

THE KRAFT SUM AS A MONOTONE FUNCTION ON THE REFINEMENT-ORDERED SET OF UNIQUELY DECIPHERABLE CODES

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Abstract. The set of all uniquely decipherable (UD) codes is partially ordered by refinement, meaning that all strings in the cruder code can be represented as concatenations of strings taken from the finer code. The Kraft sum is a monotone (increasing) function on this poset. In the refinement order, chains of UD codes having the same Kraft sum are necessarily of the simple descending type.

1. INTRODUCTION

Let A be any non-empty finite set, called *alphabet*. Let $con : A^{**} \rightarrow A^*$ be the concatenation map which to every string of strings associates their concatenation. In this note we shall call any finite subset $C \subseteq A^*$ not containing the null string a *code*. A code is said to be *uniquely decipherable (UD)* if con is injective on the subset C^* of A^{**} . (Note that several authors, including Berstel and Perrin [1], reserve the term "code" to mean UD code.)

For any codes C and D write $C \leq D$ and say that D is *finer* than C , or that it is a *refinement* of C , if $C \subseteq con[D]$. This is a partial order relation (antisymmetry is ensured by unique decipherability). We say that D is an *irredundant refinement* of C if $C \leq D$ and no proper subset of D is finer than C . Every code has infinitely many refinements. However, due to its finiteness, each code can have only finitely many irredundant refinements.

Denoting by r the number of elements of the *alphabet* A , the *Kraft sum* $K(C)$ of any code $C \subseteq A^*$ is defined as $\sum_{\mathbf{x} \in C} r^{-len(\mathbf{x})}$, where len is the length function. In [5] McMillan showed that if C is a uniquely decipherable code, then its Kraft sum is at most 1. Simplified combinatorial proofs were given by Karush [3], and by Berstel and Perrin ([1] Chapter 1, Theorem 4.2). The proof was also reformulated in [2] as an argument involving evaluations of polynomials with non-commuting indeterminates corresponding to the various (infinitely many) strings in A^* . In [2] we also concluded that for any UD codes C and D such that $C \leq D$, the inequality $K(C) \leq K(D)$ holds. Here the purely combinatorial proof due to Berstel and Perrin [1] is shown to yield the same conclusion that was reached in [2], and from

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this some further conclusions are drawn about the set of UD codes having the same Kraft sum.

The Kraft inequality as originally established by Kraft [4] stated that $K(C) \leq 1$ for instantaneous (prefix-free) codes, which are a special class of UD codes. This can be verified in several ways - for a recent approach, which also generalizes the inequality to data structures other than strings, see Valmari [6].

2. STATEMENTS AND PROOFS

For any code C and positive integer k , denote by C^k the code consisting of all possible concatenations of k (not necessarily distinct) members of C . Note that if C is a UD code, then C^k is also UD and $\text{Card}(C^k) = [\text{Card}(C)]^k$. The following appears in Berstel and Perrin [1], Chapter 1, Proposition 4.1.

Proposition 2.1 ([1]). *For any code C over a given alphabet and positive integer k , we have $K(C^k) \leq K(C)^k$ and the following conditions are equivalent:*

- (i) C is uniquely decipherable,
- (ii) $K(C^k) = K(C)^k$ for all positive integers k .

Proof. (As given by Berstel and Perrin [1]). For each positive k , denote by $C^{(k)}$ the set of strings $(\mathbf{v}_1, \dots, \mathbf{v}_k)$ of k (not necessarily distinct) words from C . Clearly, $C^{(k)} \subseteq A^{**}$.

