On the Circuit Complexity of Perfect Hashing

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July 1996, revised March 1998

Abstract

We consider the size of circuits which *perfectly hash* an arbitrary subset $S \subset \{0,1\}^n$ of cardinality 2^k into $\{0,1\}^m$. We observe that, in general, the size of such circuits is exponential in $2k - m$, and provide a matching upper bound.

Note: In contrast to our previous impression, the lower bound has been known; see analogous argument in [6, pp. 128-129].

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[†] Research was supported in part by the Wolfson Research Awards, administered by the Israel Academy of Sciences and Humanities.

Introduction

We consider the problem of *perfectly hashing* an arbitrary subset $S \subset \{0,1\}^n$ of cardinality 2^k into $\{0,1\}^m$, where $k \leq m$. That is, given an arbitrary subset $S \subset \{0,1\}^n$ of cardinality 2^k, we seek a function $h : \{0,1\}^n \mapsto \{0,1\}^m$ so that $h(x) \neq h(y)$ for every two distinct $x \neq y$ in S. Clearly, such a function always exists, the question is what is its complexity; that is, what is the size of the smallest circuit computing h.

Although much work has been done on perfect hashing, it seems surprising that this question was not addressed before (to the best of our knowledge). Two easy bounds are

1. For every $S \subset \{0,1\}^n$, there is a circuit of size $|S| \cdot n$ which perfectly hashes S into $\{0,1\}^{\lceil \log_2 |S| \rceil}$. (The circuit is merely a look-up table for S.)
2. For every $S \subset \{0,1\}^n$, there is a circuit of size $\text{poly}(n)$ which perfectly hashes S into $\{0,1\}^{2\lceil \log_2 |S| \rceil}$. (The circuit implements a suitable function from a family of Universal$_2$ Hashing [2]. Such a family always contains perfect hashing functions for S [4].)

We show that these bounds are the best possible. That is

Theorem 1 *For every n, k and $m \leq n-1$, there exists a subset $S \subset \{0,1\}^n$ of cardinality 2^k which cannot be hashed into $\{0,1\}^m$ using a circuit of size $\Omega(2^{2k-m}/n)$.*

Interestingly, the lower bound is tight for all values of $m \in [k, 2k]$ (and not only for $m = k, 2k$). That is,

Proposition 2 *For every n, m, k where $k \leq m \leq 2k$, and every subset $S \subset \{0,1\}^n$ of cardinality 2^k there exists*[1] *a circuit of size $2^{2k-m} \cdot \text{poly}(n)$ which hashes S into $\{0,1\}^m$.*

1 Proof of Theorem 1

The proof follows by a simple counting argument, combining an upper bound on the number of circuits of given size with a lower bound on the size of a family of functions that can separate all subsets of size 2^k. Improved lower bounds for the latter appears in [3, 5, 7]. For completeness we prove a weaker bound below, that is sufficient for our purposes, and present the argument in probabilistic terms.

Suppose, in contrary to Theorem 1, that for every subset $S \subset \{0,1\}^n$ of cardinality $K \stackrel{\text{def}}{=} 2^k$ there exists a circuit of size $o(2^{2k-m}/(2k-m))$ which hashes S into $\{0,1\}^k$. We will show that each circuit can serve as a perfect hashing for too few K-subsets and thus that there are too few circuits to perfectly hash all possible K-subsets. The main observation follows:

Lemma 1.1 *Let $C : \{0,1\}^n \mapsto \{0,1\}^m$ be an arbitrary circuit, and $S \subset \{0,1\}^n$ be a uniformly selected subset of cardinality $K = 2^k$. Then, the probability that C perfectly hashes S into $\{0,1\}^m$ is bounded above by*

$$2^{-\Omega(2^{2k-m})}$$

provided $m \leq n-1$.

[1] We stress that such a circuit cannot, in general, be simply described; that is, this result is completely nonuniform.

Proof: Let $N \stackrel{\rm def}{=} 2^n$ and $M \stackrel{\rm def}{=} 2^m$. Clearly, we may assume that $k \leq m$ (as otherwise the probability is zero). Let $c_1, ..., c_M$ denote the sizes of the preimages of the various m-bit strings under C (i.e., $c_i = |C^{-1}(s_i)|$, where s_i denotes the $i^{\rm th}$ (m-bit long) string by some order). Then, the probability we are interested in is

$$\begin{aligned}
\frac{\sum_{I\subseteq[M]:|I|=K} \prod_{i\in I} \binom{c_i}{1}}{\binom{N}{K}} &\leq \frac{\binom{M}{K} \cdot (N/M)^K}{\binom{N}{K}} \\
&= \prod_{i=0}^{K-1} \frac{1-(i/M)}{1-(i/N)} \\
&= \exp\left\{-\sum_{i=1}^{K-1} \ln\left(1+\frac{(i/M)-(i/N)}{1-(i/M)}\right)\right\} \\
&< \exp\left\{-\frac{K\cdot(K-1)}{2}\cdot\left(\frac{1}{M}-\frac{1}{M}\right)\right\}
\end{aligned}$$

which for $M \leq N/2$ yields $2^{-\Omega(K^2/M)}$. The lemma follows. ■

Adding up the contribution of all possible circuits, while applying Lemma 1.1 to each of them, we conclude that if too few circuits are considered then not all K-subsets can be perfectly hashed. Specifically, there are $s^{O(s)}$ possible circuits of size s, and so we need $s^{O(s)} \cdot 2^{-\Omega(2^{2k-m})} \geq 1$. Theorem 1 follows.

