From Clustering Supersequences to Entropy Minimizing Subsequences for Single and Double Deletions

Arash Atashpendar¹, Marc Beunardeau³, Aisling Connolly³, Rémi Géraud³, David Mestel², A. W. Roscoe² and Peter Y. A. Ryan¹

¹SnT, University of Luxembourg, Luxembourg
²Department of Computer Science, University of Oxford, Oxford, UK
³Département d’informatique de l’ENS, École normale supérieure, CNRS, PSL Research University, Paris, France

Abstract

A binary string transmitted via a memoryless i.i.d. deletion channel is received as a subsequence of the original input. From this, one obtains a posterior distribution on the channel input, corresponding to a set of candidate supersequences weighted by the number of times the received subsequence can be embedded in them. In a previous work it is conjectured on the basis of experimental data that the entropy of the posterior is minimized and maximized by the constant and the alternating strings, respectively. In this work, we present an algorithm for counting the number of subsequence embeddings using a run-length encoding of strings. We then describe two different ways of clustering the space of supersequences and prove that their cardinality depends only on the length of the received subsequence and its Hamming weight, but not its exact form. Then, we consider supersequences that contain a single embedding of a fixed subsequence, referred to as singletons, and provide a closed form expression for enumerating them using the same run-length encoding. We prove an analogous result for the minimization and maximization of the number of singletons, by the alternating and the uniform strings, respectively. Next, we prove the original minimal entropy conjecture for the special cases of single and double deletions using similar clustering techniques and the same run-length encoding, which allow us to characterize the distribution of the number of subsequence embeddings in the space of compatible supersequences to demonstrate the effect of an entropy decreasing operation.

Index Terms

Binary sequences, Combinatorial mathematics, Information entropy, Hamming weight, Closed-form solution

I. INTRODUCTION

The original motivation for this work goes back to an analysis of quantum key distribution (QKD) protocols [1], which among other things, suggested some modifications of the quantum bit error rate (QBER) estimations. These modifications led to an information theory problem that was first investigated in [2].

The mathematical problem encountered in the aforementioned analysis is the following. A random bit string $y$ of length $n$ emitted from a memoryless source is transmitted via an i.i.d. deletion channel such that a shorter bit string $x$ of length $m$ ($m \leq n$) is received as a subsequence of $y$, after having been subject to $n - m$ deletions. Consequently, the order in which the remaining bits are revealed is preserved, but the exact positions of the bits are not known. Given a subsequence $x$, the question is to find out how much information about $y$ is revealed. More specifically, the quantity we are interested in is the conditional entropy [3] over the set of candidate supersequences upon observing $x$, i.e., $H(Y|X = x)$ where $Y$ is restricted to the set of compatible supersequences as explained below.

The said information leakage is quantified as the drop in entropy [4] for a fixed $x$ according to a weighted set of its compatible supersequences, referred to as the uncertainty set. The uncertainty set, denoted by $\Upsilon_{n,x}$, contains all the supersequences that could have given rise to $x$ upon $n - m$ deletions. In [2], an alternative proof shows that this set’s cardinality is independent of the details of $x$ and that it is only a function of $n$ and $m$. The weight distribution used in the computation of entropy is given by the number of occurrences or embeddings of a fixed subsequence in its compatible supersequences, i.e., the number of distinct ways $x$ can be extracted from $y$ upon a fixed number of deletions, denoted by $\omega_x(y)$. Furthermore, in the same work it is conjectured that the constant subsequences consisting of all 1’s (or all 0’s), $x = 11\ldots1$, and the alternating 1’s and 0’s, i.e., $x = 1010\ldots$, minimize and maximize the said entropy, respectively.

arash.atashpendar@uni.lu
marc.beunardeau@ingenico.com
aisling.connolly@ens.fr
remi.geraud@ens.fr
david.mestel@cs.ox.ac.uk
a.w.roscoe@cs.ox.ac.uk
peter.ryan@uni.lu

arXiv:1802.00703v1 [cs.IT] 2 Feb 2018
Despite the specific context in which the problem was first encountered, the underlying mathematical puzzle is a close relative of several well-known challenging problems in formal languages, DNA sequencing and coding theory. In fact, the distribution of the number of times a string \( x \) appears as a subsequence of \( y \), lies at the center of the long-standing problem of determining the capacity of deletion channels. More precisely, knowing this distribution would give us a maximum likelihood decoding algorithm for the deletion channel \([5]\). In effect, upon receiving \( x \), every set of \( n - m \) symbols is equally likely to have been deleted. Thus, for a received sequence, the probability that it arose from a given codeword is proportional to the number of times it is contained as a subsequence in the originally transmitted codeword. More specifically, we have
\[
p(y|x) = p(x|y) p(y) = \omega_x(y) d^{n-m}(1-d)^m p(y)/p(x),
\]
with \( d \) denoting the deletion probability. Thus, as inputs are assumed to be a priori equally likely to be sent, we restrict our analysis to \( \omega_x(y) \) for simplicity.

In this work, we first study several closely-related counting problems involving (super/sub)-sequences and then we revisit the aforementioned entropy question. It is worth pointing out that while questions on the combinatorics of random subsequences requiring closed-form expressions are already quite challenging, the problem tackled in this work and first raised in \([2]\), is further complicated by the dependence of entropy on the distribution of subsequence embeddings, i.e., the number of supersequences having specific embedding weights. To put this in contrast, in a related work \([6]\), a closed-form expression is provided for computing the number of distinct subsequences that can be obtained from a fixed supersequence for the special case of two deletions, whereas here we need to account for the entire space of supersequences and characterize the number of times a given subsequence can be embedded in them in order to address the entropy question. Moreover, one would have to work out how these weights (number of embeddings) get shifted across their compatible supersequences when we move from one subsequence to another.

### A. Results and Contributions

We first present an algorithm based on a run-length encoding of strings for counting the number of embeddings of \( x \) into \( y \) as a subsequence. Similar to how the cardinality of the set of supersequences that can project to a given subsequence, i.e., \( |\Upsilon_{n,x}| \), depends only on their respective lengths, we prove that the number of supersequences that admit an initial embedding of a subsequence such that the last index of their initial embedding overlaps with their last bit, also depends only on \(|y|=n\) and \(|x|=m\). We then describe two clustering techniques that give rise to subspaces in \( \Upsilon_{n,x} \) whose sizes depend only on \( n, m \) and the Hamming weight of \( x \), but not the exact form of \( x \). We derive analytic expressions, as well as a recurrence, for the cardinality of these sets. The approach and methodology used for deriving our clustering results depend heavily on the notion of initial or canonical embeddings of subsequences in their compatible supersequences, which provide further insight into the importance of initial embeddings.

Next, we consider the problem of enumerating supersequences that admit exactly a single occurrence of a subsequence, referred to as singletons, and give an analytic expression for their count. Furthermore, we prove a similar result for the maximization and minimization of the number of singletons by the constant and alternating strings, respectively.

Finally, we revisit the original entropy extremization question and prove the minimal entropy conjecture for the special cases of single and double deletions, i.e., for \( n = m+1 \) and \( n = m+2 \). The entropy result is obtained via a characterization of the number of strings with specific weights, along with an entropy decreasing operation. This is achieved using clustering techniques and a run-length encoding of strings: we identify groupings of supersequences with specific weights by studying how they can be constructed from a given subsequence using different insertion operations, which are in turn based on analyzing how runs of 1’s and 0’s can be extended or split. The methods used in the analysis of the underlying combinatorial problems, based on clustering techniques and the run-length encoding of strings may be of interest in their own right.

### B. Structure

We begin by providing a survey of related work in Section \([II]\). In Section \([III]\), we introduce our notation and describe the main definitions, models, and building blocks used in our study. Next, in Section \([IV]\), we present an algorithm for counting the number of subsequence embeddings, which relies on the run-length encoding of strings. We then explore counting problems and clustering techniques in the space of supersequences including an analysis of a class of supersequences, referred to as singletons, that admit exactly a single embedding of a given subsequence and prove similar extremization results for their count. Finally, we turn to the original entropy question in Section \([V]\) and prove the minimal entropy conjecture for the special cases of single and double deletions. Finally, we conclude by summarizing our findings and stating some open problems in Section \([VI]\).

## II. RELATED WORK

Studies involving subsequences and supersequences encompass a wide variety of problems that arise in various contexts such as formal languages, coding theory, computer intrusion detection and DNA sequencing to name a few. Despite their prevalence in such a wide range of disciplines, they remain largely unexplored and still present a considerable wealth of unanswered questions. In the realm of stringology and formal languages, the problem of determining the number of distinct subsequences...
obtainable from a fixed number of deletions, and closely related problems, have been studied extensively in \cite{7,8,9,10}. Perhaps it is worth noting that the same entropy minimizing and maximizing strings conjectured in \cite{2} and characterized in the present work, have been shown to lead to the minimum and maximum number of distinct subsequences, respectively. The problems of finding shortest common supersequences (SCS) and longest common subsequences (LCS) represent two well-known NP-hard problems \cite{11,12} that involve subproblems similar to our work. Finally, devising efficient algorithms for subsequence combinatorics based on dynamic programming for counting the number of occurrences of a subsequence in DNA sequencing is yet another important and closely related line of research \cite{14,15}.

In coding theory, and more specifically in the context of insertion and deletions channels, similar long-standing problems have been studied extensively, and yet many problems still remain elusive. This includes designing optimal coding schemes and determining the capacity of deletion channels, both of which incorporate the same underlying combinatorial problem addressed in the present work. Considering a finite number of insertions and deletions for designing correcting codes, which represents the holy grail in the finite-length regime remains rather limited in scope. More precisely, the distribution of the number of occurrences constitutes a central problem in coding theory, with a maximum likelihood decoding argument, which represents the holy grail in the study of deletion channels. A graph-theoretic approach for deletion correcting codes, closely related to our clustering analysis, including an alternative proof for the Hamming weight clustering given in Theorem \cite{IV.5} based on a different approach, is given in \cite{22}.

An important body of research in this area is dedicated to deriving tight bounds on the capacity of deletion channels \cite{23,24,25} and developing bounding techniques \cite{27}.

Perhaps rather surprisingly, the problem of determining the number of occurrences of a fixed subsequence in random sequences has not received the same amount and level of attention from the various communities. The state-of-the-art in the finite-length regime remains rather limited in scope. More precisely, the distribution of the number of occurrences constitutes a central problem in coding theory, with a maximum likelihood decoding argument, which represents the holy grail in the study of deletion channels. A comprehensive survey, which among other things, outlines the significance of figuring out this particular distribution is given by Mitzenmacher in \cite{5}.

III. FRAMEWORK

We consider a memoryless source that emits symbols of the supersequence, drawn independently from the binary alphabet $\Sigma = \{0, 1\}$. Given an alphabet $\Sigma = \{0, 1\}$, $\Sigma^n$ denotes the set of all $\Sigma$-strings of length $n$. Let $p_0$ denote the probability of the symbol $0 \in \Sigma$ being emitted, which in the binary case simplifies to $p_0 = 0.5$. This means that the probability of occurrence of a random supersequence $y$ is given by $P(y) = \prod_{i=1}^{n} p_0$. The probability of a subsequence of length $m$ is defined in a similar manner. Throughout, we use $h(s)$ to denote the Hamming weight of the binary string $s$.

a) Notation: We use the notation $[n] = \{1, 2, \ldots, n\}$ and $[n_1, n_2]$ to denote the set of integers between $n_1$ and $n_2$; individual bits from a string are indicated by a subscript denoting their position, starting at 1, i.e., $y = (y_i)_{i \in [n]} = (y_1, \ldots, y_n)$. We denote by $|S|$ the size of a set $S$, which for binary strings also corresponds to their length in bits. We also introduce the following notation: when dealing with binary strings, $[n]^{k}$ means $k$ consecutive repetitions of $a \in \{0, 1\}$.

b) Subsequences and Supersequences: Given $x \in \Sigma^n$ and $y \in \Sigma^m$, let $x = x_1x_2 \cdots x_m$ denote a subsequence obtained from $y = y_1y_2 \cdots y_n$ with a set of indexes $1 \leq i_1 < i_2 < \cdots < i_m \leq n$ such that $y_{i_1} = x_1, y_{i_2} = x_2, \ldots, y_{i_m} = x_m$. Subsequences are obtained by deleting characters from the original string and thus adjacent characters in a given subsequence are not necessarily adjacent in the original string.

c) Projection Masks: We define $y_\pi = (y_i)_{i \in \pi} = x$ to mean that the string $y$ filtered by the mask $\pi$ gives the string $x$. Let $\pi$ denote a set of indexes $\{j_1, \ldots, j_m\}$ of increasing order that when applied to $y$, yields $x$, i.e., $x = y_{j_1}y_{j_2} \cdots y_{j_m}$ and $1 \leq j_1 < j_2 < \cdots < j_m \leq n$.

d) Deletion Masks: A deletion mask $\delta$ represents the set of indexes that are deleted from $y$ to obtain $x$, i.e., $\delta \in [n] \setminus \pi$ and $|\delta| = n - m$, whereas a projection mask $\pi$ denotes indexes that are preserved. Thus, similarly, $\delta$ is a subset of $[n]$ and the result of applying a mask $\delta$ on $y$ is denoted by $y_\delta = x$.

