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RESEARCH ARTICLE

The proportion of derangements characterizes the symmetric and alternating groups

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Abstract

Let G be a subgroup of the symmetric group S_n . If the proportion of fixed-point-free elements in G (or a coset) equals the proportion of fixed-point-free elements in S_n , then $G = S_n$. The analogue for A_n holds if $n \geq 7$. We give an application to monodromy groups.

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1 | INTRODUCTION

1.1 | Derangements in permutation groups

Motivated by an application to monodromy groups, we prove the following.

Theorem 1.1. *Let G be a subgroup of the symmetric group S_n for some $n \geq 1$. Let C be a coset of G in S_n . If*

$$\frac{|\{\sigma \in C : \sigma \text{ has no fixed points}\}|}{|C|} = \frac{|\{\sigma \in S_n : \sigma \text{ has no fixed points}\}|}{|S_n|}, \quad (1)$$

then $G = C = S_n$.

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Elements of S_n with no fixed points are called derangements. Let D_n be the number of derangements in S_n . The right side of (1) is

$$\frac{D_n}{n!} = \sum_{i=0}^n \frac{(-1)^i}{i!};$$

see [10, Example 2.2.1], for instance. When the denominator of $D_n/n!$ in lowest terms is $n!$, the conclusion of Theorem 1.1 follows immediately, but controlling $\gcd(D_n, n!)$ in general is nontrivial. Our proof requires an irrationality measure for e , divisibility properties of D_n , and a bound on the orders of primitive permutation groups.

Remark 1.2. The proof shows also that for $n \geq 5$, if C is not necessarily a coset but just any subset of S_n having the same size as G , then (1) implies that G is A_n or S_n . In fact, we prove that if a subgroup G of S_n has order divisible by the denominator of $D_n/n!$, then G is A_n or S_n .

Remark 1.3. We also prove an analogue of Theorem 1.1 in which both appearances of S_n on the right side of (1) are replaced by the alternating group A_n for some $n \geq 7$; see Theorem 5.1. But there are counterexamples for smaller alternating groups. For example, the order 10 dihedral group in A_5 has the same proportion of derangements as A_5 , namely $4/10 = 24/60$.

1.2 | Application to monodromy

Let \mathbb{F}_q be the finite field of q elements. Let $f(T) \in \mathbb{F}_q[T]$ be a polynomial of degree n . Birch and Swinnerton-Dyer [2] define what it means for f to be ‘general’ and estimate the proportion of field elements in the image of a general f :

$$\frac{|f(\mathbb{F}_q)|}{q} = 1 - \sum_{i=0}^n \frac{(-1)^i}{i!} + O_n(q^{-1/2}).$$

More generally, let $f: X \rightarrow Y$ be a degree n generically étale morphism of schemes of finite type over \mathbb{F}_q , with Y geometrically integral. The geometric and arithmetic monodromy groups G and A are subgroups of S_n fitting in an exact sequence

$$1 \longrightarrow G \longrightarrow A \longrightarrow \mathrm{Gal}(\mathbb{F}_{q^r}/\mathbb{F}_q) \longrightarrow 1$$

for some $r \geq 1$; see [4, Section 4] for an exposition. Let C be the coset of G in A mapping to the Frobenius generator of $\mathrm{Gal}(\mathbb{F}_{q^r}/\mathbb{F}_q)$. Let M be a bound on the geometric complexity of X and Y . Assume that $Y(\mathbb{F}_q) \neq \emptyset$, which is automatic if q is large relative to M . Then the Lang-Weil bound implies

$$\frac{|f(X(\mathbb{F}_q))|}{|Y(\mathbb{F}_q)|} = \frac{|\{\sigma \in C : \sigma \text{ has at least one fixed point}\}|}{|C|} + O_{n,M}(q^{-1/2}); \quad (2)$$

see [4, Theorem 3], for example. In particular, if $G = S_n$, then

$$\frac{|f(X(\mathbb{F}_q))|}{|Y(\mathbb{F}_q)|} = 1 - \sum_{i=0}^n \frac{(-1)^i}{i!} + O_{n,M}(q^{-1/2}). \quad (3)$$

We prove a *converse*, that an estimate as in (3) on the proportion of points in the image implies that the geometric monodromy group of f is the full symmetric group S_n :

Corollary 1.4. *Given n and M , there exists an effectively computable constant $c = c(n, M)$ such that for any $f : X \rightarrow Y$ as above, with $\deg f = n$ and the complexities of X and Y bounded by M , if*

$$\frac{|f(X(\mathbb{F}_q))|}{|Y(\mathbb{F}_q)|} = 1 - \sum_{i=0}^n \frac{(-1)^i}{i!} + \epsilon, \quad \text{where } |\epsilon| < \frac{1}{n!} - cq^{-1/2},$$

then $G = S_n$.

