, and thus $\sigma(x) = k$ as well. In other words, we can find $\sigma(x)$ by contracting x until it can be contracted no more.

To add both intuition and more detail to this process, think of any sum-positive sequence x as consisting of subsequences starting with x_j for each positive-sum shift index j . For example, suppose sequence x has positive-sum shift indexes 1, 3, and 4. Then

$$\langle x_1, x_2, x_3, x_4, x_5, x_6 \rangle = \langle x_1, x_2 \rangle \langle x_3 \rangle \langle x_4, x_5, x_6 \rangle.$$

Contractions effectively work within these subsequences. A contraction can never combine elements across a subsequence boundary because the first element of

any subsequence must be positive. Our last proof showed that the set $S(x)$ is preserved by contraction. That proof also showed that the indexes j_1, \dots, j_k with $\{s_{j_1}, \dots, s_{j_k}\} = S(x)$ are preserved as well, excepting a possible shift-by-one in the latter elements to account for the contraction. In other words, if an element x_j begins a subsequence before a contraction, then it will be mapped to x'_k with either $k = j$ or $k = j - 1$, with $x'_k = x_j$, and with x'_k also acting as a positive-sum shift for x' .

The final result of any maximal series of contractions is therefore deterministic: we must arrive at exactly the sequence of sums of the original subsequences. Using our last example sequence, we may make the following series of underlined contractions:

$$\begin{array}{rcl}
& \langle x_1, x_2 \rangle & \langle x_3 \rangle & \langle x_4, x_5, x_6 \rangle \\
\rightarrow & \langle x_1, x_2 \rangle & \langle x_3 \rangle & \langle \underline{x_4 + x_5}, x_6 \rangle \\
\rightarrow & \langle \underline{x_1 + x_2} \rangle & \langle x_3 \rangle & \langle x_4 + x_5, x_6 \rangle \\
\rightarrow & \langle x_1 + x_2 \rangle & \langle x_3 \rangle & \langle x_4 + \underline{x_5 + x_6} \rangle.
\end{array}$$

The final sequence has 3 positive elements, so we can't perform any more contractions. We have freedom in the order in which we execute those contractions, but the end result is independent of this order. Note that, although we've highlighted the subsequence structure here, we don't need to be aware of that structure to execute the contractions.

3 Random sequences

(NOTE This section is kind of messed up currently while I fix some major plot holes.)

In this section, we'll consider a finite sequence $s = \langle s_1, \dots, s_n \rangle$ whose elements s_i are independent random variables, each uniformly distributed in the interval $(0, 1]$. These are the partial sums of the sequence $x_i = s_i - s_{i-1}$, where we define $s_0 = 0$. Generating x in this manner ensures it is sum-positive.

Notice that, if $i \neq j$, then $s_i \neq s_j$ with probability 1. We'll focus on finding the expected value of $\sigma(x)$; in that context we can thus assume without loss of generality that we're only considering sequences x with distinct partial sums s_i .

The remark below will help us formally establish that the order of the elements of s_i is essentially chosen as a uniformly random permutation.

From here on, the term *n-permutation* refers to a bijective map $\pi : \{1, \dots, n\} \rightarrow \{1, \dots, n\}$. A *swap of i and j* is a permutation ρ such that the distinct elements i, j in its range have $\rho(i) = j$, $\rho(j) = i$, and for which $\rho(k) = k$ when $k \neq i, j$. Given two n -permutations π_1 and π_2 , we'll use the equivalent notations $\pi_1(\pi_2)$ and $\pi_1 \circ \pi_2$ to denote the composed permutation π_3 defined by $\pi_3(i) = \pi_1(\pi_2(i))$.

Remark Suppose we have a probability space over the set of n -permutations, and that, for any n -permutation π and swap ρ , $\text{Prob}(\pi) = \text{Prob}(\rho(\pi))$. Then all length- n permutations are equally likely in this space.

Proof Let ρ_{ij} denote the swap of i and j . Then the set of swaps $\{\rho_{ij} | 1 \leq i < j \leq n\}$, when closed under composition, generates the set of all n -permutations. One way to see this is by considering the Steinhaus-Johnson-Trotter algorithm, which enumerates all n -permutations using a single swap between any two successive elements (Wikipedia 2015).

Since any pair of n -permutations π_1 and π_2 are a finite pair of swaps apart, they must have the same probability. More formally, there must exist a finite sequence of swaps ρ_1, \dots, ρ_k so that $\pi_1 = \rho_1 \circ \dots \circ \rho_k \circ \pi_2$. Then

$$\text{Prob}(\pi_2) = \text{Prob}(\rho_k \circ \pi_2) = \dots = \text{Prob}(\rho_1 \circ \dots \circ \rho_k \circ \pi_2) = \text{Prob}(\pi_1).$$

□

(TODO stuff below here will be heavily edited or rewritten altogether.)