e) Compatible Supersequences: We define the uncertainty set, $T_{n,x}$, as follows. Given $x$ and $n$, this is the set of $y$ strings that could project to $x$ for some projection mask $\pi$.

\[ T_{n,x} := \{ y \in \{0, 1\}^n : (\exists \pi) (y_\pi = x) \} = \{ y \in \{0, 1\}^n : (\exists \delta) (y_\delta = x) \} \]

f) Number of Masks or Embeddings: Let $\omega_z(y)$ denote the number of distinct ways that $y$ can project to $x$:

\[ \omega_z(y) := |\{ \pi \in \mathcal{P}([n]) : y_\pi = x \}| = |\{ \delta \in \mathcal{P}([n]) : y_\delta = x \}| \]

we refer to the number of masks associated with a pair $(y, x)$ as the weight of $y$, i.e., the number of times $x$ can be embedded in $y$ as a subsequence.

g) Initial Projection Masks or Canonical Embeddings: Given $y_\pi = x$, we define $\pi$ to be initial if there is no lexicographically earlier mask $\pi'$ such that $y_{\pi'} = x$. $\pi'$ is a lexicographically earlier mask than $\pi$ if, for some $r$, the smallest $r$ members of $\pi$ and $\pi'$ are the same, but the $(r + 1)$-th of $\pi'$ is strictly smaller than that of $\pi$. Throughout, we will use $\hat{\pi}$ to denote
an initial projection mask. The first embedding of a subsequence $x$ in $y$ is also often referred to as the canonical embedding in the literature. Note that for a fixed mask or embedding $\pi$, the members of $y$ up to the last member of $\pi$ are completely determined if $\pi$ is initial.

h) Run-Length Encodings: A substring $T$ of a string $Y = y_1 y_2 \ldots y_n$ over $\Sigma$ is called a run of $Y$ if $T$ is a consecutive sequence of the same character (i.e., $T \in \alpha^+$ for an $\alpha \in \Sigma$). Let $\mathcal{R}_{x,\alpha}$ denote the set of runs of $\alpha$ in $x$. The notion of run-length encoding will be central to our analysis. Given an $n$-bit binary string $y$, its run-length encoding (RLE) is the sequence $r_j = (a_j, b_j)$, $1 \leq j \leq m$, such that

$$y = [a_1]^b_1 [a_2]^b_2 \ldots [a_m]^b_m, \quad m \leq n.$$  

with $a_j \in \{0, 1\}$ and $b_j \in \{1, \ldots, n\}$. This encoding is unique if we assume that $a_i \neq a_{i+1}$, at which point we only need to specify a single $a_i$ (e.g., the first one) to deduce all the others.

Thus the RLE$^1$ for a string $y$ is denoted by

$$y = [a_1; b_1, b_2, \ldots, b_m].$$

When the value of $a_1$ is irrelevant, which will often be the case later on$^2$, we will drop it from the notation. Consecutive zeros or ones in a binary string will be referred to as blocks or runs.

Example III.1. Let $y = 0011010001$; then we have $y = [0; 2, 2, 1, 3, 1]$ as the first bit is zero; and we have 2 zeros, 2 ones, 1 zero, 1 one, 3 zeros, 1 one. Alternatively, $[2, 2, 1, 3, 1]$ designates simultaneously $0011010001$ and $1100101110$.

i) Entropy: For a fixed subsequence $x$ of length $m$, the underlying weight distribution used in the computation of the entropy is defined as follows. Upon receiving a subsequence $x$, we consider the set of compatible supersequences $\mathcal{Y}_{n,x}$ of length $n$ (denoted by $\mathcal{Y}_{n,x}$) that can project to $x$ upon $n - m$ deletions. Every $y \in \mathcal{Y}_{n,x}$ is assigned a weight given by its number of masks $\omega_x(y)$, i.e., the number of times $x$ can be embedded in $y$ as a subsequence. We consider the conditional Shannon entropy $H(Y|X = x)$ where $Y$ is confined to the space of compatible supersequences $\mathcal{Y}_{n,x}$. The total number of masks in $\mathcal{Y}_{n,x}$ is given by

$$\mu_{n,m} = \binom{n}{m} \cdot 2^{n-m}$$

Thus, forming the normalized weight distribution

$$P_x = \left\{ \frac{\omega_x(y_1)}{\mu_{n,m}}, \ldots, \frac{\omega_x(y_n)}{\mu_{n,m}} \right\}.$$  

Finally, for simplicity we use $H_n(x)$ throughout this work to refer to the entropy of a distribution $P$ corresponding to a subsequence $x$ as defined below

$$H_n(x) = -\sum_i p_i \cdot \log_2(p_i)$$

where $p_i$ is given by

$$p_i = \frac{\omega_x(y_i)}{\mu_{n,m}}.$$  

IV. CLUSTERING SUPERSEQUENCES AND COUNTING SUBSEQUENCES

We now briefly review the results of the entropy analysis presented in$^2$, in which it is conjectured that the constant/uniform string consisting of all 1’s (or all 0’s), $x = 11 \ldots 1$, and the alternating $x$ string, i.e., $x = 1010 \ldots$ minimize and maximize the entropy $H_n(x)$, respectively. To illustrate this, the plot given in Figure 1 shows the values of the min-entropy ($H_\infty$), the second-order Rényi entropy ($R$) and the Shannon entropy ($H$) computed for all $x$ strings of length 5, with $n = 8$.

Counting multisets: Throughout, we use the combinatorics of counting multisets, also referred to as the method of stars and bars, to enumerate all possibilities for placing $n$ indistinguishable objects into bins marked by $m$ distinguishable separators such that the resulting configurations are distinguished only by the number of objects present in each bin, which is given by $\binom{n+m-1}{n}$.

A. Compatible Supersequences and Subsequence Embeddings

Recall that for a fixed subsequence $x$ of length $m$, we consider the set of $y$ strings of length $n$ ($n \geq m$), referred to as compatible supersequences, that can contain $x$ as a subsequence embedding. The set of compatible supersequences is denoted by $\mathcal{Y}_{n,x}$. It is known that the cardinality of $\mathcal{Y}_{n,x}$ is independent of the form of $x$ and that it is only a function of $n$ and $m$.

$$|\mathcal{Y}_{n,x}| = \sum_{r=m}^{n} \binom{n}{r}$$

$^1$The notation $[n]$ is overloaded, but the difference will be clarified when it is not clear from the context.

$^2$Indeed, if $x = y_x$, then $\mathcal{Y} = \mathcal{T}_\pi$ and $\omega_x(y) = \omega_\pi(y)$.
Subsequence Entropy Analysis for $n=8$ and $m=5$

We provided an alternative proof for this based on a simple recursion in [2]. The original motivation for the clustering scheme presented here was to have a more fine-grained view of the distribution of masks in the space of supersequences. This approach led to the discovery of similar structures in $\Upsilon_{n,x}$, in that their cardinality does not depend on the form of $x$, analogous to how $|\Upsilon_{n,x}|$ depends only on $n$ and $m$.

**B. Counting Subsequence Embeddings via Runs**

Efficient dynamic programming algorithms for computing the number of subsequence embeddings are known in the literature, e.g., a recursive algorithm requiring $\Theta(n \times m)$ operations [15]. Here we provide an alternative algorithm, which is primarily based on the run-length encoding of strings.

Using the RLE notation, there are a few cases in which this question is easy to answer. For instance, if $y = [a; k_1, \ldots, k_\ell]$ and $x = [a; k'_1, \ldots, k'_\ell]$, with the same value of $\ell$, i.e., we have the same number of blocks in $x$ and $y$, then it is easy to see that there is a one-to-one sequential mapping of blocks between $x$ and $y$. This allows us to enumerate the different masks depending on how they map the blocks to each other as follows:

$$
\omega_x(y) = \prod_{i=1}^{\ell} \left( \begin{array}{c} k_i \\ k'_i \end{array} \right). 
$$

If $y = [a; k_1, \ldots, k_\ell]$ and $x = [\overline{a}; k'_1, \ldots, k'_\ell]$ do not start with the same character, we have to delete the first block to recover the case $y = [a; k_2, \ldots, k_\ell]$, and $x = [a; k'_2, \ldots, k'_\ell]$. We will now suppose that $x$ and $y$ start with the same character. However, in the general case, this property does not hold and the number of blocks in $x$ and $y$ can also be different.

Here we describe an algorithm wherein for a fixed pair of $x$ and $y$ strings, we structure and enumerate the corresponding space of masks by accounting for the number of different ways we can delete characters in order to merge blocks/runs such that we can recover the simple case given in Equation (5). In the more general case, let $y = [k_1, \ldots, k_\ell]$ and $x = [k'_1, \ldots, k'_\ell]$.

**Definition IV.1.** Let $S$ be the set of maps $f : [\ell'] \rightarrow [\ell]$ that satisfy the following properties: $f$ is strictly increasing and $f(i) \equiv i \mod 2$. A function $f$ will define a subset of masks, by specifying blocks that will have to be completely deleted. We group the masks according to a set of functions $f$ that map indexes of blocks of $x$ to indexes of blocks of $y$. Intuitively, $f$ maps the $i$-th block of $x$ to the block of $y$ that contains the last letter of the $i$-th block of $x$. Therefore, all blocks of $y$ between
shown in Equation (5). We first count the number of ways to choose $y$ where $\delta$ are in increasing order. Therefore, we have for all $\forall i: \cup_{j \in F(i)} k^*_f \subset \delta$
\item $\forall i: k^*_f \cup \delta$ (this allows us to have a partition)

We call $\omega_f$ the set of masks corresponding to $f$.

**Theorem IV.1.** The family $(\omega_f)_{f \in S}$ defines a partition on the set of masks from $y$ to $x$.

**Proof:** We first show that for $f \neq f' \in S$, every deletion mask $\delta$ corresponding to $f$ is different from every mask $\delta'$ associated with $f'$ (i.e., $\omega_f \cap \omega_{f'} = \emptyset$). Since $f \neq f'$, we have a smallest integer $i \in [\ell]$ such that $f(i) \neq f'(i)$. We assume without loss of generality that $f'(i - 1) = f(i - 1) < f(i) < f'(i)$. Due to the condition on parity, $f(i + 1) \neq f'(i)$. We distinguish between two cases:

- If $f'(i - 1) < f(i + 1) < f'(i)$, then $k_{f(i+1)} \not\subset \delta$, and $k_{f(i+1)} \subset \delta'$ since $f(i + 1) \in F^*(i - 1)$.
- Conversely if $f'(i - 1) < f'(i) < f(i + 1)$, then $k_{f'(i)} \not\subset \delta'$, and $k_{f'(i)} \subset \delta$ since $f'(i) \in F^*(i + 1)$.

Therefore, we have $\delta \neq \delta'$. We now show that $\cup_{f \in S} \omega_f$ is the set of masks from $y$ to $x$. We will use projection masks here as they are more suitable for this proof. Let $\pi$ be a projection mask such that $y_\pi = x$. We let $\pi = \{\pi_1, \ldots, \pi_m\}$, where the $\pi_i$ are in increasing order. Therefore, we have for all $i, y_{\pi_i} = x_i$. We define $\phi : [\ell] \rightarrow [f]$ to be the mapping that takes an index of $y$ and returns the index of the block/run it belongs to, i.e., $\phi(a)$ returns the smallest $i$ such that $\sum_{j=1}^{i} k_j \geq a$. We define $f$ such that $f \in S$ and $\pi$ is in $\omega_f$, by $f(i) = \phi(\pi_{\sum_{j=1}^{i} k_j})$. To prove that $f$ is in $S$, note that given $i$:

- We have that $f(i) \leq f(i + 1)$ since the $\pi_i$ are in increasing order.
- Moreover, $\pi_{\sum_{j=1}^{i} k_j}$ and $\pi_{\sum_{j=1}^{i+1} k_j}$ correspond to indexes (of $y$) of opposite letter (if the first one is a 1, the second is a 0 and vice versa) since $\sum_{j=1}^{i} k_j$ and $\sum_{j=1}^{i+1} k_j$ correspond to indexes (of $x$) of opposite letter.

Therefore, $f(i)$ and $f(i + 1)$ are of opposite parity and $f(i) < f(i + 1)$.

We now prove that $\pi$ corresponds to $f$. For a fixed $i \in [\ell]$, let $k^*_{f(i-1)} = b^{f(i-1)}$, i.e., the $(f(i) - 1)$-th block of $y$ is made of letters $b$. Therefore, $k^*_f = b^t$ for $t \in F(i)^*$, since $t$ has the same parity as $f(i - 1)$. Moreover, we have $b = x_{\sum_{j=1}^{i} k_j}$ according to the definition of $f$. So for every index $h$ between $\sum_{j=1}^{i} k_j + 1$ and $\sum_{j=1}^{i+1} k_j$, $x_h = y_{\pi_h} = b$, and for $t \in F(i)^*$, we have $k^*_f \cap \pi = \emptyset$ (equivalently with the deletion mask $\delta$, $k^*_f \subset \delta$). By definition, $\pi_{\sum_{j=1}^{i} k_j} \in k^*_f$ so $\pi \cap k^*_f = \emptyset$ (equivalently with the deletion mask $\delta$, $k^*_f(\delta) \not\subset \delta$).

