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ON THE NUMBER OF EQUIVALENCE CLASSES OF INVERTIBLE BOOLEAN FUNCTIONS UNDER ACTION OF PERMUTATION OF VARIABLES ON DOMAIN AND RANGE

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Abstract. Let V_n be the number of equivalence classes of invertible maps from $\{0,1\}^n$ to $\{0,1\}^n$, under action of permutation of variables on domain and range. So far, the values V_n have been known for $n \leqslant 6$. This paper describes the procedure by which the values of V_n are calculated for $n \leqslant 30$.

1. Introduction

Let V_n be the number of equivalence classes of invertible maps from $\{0,1\}^n$ to $\{0,1\}^n$, under action of permutation of variables on domain and range. Lorens [**1**] gave a method for calculating the number of equivalence classes of invertible Boolean functions under the following group operations on the input and output variables: complementation, permutation, composition of complementation and permutation, linear transformations and affine transformations. In particular, he calculated the values V_n for $n \leqslant 5$. Irvine [**4**] in 2011 calculated V_6 (the sequence A000653). In this paper using a more efficient procedure, the values V_n are calculated for $n \leqslant 30$.

2. Notation

Let S_r denote symmetric group on r letters. Consider a set of vectorial invertible Boolean functions (hereinafter referred to as functions), i.e., the set S_N of permutations of $B_n = \{0,1\}^n$ where $N = 2^n$. The function $F \in S_N$ maps the n-tuple $X = (x_1, \dots, x_n) \in B_n$ into $Y = (y_1, \dots, y_n) = F(X)$. For some permutation $\sigma \in S_n$, the result of its action on $X = (x_1, \dots, x_n) \in B_n$ is $\sigma'(X) = (x_{\sigma(1)}, \dots, x_{\sigma(n)}) \in B_n$.

An arbitrary pair $(\rho, \sigma) \in S_n^2$ determines mapping $T_{\rho,\sigma} : S_N \to S_N$, defined by $T_{\rho,\sigma}(F) = \rho' \circ F \circ \sigma'$ where $F \in S_N$; in other words, if $F' = T_{\rho,\sigma}(F)$ then

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$F'(X) = \rho'(F(\sigma'(X)))$ for all $X \in B_n$. The set of all mappings $T_{\rho,\sigma}$ with respect to composition is a subgroup of $S_{N!}$.

The two functions $F, H \in S_N$ are considered equivalent if there exist permutations $\rho, \sigma \in S_n$ such that $H = T_{\rho,\sigma}(F)$, i.e., if they differ only by a permutation of input or output variables.

Let ι denote the identity permutation. Every permutation $\sigma \in S_n$ uniquely determines the permutation $\sigma' \in S_N$. Let S'_n denote the subgroup of S_N consisting of all permutations σ' corresponding to permutations $\sigma \in S_n$. The mapping $\sigma \mapsto \sigma'$ is a monomorphism from S_n to S_N (see [**2**]).

Let $\sigma \in S_r$. Let p_i, $1 \leqslant i \leqslant r$, denote the number of cycles of length i in a cycle decomposition of σ; here $\sum_{i=1}^{r} ip_i = r$. The cycle index monomial of σ is the product $\prod_{i=1}^{r} t_i^{p_i}$ where t_i, $1 \leqslant i \leqslant r$, are independent variables. It can be equivalently described by the vector $\operatorname{spec}(\sigma) = p = (p_1, p_2, \dots, p_r)$. For an arbitrary positive integer n let $P_n = \{(p_1, p_2, \dots, p_n) \mid p_i \geqslant 0, \sum_{i=1}^{n} ip_i = n\}$ denote the set of partitions of n. For some $p \in P_n$ let $S_{n,p} = \{\sigma \in S_n \mid \operatorname{spec}(\sigma) = p\}$. An arbitrary partition p corresponds to the decomposition $n = k_{p,1} + k_{p,2} + \dots + k_{p,m(p)}$ into positive summands $k_{p,1} \geqslant k_{p,2} \geqslant \dots \geqslant k_{p,m(p)} > 0$ where summand $i = n, n-1, \dots, 1$ in this sum appears p_i times.

Let $\langle r, s\rangle$ and (r, s) denote the least common multiple and the greatest common divisor of r and s, respectively.

3. Preliminaries

The calculation of V_n is based on the following known facts (see e.g., [**1–3**]):

(1) The cardinality of $S_{n,p}$ equals to

$$|S_{n,p}| = \frac{n!}{\prod_i i^{p_i} p_i!}.$$

(2) Let $\sigma_1, \sigma_2 \in S_n$ be permutations such that $\operatorname{spec}(\sigma_1) = \operatorname{spec}(\sigma_2)$. Then $\operatorname{spec}(\sigma'_1) = \operatorname{spec}(\sigma'_2)$. In other words, permutations with the same cycle index in S_n induce the permutations with the same cycle index in S'_n.

