On the Maximum Number of Distinct Factors of a Binary String

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Abstract.

In this note we prove that a binary string of length n can have no more than $2^{k+1}-1+\binom{n-k+1}{2}$ distinct factors, where k is the unique integer such that $2^k+k-1 \le n < 2^{k+1}+k$. Furthermore, we show that for each n, this bound is actually achieved. The proof uses properties of the de Bruijn graph.

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I. Introduction.

Let w be a string of 0's and 1's, i.e. $w \in (0+1)^*$. We say that $z \in (0+1)^*$ is a *factor* of w if there exist $x, y \in (0+1)^*$ such that

$$w = xzy.$$

In analogy with the function that counts the number of divisors of a positive integer n, define $d(w)$ to be the *total number of distinct factors* of the string w. For example, $d(10110) = 12$, as its set of factors is given by

$$\{\epsilon, 0, 1, 01, 10, 11, 011, 101, 110, 0110, 1011, 10110\}.$$

Note that we count ϵ, the empty string, as a factor of every string.

In this note we discuss the maximum order of $d(w)$.

II. The Main Results.

Theorem 1. *Let $|w| = n$. Then*

$$\begin{aligned} d(w) &\leq \sum_{0 \leq i \leq n} \min(2^i, n-i+1) \\ &= \binom{n-k+1}{2} + 2^{k+1} - 1, \end{aligned}$$

where k is the unique integer such that $2^k + k - 1 \leq n < 2^{k+1} + k$.

Proof.

The first inequality is clear, as there are precisely $n - i + 1$ possible factors of length i, of which at most 2^i can be distinct.

To see the second equality, note that if $2^k + k - 1 \leq n < 2^{k+1} + k$, then $2^k \leq n - k + 1$ and $2^{k+1} > n - k$. Hence

$$\begin{aligned} \sum_{0 \leq i \leq n} \min(2^i, n-i+1) &= \sum_{0 \leq i \leq k} 2^i + \sum_{k < i \leq n} (n-i+1) \\ &= 2^{k+1} - 1 + \binom{n-k+1}{2}. \end{aligned}$$

This completes the proof. ■

Theorem 2. *The upper bound in Theorem 1 is actually attained for all n.*

To prove Theorem 2, we use the *de Bruijn graph B_k*. This graph was apparently first studied by Flye-Sainte Marie in 1894 [FSM]. Good [G] and de Bruijn [B] independently rediscovered the graph in 1946. A more accessible reference is Bondy and Murty [BM, pp.

181-183] or van Lint [L, pp. 82-92]. For a survey of results on this graph until 1982, see Fredricksen [F].

Recall that B_k is a directed graph with 2^k vertices $\{0,1\}^k$, and 2^{k+1} directed edges with labels $\{0,1\}^{k+1}$. There is a directed edge from the head vertex, labeled $a_1 a_2 \cdots a_k$, to the tail vertex, labeled $b_1 b_2 \cdots b_k$, iff $a_2 \cdots a_k = b_1 \cdots b_{k-1}$. In this case the edge is labeled $a_1 a_2 \cdots a_k b_k$.

For example, below is the de Bruijn graph B_3:

A *chain* is an alternating sequence of distinct edges and possibly non-distinct vertices, $v_1, e_2, v_2, \ldots, e_j, v_j$, where v_i, $2 \leq i \leq j$, is the tail of e_i and v_i, $1 \leq i \leq j-1$, is the head of e_{i+1}. If $v_1 = v_j$, this is a *closed chain.* A closed chain with distinct vertices (other than $v_1 = v_j$) is a *cycle.* The *length* of a chain is the number of edges it contains.

We need the following lemma:

Lemma 3.

For each i with $2^k \leq i \leq 2^{k+1}$, the graph B_k contains a closed chain of length k that visits every vertex at least once.

Note that for $i = 2^k$, this is a Hamiltonian cycle, and for $i = 2^{k+1}$, this is an Eulerian tour.

Proof.