**Definition IV.3.** We now introduce the quantity $\Omega_f$, which is the number of masks corresponding to $f$ for $f \in S$.

$$\Omega_f = \ell \cdot \left(\sum_{j \in F(i)^*} k_j^* \right) - \sum_{j \in F(i) \setminus \{f(i)\}} k_j^*$$

where

$$F(i) = \{f(i - 1) + 1, f(i - 1) + 3, \ldots, f(i)\}$$

**Theorem IV.2.** $\Omega_f = |\omega_f|$ for all $f \in S$.

**Proof:** Upon the deletion induced by $f$, we obtain a string of the form $[\sum_{j \in F(1)} k_j, \ldots, \sum_{j \in F(\ell) k_j}]$. Therefore, we have the same number of blocks in both the $y$ string as well as the $x$ string, and the number of masks can be computed easily as shown in Equation (5). We first count the number of ways to choose $k^*_f$ elements from $k_{F(i)}$ and then subtract the number of combinations not using any of the $k_{F(i)}$.

**Remark IV.1.** We can note that $F(i)$ and $F(i)^*$ form a partition of $[\ell]$.

Following from the preceding theorems, the total number of masks that can be computed as follows

$$\omega_x(y) = \sum_{f \in S} \Omega_f$$

By summing over all $f \in S$, we get the total number $\Omega$ of compatible masks. Note that it may happen that $\Omega_f = 0$; this happens when we try to trace a large block of $x$ from a smaller block of $y$. 
The Set $S$: We now determine the size of $S$, as a function of $\ell$ and $\ell'$. Let this size be denoted by $\sigma(\ell', \ell)$. We denote $u = \lfloor(\ell - \ell')/2\rfloor$. If $f(1) = 1$, then we get $\sigma(\ell' - 1, \ell - 1)$; if $f(1) = 3$, we get $\sigma(\ell' - 1, \ell - 3)$, etc. We also know that $\sigma(x, x) = 1$ for all $x$, and that $\sigma(x, y) = 0$ for all $x, y$ such that $y < x$. We therefore get the following recurrence:

$$
\sigma(\ell', \ell) = \sum_{i=0}^{u} \sigma(\ell' - 1, \ell - 1 - 2i)
$$

Iterating this recursion, we get

$$
\sigma(\ell', \ell) = \sum_{i=0}^{u} \sum_{j=0}^{u-i} \sigma(\ell' - 2, \ell - 2 - 2i - 2j),
$$

and grouping the terms yields

$$
\sigma(\ell', \ell) = \sum_{i=0}^{u} (i + 1)\sigma(\ell' - 2, \ell - 2 - 2i).
$$

We now describe a direct combinatorial argument which gives a closed form formula for $\sigma(\ell', \ell) = |S|$. First note that if $\ell \not\equiv \ell' \mod 2$ then $\ell$ cannot be in the image of $\tilde{f}$. So let $\tilde{\ell} = \ell$ if $\ell \equiv \ell' \mod 2$ and $\tilde{\ell} = \ell - 1$ if not. Now the problem is to choose $[\ell']$ elements from $[\tilde{\ell}]$ such that all the gaps have even width. Equivalently, we are interleaving the $\ell'$ chosen elements with $u = (\tilde{\ell} - \ell')/2$ gap-segments of width 2. The number of ways to do this is plainly

$$
|S| = \sigma(\ell', \ell) = \binom{\ell' + u}{u}.
$$
(8)

**Example IV.1.** For $y = 0000111111110011$ and $x = 0011$, we obtain $\omega_y(x) = 300$. We now compute the number of embeddings using the run-based algorithm described above. We have $\ell = 4$, $\ell' = 2$ and $u = (\ell - \ell')/2$, which means the size of $S$ is $|S| = \sigma(\ell', \ell) = \binom{\ell' + u}{u} = \binom{2+1}{1} = 3$. The three deletions $S = \{f_1, f_2, f_3\}$ are computed as follows: $y_{f_1} = [k_1, k_2] = 00001111$, which amounts to $\omega_{f_1} = \binom{2}{1} = 2 = 36$. Similarly, for $f_2$ and $f_3$, we get $y_{f_2} = [k_1 + k_3, k_4] = 0000000000111111$, the two of which add up to $2 \times \left(\binom{6}{2} - \binom{4}{2}\right) = 2 \times 132 = 264$. So the total is $\omega_y(x) = \sum_{f\in S} \omega_f = 36 + 132 + 132 = 300$.

**C. From Maximal Initials to Hamming Clusters**

**Definition IV.4.** Let $\Upsilon^c_{n,x}$ be the cluster of supersequences that have $c$ extra 1’s with respect to $x$, where $0 \leq c \leq n - m$.

$$
\Upsilon^c_{n,x} = \{y \in \Upsilon_{n,x} \mid h(y) - h(x) = c\}.
$$

The set of compatible supersequences is thus broken down into $n - m + 1$ disjoint sets indexed from 0 to $n - m$ such that strings in cluster $c$ contain $h(x) + c$ 1’s:

$$
\Upsilon_{n,x} = \bigcup_{c=0}^{n-m} \Upsilon^c_{n,x}.
$$

**Definition IV.5.** Maximal initials represent $y$ strings for which the largest index of their initial mask, $\pi$, overlaps with the last bit of $y$. In other words, the last index of the canonical embedding of $x$ in $y$ overlaps with the last bit of $y$. Recall that we use $\tilde{\pi}$ to denote a mask $\pi$ that is initial.

$$
\mathcal{M}_{n,x} = \{y \in \Upsilon_{n,x} \mid (\exists \overline{\pi})[y_{\overline{\pi}} = x \land \max(\overline{\pi}) = |y| = n]\}.
$$

Similarly, we define a clustering for maximal initials based on the Hamming weight of the $y$ strings

$$
\mathcal{M}^c_{n,x} = \{y \in \mathcal{M}_{n,x} \mid h(y) = h(x) + c\}.
$$

**Example IV.2.** For example, the initial embedding of $x = 1011$ in $y = 110011$ given by $\tilde{\pi} = \{1, 3, 5, 6\}$ is maximal, whereas its initial embedding in $y' = 101011$ given by $\tilde{\pi}' = \{1, 2, 3, 5\}$ is not maximal as the last index of $\tilde{\pi}'$ does not overlap with the position of the last bit of $y'$.

A more exhaustive example illustrating these concepts is given in Table II. In addition to the distribution of weights, i.e., number of masks per $y$, clusters and maximal initials are indicated by horizontal separators and bold font, respectively.

**Theorem IV.3.** For given $n$, the cardinality of $\mathcal{M}_{n,x}$ is independent of the exact $x$.

**Proof:** It is clear that every $n$-element sequence that has $x$ as an $m$-element subsequence has a unique initial mask $\tilde{\pi}$ that gives $x$. Furthermore, if we fix $\pi$, then the members of $y$ up to the last member of $\pi$ are completely determined if $\pi$ is initial. To see this, consider the case $i \in \pi$, then $y_i$ (the $i$-th member of $y$) must correspond to $x_j$, where $i$ is the $j$-th smallest member of $\tilde{\pi}$. If $i \notin \pi$, but smaller than $\max(\tilde{\pi})$, then the $i$-th member of $y$ must correspond to $x_{j+1}$, where $j$ is the number of members of $\tilde{\pi}$ smaller than $i$. The latter follows because if this bit were $x_{j+1}$, then the given $\pi$ would not be initial.
We also need to observe that for a given $\tilde{\pi}$, there always exists a $y$ that has $x$ initially in $\tilde{\pi}$: suppose that $x$ starts with a 0, we set all the bits of $y$ before $\tilde{\pi}$ to be 1. For a given value $\ell$ of $\max(\tilde{\pi})$ - which can range from $m$ to $n$ - there are exactly $\binom{\ell-1}{m-1}$ $\tilde{\pi}$'s, one for each selection of the other $m-1$ members of $\tilde{\pi}$ amongst the $\ell-1$ values less than $\ell$.

Moreover, here we have an additional constraint, namely that the initial masks should be maximal as well, i.e., $\max(\tilde{\pi}) = n$. This means that $\ell = n$ and so we can count the number of distinct initials for the remaining $m-1$ elements of $x$ in the remaining $(n-1)$-long elements of $y$ strings, which is simply given by

$$|\mathcal{M}_{n,x}| = |\mathcal{M}_{n,m}| = \binom{n-1}{m-1}$$

(9)

 Clearly the cardinality of the set of maximal initials is independent of the form of $x$ and depends only on $n$ and $m$.

*Remark IV.2.* Note that if we extend the analysis in the proof of Theorem IV.3 and let $\ell$ run over the range $[m, n]$, we can count all the distinct initial embeddings in $\Upsilon_{n,x}$, given by $\sum_{0 \leq \ell < m} \binom{\ell-1}{m-1}$.

Moreover, since the bits beyond $\max(\tilde{\pi})$ are completely undetermined, for a given $\tilde{\pi}$, there are exactly $2^{n-\max(\tilde{\pi})}$ $y$'s that have $\tilde{\pi}$ in common, which, incidentally, provides yet another proof for the fact that $|\Upsilon_{n,x}|$ is a function of only $n$ and $m$ since $|\Upsilon_{n,x}| = \sum_{\ell=m}^{n} \binom{\ell-1}{m-1} 2^{n-\ell}$. This allows us to choose the $x$ comprising $m$ $0$'s and the result in Equation (4) follows immediately.

*Theorem IV.4.* All $x$ strings of length $m$ that have the same Hamming weight, give rise to the same number of maximal initials in each cluster.

$$\forall x, x' \in \sum^m, h(x) = h(x') \implies |\mathcal{M}_{n,x}| = |\mathcal{M}_{n,x'}|.$$

*Proof*: We now describe a simple combinatorial argument for counting the number of maximal initials in each cluster indexed by $c$, i.e., a grouping of all $y \in \Upsilon_{n,x}^c$ such that $h(y) = h(x) + c$. Let $p$ and $q$ denote the number of additional $0$'s and $1$'s contributed by each cluster, respectively. Furthermore, let $a$ and $b$ denote the number of $1$'s and $0$'s in $x$, respectively.

Similar to the method used in the proof of Theorem IV.3 due to maximality we fix the last bit of $y$ and $x$, and consider $y' = y - \text{tail}(y)$ and $x' = x - \text{tail}(x)$ where $\text{tail}(s)$ denotes the last bit of $s$. Now the problem amounts to counting distinct initials of length $m - 1$ in $(n-1)$-long elements in each cluster by counting the number of ways distinct configurations can be formed as a result of distributing $c$ 1's and $(n-m-c)$ 0's around the bars/separators formed by the $b$ 0's and $a$ 1's in $x$, respectively.

We now need to observe that to count such strings with distinct initials, we can fix the $m-1$ elements of $x'$ as distinguished elements and count all the unique configurations formed by distributing $p$ indistinguishable 0's and $q$ indistinguishable 1's among bins formed by the fixed 1’s and 0’s of $x$’s such that each such configuration is distinguished by a unique initial.

Equivalently, we are counting the number of ways we can place the members of $x'$ among $n-1$ positions comprising $p$ 0’s and $q$ 1’s without changing the relative order of the elements of $x'$ such that these configurations are uniquely distinguished by the positions of the $m-1$ elements.
Intuitively, the arrangements are determined by choosing the positions of the \( m - 1 \) bits of \( x' \); by counting all the unique distributions of bits of opposite value around the elements of \( x' \), we are simply displacing the elements of \( x' \) in the \( n - 1 \) positions, thereby ensuring that each configuration corresponds to a unique initial.

Note that this coincides exactly with the multiset coefficient (computed via the method of stars and bars) as we can consider the elements of the runs of \( x \) to be distinguished elements forming bins among which we can distribute indistinguishable bits of opposite value to count the number of configurations that are distinguished only by the number of 1’s and 0’s present in the said bins.

Thus we count the number of unique configurations formed by distributing \( p \) 0’s and \( q \) 1’s among the \( a \) 1’s and \( b \) 0’s of \( x \), respectively. The total count for each cluster \( c \) is given by: \((p+a-1)(q+b-1)\), which expressed in terms of the Hamming weight of \( x \) gives

\[
|\mathcal{M}_{n,x}^c| = \binom{(n-m-c)+h(x)-1}{n-m-c \choose c} (m-h(x)+1) - 1
\]  
(10)

With the total number of maximal initials in \( \Upsilon_{n,x} \) given by

\[
|\mathcal{M}_{n,x}| = \sum_{c=0}^{n-m} |\mathcal{M}_{n,x}^c| = \binom{n-1}{m-1}.
\]

\[\blacksquare\]

**Theorem IV.5.** The size of a cluster is purely a function of \( n, m, c \) and \( h(x) \)

\[
\forall x, x' \in \Sigma^n, h(x) = h(x') \implies |\Upsilon_{n,x}^c| = |\Upsilon_{n,x'}^c|
\]

*Proof:* Let \( \ell \) denote the position of the last bit of \( y \) ranging from \( |x| = m \) to \( |y| = n \). Starting from a fixed \( x \) string, we enumerate all \( y \) strings in cluster \( c \) by considering maximal initials within the range of \( \ell \), i.e., \( \ell \in [1, \ldots, n] \).