Proof. Combine (2) and Theorem 1.1. □

Remark 1.5. We originally proved Corollary 1.4 in order to prove a version of [8, Theorem 1.9], about specialization of monodromy groups, but later we found a more natural argument.

1.3 | Structure of the paper

The proof of Theorem 1.1 occupies the rest of the paper, which is divided in sections according to the properties of G . Throughout, we assume that G , C , and n are such that (1) holds. The cases with $n \leq 4$ can be checked directly, so assume that $n \geq 5$ and $G \neq S_n$.

2 | PRIMITIVE PERMUTATION GROUPS

The proportion of derangements in A_n is given by the inclusion–exclusion formula; it differs from $D_n/n!$ by the nonzero quantity $\pm(n-1)/n!$. The proportion for S_n is the average of the proportions for A_n and $S_n - A_n$, so the proportion for $S_n - A_n$ also differs from $D_n/n!$. Thus $G \neq A_n$.

Suppose that G is primitive, $n \geq 5$, and $G \neq A_n, S_n$. The main theorem in [9]¹ gives $|G| < 4^n$. On the other hand, $D_n/n!$ is close to $1/e$ and hence cannot equal a rational number with small denominator; this will show that $|G|$ is at least about $\sqrt{n!}$. These will give a contradiction for large n . We now make this precise.

Let $a = |\{\sigma \in C : \sigma \text{ has no fixed points}\}|$ and $b = |C| = |G|$, so $a \leq b = |G| < 4^n$. Then

$$\left| \frac{a}{b} - \frac{1}{e} \right| = \left| \frac{D_n}{n!} - \frac{1}{e} \right| < \frac{1}{(n+1)!}.$$

No rational number with numerator ≤ 4 is within $1/6!$ of $1/e$, so $a \geq 5$. By the main result of [7] (see also [1]),

$$\left| e - \frac{b}{a} \right| > \frac{\log \log a}{3a^2 \log a}.$$

¹ This is independent of the classification of finite simple groups. Using the classification, [6] gives better bounds.

Combining the two displayed inequalities yields

$$\frac{1}{(n+1)!} > \left| \frac{a}{b} - \frac{1}{e} \right| = \frac{a}{be} \left| e - \frac{b}{a} \right| > \frac{1}{be} \cdot \frac{\log \log a}{3a \log a} > \frac{\log \log 4^n}{3e(4^n)^2 \log 4^n}; \quad (4)$$

the last step uses that $a, b < 4^n$ and that $\frac{\log \log x}{x \log x}$ is decreasing for $x \geq 5$. Inequality (4) implies $n \leq 41$.

Let d_n be the denominator of the rational number $\frac{D_n}{n!} = \frac{a}{b}$. Then $d_n \mid b$, so $d_n \leq b < 4^n$. For $11 < n \leq 41$, the inequality $d_n < 4^n$ fails. For $n \leq 11$, a Magma computation [5] shows that there are no degree n primitive subgroups $G \neq A_n, S_n$ for which $d_n \mid b$.

3 | IMPRIMITIVE BUT TRANSITIVE PERMUTATION GROUPS

Suppose that G is imprimitive but transitive. Then G preserves a partition of $\{1, \dots, n\}$ into l subsets of equal size k , for some $k, l \geq 2$ with $kl = n$. The subgroup of S_n preserving such a partition has order $(k!)^l l!$ (it is a wreath product $S_k \wr S_l$). Thus $|G|$ divides $(k!)^l l!$.

For a prime p , let ν_p denote the p -adic valuation. Since $\frac{a}{|G|} = \frac{D_n}{n!}$, every prime $p \nmid D_n$ satisfies $\nu_p(n!) \leq \nu_p(|G|) \leq \nu_p((k!)^l l!) \leq \nu_p(n!)$. Thus for every prime $p \nmid D_n$, the inequality $\nu_p((k!)^l l!) \leq \nu_p(n!)$ is an equality. The third of the three following lemmas will prove that this is impossible for $n \geq 5$.