2 Proof of Proposition 2

We consider two cases. In case $m \leq k + \log_2 n$ then the proposition follows by constructing an obvious circuit which maps each string in S to its rank (in S) represented as an m-bit long string. This circuit has size $|S| \cdot n \leq 2^{2k-m} \cdot n^2$ and the proposition follows.

The less obvious case is when $m \geq k + \log_2 n$. Here we use a family of n-wise independent functions mapping $\{0,1\}^n$ onto $\{0,1\}^\ell$, where $\ell \stackrel{\rm def}{=} m - \log_2 n$. Function in such a family can be evaluated by poly(n)-size circuits; cf., [1]. We consider the collisions caused by a uniformly chosen function from this family applied to S. Specifically,

Lemma 2.1 *Let H be a family of functions $\{h : \{0,1\}^n \mapsto \{0,1\}^\ell\}$ so that* ${\rm Prob}_{h\in H}(\wedge_{i=1}^n h(\alpha_i) = \beta_i) = 2^{-n\ell}$*, for every n distinct $\alpha_1, ..., \alpha_n \in \{0,1\}^n$ and for every $\beta_1, ..., \beta_n \in \{0,1\}^\ell$. Then, for every $S \subset \{0,1\}^n$ of cardinality $2^k \leq 2^\ell$, there exists $h \in H$ so that*

1. *$|h^{-1}(\beta) \cap S| \leq n$, for every $\beta \in \{0,1\}^\ell$.*
2. *$|\{\beta \in \{0,1\}^\ell : |h^{-1}(\beta) \cap S| > 1\} \leq 2^{2k-\ell}$*

Proof: Fixing an arbitrary 2^k-subset, S, and uniformly selecting $h \in H$, we consider the probability that the two items (above) hold. Firstly, we consider the probability that h maps n elements of S to the same image. Using the n-wise independence of the family H, the probaility of this event is bounded by

$$\binom{2^k}{n} \cdot 2^{-\ell n} < \frac{2^{kn}}{2^k!} \cdot 2^{-kn} < \frac{1}{2}$$

Thus, the probability that Item (1) does not hold is less than 1/2. Next, we consider the probability that Item (2) does not hold. We start by using the pairwise independence of H to note that the collision probability is $2^{-\ell}$ (i.e., $\mathrm{Prob}_{h\in H}(h(\alpha_1)=h(\alpha_2)) = 2^{-\ell}$, for any $\alpha_1 \neq \alpha_2 \in \{0,1\}^n$). It follows that the expected number of h-images which have more than a single preimage in S is bounded above by the expected number of collisions; that is, by $\binom{2^k}{2} \cdot 2^{-\ell} < \frac{1}{2} \cdot 2^{2k-\ell}$. Applying Markov's Inequality, we conclude that the probability that Item (2) does not hold is less than 1/2. The lemma follows. ■

Using Lemma 2.1, we are now ready to present a circuit which perfectly hashes an arbitrary 2^k-subset, $S \subset \{0,1\}^n$, into $\{0,1\}^m$. Our construction uses the double hashing paradigm (e.g., [4]). Let $h:\{0,1\}^n \mapsto \{0,1\}^{k-\log_2 n}$ be as guaranteed by the lemma. We define a perfect hashing function $f:\{0,1\}^n \mapsto \{0,1\}^k$ for S by letting

$$f(\alpha) \stackrel{\mathrm{def}}{=} h(\alpha) \circ \mathrm{rank}_{S\cap h^{-1}(h(\alpha))}(\alpha)$$

where $\mathrm{rank}_P(\alpha)$ is an $\log_2 n$-bit long string representing the rank of α among the elements of P. A circuit computing the function f is constructed as follows. For each β having more than a unique h-preimage in S we maintain a table ranking these preimages in S. By Item (1) of Lemma 2.1, such a table need only contain n entries; whereas by Item (2) we only need $2^{2k-\ell}$ such tables. (We stress that if a string, α, does not appear in any of the tables then $f(\alpha) = h(\alpha) \circ 0^{\log_2 n}$.) The size of the circuit is $2^{2k-\ell} \cdot n^2 = 2^{2k-m} \cdot n^3$ and so Proposition 2 follows.

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