Let \( q \) denote the number of 1’s belonging to the surplus bits in cluster \( c \) constrained within the range of the maximal initial, \([1, \ldots, \ell] \). For each \( \ell \), compute \( |\mathcal{M}_{\ell,x}^q| \) and count the combinations of choosing the remaining \( c - q \) additional bits in the remaining \( n - \ell \) bits. Let \( UB = \min(c, \ell - m) \) and \( LB = \max(0, c - (n - \ell)) \) and thus we get the following:

\[
|\Upsilon_{n,x}^c| = \sum_{\ell=m}^{\min(c,\ell-m)} \sum_{q=\max(0,c-(n-\ell))}^{\ell-m} |\mathcal{M}_{\ell,x}^q| \binom{n-\ell}{c-q}
\]  
(11)

Finally, inserting Equation (10) into Equation (11) gives

\[
|\Upsilon_{n,x}^c| = \sum_{\ell=m}^{UB} \sum_{g=LB}^{EL} \binom{(\ell-m-g)+h(x)-1}{\ell-m-g} (g+(m-h(x))-1) \binom{n-\ell}{g} \binom{n-\ell}{c-g}.
\]  
(12)

As shown in Equation (12), \( |\Upsilon_{n,x}^c| \) depends on the length and the Hamming weight of \( x \), but it is independent of the exact form of \( x \).

\[\blacksquare\]

**D. Simple closed form expression for the size of a cluster**

We have shown that \( |\Upsilon_{n,x}^c| \) is independent of the form of \( x \). We can now derive a more simplified analytic expression for this count by considering an \( x \) string of the following form: \( x = 11\ldots11a00\ldots0m \), i.e., a 1’s followed by \( b \) 0’s, with \( a > 0 \) and \( b = m - a \).

The \( y \) strings in each cluster are precisely the strings of length \( n \) that have \( a + c \) 1’s in them (and \( n - a - c \) 0’s) where the \( a \)-th 1 (i.e., the last one in an initial choice for \( x \)) occurs before at least \( b \) 0’s. Clearly there are \( \binom{n}{a+c} \) strings with exactly \( a + c \) 1’s, but some of these will violate the second principle. To find an expression for counting the valid instances, we sum over the positions of the \( a \)-th 1, which must be between \( a \) and \( a + z \), where \( z = n - a - b - c \) is the number of added 0’s. Thus we get the following expression

\[
|\Upsilon_{n,x}^c| = \binom{h(x)+z}{p} \binom{p-1}{p} \binom{n-p}{c}.
\]  
(13)

With \( z = n - m - c \) and \( p \) denoting the index of the \( a \)-th 1, we thus count the number of ways of picking 1’s before \( p \) and the \( c \) 1’s after \( p \). Note that for \( h(x) = 0 \), the cardinality of cluster \( c \) is simply given by \( \binom{n}{c} \).

**E. Recursive expression for the size of a cluster**

We present a recurrence for computing the size of a cluster by considering overlaps between the first bits of \( x \) and \( y \), respectively. Let \( \bullet \) and \( \varepsilon \) denote concatenation and the empty string, respectively. Moreover, let \( x' \) be the tail of \( x \) (resp. \( y' \) the tail of \( y \)).
\[ \Upsilon_{n,\rho} = \Upsilon_{n-1,\rho} + \Upsilon_{n-1,0} \]
- First term: first bit of \( y \) is 0, find \( x' \) in \( y' \)
- Second term: first bit of \( y \) is 1 (part of cluster), so we reduce \( c \) and find \( x \) in \( y' \)

\[ \Upsilon_{n,\rho} = \Upsilon_{n-1,\rho} + \Upsilon_{n-1,0} \]
- Same arguments as above, but for \( x \) starting with 1

**Base cases:**
- \( \Upsilon_{0,\rho} = 0 \)
- \( \Upsilon_{0,\rho} = \Upsilon_{0,\rho} + \Upsilon_{0,0} \)
- \( \Upsilon_{0,\rho} = \binom{0}{c} \)
- if \( c + |x| > n \) then return 0 else \( \Upsilon_{n,\rho} \)

It is worth pointing out that since this recursion depends on the form of \( x \), i.e., whether or not \( x \) starts with a 0 or 1, it does not explicitly capture the bijection between clusters of \( x \) strings that have the same Hamming weight, as proved in Theorem IV.5

**F. Enumerating Singletons via Runs**

Let **singletons** define supersequences in \( \Upsilon_{n,\rho} \) that admit exactly a single mask for a fixed subsequence \( x \) of length \( m \), i.e., they give rise to exactly a single occurrence of \( x \) upon \( n - m \) deletions. We use \( S_{n,x} \) to denote this set.

\[ S_{n,x} = \{ y \in \Upsilon_{n,\rho} \mid \omega_x(y) = 1 \} \]

To compute the cardinality of \( S_{n,x} \), we describe a counting technique based on splitting runs of 1’s and 0’s in \( x \) according to the following observations: (i) inserting bits of opposite value to either side of the framing bits in \( x \), i.e., before the first or after the last bit of \( x \), does not alter the number of masks. (ii) Splitting runs of 0’s and 1’s in \( x \), i.e., insertion of bits of opposite value in between two identical bits, does not modify the count. This amounts to counting the number of ways that singletons can be obtained from a fixed \( x \) string via weight preserving insertions.

The number of possible run splittings corresponds to the number of distinct ways that \( c \) 1’s and \( (n - m - c) \) 0’s can be placed in between the bits of the runs of 0’s and 1’s in \( x \), respectively. Again, this count is given by the multiset number \( \binom{n + b - 1}{a} \), where we count the number of ways \( a \) indistinguishable objects can be placed into \( b \) distinguishable bins. Note that the number of singletons depends heavily on the number of runs in \( x \) and their corresponding lengths. The counting is done by summing over all \( n - m \) clusters and computing the configurations that lead to singletons as a function of the runs in \( x \) and the number of additional 1’s and 0’s contributed by each cluster at index \( c \).

In order to do this computation, we first count the number of insertions slots in \( x \) as a function of its runs of 1’s and 0’s, given by \( \rho_0(x) \) and \( \rho_1(x) \), respectively. Let \( r_i^j \) be a run with \( i \) and \( j \) denoting its first and last index and let \( \rho_\alpha(x) \) denote the number of insertion slots in \( x \) as a function of its runs of \( \alpha \). To compute \( \rho_\alpha(x) \), we iterate through the runs of \( \alpha \) and in \( x \) and count the number of indexes at which we can split runs as follows

\[ \rho_\alpha(x) = \sum_{r \in R_{x,\alpha}} f(r) \]

where

\[ f(r) = \begin{cases} |r_i^j| + 1, & \text{if } i = 1 \land j = n \\ |r_i^j|, & \text{if } (i = 1 \land j < n) \lor (i > 1 \land j = n) \\ |r_i^j| - 1, & \text{otherwise} \end{cases} \]

Note that if either the first bit or the last bit of a run overlaps with the first or last bit of \( x \), the number of bars is equal to the length of the run. If the said indexes do not overlap with neither the first nor the last bit of \( x \), the count is equal to the length of the run minus 1, and finally if both indexes overlap with the first and last bit of \( x \) the count is equal to the length of the run plus 1.

We can now count the total number of singletons for given \( n \) and \( x \) as follows. Let \( c \) and \( b \) \((b = n - m - c)\) denote the number of 1’s and 0’s contributed by the \( c \)-th cluster, and the total number of singletons is given by

\[ |S_{n,x}| = \binom{n - m + \rho_1(x) - 1}{n - m} + \sum_{c=1}^{n-m-1} \left( \binom{b + \rho_1(x) - 1}{b} \right) \left( \binom{c + \rho_0(x) - 1}{c} \right) + \binom{n - m + \rho_0(x) - 1}{n - m} \]

The first and last terms correspond to the number of singletons in the first and last cluster, respectively, where we insert either 1’s or 0’s, but not both. The summation over the remaining clusters counts the configurations that incorporate both additional 1’s and 0’s.

**Theorem IV.6.** The constant (i.e., \( x = 11 \ldots 1 \) or \( x = 00 \ldots 0 \)) and the alternating \( x \) strings maximize and minimize the number of singletons, respectively.
Proof: This follows immediately from a maximization and minimization of the number of runs in \( x \), i.e., \( \rho_x(x) \). In the case of the all 1’s \( x \) string, which comprises a single run, every index in \( x \) can be used for splitting. Conversely, the alternating \( x \) has the maximum number of runs \( |R| = m \), where \( \forall r \in R_x : |r| = 1 \), thus splittings are not possible, i.e., no operations of type \( (ii) \), and the insertions are confined to pre-pending and appending bits of opposite values to the first and last bit of \( x \), respectively.

\[
\begin{align*}
\text{Lemma V.1.} & \quad \text{preserving insertions}.
\end{align*}
\]

The last three cases will be referred to as “weight preserving insertions”, and denoted by \( g_{x/\ell} \). The first case will be referred to as a “weight increasing insertion”, denoted by \( g_{x/\ell} \).

\[
\begin{align*}
\text{V. Entropy Minimization}
\end{align*}
\]

We now prove the minimal entropy conjecture for the special cases of one and two deletions. Our approach incorporates two key steps: first we work out a characterization of the number of \( g \) strings that have specific weights \( \omega_z(y) \). We then consider the impact of applying an entropy decreasing transformation to \( x \), denoted by \( g(x) \), and prove that this operation shifts the weights in the space of supersequences such that it results in a lowering of the corresponding entropy. This is achieved using clustering techniques and a run-length encoding of strings: we identify groupings of supersequences with specific weights by studying how they can be constructed from a given subsequence using different insertion operations, which are in turn based on analyzing how runs of 1’s and 0’s can be extended or split.

**Definition V.1.** We now define the transformation \( g \) on strings of length \( m \) as follows:

\[
\begin{align*}
g([k_1, \ldots, k_\ell]) &= \begin{cases} 
[k_1 + k_2, k_3, \ldots, k_\ell] & \text{if } \ell > 1 \\
g([m]) &= [m] 
\end{cases}
\end{align*}
\]

Thus, one can start from any subsequence \( x \) and apply the transformation \( g \) until the string becomes \( [m] \), i.e., \( [0]^m \) or \( [1]^m \). As a result, \( [m] \) exhibits minimal entropy and thus the highest amount of leakage in the original key exchange problem. Note that, as indicated implicitly in the definition above, this transformation always reduces the number of runs by one by flipping the first run to its complement.

Thus we avoid cases where merging two runs would lead to connecting to a third neighboring run, thereby resulting in a reduction of runs by two. For example, \( g \) transforms the string \( x = 10011\overline{1}0 = [1; 1, 2, 3, 1] \) into \( x = 00011\overline{1}0 = [0; 3, 3, 1] \), as opposed to \( x = 111\overline{1}1\overline{1}0 = [1; 6, 1] \).

The plots shown in Figure 2 illustrate the impact of the transformation \( g \) on the weight distribution as we move from \( x = 101010 \) to \( x' = 000000 \) (101010 \( \rightarrow \) 001010 \( \rightarrow \) 111010 \( \rightarrow \) 000110 \( \rightarrow \) 111110 \( \rightarrow \) 000000).

**A. Single Deletions**

In this section we consider the case of a single deletion. Let \( x \) be a fixed string of length \( m \). We study the space of \( y \) strings of length \( n = m + 1 \) that can be masked to yield \( x \), i.e., \( Y_1 = \{ y \in \{0, 1\}^n \mid \exists \delta \in \mathcal{P}([n]), y_\delta = x \} \). Recall that we associate a weight \( \omega_1(x, y) \) to each \( y \in Y_1 \), defined as the number of ways that \( y \) can be masked into \( x \). Finally, we define the entropy associated to \( x \) as the Shannon entropy of the variable \( Z \in \{0, 1\}^n \) having distribution

\[
\Pr[Z = y] = \frac{1}{\mu_1} w_x(y).
\]

where \( \mu_1 = \sum_{y \in \mathcal{R}_{n,x}} \), which for the case \( m = n - 1 \) gives \( \omega_1(x, y) = (\frac{n}{m})2^{n-m} = (\frac{n}{m-1})2^{n-(n-1)} = 2n \).

1) Clustering Supersequences via Single Insertions: Let \( x = [k_1, \ldots, k_\ell] \). A string \( y \in Y_1 \) can take only one of the following forms:

1. \( y = [k_1, \ldots, k_{i-1}, k_i + 1, k_{i+1}, \ldots, k_\ell] \) for some \( i \in [\ell] \);
2. \( y = [k_1, \ldots, k_{i-1}, k'_i, 1, k''_i, k_{i+1}, \ldots, k_\ell] \) for some \( i \in [\ell] \) and where \( k'_i + k''_i = k_i \) and \( k'_i \neq 0 \) and \( k''_i \neq 0 \);
3. \( y = [1, k_1, \ldots, k_\ell] \);
4. \( y = [k_1, \ldots, k_\ell, 1] \).