(3) The permutation $T_{\rho,\sigma}$ has at least one fixed point if and only if $\operatorname{spec}(\sigma) = \operatorname{spec}(\rho)$.

(4) Let $\sigma \in S_{n,p}$ and let $\operatorname{spec}(\sigma') = p' = (p'_1, p'_2, \dots, p'_N)$. The number of fixed points of $T_{\sigma,\sigma}$ is

$$N_p = \prod_i i^{p'_i} p'_i!.$$

(5) If $\sigma \in S_n$ is a cyclic permutation (a permutation having only one cycle of the length n), then the cycle index monomial of the permutation σ' is

$$\prod_{d|n} f_d^{e(d)},$$

where the numbers $e(k), k \geqslant 1$ are defined by the recurrent relation

$$e(k) = \frac{1}{k}\Big(2^k - \sum_{d|k, d<k} d \cdot e(d)\Big), \quad k > 1.$$

with the initial value $e(1) = 2$.

(6) If α is a permutation on a set X with $|X| = a$ and α has a cycle index monomial $f_1^{j_1} \cdots f_a^{j_a}$, and β is a permutation on Y with $|Y| = b$ and β has a cycle index monomial $f_1^{k_1} \cdots f_b^{k_b}$, then the permutation (α, β) acting on $X \times Y$ by the rule

$$(\alpha, \beta)(x, y) = (\alpha(x), \beta(y))$$

has cycle index monomial given by

$$\Big(\prod_{p=1}^{a} f_p^{j_p}\Big) \bigtimes \Big(\prod_{q=1}^{b} f_q^{k_q}\Big) = \prod_{p=1}^{a}\prod_{q=1}^{b}(f_p^{j_p} \times f_q^{k_q}) = \prod_{p=1}^{a}\prod_{q=1}^{b} f_{\langle p,q\rangle}^{j_p k_q (p,q)}.$$

4. The number of equivalence classes

The value of V_n is determined by the following theorem.

THEOREM 4.1. *For an arbitrary $p \in P_n$ let $\sigma \in S_{n,p}$. If* $\operatorname{spec}(\sigma') = (p'_1, \ldots, p'_n)$, *then*

$$V_n = \sum_{p \in P_n} \frac{\prod_i i^{p'_i} p'_i!}{\left(\prod_i i^{p_i} p_i!\right)^2}. \tag{4.1}$$

PROOF. The permutation $F \in S_N$ is a fixed point of $T_{\rho,\sigma}$ if $T_{\rho,\sigma}(F(X)) = F(X)$ holds for all $X \in B_n$. Let $I(\rho, \sigma)$ be a number of fixed points of $T_{\rho,\sigma}$. By the Frobenius lemma (see e.g. [**1**]) the number of equivalence classes is equal to

$$V_n = \frac{1}{(n!)^2} \sum_{\sigma \in S_n} \sum_{\rho \in S_n} I(\rho, \sigma) = \frac{1}{(n!)^2} \sum_{p \in P_n} \sum_{\rho \in S_{n,p}} \sum_{q \in P_n} \sum_{\sigma \in S_{n,q}} I(\rho, \sigma).$$

By the facts (2)–(4) from Preliminaries, the number of fixed points of $T_{\rho,\sigma}$ corresponding to fixed permutations $\rho \in S_{n,p}$, $\sigma \in S_{n,q}$ is equal to

$$I(\rho, \sigma) = \begin{cases} 0, & p \neq q \\ N_p, & p = q \end{cases}$$

Therefore

$$\begin{aligned} V_n &= \frac{1}{(n!)^2} \sum_{p \in P_n} \sum_{\rho \in S_{n,p}} \sum_{q \in \{p\}} \sum_{\sigma \in S_{n,p}} N_p = \frac{1}{(n!)^2} \sum_{p \in P_n} \sum_{\rho \in S_{n,p}} \sum_{\sigma \in S_{n,p}} N_p \\ &= \frac{1}{(n!)^2} \sum_{p \in P_n} N_p \sum_{\rho \in S_{n,p}} \sum_{\sigma \in S_{n,p}} 1 = \frac{1}{(n!)^2} \sum_{p \in P_n} N_p \cdot |S_{n,p}|^2 \\ &= \sum_{p \in P_n} \frac{\prod_i i^{p'_i} p'_i!}{\left(\prod_i i^{p_i} p_i!\right)^2}. \end{aligned}$$