Lemma 3.1. *Let $k, l \geq 2$ and let p be a prime. The inequality*

$$\nu_p((k!)^l l!) \leq \nu_p(kl!) \quad (5)$$

is an equality if and only if at least one of the following holds:

- k is a power of p ;
- there are no carry operations in the l -term addition $k + \dots + k$ when k is written in base p (in particular, $l < p$).

Proof. Let $s_p(k)$ denote the sum of the p -adic digits of a positive integer k ; then $\nu_p(k!) = \frac{k - s_p(k)}{p-1}$. Thus equality in (5) is equivalent to equality in

$$l + s_p(kl) \leq s_p(k) + s_p(l). \quad (6)$$

We always have

$$l + s_p(kl) \leq l + s_p(k)s_p(l) \leq s_p(k) + s_p(l); \quad (7)$$

the first follows from $s_p(kl) \leq s_p(k)s_p(l)$, and the second is simply

$$(s_p(k) - 1)(l - s_p(l)) \geq 0.$$

Thus equality in (6) is equivalent to equality in both inequalities of (7).

The second inequality of (7) is an equality if and only if either k is a power of p or $l < p$; in each case, we must check when equality holds in the first inequality (7), that is, when $s_p(kl) = s_p(k)s_p(l)$. If k is a power of p , then it holds. If $l < p$, then it holds if and only if $s_p(kl) = ls_p(k)$, which holds if and only if there are no carry operations in the l -term addition $k + \dots + k$ when k is written in base p . \square

The following lemma will help us produce primes p not dividing D_n .

Lemma 3.2. *For $0 \leq m \leq n$, we have $D_n \equiv (-1)^{n-m} D_m \pmod{n-m}$. In particular,*

$$D_n \equiv \pm 1 \pmod{n} \quad (8)$$

$$D_n \equiv \pm 1 \pmod{n-2} \quad (9)$$

$$D_n \equiv \pm 2 \pmod{n-3}. \quad (10)$$

Proof. Reduce each term in D_n modulo $n-m$; most of them are 0. \square

Lemma 3.3. *Let $k, l \geq 2$. Set $n = kl$ and assume $n > 4$. Then there exists a prime $p \nmid D_n$ such that*

$$\nu_p((k!)^l l!) < \nu_p(n!).$$

Proof. **Case 1. $l \geq 3$ and $n-2$ is not a power of 2.**

Let $p \geq 3$ be a prime with $p \mid n-2$. By (9), $p \nmid D_n$, so $\nu_p((k!)^l l!) = \nu_p(n!)$. Apply Lemma 3.1. If k is a power of p , then p divides k , which divides n , so $p \mid n - (n-2) = 2$, contradicting $p \geq 3$. Otherwise, there are no carry operations in the l -term addition $k + \dots + k$ in base p . This is impossible because the last digit of n is 2 (since $p \mid n-2$ and $p \geq 3$) and $l \geq 3$.

Case 2. $l = 2$.

Then $2 \mid n$. By (8), $2 \nmid D_n$. By Lemma 3.1, k is a power of 2 (since $l < 2$ is violated). Thus $n = 2k$ is a power of 2.

Since $n \geq 5$, there exists a prime $p \mid n-3$. Since n is a power of 2, this implies $p \geq 5$. By (10), $p \nmid D_n$. Apply Lemma 3.1. Note that k is not a power of p , since k is a power of 2 and $p \neq 2$. Therefore, there are no carry operations in $k + k = n$, so the last digit of n is even. But $p \mid n-3$ and $p \geq 5$, so the last digit of n is 3.

Case 3. $l = 3$ and $n-2$ is a power of 2.

Then $3 \mid n$. By (8), $3 \nmid D_n$. By Lemma 3.1, k must be a power of 3 (since $l < 3$ is violated). Then $n = 3k$ is a power of 3, contradicting the fact that n is even.

Case 4. $l > 3$ and $n-2$ is a power of 2.

In particular, $n = kl > 6$. Then $n-3$ is not a power of 3, because otherwise we would have a solution to $3^u = 2^v - 1$ with $u > 1$, whereas the only solution in positive integers is $(u, v) = (1, 2)$ (proof: $3 \mid 2^v - 1$, so v is even, so $2^{v/2} - 1$ and $2^{v/2} + 1$ are powers of 3 that differ by 2, so they are 1 and 3).