The first case will be referred to as a “weight increasing insertion”, denoted by 1/0, which corresponds to extending runs/blocks. The last three cases will be referred to as “weight preserving insertions”, and denoted by 0/1, corresponding to splitting runs or adding a new run of length 1. For the remainder of our discussion, \( a/b \) means: “a weight increasing insertions and \( b \) weight preserving insertions”.

**Lemma V.1.** \( Y_1 \) is composed of \( [3] \)

- \( \ell \) weight increasing insertions, resulting in strings of respective weights \( k_1 + 1, k_2 + 1, k_3 + 1, \ldots, k_\ell + 1 \); and
- \( m - \ell + 2 \) weight preserving insertions, i.e., strings of weight 1.

A sanity check can be done to verify that we do not miss any strings, since \( \binom{m+1}{m} + \binom{m+1}{m+1} = \ell + m - \ell + 2 \).
2) Minimal Entropy For Single Deletions:

Lemma V.2. The transformation \( g \) decreases the entropy \( H_n(x) \) for single deletions, i.e., \( m = n - 1 \).

Proof: The proof consists of computing the difference between the entropy before and after applying \( g \), i.e., \( \Delta_1 = H_n(x) - H_n(g(x)) \), and showing that this difference is positive. From Lemma V.1 after applying \( g \).

- The weight increasing insertions give \( \ell - 1 \) strings of respective weights \( k_1 + 1 + k_2 + 1 - 1, k_3 + 1, \ldots, k_\ell + 1 \).
- The weight preserving insertions give \( m + 2 - (\ell - 1) \) strings of weight 1.

We now compute the difference of the entropies thanks to the analyses of \( [k_1, k_2, k_3, \ldots, k_\ell] \) and \( [k_1 + k_2, k_3, \ldots, k_\ell] \), which after simplification gives

\[
\Delta_1(k_1, \ldots, k_\ell) = (k_1 + 1) \log \frac{1}{k_1 + 1} + (k_2 + 1) \log \frac{1}{k_2 + 1} - (k_1 + k_2 + 1) \log \frac{1}{k_1 + k_2 + 1}
\]

To show that this is positive when \( k_1 \geq 1 \) and \( k_2 \geq 1 \), it suffices to compute the partial derivatives along each axis, which are positive, and evaluate the function in \( k_1 = k_2 = 1 \), which is also positive.

Corollary V.2.1. For all \( n \) and any subsequence \( x \) of length \( m = n - 1 \), we have

\[
H_n(x) \geq H_n([m]),
\]

with equality only if \( x \in \{0^m, 1^m\} \).

Proof: Given any \( x \neq [m] \) of length \( m = n - 1 \), it can be transformed into the string \([m]\) by a series of consecutive \( g \) operations, as defined in Definition V.1. Each such operation can only decrease the entropy, as shown in Lemma V.2, and thus we get a proof for the fact that \( H_n(x) \geq H_n([m]) \).

Remark V.1. It is worth pointing out that for the special case of single deletions, the minimization of entropy by the constant string, \( x = [m] \), can also be proved using a simple combinatorial argument as follows. For \( m = n - 1 \), in cluster \( c = 1 \) we get a single \( y \) string with maximum weight, \( \omega_y(x) = \binom{n}{m} \), corresponding to \( y = [n] \) and \( x = [m] \), and the remaining strings in cluster \( c = 0 \) are all singletons, \( \omega_x(y) = 1 \). This is clearly the most concentrated distribution and hence the least entropic one.
B. Double Deletions

In the case of two deletions, there are three types of insertions to consider; using the notation introduced in the previous section, these are 2/0, 1/1, and 0/2 insertions. For a fixed string \( x = [k_1, \ldots, k_\ell] \), we now analyze each case to account for the corresponding number of supersequences and their respective weights in each cluster. We will then study how this distribution changes when we go from \( x \) to \( g(x) \) in order to prove the following lemma:

**Lemma V.3.** The transformation \( g \) decreases the entropy \( H_n(x) \) for single deletions, i.e., \( m = n - 2 \).

Note that while this technique could be applied to a higher number of insertions, the complexity of the analysis blows up already for two deletions, as the next section will show.

1) Clustering Supersequences via Double Insertions:

a) Case 2/0: The case 2/0 corresponds to the situation where the insertions do not create new blocks. This happens when both bits are added to the same block, or when they are added to two different blocks, as follows.

The former corresponds to

\[ y = [k_1, \ldots, k_{i-1}, k_i+2, k_{i+1}, \ldots, k_\ell] \]

for some \( i \in [\ell] \), which has weight \( \omega_x(y) = \binom{k_i+2}{2} \). There are \( \ell \) strings of this type.

The latter corresponds to

\[ y = [k_1, \ldots, k_{i-1}, k_i+1, k_{i+1}, \ldots, k_{j-1}, k_j+1, k_{j+1}, \ldots, k_\ell] \]

for \( 1 \leq i < j \leq \ell \), and has weight \( \omega_x(y) = (k_i+1)(k_j+1) \). There are \( \frac{\ell(\ell+1)}{2} \) strings with this weight. In total, there are \( \frac{\ell(\ell+1)}{2} \) strings for the case 2/0.

b) Case 0/2: In the 0/2 case, there are only weight preserving insertions, hence all strings have weight 1. Weight preserving insertions may happen in a single block, or in two separate blocks. To ease notation, we introduce

\[ \widetilde{k}_i = \begin{cases} k_i - 1 & \text{if } i \in [2, \ell - 1] \\ k_i & \text{if } i = 1 \text{ or } i = \ell \end{cases} \]

The different treatments for “endpoints” \( 1 \) and \( \ell \) correspond to cases \( [1, k_1, \ldots, k_\ell] \) and \( [k_1, \ldots, k_\ell, 1] \), whereas a weight preserving insertion in the \( i \)-th block can happen at only \( k_i - 1 \) places.

- If we insert into the first or the last block, we choose respectively \( k_1 \) and \( k_\ell \) positions, i.e., there are respectively \( k_1 \) and \( k_\ell \) different strings.
- If we insert into any other block \( i \), we choose amongst \( k_i - 1 \) positions, which yields \( k_i - 1 \) different strings.
- If we insert in different blocks, we apply the same analysis twice, independently, which gives \( k_i k_j \) different strings.
- If we insert twice in the same block, we get \( \binom{k_i+1}{2} \) different strings.

In the end, the total number of 0/2 insertions is

\[ \sum_{1 \leq i < j \leq \ell} \widetilde{k}_i \widetilde{k}_j + \sum_{i=1}^\ell \frac{(k_i+1)}{2} \]

**Example V.1.** If \( k_1 = \cdots = k_\ell = 1 \), so that \( \widetilde{k}_1 = \widetilde{k}_\ell = 1 \) and \( \widetilde{k}_2 = \cdots = \widetilde{k}_{\ell-1} = 0 \), we count 3 strings.

**Example V.2.** For example, for \( 1 < i < j < \ell \) we get for all \( a_1, a_2, b_1, b_2 \geq 0 \) such that \( a_1 + a_2 = k_i \) and \( b_1 + b_2 = k_j \), the string \( k_1 \ldots k_{i-1}a_1a_2k_{i+1} \ldots k_{j-1}b_1b_2k_{j+1} \ldots k_\ell \). The number of such strings is \( (k_i)(k_j) \).

Another example: for the particular cases \( i = j = 1 \) we get for all \( a_1, a_2, a_3 \in \mathbb{N} \) with \( a_2 \) strictly positive such that \( a_1 + a_2 + a_3 = k_1 \), the string \( a_1a_2a_3k_2k_1 \) or (case \( a_2 = 0 \)) \( a_12a_3k_2k_1 \). The number of such strings is \( \binom{k_1+1}{2} \).

c) Case 1/1: As in the previous case, we choose a block in which we apply a weight increasing insertion, yielding \( k_i + 1 \) masks; then we choose a block for a weight preserving insertion, yielding \( k_i \) strings. However, one must be careful: to see why, consider the following string \( x = 00111 = [3, 3] \).

- If we insert a weight increasing \( 0 \) in the first block, and then a weight preserving \( 1 \) in the last-but-one position of the first block, we get the string \( y = 0010111 = [3, 1, 1, 3] \). This string is of weight \((3 + 1) + (3 + 1)\), since we can delete the \( 0 \) then one of the four \( 1 \), or the \( 1 \) then one of the four \( 0 \).
- If we insert a weight increasing \( 1 \) in the second block, followed by a weight preserving \( 0 \) in the second position of the second block, we obtain the same string \( y = 00110111 = [0; 3, 1, 1, 3] \).

Hence there are two ways to get each \( y \). We will therefore exercise a preference toward the first situation, where we perform a weight increasing insertion in the first block, followed by a weight preserving insertion in the first block’s last-but-one position. Let \( i \in [\ell] \).

- If \( i = 1 \), we get \( \sum_{j=1}^\ell \widetilde{k}_j(= m - \ell + 2) \) strings of weight \( k_1 + 1 \), as well as a string of weight \( k_1 + k_2 + 2 \). In total, we get \( m - \ell + 3 \) strings.
• If $1 < i < \ell$, we perform a weight increasing insertion in the block $i$, the number of strings we will get is $(\sum \bar{k}_i)$. Indeed the string $[k_1, \ldots, k_{i-1}, 1, 1, k_i, k_{i+1}, \ldots, k_\ell]$ will be counted for the case $i-1$. Each of these strings has weight $k_i + 1$, except one $([k_1, \ldots, k_i, 1, 1, k_{i+1}, \ldots, k_\ell])$ which has weight $k_i + 1 + k_{i+1} + 1$ (the string that we will not count for the next example).

• If $i = \ell$, we can keep the same formula by introducing $k_{\ell+1} = 0$ for the weight of the string $[k_1, \ldots, k_\ell, 1, 1]$.

**Remark V.2** (Sanity check for the number of strings). As in the case of one deletion, we will count the number of strings considered to make sure that we do not miss anything. We have:

- case 2/0: $\frac{\ell(\ell+1)}{2}$
- case 0/2: $\sum_{1 \leq i < j \leq \ell} \bar{k}_i \bar{k}_j + \sum_{i=1}^{\ell} \left( \bar{k}_i + 1 \right)$
- case 1/1: $1 + \ell(\ell-\ell-2)$

We give an algebraic proof in Section B showing that if there exist positive integers $(k_i)_{i \in \{1, \ldots, \ell\}}$ such that $m = \sum_{i=1}^{\ell} k_i$, then we have $\sum_{1 \leq i < j \leq \ell} \bar{k}_i \bar{k}_j + \sum_{i=1}^{\ell} \left( \bar{k}_i + 1 \right) 1 + \ell(\ell-\ell-2) = (m+2) + (m+2) + (m+2)$, to make sure we have not missed or double-counted any strings.

2) **Minimal Entropy For Double Deletions**: As in Section V-A, we analyze the effects of the merging operation $g$ on entropy. For this, we consider the impact of $g(x) = [k_1 + k_2, k_3, \ldots, k_\ell]$ on the clustering results developed in Section V-BI. We will omit the analyses when no insertions are made in the first or second block, since we will get the same weight and this will disappear in the difference.

a) **Case 2/0**: For $x$, we had $\frac{\ell(\ell+1)}{2}$ strings of this type, we now have $\frac{\ell(\ell-1)}{2}$, there are $\ell$ less strings and $\ell - 1$ that grow bigger. The rest remains the same.

b) **Case 0/2**: Similar to $x$, we have a certain number of strings with weight 1 counted as before

$$\sum_{3 \leq i \leq j \leq \ell} \bar{k}_i \bar{k}_j + \sum_{3 \leq i \leq \ell} \left( \bar{k}_i + 1 \right)$$

However, a part of the formula changes:

$$\left( \frac{k_1 + k_2 + 1}{2} \right) + (k_1 + k_2) \sum_{3 \leq i \leq \ell} \bar{k}_i$$

Then, for the part of the analysis of $g(x)$ equivalent with that of $x$ we get

$$\left( \frac{k_1 + 1}{2} \right) + \left( \frac{k_2}{2} \right) + (k_1 + k_2 - 1) \times \sum_{3 \leq i \leq \ell} \bar{k}_i + k_1(k_2 - 1)$$

now we take the difference between Equation [18] and Equation [19]

$$\sum_{3 \leq i \leq \ell} \bar{k}_i + \left( \frac{k_1 + k_2 + 1}{2} \right) - \left( \left( \frac{k_1 + 1}{2} \right) + \left( \frac{k_2}{2} \right) + k_1(k_2 - 1) \right)$$

After simplifications, we obtain $\sum_{1 \leq i \leq \ell} \bar{k}_i + 1$.

c) **Case 1/1**: In the case of $x$, we had

$$(\ell - 1) \sum_{1 \leq i \leq \ell} (\bar{k}_i - 1) + \sum_{1 \leq i \leq \ell} \bar{k}_i.$$

We now have

$$(\ell - 2) (\sum_{1 \leq i \leq \ell} (\bar{k}_i - 1) + 1) + \sum_{1 \leq i \leq \ell} \bar{k}_i + 1.$$

Taking the difference between now and before we get $\sum_{1 \leq i \leq \ell} \bar{k}_i + 1 - \ell$. We have $(\sum_{1 \leq i \leq \ell}(\bar{k}_i - 1) + 1)$ weights (the weight increasing insertion in the first block) that grow bigger, the rest stays the same.