In this section, we'll consider a finite sequence x of length n whose elements x_i are independent random variables, each uniformly distributed in the interval $[-1, 1]$.

The partial sums of such a sequence have two interesting properties:

1. If $i \neq j$, then $s_i \neq s_j$ with probability 1.
2. $\text{Prob}(s_i > s_j) = \text{Prob}(s_i < s_j)$.

To see the first property, suppose $i < j$ and that we're given the values of x_1, \dots, x_{j-1} . If we are about to choose a random value $x_j \in [-1, 1]$, then there is at most one value which could give $s_i = s_j$, so that the event must have probability zero.

We can verify the second property by a symmetry argument. Notice that any fixed value for x_i is as likely as its opposite value $-x_i$. This means that every measurable set of sequences X has the same probability as its negation $\{-x = \langle -x_1, \dots, -x_n \rangle | x \in X\}$. So the set $\{x | s_i < s_j\}$ has the same probability as the set $\{x | s_i > s_j\}$.

So, almost surely, $\text{Prob}(s_i > s_j) = \text{Prob}(s_i < s_j) = 1/2$ for any i, j with $0 \leq i < j \leq n$. As we'll explain in more detail below, this means that the sequence $s = \langle s_0, \dots, s_n \rangle$, seen as a permutation, is probabilistically equivalent to a uniformly random permutation.

(TODO argue that this means almost surely that the order of the s_i sequence is probabilistically equivalent to a uniformly random permutation. Also improve the phrasing in the last paragraph.)

TODO transition into the remark below TEMP Remove the two horizontal breaks below and these remarks (including the TODO above)

Remark Suppose we have a probability space whose elements are length- n permutations, and that $\text{Prob}(\pi(i) < \pi(j)) = 1/2$ for all $i \neq j$. Then all length- n permutations are equally likely in this space.

Proof This is not actually true. Consider

1 2 3 4
4 3 2 1

Oh, dear. \square

So we can learn more about our random sequence x by considering what we can learn about a partial order sequence s which is directly chosen as a uniformly random permutation. The next property focuses on the expected value of $\sigma(x)$ in this setting. It will be useful to define the n^{th} harmonic number H_n as $\sum_{i=1}^n 1/i$.

Property 7 Suppose that the random length- n sequence x has i^{th} partial sum s_i , that $s_i > 0$ for $1 \leq i \leq n$, and that $\text{Prob}(s_i > s_j) = \text{Prob}(s_j > s_i) = 1/2$ for any i, j with $0 \leq i < j \leq n$. Then the expected value of $\sigma(x)$ is H_n .

This property immediately tells us that $\sigma(x)$ averages to H_n across all x with sum $s_n > 0$ since we can always shift x so that $s_i > 0$ for $i > 0$ without changing $\sigma(x)$. To make this even more general, we can notice that $\text{Prob}(s_n > 0) = \text{Prob}(s_n < 0) = 1/2$. There are zero positive-sum shifts when $s_n < 0$, so the average of $\sigma(x)$ for an arbitrary length- n sequence is exactly $H_n/2$.

Proof of property 7 We can assume without loss of generality that $s_i \neq s_j$ for $i \neq j$; this is excluding a zero-probability case, so it doesn't affect the expected value of $\sigma(x)$.

We'll say that s_i , with $1 \leq i \leq n$, is the j^{th} smallest partial sum iff $j = \#\{s_k | s_k < s_i, 0 \leq k \leq n\}$. Now we can define a map $\pi : [1, n] \rightarrow [1, n]$ so that $s_{\pi(i)}$ is the i^{th} smallest partial sum. Effectively, π is a permutation that captures the order of the elements of s_1, \dots, s_n ; $s_{\pi(i)} < s_{\pi(j)}$ iff $i < j$.

We can use the set $S(x)$ to determine $\sigma(x)$. Notice that $s_{\pi(k)} \in S(x)$ iff $\pi(i) < \pi(k)$ for all $i < k$; call this event e_k . This event is entirely determined by the order of $\pi(1), \dots, \pi(k)$, of which there are $k!$ equally likely possibilities. Exactly $1/k$ of those orderings have $\pi(k)$ as the largest element. Thus, $\text{Prob}(e_k) = 1/k$.

Finally, the expected value of $\sigma(x)$ is

$$\sum_{k=1}^n \text{Prob}(e_k) = \sum_{k=1}^n 1/k = H_n,$$

using the linearity of the expected value. This completes the proof. \square

(TODO 1. Figure out the statement of the property. 2. Prove it. 3. Go back and review whatever depth of connection I want to make with uniformly random permutations.)

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.

Wikipedia. 2015. “Steinhaus-Johnson-Trotter Algorithm — Wikipedia, the Free Encyclopedia.” http://en.wikipedia.org/wiki/Steinhaus-Johnson-Trotter_algorithm.