Let $p \neq 3$ be a prime divisor of $n-3$. Then $p \geq 5$. Apply (10) and Lemma 3.1. If k is a power of p , then $p \mid n$, so $p \mid n - (n-3) = 3$, contradicting $p \neq 3$. Therefore, there are no carry operations

in the l -term addition $k + \dots + k$. This is impossible, since the last digit of kl is 3 (since $p \mid n - 3$ and $p \geq 5$) and $l > 3$. \square

4 | INTRANSITIVE PERMUTATION GROUPS

Suppose that G is intransitive. Then G embeds in $S_u \times S_v \subset S_n$ for some $u, v \geq 1$ with $u + v = n$.

Consider a prime $p \mid n$. By (8), $p \nmid D_n$. Then, analogously to the second paragraph of Section 3, $\nu_p(n!) \leq \nu_p(|G|) \leq \nu_p(u!v!) \leq \nu_p(n!)$, so $\nu_p(u!) + \nu_p(v!) = \nu_p(n!)$; equivalently, $s_p(u) + s_p(v) = s_p(n)$. So there are no carry operations in $u + v$. Let $e = \nu_p(n)$, so the last e base p digits of n are zero; then the same holds for u and v . In other words, $p^e \mid u, v$ as well. Since this holds for each $p \mid n$, we conclude that $n \mid u, v$. This contradicts $0 < u, v < n$.

This completes the proof of Theorem 1.1.

5 | ALTERNATING GROUP

Theorem 5.1. *Let G be a subgroup of the symmetric group S_n for some $n \geq 7$. Let C be a coset of G in S_n having the same proportion of fixed-point-free elements as A_n . Then $G = A_n$.*

Remark 5.2. For $n \leq 6$, the subgroups of S_n other than A_n for which some coset has the same proportion as A_n , up to conjugacy, are:

- the order 4 subgroup of S_4 generated by (1423) and (12)(34);
- the order 4 subgroup of S_4 generated by (34) and (12)(34);
- the order 8 subgroup of S_4 ;
- the subgroups of S_5 of order 5, 10, or 20;
- the order 36 subgroup of S_6 generated by (1623)(45), (12)(36), (124)(365), and (142)(365);
- the order 36 subgroup of S_6 generated by (13)(25)(46), (14)(36), (154)(236), and (145)(236).

The proof of Theorem 5.1 follows the proof of Theorem 1.1; we highlight only the differences. The proportion of fixed-point-free elements in A_n is $E_n/n!$, where $E_n := D_n + (-1)^{n-1}(n-1)$.

5.1 | Primitive permutation groups

Suppose $G \neq A_n$. The first paragraph of Section 2 shows that $G \neq S_n$. For $7 \leq n \leq 13$, we use Magma to check Theorem 5.1 for each primitive subgroup of S_n . So assume $n \geq 14$. Define a and b as in Section 2. We have

$$\left| \frac{a}{b} - \frac{1}{e} \right| = \left| \frac{E_n}{n!} - \frac{1}{e} \right| \leq \left| \frac{E_n - D_n}{n!} \right| + \left| \frac{D_n}{n!} - \frac{1}{e} \right| < \frac{n-1}{n!} + \frac{1}{(n+1)!} = \frac{n^2}{(n+1)!}.$$

No a/b with $a < 5$ is within $15^2/16!$ of $1/e$, so $a \geq 5$. Inequality (4) with $1/(n+1)!$ replaced by $n^2/(n+1)!$ implies $n \leq 49$.

Let e_n be the denominator of $E_n/n!$, so e_n divides $|G|$, which is less than 4^n . But for $13 < n \leq 49$, the inequality $e_n < 4^n$ fails.

5.2 | Imprimitive permutation groups that preserve a partition into blocks of equal size

To rule out imprimitive permutation groups that preserve a partition into l blocks of size k , we argue as in Section 3, but with Lemma 3.3 replaced by the following.

Lemma 5.3. *Let $k, l \geq 2$. Set $n = kl$ and assume $n > 6$. Then there exists a prime $p \nmid E_n$ such that*

$$\nu_p((k!)^l l!) < \nu_p(n!).$$

Proof of Lemma 5.3. For each integer $n \in (6, 30]$, we check directly that there exists a prime $p \in (n/2, n]$ such that $p \nmid E_n$. Assume from now on that $n > 30$.