**Remark V.3** (Sanity check). We can check that the numbers of strings is constant:

- Case 0/2: $\sum_{1 \leq i \leq \ell} \bar{k}_i + 1$ more strings
- Case 1/1: $(\sum_{1 \leq i \leq \ell} \bar{k}_i + 1 - \ell)$ less strings
- Case 2/0: $\ell$ less strings.

and $\sum_{1 \leq i \leq \ell} \bar{k}_i + 1 - (\sum_{1 \leq i \leq \ell} \bar{k}_i + 1 - \ell) - \ell = 0$.

We can now compute the difference of the two entropies. Note that instead of working with the probabilities, we will multiply everything by $4^{(m+2)}$. We can focus on the very few strings that show a change in weight (when an insertion is
made in the first or second block).

**Case 2/0**: For \(x\), we have 1 string for each of the weights

\[
(k_1 + 1)(k_2 + 1), (k_1 + 1)(k_3 + 1), \ldots, \\
(k_1 + 1)(k_1 + 1), (k_2 + 1)(k_3 + 1), (k_2 + 1)(k_4 + 1), \ldots, \\
(k_2 + 1)(k_1 + 1), \left(\frac{k_1 + 2}{2}\right) \left(\frac{k_2 + 2}{2}\right)
\]

For \(g(x)\), we still have 1 string for each of the following weights:

\[
(k_1 + k_2 + 1)(k_3 + 1), (k_1 + k_2 + 1)(k_4 + 1), \ldots, (k_1 + k_2 + 1)(k_l + 1), \left(\frac{k_1 + k_2 + 2}{2}\right)
\]

**Case 0/2**: For \(g(x)\), we have \(\sum_{1 \leq i \leq \ell} k_i + 1\).

**Case 1/1**: For \(x\), the remaining strings are:

| Multiplicity | Weight          |
|--------------|----------------|
| \(\sum_{i=1}^{\ell} k_i\) | \(k_1 + 1\)   |
| \(\sum_{i=1}^{\ell} k_i - 1\) | \(k_2 + 1\)   |
| 1            | \(k_1 + k_2 + 2\) |
| 1            | \(k_2 + k_3 + 2\) |

There remains, for \(g(x)\), one string for each of the following weights \(k_3 + 1, k_4 + 1, \ldots, k_l + 1\) and \(\sum_{1 \leq i \leq \ell} k_i + 1\) strings of weight \(k_1 + k_2 + 1\) along with 1 string of weight \(k_1 + k_2 + k_3 + 2\). The difference of entropies is equal to the difference between \(A\) and \(B\) defined in the following equations:

\[
A = \sum_{2 \leq i \leq \ell} (k_1 + 1)(k_i + 1) \log \frac{1}{(k_1 + 1)(k_i + 1)} + \left(\frac{k_1 + 2}{2}\right) \log \frac{1}{\left(\frac{k_1 + 2}{2}\right)} + \left(\frac{k_2 + 2}{2}\right) \log \frac{1}{\left(\frac{k_2 + 2}{2}\right)}
+ \sum_{1 \leq i \leq \ell} \tilde{k}_i (k_1 + 1) \log \frac{1}{(k_1 + 1)} + (k_1 + k_2 + 2) \log \frac{1}{(k_1 + k_2 + 2)}
+ \left(\sum_{1 \leq i \leq \ell} \tilde{k}_i - 1\right)(k_2 + 1) \log \frac{1}{(k_2 + 1)}
+ (k_2 + k_3 + 2) \log \frac{1}{(k_2 + k_3 + 2)}
\]

\[
B = \sum_{3 \leq i \leq \ell} (k_i + 1) \log \frac{1}{(k_i + 1)} + \left(\sum_{1 \leq i \leq \ell} \tilde{k}_i + 1\right)(k_1 + k_2 + 1) \log \frac{1}{(k_1 + k_2 + 1)}
+ (k_1 + k_2 + k_3 + 2) \log \frac{1}{(k_1 + k_2 + k_3 + 2)}
+ \sum_{3 \leq i \leq \ell} (k_1 + k_2 + 1)(k_i + 1) \log \frac{1}{(k_1 + k_2 + 1)(k_i + 1)}
+ \left(\frac{k_1 + k_2 + 2}{2}\right) \log \frac{1}{\left(\frac{k_1 + k_2 + 2}{2}\right)}
\]

where \(A\) corresponds to \(x\), and \(B\) corresponds to \(g(x)\). We are now in a position to conclude the proof of Lemma V.3.

**Lemma V.4.** The transformation \(g\) decreases the entropy \(H_n(x)\) for double deletions, i.e., \(m = n - 2\).

**Proof:** To prove this, it suffices to show that for \(\ell \geq 2\), \(A - B > 0\). The proof mostly consists of computing partial derivatives to show that the function is increasing. We refer the reader to Section A for details.

**Corollary V.4.1.** For all \(n\) and any subsequence \(x\) of length \(m = n - 2\), we have

\[
H_n(x) \geq H_n([m]),
\]

with equality only if \(x \in \{0^m, 1^m\}\).

**Proof:** Given any \(x \neq [m]\) of length \(m = n - 2\), it can be transformed into the string \([m]\) by a series of consecutive \(g\) operations (cf. Definition V.1). Similar to the single-bit deletion case, each such operation can only decrease the entropy, as proved in Lemma V.3 and thus we get a proof for the fact that \(H_n(x) \geq H_n(0^m)\).
VI. Concluding Remarks

From the original cryptographic motivation of the problem, the minimal entropy case corresponding to maximal information leakage is arguably the case that interests us the most. While our results shed more light on various properties of the space of supersequences and the combinatorial problem of counting the number of embeddings of a given subsequence in the set of its compatible supersequences, the original entropy maximization conjecture remains an open problem. Finally, proving the entropy minimization conjecture for an arbitrary number of deletions as well as a more general characterization of the distribution of the number of subsequence embeddings in supersequences of finite-length present some further open problems.

Appendix A
Proof of Lemma V.4

Proof. The proof consists of two steps: first we show that \( A - B > 0 \) when \( k_1 = \cdots = k_\ell = 1 \); then we show that \( \nabla (A - B) \) is positive along all directions, so that an increase in any of the \( k_i \), results in an increase of \( A - B \).

- **Step 1.** For \( k_1 = \cdots = k_\ell = 1 \), we have:

\[
A = - \sum_{2 \leq i \leq \ell} 4 \log 4 - 3 \log 3 - 3 \log 3 \\
- \sum_{1 \leq i \leq \ell} 2 \tilde{k}_i \log 2 - 4 \log 4 \\
- 2 \log 2 \sum_{1 \leq i \leq \ell} (\tilde{k}_i - 1) \\
- 4 \log 4 \\
= - 8(\ell - 1) - 6 \log 3 - 2 \sum_{i=1}^{\ell} \tilde{k}_i - 8 + 2 \ell - 2 \sum_{i=1}^{\ell} \tilde{k}_i - 8 \\
= - 6\ell - 6 \log 3 - 16.
\]

Similarly,

\[
B = - \sum_{3 \leq i \leq \ell} 2 \log 2 - 3 \log 3 \sum_{1 \leq i \leq \ell} (\tilde{k}_i + 1) \\
- 5 \log 5 \\
- \sum_{3 \leq i \leq \ell} 6 \log 6 \\
- 6 \log 6 \\
= - 2(\ell - 2) - 3 \ell \log 3 - 3 \log 3 \sum_{i=1}^{\ell} \tilde{k}_i - 5 \log 5 - 6(\ell - 1) \log 6 \\
= - 2\ell - 6 \ell \log 6 - 3 \ell \log 3 + 4 - 6 \log 3 - 5 \log 5 + 6 \log 6 \\
= -(2 + 6 + 6 \log 3 + 3 \log 3)\ell + 4 - 6 \log 3 - 5 \log 5 + 6 + 6 \log 3 \\
= -(8 + 9 \log 3)\ell + 10 - 5 \log 5 \\
\]

Thus,

\[
A - B = - 6\ell - 6 \log 3 - 16 - (-(8 + 9 \log 3)\ell + 10 - 5 \log 5) \\
= (2 + 9 \log(3))\ell - 26 + 5 \log(5) - 6 \log(3) \\
\]

Therefore, \( A - B > 0 \) iff \( \ell > (26 + 6 \log(3) - 5 \log(5))/(2 + 9 \log(3)) \approx 1.46 \). For \( \ell \geq 2 \), and \( k_1 = \cdots = k_\ell = 1 \), we therefore have \( A - B > 0 \).

- **Step 2.** To simplify computations, we introduce the function \( e(x) = -x \log_2 x \). We also use the fact that \( e(xy) = xe(y) + ye(x) \), and develop the binomial coefficients: \( e \left( \binom{a+b}{2} \right) = \binom{a+b}{2} + e((a+b)(a+b-1)) \). Then we match the sum indexes. We also introduce the notation \( e_i = e(\tilde{k}_i + 1) \).
Thus we can write:

\[
A = \sum_{2 \leq i \leq \ell} e((k_1 + 1)(k_i + 1)) + \sum_{2 \leq i \leq \ell} e\left(\binom{k_1 + 2}{2}\right) + \sum_{2 \leq i \leq \ell} e\left(\binom{k_2 + 2}{2}\right) \\
+ e(k_1 + 1) \sum_{1 \leq i \leq \ell} \tilde{k}_i + e(k_1 + k_2 + 2) \\
+ e(k_2 + 1) \sum_{1 \leq i \leq \ell} (\tilde{k}_i - 1) \\
+ e(k_2 + k_3 + 2) \\
= \sum_{3 \leq i \leq \ell - 1} e((k_1 + 1)(k_i + 1)) + e((k_1 + 1)(k_2 + 1)) + e((k_1 + 1)(k_\ell + 1)) \\
+ \binom{k_1 + 1}{2} + e((k_1 + 1)(k_1 + 2)) \\
+ \binom{k_2 + 1}{2} + e((k_2 + 1)(k_2 + 2)) \\
+ e(k_1 + 1) \sum_{3 \leq i \leq \ell - 1} \tilde{k}_i + e(k_1 + k_2 + 2) + e(k_1 + 1)\tilde{k}_1 + e(k_1 + 1)\tilde{k}_2 + e(k_1 + 1)\tilde{k}_\ell \\
+ e(k_2 + 1) \sum_{3 \leq i \leq \ell - 1} \tilde{k}_i + \ell e(k_2 + 1) + e(k_2 + 1)\tilde{k}_1 + e(k_2 + 1)\tilde{k}_2 + e(k_2 + 1)\tilde{k}_\ell \\
+ e(k_2 + k_3 + 2) \\
= (k_1 + 1) \sum_{3 \leq i \leq \ell - 1} e_i + (k_1 + 1) \sum_{3 \leq i \leq \ell - 1} (k_i + 1) \\
+ (k_2 + 1)e_1 + (k_1 + 1)e_2 + (k_1 + 1)e_\ell + (k_\ell + 1)e_1 \\
+ \binom{k_1 + 1}{2} + (k_1 + 2)e_1 + (k_1 + 1)e(k_1 + 2) \\
+ \binom{k_2 + 1}{2} + (k_2 + 2)e_2 + (k_2 + 1)e(k_2 + 2) \\
+ e_1 \sum_{3 \leq i \leq \ell - 1} k_i - (\ell - 3)e_1 + e(k_1 + k_2 + 2) + e_1k_1 + e_1k_2 - e_1 + e_1k_\ell \\
+ e_2 \sum_{3 \leq i \leq \ell - 1} k_i - (\ell - 3)e_2 - \ell e_2 + e_2k_1 + e_2k_2 - e_2 + e_2k_\ell \\
+ e(k_2 + k_3 + 2)
\]