□

By induction the following generalization of the fact (6) can be proved. If α_i is permutation on Z_i, $|Z_i| = k_i$, $i = 1, \dots, n$, and if the cycle index monomial of α_i is $f_1^{y_{i,1}} \cdots f_{k_i}^{y_{i,k_i}}$, then the permutation $(\alpha_1, \dots, \alpha_n)$ acting on $Z_1 \times Z_2 \times \cdots \times Z_n$ by the rule

$$(\alpha_1, \dots, \alpha_n)(z_1, \dots, z_n) = (\alpha_1(z_1), \dots, \alpha_n(z_n))$$

has cycle index monomial given by

$$\begin{aligned} \bigtimes_{i=1}^{n}\left(\prod_{z_i=1}^{k_i} f_{z_i}^{y_{i,z_i}}\right) &= \prod_{z_1=1}^{k_1}\prod_{z_2=1}^{k_2}\cdots\prod_{z_n=1}^{k_n}\bigtimes_{i=1}^{n} f_{z_i}^{y_{i,z_i}} \\ &= \prod_{z_1=1}^{k_1}\prod_{z_2=1}^{k_2}\cdots\prod_{z_n=1}^{k_n} f_{\langle z_1,z_2,\dots,z_n\rangle}^{\prod_{i=1}^{n}(z_i y_{i,z_i})/\langle z_1,z_2,\dots,z_n\rangle} \end{aligned} \tag{4.2}$$

The proof is based on the fact, also proved by induction, that the cycle index monomial of the direct product of n permutations with cycle index monomials $f_{z_i}^{y_i}$, $1 \leqslant i \leqslant n$ is equal to

$$\bigtimes_{i=1}^{n} f_{z_i}^{y_i} = f_{\langle z_1,z_2,\dots,z_n\rangle}^{\prod_{i=1}^{n}(z_i y_i)/\langle z_1,z_2,\dots,z_n\rangle}$$

Using this generalization, the following theorem shows how to obtain the cycle index p' of σ', used in previous theorem.

THEOREM 4.2. *Let $p \in P_n$ be an arbitrary partition and let $\sigma \in S_{n,p}$. Let $\sigma = \alpha_1\alpha_2\dots\alpha_m$ be a decomposition of σ into disjoint cycles. Let the length of α_i be k_i, $1 \leqslant i \leqslant m$. The cycle index monomial $\prod_i f_i^{p_i'}$ of the corresponding σ' is given by*

$$\bigtimes_{i=1}^{m}\left(\prod_{z_i|k_i} f_{z_i}^{e(z_i)}\right) = \prod_{z_1|k_1}\prod_{z_2|k_2}\cdots\prod_{z_m|k_m} f_{\langle z_1,z_2,\dots,z_m\rangle}^{\prod_{i=1}^{m} z_i e(z_i)/\langle z_1,z_2,\dots,z_m\rangle} \equiv \prod_i f_i^{p_i'}.$$

PROOF. The cycle of length k_i in σ induces the product of cycles in σ' with the cycle index monomial $\prod_{z_i|k_i} f_{z_i}^{e(z_i)}$. The product of permutations with cycle index monomial $\prod_{i=1}^{n} t_i^{p_i} = \prod_{i=1}^{m} t_{k_i}$ in σ induces a permutation with the cycle index monomial $\bigtimes_{i=1}^{m}\prod_{z_i|k_i} f_{z_i}^{e(z_i)}$ in σ'. The cycle index of σ' is then obtained using (4.2)

$$\prod_i f_i^{p_i'} = \prod_{z_1|k_1}\prod_{z_2|k_2}\cdots\prod_{z_m|k_m} f_{\langle z_1,z_2,\dots,z_m\rangle}^{\prod_{i=1}^{m} z_i e(z_i)/\langle z_1,z_2,\dots,z_m\rangle}. \qquad \square$$

The following diagram displays the dependence of the computation time on n. More precisely, the natural logarithms of the two times (in seconds), denoted by T_n and T_n', respectively, are displayed—the time needed to compute V_n, and the time needed to compute only cycle indexes of $\sigma \in S_{n,p}$ and σ' for all partitions $p \in P_n$. It is seen that the most time-consuming part of the algorithm is the calculation including large numbers.

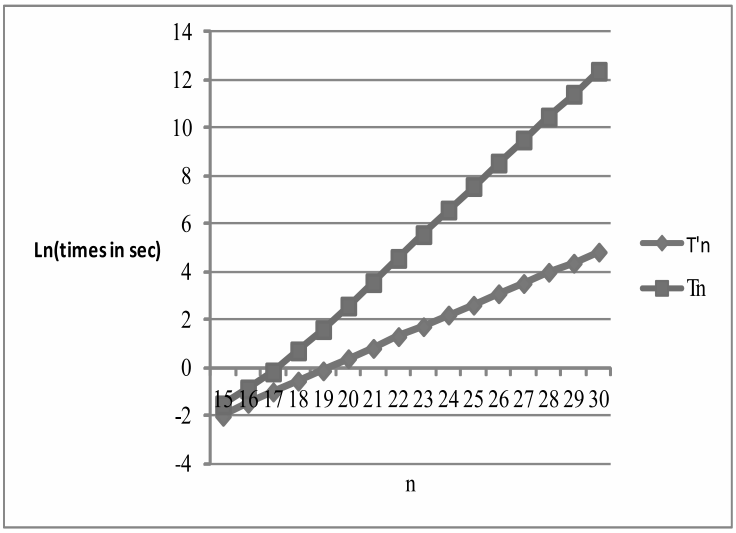

FIGURE 1. Computation time.

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