We claim that C is UD if and only if concatenation restricted to $C^{(k)}$ is an injective map for every k . These injectivity conditions are clearly necessary for C to be UD. On the other hand, if C is not UD, then, for some positive m, n , two different strings of words, $x = (\mathbf{x}_1, \dots, \mathbf{x}_m) \in C^{(m)}$ and $y = (\mathbf{y}_1, \dots, \mathbf{y}_n) \in C^{(n)}$ yield the same concatenation, $\text{con } x = \text{con } y$. Let $k = m + n$. The strings of words $(\mathbf{x}_1, \dots, \mathbf{x}_m, \mathbf{y}_1, \dots, \mathbf{y}_n)$ and $(\mathbf{y}_1, \dots, \mathbf{y}_n, \mathbf{x}_1, \dots, \mathbf{x}_m)$ are both in $C^{(k)}$, they are distinct, and they yield the same concatenation, proving the claim.

Observe that concatenation restricted to $C^{(k)}$ is always a surjective map onto C^k .

For $(\mathbf{v}_1, \dots, \mathbf{v}_k) \in C^{(k)}$ the word $\text{con}(\mathbf{v}_1, \dots, \mathbf{v}_k)$ in C^k contributes to the Kraft sum $K(C^k)$, a term equal to the product of the terms $r^{-\text{len}(\mathbf{v}_i)}$, $1 \leq i \leq k$ of the Kraft sum of C . Sum of these products over all members of $C^{(k)}$ equals $K(C)^k$ and it yields exactly $K(C^k)$ if the map con is injective on $C^{(k)}$, otherwise it yields a strict upper bound of $K(C^k)$. \square

We can apply to two codes comparable by refinement the reasoning presented in Berstel and Perrin's proof of Theorem 4.2 in Chapter 1 of [1]. Let C be a UD code and let D be any code finer than C . There is a positive integer m such that for all integers $n > m$, C is disjoint from D^n . For any fixed positive integer k , we have (by an obvious induction with respect to k) that

$$C^k \subseteq D^k \cup D^{k+1} \cup \dots \cup D^{mk}$$

and $K(C)^k = K(C^k)$ is less than or equal to

$$\begin{aligned} & K(D^k \cup D^{k+1} \cup \dots \cup D^{mk}) \\ & \leq K(D^k) + K(D^{k+1}) + \dots + K(D^{mk}) \\ & \leq K(D)^k + K(D)^{k+1} + \dots + K(D)^{mk} \\ & = K(D)^k [1 + K(D) + \dots + K(D)^{(m-1)k}]. \end{aligned}$$

First, when we choose the finest code D consisting of all the words of length 1, we get $K(C)^k \leq (m-1)k + 1$. It follows that $K(C) \leq [(m-1)k + 1]^{1/k}$, for every k . Necessarily, $K(C) \leq 1$. Second, if we assume that code D is also UD, and thus, its Kraft sum is at most 1, we get

$$\left[\frac{K(C)}{K(D)} \right]^k \leq 1 + K(D) + \dots + K(D)^{(m-1)k} \leq (m-1)k + 1$$

which is true for all k , implying that the ratio on the left hand side is at most 1, $K(C) \leq K(D)$. This yields the following extension of McMillan's Theorem:

Proposition 2.2. *The Kraft sum is a monotone (increasing) function on the refinement-ordered set of uniquely decipherable codes. For each UD code C , there are only finitely many finer UD codes with the same Kraft sum.*

The second statement follows from the fact, noted above, that a UD code C has only finitely many irredundant refinements, and from the observation that for a code D finer than C that is not an irredundant refinement of C , the Kraft sums cannot be equal, the inequality between them has to be strict, $K(C) < K(D)$. By Proposition 2, every UD code C has at least one UD refinement D with the same Kraft sum that can no longer be properly refined without increasing the Kraft sum. As a further consequence, we have:

Proposition 2.3. *In the refinement-ordered set of UD codes, all infinite chains of UD codes with the same Kraft sum are of type ω^* (i.e. of the same order type as the negative integers).*

Infinite chains of UD codes all having the same Kraft sum exist indeed, in fact there is such a chain below every member of the poset of UD codes: for any UD code C , consider for example $C > C^2 > C^4 > \dots > C^{2^n} > \dots$

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