At this point we regroup all terms in \( e_i \) together:

\[
A = \left(2k_1 + 2k_2 + 2k_\ell - 3 + 2 \sum_{3 \leq i \leq \ell - 1} k_i\right) e_1 \\
+ \left(2k_1 + 2k_2 + k_\ell - 2\ell - 1 + \sum_{3 \leq i \leq \ell - 1} k_i\right) e_2 \\
+ (k_1 + 1) \sum_{3 \leq i \leq \ell - 1} e_i \\
+ (k_1 + 1)e_\ell \\
+ e(k_1 + k_3 + 2) + (k_1 + 1)e(k_1 + 2) + (k_2 + 1)e(k_2 + 2) + e(k_2 + k_3 + 2) \\
+ \binom{k_1 + 1}{2} + \binom{k_2 + 1}{2}
\]
We simplify the expression for $B$ in the same fashion:

$$B = 2e(k_1 + k_2 + 1) \sum_{3 \leq i \leq \ell - 1} k_i + k_1 e(k_1 + k_2 + 1) + k_2 e(k_1 + k_2 + 1) + k_\ell e(k_1 + k_2 + 1)$$

$$+ e(k_1 + k_2 + k_3 + 2) + (\ell - 3)e(k_1 + k_2 + 1) + (k_1 + k_2 + 2) \sum_{3 \leq i \leq \ell} e_i$$

$$+ \left(\frac{k_1 + k_2 + 2}{2}\right) + e((k_1 + k_2 + 1)(k_1 + k_2 + 2))$$

$$= (k_1 + k_2 + 2) \sum_{3 \leq i \leq \ell - 1} e_i$$

$$+ \left(\frac{2k_1 + 2k_2 + k_\ell + \ell - 1 + 2 \sum_{3 \leq i \leq \ell - 1} k_i}{2}\right) e(k_1 + k_2 + 1)$$

$$+ e(k_1 + k_2 + k_3 + 2) + (k_1 + k_2 + 1)e(k_1 + k_2 + 2) + (k_1 + k_2 + 2)e_\ell$$

$$+ \left(\frac{k_1 + k_2 + 2}{2}\right)$$

so that we can now compute the difference:

$$A - B = \left(-3 + 2 \sum_{1 \leq i \leq \ell} k_i\right) e_1$$

$$+ \left(k_1 + k_2 - 2\ell - 1 + \sum_{1 \leq i \leq \ell} k_i\right) e_2$$

$$- (k_2 + 1) \sum_{3 \leq i \leq \ell} e_i$$

$$+ (k_1 + 1)e(k_1 + 2) + (k_2 + 1)e(k_2 + 2)$$

$$+ 1 - k_1 k_2$$

$$- \left(-\frac{k_\ell}{2} + \ell - 1 + 2 \sum_{1 \leq i \leq \ell} k_i\right) e(k_1 + k_2 + 1)$$

$$- (k_1 + k_2)e(k_1 + k_2 + 2) - e(k_1 + k_2 + k_3 + 2) + e(k_2 + k_3 + 2)$$

$$= P(\vec{k})e_1 + Q(\vec{k})e_2 - (k_2 + 1) \sum_{i=3}^\ell e_i + (k_1 + 1)e(k_1 + 2) + (k_2 + 1)e(k_2 + 2)$$

$$+ 1 - k_1 k_2 - R(\vec{k})e(k_1 + k_2 + 1) - (k_1 + k_2)e(k_1 + k_2 + 2) - e(k_1 + k_2 + k_3 + 2)$$

$$+ e(k_2 + k_3 + 2).$$

Where

$$P(\vec{k}) = -3 + 2 \sum_{1 \leq i \leq \ell} k_i,$$

$$Q(\vec{k}) = k_1 + k_2 - 2\ell - 1 + \sum_{1 \leq i \leq \ell} k_i,$$

$$R(\vec{k}) = -k_\ell + \ell - 1 + 2 \sum_{1 \leq i \leq \ell} k_i.$$
The gradient can be computed term by term thanks to linearity, observing that for any polynomial $S(\vec{k})$,
\[
\partial_i e_i = -\log_2(k_1 + 1) - \frac{1}{\ln(2)}
\]
\[
\partial_i e_j = 0 \quad (i \neq j)
\]
\[
\nabla S(\vec{k}) e_j = \left( e_j \partial_i S(\vec{k}) + S(\vec{k}) \partial_i e_j \right)_{i=1}^\ell
\]

Hence, by denoting $\vec{u}_1, \ldots, \vec{u}_\ell$ the canonical basis, we have:
\[
\nabla P(\vec{k}) e_1 = \left( e_1 \partial_i P(\vec{k}) \right)_{i=1}^\ell = \partial_1 e_1 P(\vec{k}) \vec{u}_1 + e_1 (\partial_i P(\vec{k}))_{i=1}^\ell
\]
\[
= \partial_1 e_1 P(\vec{k}) \vec{u}_1 + 2(\vec{u}_1 + \cdots + \vec{u}_\ell)
\]
\[
= (2 + \partial_1 e_1 P(\vec{k})) \vec{u}_1 + 2\vec{u}_2 + \cdots + 2\vec{u}_\ell
\]
\[
\nabla Q(\vec{k}) e_2 = \left( e_2 \partial_i Q(\vec{k}) \right)_{i=1}^\ell = \partial_2 e_2 Q(\vec{k}) \vec{u}_2 + (\partial_i S(\vec{k}))_{i=1}^\ell
\]
\[
= \partial_2 e_2 Q(\vec{k}) \vec{u}_2 + \vec{u}_1 + \vec{u}_2 + \vec{u}_1 + \cdots + \vec{u}_\ell
\]
\[
= 2\vec{u}_1 + (2 + \partial_2 e_2 Q(\vec{k})) \vec{u}_2 + \vec{u}_3 + \cdots + \vec{u}_\ell
\]
\[
-\nabla \left( (k_2 + 1) \sum_{i=3}^\ell e_i \right) = -(k_2 + 1) \nabla \sum_{i=3}^\ell e_i - (\nabla (k_2 + 1)) \sum_{i=3}^\ell e_i
\]
\[
= -((k_2 + 1) \partial_i e_i \vec{u}_i)_{i=3}^{\ell} - \left( \sum_{i=3}^\ell e_i \right) \vec{u}_2
\]
\[
\nabla ((k_3 + 1)e(k_3 + 2)) = - \left( \log_2(k_3 + 2) + \frac{k_3 + 1}{\ln(2) k_3 + 2} \right) \vec{u}_3
\]
\[
\nabla (1 - k_1 k_2) = -k_2 \vec{u}_1 - k_1 \vec{u}_2
\]
\[
-\nabla \left( R(\vec{k}) e(k_1 + k_2 + 1) \right) = -R(\vec{k}) \nabla e(k_1 + k_2 + 1) - e(k_1 + k_2 + 1) \nabla R(\vec{k})
\]
\[
= R(\vec{k}) \left( \log_2(k_1 + k_2 + 1) + \frac{1}{\ln(2)} \right) \left( \vec{u}_1 + \vec{u}_2 \right)
\]
\[
- e(k_1 + k_2 + 1) (\partial_i R(\vec{k}))_{i=1}^\ell
\]
\[
= R(\vec{k}) \left( \log_2(k_1 + k_2 + 1) + \frac{1}{\ln(2)} \right) \left( \vec{u}_1 + \vec{u}_2 \right)
\]
\[
- e(k_1 + k_2 + 1) (2\vec{u}_1 + \cdots + 2\vec{u}_\ell) \vec{u}_3
\]
\[
-\nabla (k_1 + k_2) e(k_1 + k_2 + 2) = -(k_1 + k_2) \nabla e(k_1 + k_2 + 2) - e(k_1 + k_2 + 2) \nabla (k_1 + k_2)
\]
\[
= (k_1 + k_2) \left( \log_2(k_1 + k_2 + 2) + \frac{1}{\ln(2)} \right) \left( \vec{u}_1 + \vec{u}_2 \right)
\]
\[
- e(k_1 + k_2 + 2) \left( 2\vec{u}_1 + \cdots + 2\vec{u}_\ell \right) \vec{u}_3
\]
\[
-\nabla e(k_1 + k_2 + 3) = -(k_1 + k_2 + 3) \nabla e(k_1 + k_2 + 3) - e(k_1 + k_2 + 3) \nabla (k_1 + k_2 + 2)
\]
\[
= \left( \log_2(k_1 + k_2 + 3) + \frac{1}{\ln(2)} \right) \left( \vec{u}_1 + \vec{u}_2 + \vec{u}_3 \right)
\]
\[
\nabla e(k_2 + k_3 + 2) = - \left( \log_2(k_2 + k_3 + 2) + \frac{1}{\ln(2)} \right) \left( \vec{u}_2 + \vec{u}_3 \right)
\]

As is clearly visible from the above equations, we only need to consider the components along $\vec{u}_1, \vec{u}_2, \vec{u}_3, \vec{u}_\ell$, and along $\vec{u}_i$ for any $3 < i < \ell$. For the latter, we have
\[
(\nabla (A - B))_i = 2 + 1 - (k_2 + 1) \partial_i e_i - 2e(k_1 + k_2 + 1)
\]
\[
= 3 + 2(k_1 + k_2 + 1) \log_2(k_1 + k_2 + 1) + (k_2 + 1) \left( \log_2(k_1 + 1) + \frac{1}{\ln(2)} \right)
\]
\[
> 0.
\]
Now, along the very similar \( \vec{u}_\ell \) axis,

\[
(\nabla(A - B))_\ell = 2 + 1 - (k_2 + 1) \partial_\ell e_\ell - e(k_1 + k_2 + 1) \\
= 3 + (k_1 + k_2 + 1) \log_2(k_1 + k_2 + 1) + (k_2 + 1) \left( \log_2(k_\ell + 1) + \frac{1}{\ln(2)} \right) \\
> 0.
\]

Along \( \vec{u}_3 \),

\[
(\nabla(A - B))_3 = 2 + 1 - (k_2 + 1) \partial_3 e_3 - 2e(k_1 + k_2 + 1) + \log_2(k_1 + k_2 + k_3 + 2) + \frac{1}{\ln(2)} \\
- \log_2(k_2 + k_3 + 2) + \frac{1}{\ln(2)} \\
= 3 + 2(k_1 + k_2 + 1) \log_2(k_1 + k_2 + 1) + (k_2 + 1) \left( \log_2(k_3 + 1) + \frac{1}{\ln(2)} \right) \\
+ \log_2(k_1 + k_2 + k_3 + 2) - \log_2(k_2 + k_3 + 2) \\
> 0.
\]

Along \( \vec{u}_2 \),

\[
(\nabla(A - B))_2 = 2 + 2 + Q(\vec{k}) \partial_2 e_2 - (k_2 + 1) \partial_2 e_2 \\
- \sum_{i=3}^\ell e_i - \left( \log_2(k_2 + 2) + \frac{1}{\ln(2)} \frac{k_2 + 1}{k_2 + 2} \right) - k_1 \\
+ R(\vec{k}) \left( \log_2(k_1 + k_2 + 1) + \frac{1}{\ln(2)} \right) - 2e(k_1 + k_2 + 1) \\
+ \left( (k_1 + k_2) \left( \log_2(k_1 + k_2 + 2) + \frac{1}{\ln(2)} \right) - e(k_1 + k_2 + 2) \right) \\
+ \log_2(k_1 + k_2 + k_3 + 2) + \frac{1}{\ln(2)} - \log_2(k_2 + k_3 + 2) - \frac{1}{\ln(2)} \\
= 4 - (Q(\vec{k}) - k_2 - 1) \left( \log_2(k_2 + 1) + \frac{1}{\ln(2)} \right) - \frac{1}{\ln(2)} \frac{k_2 + 1}{k_2 + 2} - k_1 \\
+ \sum_{i=3}^\ell (k_1 + 1) \log_2(k_i + 1) \\
+ R(\vec{k}) \left( \log_2(k_1 + k_2 + 1) + \frac{1}{\ln(2)} \right) - 2e(k_1 + k_2 + 1) \\
+ (k_1 + k_2) \left( \log_2(k_1 + k_2 + 2) + \frac{1}{\ln(2)} \right) - e(k_1 + k_2 + 2) \\
+ \log_2(k_1 + k_2 + k_3 + 2) - \log_2(k_2 + k_3 + 2) - \log_2(k_2 + 2)
Finally, along $\tilde{u}_1$,

$$\nabla (A - B)_{1} = 2 + \partial_1 e_1 P(\tilde{k}) + 2 - (k_2 + 1)\partial_1 e_1 - \left( \log_2(k_1 + 2) + \frac{1}{\ln(2)} \frac{k_1 + 1}{k_1 + 2} \right) - k_2$$

$$+ R(\tilde{k}) \left( \log_2(k_1 + k_2 + 1) + \frac{1}{\ln(2)} \right) - 2e(k_1 + k_2 + 2)$$

$$+ (k_1 + k_2) \left( \log_2(k_1 + k_2 + 2) + \frac{1}{\ln(2)} \right) - e(k_1 + k_2 + 2)$$

$$+ \log_2(k_1 + k_2 + k_3 + 2) + \frac{1}{\ln(2)}$$

$$= 4 - (P(\tilde{k}) - k_2 - 1) \left( \log_2(k_1 + 1) + \frac{1}{\ln(2)} \right) - k_2$$

$$+ R(\tilde{k}) \left( \log_2(k_1 + k_2 + 1) + \frac{1}{\ln(2)} \right) - 2e(k_1 + k_2 + 2)$$

$$+ (k_1 + k_2) \left( \log_2(k_1 + k_2 + 2) + \frac{1}{\ln(2)} \right) - e(k_1 + k_2 + 2)$$

$$+ \log_2(k_1 + k_2 + k_3 + 2) - \log_2(k_1 + 2) + \frac{1}{\ln(2)} \left( 1 - \frac{k_1 + 1}{k_1 + 2} \right)$$