This theorem can be derived from results in a paper of Yoeli [Y], although it is not explicitly stated there.

Yoeli proved the following theorems:

Theorem A.

If B_k has a cycle of length i, then it has a closed chain of length $i + 2^k$.

Theorem B.

B_k contains a cycle of length i for any i, $0 < i \leq 2^k$.

Combining these two theorems, we see that B_k has a closed chain of any length between 2^k and 2^{k+1}. However, it remains to see there exists such a chain that visits every vertex of B_k. Yoeli's proof of Theorem A does in fact construct a closed chain that visits every vertex of B_k. Since this is nowhere stated in his paper, we briefly go through the argument.

Yoeli proves the following three lemmas:

Lemma 4. *B_k is strongly connected.*

Define a *P-set* of cycles of B_k to be a set of vertex-disjoint cycles covering all the vertices. (Each cycle must have at least one edge; thus a P-set of B_k has 2^k edges.)

Lemma 5.

Let C be a cycle of B_k. Then there exists a P-set of cycles of B_k including no edge of C.

Lemma 6.

Let C' and C'' be vertex-disjoint cycles of B_k and let $e = (u, v)$ be an edge with u in C' and v in C''. Then there is an edge e' from v's predecessor in C'' to u's predecessor in C', and a cycle on the vertex set of $C' \cup C''$ can be formed using edges of $C' \cup C''$ together with e and e'.

Now we can complete the proof of Lemma 3, following the proof Yoeli gave for his Theorem A.

Let C be a cycle in B_k of length i. By Lemma 5 there exists a P-set of cycles P_1 of B_k including no edge of C. Let H_1 be the subgraph of B_k formed by the edges of P_1 and C. If the underlying undirected graph of H_1 consists of more than one connected component, then by Lemma 4 there must be an edge e in B_k joining two components of H_1. Edge e must join two vertex disjoint cycles D' and D'' in P_1, where no edge of H_1 goes between D' and D''. Applying Lemma 6 to combine D' and D'', we obtain a P-set of cycles P_2 including no edge of C, and such that $H_2 = C \cup P_2$ has one fewer connected component. Continuing in this fashion leads to a connected subgraph H_r, consisting of $C \cup P_r$, where P_r is a P-set. Since H_r is connected, with each vertex's in-degree equal to its out-degree, H_r has an Eulerian tour. This provides a closed chain of length $2^k + i$ visiting all vertices. ■

Using Yoeli's result we can construct a string that achieves the upper bound:

Proof of Theorem 2.

Let n be given, and let k be the unique integer such that $2^k + k - 1 \leq n < 2^{k+1} + k$. Consider the de Bruijn graph B_k. By Lemma 3 there exists a closed chain C of length $n - (k - 1)$ traversing each vertex in B_k and repeating no edges. Take the string formed by the k letters of the vertex label of the first vertex in C, followed by the last letter in the labels of all subsequent edges in C. The result is a string of length n, and we claim it is the desired one.

Now this closed chain visits every vertex of B_k; hence w contains all factors of length k, and hence all factors of lengths $0, 1, 2, \ldots k - 1$.

On the other hand, the chain C does not repeat any edge, so all the factors of length $k+1$ are distinct. Hence so are all the factors of lengths $k+2, k+3, \ldots, n$, since any two factors of the same length must differ in the first $k+1$ positions.

Thus we see

$$d(w) = \sum_{0 \le i \le k} 2^i + \sum_{k < i \le n} n - i + 1,$$

and so the upper bound is achieved. ■

An Example.

Let $n = 14$. Then $k = 3$ and $n - (k-1) = 12$. Looking at B_3, we see there is a closed chain of length 12, as follows (listing only the vertices):

$$000 \to 001 \to 010 \to 100 \to 001 \to 011 \to 110 \to$$

$$101 \to 011 \to 111 \to 110 \to 100 \to 000.$$

This corresponds to the string 000100110111000 of length 14. It has $15 + 66 = 81$ distinct factors, which is the maximum possible for any binary string of length 14.

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