**Lemma A.1.** $(\nabla (A - B))_{1} > 0$.

**Proof of Lemma A.1.** It suffices to check that $(k_1 + k_2)(\lambda + \log_2(k_1 + k_2 + 1)) - k_2 > 0$, that $\log_2(k_1 + k_2 + k_3 + 2) - \log_2(k_1 + 2) > 0$, and that all the remaining quantities are positive. □

**Lemma A.2** (Sublemma). $(\nabla (A - B))_{2} > 0$.

**Proof of Lemma A.2**.

$$- (Q(\tilde{k}) - k_2 - 1)(\log_2(k_2 + 1) + \lambda) - \lambda \frac{k_2 + 1}{k_2 + 2} - k_1 + \sum_{i=3}^{\ell} (k_i + 1) \log_2(k_i + 1)$$

$$+ R(\tilde{k})(\lambda + \log_2(k_1 + k_2 + 1))$$

$$= \lambda \left( R(\tilde{k}) - Q(\tilde{k}) + k_2 + 1 - \frac{k_2 + 1}{k_2 + 2} \right) + R(\tilde{k}) \log_2(k_1 + k_2 + 1)$$

$$+ \sum_{i=3}^{\ell} (k_i + 1) \log_2(k_i + 1) - Q(\tilde{k}) \log_2(k_2 + 1)$$

$$= \lambda \left( \sum_{i=2}^{\ell} k_i + 3\ell + 1 - \frac{k_2 + 1}{k_2 + 2} \right) + \sum_{i=3}^{\ell} (k_i + 1) \log_2(k_i + 1)$$

$$+ R(\tilde{k}) \log_2(k_1 + k_2 + 1) - Q(\tilde{k}) \log_2(k_2 + 1).$$

The last line is positive since in particular $R(\tilde{k}) \log_2(k_1 + k_2 + 1) - Q(\tilde{k}) \log_2(k_2 + 1) > (R(\tilde{k}) - Q(\tilde{k})) \log_2(k_2 + 1)$. □

As a result, we have that $A - B > 0$ for all $\tilde{k}$ such that $k_i \geq 1$, which establishes the theorem. □

**Appendix B**

**Proof of Remark V.2.**

We prove that for all positive integer sequences $(k_i)_{i \in \{1, \ldots, \ell\}}$ such that $\sum_{i=1}^{\ell} = m$ we have:

$$\frac{\ell(\ell + 1)}{2} + \sum_{1 \leq i < j \leq \ell} \tilde{k}_i \tilde{k}_j + \sum_{i=1}^{\ell} \left( \tilde{k}_i + 1 \right) + 1 + \ell(m - \ell - 2) = \left( \frac{m + 2}{m} \right) + \left( \frac{m + 2}{m + 1} \right) + \left( \frac{m + 2}{m + 2} \right)$$

We fix $\ell$ and $m$, then proceed by induction on the sequences of $(k_i)_{i \in \{1, \ldots, \ell\}}$. We first show the equality for $k_1 = m - \ell + 1$, and $k_i = 1$ for all $i > 1$. 
Proof. We have
\[
\ell(\ell + 1) + \sum_{1 \leq i < j \leq \ell} k_i k_j + \sum_{i=1}^{\ell} \left( \frac{k_i + 1}{2} \right) + 1 + \ell(m - \ell - 2)
\]
\[
= \frac{\ell(\ell + 1)}{2} + 1 + \ell(m - \ell - 2) + (m - \ell + 1) \sum_{j=2}^{\ell} k_j + \left( \frac{2}{2} \right) + \left( \frac{m - \ell + 2}{2} \right)
\]
\[
= \frac{1}{2} \left( \ell(\ell + 1) + (m - \ell + 2)(m - \ell + 1) \right) + (\ell + 1)(m - \ell + 2) + 1
\]
\[
= \frac{1}{2} \left( m^2 + 3m + 2 \right) + m + 3
\]
\[
= \left( \frac{m + 2}{m} \right) + \left( \frac{m + 2}{m + 1} \right) + \left( \frac{m + 2}{m + 2} \right)
\]
which concludes the initialization. 

We now fix a sequence \((k_i)_{i \in \{1, \ldots, t\}}\), and \(i_0 \in \{1, \ldots, \ell\}\). We assume that the equality holds for this sequence and show that it is true for the sequence \((k'_i)_{i \in \{1, \ldots, t\}}\) defined as \(k'_i = k_i\) if \(i \neq i_0\) and \(i \neq i_0 + 1\), \(k'_{i_0} = k_{i_0} - 1\) and \(k'_{i_0+1} = k_{i_0+1} + 1\).

Proof. We first note that only a part of the formula on the left hand side depends on \((k_i)_{i \in \{1, \ldots, t\}}\). Letting
\[
F \left( (k_i)_{i \in \{1, \ldots, t\}} \right) = \sum_{1 \leq i < j \leq \ell} \tilde{k}_i \tilde{k}_j + \sum_{i=1}^{\ell} \left( \tilde{k}_i + 1 \right)
\]
we just have to prove that
\[
F \left( (k_i)_{i \in \{1, \ldots, t\}} \right) - F \left( (k'_i)_{i \in \{1, \ldots, t\}} \right) = 0.
\]

Expanding the above difference, we have:
\[
(\tilde{k}_{i_0} - \tilde{k}'_{i_0})(\sum_{i=1}^{i_0-1} \tilde{k}_i) + (\tilde{k}_{i_0+1} - \tilde{k}'_{i_0+1})(\sum_{i=1}^{i_0-1} \tilde{k}_i) + \tilde{k}_{i_0} \tilde{k}_{i_0+1} - \tilde{k}'_{i_0} \tilde{k}'_{i_0+1}
\]
\[
+ (\tilde{k}_{i_0} - \tilde{k}'_{i_0})(\sum_{i=i_0+1}^{\ell} \tilde{k}_i) + (\tilde{k}_{i_0+1} - \tilde{k}'_{i_0+1})(\sum_{i=i_0+2}^{\ell} \tilde{k}_i)
\]
\[
+ \left( \frac{\tilde{k}_{i_0} + 1}{2} \right) - \left( \frac{\tilde{k}'_{i_0} + 1}{2} \right) + \left( \frac{\tilde{k}_{i_0+1} + 1}{2} \right) - \left( \frac{\tilde{k}'_{i_0+1} + 1}{2} \right)
\]
This is equal to
\[
\tilde{k}_{i_0} \tilde{k}_{i_0} - (\tilde{k}_{i_0} - 1)(\tilde{k}_{i_0+1} + 1) + \tilde{k}_{i_0+1} + \frac{1}{2} \left( \tilde{k}_{i_0}(\tilde{k}_{i_0} + 1) - (\tilde{k}_{i_0} + 1)\tilde{k}_{i_0} \right)
\]
\[
- \frac{1}{2} (\tilde{k}_{i_0+1}(\tilde{k}_{i_0+1} + 1) - (\tilde{k}_{i_0+1} + 2)\tilde{k}_{i_0+1} + 1)
\]
\[
= -\tilde{k}_{i_0} + \tilde{k}_{i_0+1} + 1 + \frac{1}{2} (2\tilde{k}_{i_0} - 2\tilde{k}_{i_0+1} - 2)
\]
\[
= 0.
\]
This concludes the proof. 

\[\square\]
REFERENCES

[1] P. Y. Ryan and B. Christianson, “Enhancements to prepare-and-measure based qkd protocols,” in Security Protocols XXI. Springer, 2013, pp. 123–133.

[2] A. Atashpendar, A. Roscoe, and P. Y. Ryan, “Information leakage due to revealing randomly selected bits,” in Security Protocols XXIII. Springer, 2015, pp. 325–341.

[3] T. M. Cover and J. A. Thomas, Elements of information theory. John Wiley & Sons, 2012.

[4] C. E. Shannon, “A mathematical theory of communication,” ACM SIGMOBILE Mobile Computing and Communications Review, vol. 5, no. 1, pp. 3–55, 2001.

[5] M. Mitzenmacher, “A survey of results for deletion channels and related synchronization channels,” in Algorithm Theory - SWAT 2008, 11th Scandinavian Workshop on Algorithm Theory, Gothenburg, Sweden, July 2-4, 2008. Proceedings, ser. Lecture Notes in Computer Science, J. Gudmundsson, Ed., vol. 5124. Springer, 2008, pp. 1–3. [Online]. Available: https://doi.org/10.1007/978-3-540-69905-3_1

[6] T. G. Swart and H. C. Ferreira, “A note on double insertion/deletion correcting codes,” IEEE Transactions on Information Theory, vol. 49, no. 1, pp. 269–273, 2003.

[7] P. J. Chase, “Subsequence numbers and logarithmic concavity,” Discrete Mathematics, vol. 16, no. 2, pp. 123–140, 1976.

[8] A. Flaxman, A. W. Harrow, and G. B. Sorkin, “Strings with maximally many distinct subsequences and substrings,” Electr. J. Comb., vol. 11, no. 1, 2004. [Online]. Available: http://www.combinatorics.org/VOLUME_11/Abstracts/v11i1r8.html

[9] D. S. Hirschberg, “Bounds on the number of string subsequences,” in Combinatorial Pattern Matching, 10th Annual Symposium, CPM 99, Warwick University, UK, July 22-24, 1999. Proceedings, ser. Lecture Notes in Computer Science, M. Crochemore and M. Paterson, Eds., vol. 1645. Springer, 1999, pp. 115–122. [Online]. Available: https://doi.org/10.1007/3-540-48452-3_9

[10] T. Jiang and M. Li, “On the approximation of shortest common supersequences and longest common subsequences,” Journal of Discrete Algorithms, vol. 1, no. 1, pp. 123–132, 2000.

[11] D. S. Hirschberg and M. Regnier, “Tight bounds on the number of string subsequences,” Journal of Discrete Algorithms, vol. 1, no. 1, pp. 123–132, 2000.

[12] Y. Kanoria and A. Montanari, “Optimal coding for the binary deletion channel with small deletion probability,” IEEE Transactions on Information Theory, vol. 59, no. 10, pp. 6192–6219, 2013.

[13] B. Graham, “A binary deletion channel with a fixed number of deletions,” Combinatorics, Probability and Computing, vol. 24, no. 03, pp. 486–489, 2015.

[14] F. Sala, “Counting sequences obtained from the synchronization channel,” in Proceedings of the 2013 IEEE International Symposium on Information Theory, Istanbul, Turkey, July 7-12, 2013. IEEE, 2013, pp. 2925–2929. [Online]. Available: https://doi.org/10.1109/ISIT.2013.6620761

[15] F. Sala, R. Gabrys, C. Schoeny, and L. Dolecek, “Three novel combinatorial theorems for the insertion/deletion channel,” in IEEE International Symposium on Information Theory, ISIT 2015, Hong Kong, China, June 14–19, 2015. IEEE, 2015, pp. 2702–2706. [Online]. Available: https://doi.org/10.1109/ISIT.2015.7282947

[16] Y. Liron and M. Langberg, “A characterization of the number of subsequences obtained via the deletion channel,” IEEE Transactions on Information Theory, vol. 61, no. 5, pp. 2300–2312, 2015.

[17] D. Cullina, A. A. Kulkarni, and N. Kiyavash, “A coloring approach to constructing deletion correcting codes from constant weight subgraphs,” in Proceedings of the 2012 IEEE International Symposium on Information Theory, ISIT 2012, Cambridge, MA, USA, July 1-6, 2012. IEEE, 2012, pp. 513–517. [Online]. Available: https://doi.org/10.1109/ISIT.2012.6224282

[18] S. Diggavi, M. Mitzenmacher, and H. Pfister, “Capacity upper bounds for deletion channels,” in Proceedings of the International Symposium on Information Theory, 2007, pp. 1716–1720.

[19] A. Kalai, M. Mitzenmacher, and M. Sudan, “Tight asymptotic bounds for the deletion channel with small deletion probabilities,” in IEEE International Symposium on Information Theory, ISIT 2010, June 13-18, 2010, Austin, Texas, USA, Proceedings. IEEE, 2010, pp. 997–1001. [Online]. Available: https://doi.org/10.1109/ISIT.2010.5513746

[20] M. Rahmati and T. M. Duman, “Bounds on the capacity of random insertion and deletion-additive noise channels,” IEEE Transactions on Information Theory, vol. 59, no. 9, pp. 5534–5546, 2013.

[21] D. Cullina and N. Kiyavash, “An improvement to levenshtein’s upper bound on the cardinality of deletion correcting codes,” IEEE Transactions on Information Theory, vol. 60, no. 7, pp. 3862–3870, 2014.

[22] O. Ordentlich and O. Shayevitz, “Bounding techniques for the intrinsic uncertainty of channels,” in 2014 IEEE International Symposium on Information Theory, Honolulu, HI, USA, June 29 - July 4, 2014. IEEE, 2014, pp. 3082–3086. [Online]. Available: https://doi.org/10.1109/ISIT.2014.6875401