Suppose the statement is false. Then whenever a prime p satisfies $p \nmid E_n$, (5) is an equality and Lemma 3.1 applies.

By using $D_n \equiv (-1)^{n-s} D_s \pmod{n-s}$ and $E_n = D_n + (-1)^{n-1}(n-1)$, we obtain

$$E_n \equiv 2(-1)^n \pmod{n} \quad (11)$$

$$E_n \equiv 4(-1)^{n-1} \pmod{n-3} \quad (12)$$

$$E_n \equiv 6(-1)^n \pmod{n-4} \quad (13)$$

$$E_n \equiv (-1)^{n-1} 2^4 \times 3 \pmod{n-5} \quad (14)$$

Case 1. $n - 4$ is a power of 2.

Then $n - 3$ is not a power of 3 because otherwise, we have a solution to $3^u - 1 = 2^v$ with $u \geq 3$; working modulo 4 shows that u is even, and factoring the left side leads to a contradiction. Let $p \neq 3$ be a prime with $p \mid n - 3$. Since $n - 3$ is odd, $p \geq 5$. By (12), $p \nmid E_n$, so we have one of the conclusions of Lemma 3.1.

If k is a power of p , then $p \mid k \mid n$, which, combined with $p \mid n - 3$ gives $p = 3$, a contradiction.

Suppose that there is no carry in $k + \dots + k$ (l terms). This sum has last digit 3 in base p , so $l = 3$, so $3 \mid n$, and hence $3 \nmid E_n$ by (11). Apply Lemma 3.1 for the prime 3. Since $l < 3$ is violated, we deduce that k is a power of 3. Then $n = kl$ is also a power of 3, but this contradicts the fact that n is even.

Case 2. $n - 3$ is a power of 2 and $l \neq 2, 4$.

Then $n - 4$ is odd and is not a power of 3. Let $p \neq 3$ be a prime with $p \mid n - 4$. Then $p \geq 5$, so $p \nmid E_n$ by (13). If k is a power of p , then $p \mid k \mid n$, which contradicts $p \mid n - 4$ since $p \geq 5$. If there are no carry operations in the l -term addition $k + \dots + k$ (which has last digit 4 in base p), then $l = 2$ or $l = 4$, contrary to assumption.

Case 3. $l = 3$.

Then $3 \mid n$, hence $3 \nmid E_n$ by (11). Apply Lemma 3.1 for the prime 3. Since $3 < l$ is violated, k is a power of 3. Then $n = kl$ is also a power of 3. Then $n - 4$ is odd and not divisible by 3. Let q be a prime with $q \mid n - 4$. Then $q \geq 5$, and hence $q \nmid E_n$ by (13). Since k is a power of 3, it is not a power of q . So there is no carry in $k + k + k$ in base q . But this sum has last digit 4 in base q , which is a contradiction.

Case 4. $l \neq 2, 4$.

By the previous cases, we may assume in addition that $n - 4$ and $n - 3$ are not powers of 2 and $l \neq 3$.

Let $p \neq 2$ be a prime with $p \mid n - 3$. Then $p \nmid E_n$ by (12). Since the l -term addition $k + \dots + k$ has last digit 3 and $l \neq 3$, there is some carry. Therefore k is a power of p . Then $p \mid k \mid n$, which, combined with $p \mid n - 3$, gives $p = 3$. In particular, $3 \mid n$.

Let $q \neq 2$ be a prime with $q \mid n - 4$. Since $3 \mid n$, we have $q \neq 3$ so $q \geq 5$. By (13), $q \nmid E_n$. If k is a power of q , then $q \mid n$, hence $q \mid 4$ — contradiction. Therefore there is no carry in the l -term addition $k + \dots + k$ in base q . This sum has last digit 4 and $l \neq 2, 4$, so this case is impossible.

Case 5. $l = 2$ or $l = 4$.

Then n is even, so $n - 3$ and $n - 5$ are odd.

Subcase 5.1: $n - 3$ is not a power of 3.

Let $p \neq 3$ be a prime such that $p \mid n - 3$. Then $p \geq 5$ and $p \nmid E_n$ by (12). If k is a power of p , then $p \mid k \mid n$, giving $p = 3$, which is a contradiction. However, there is carry in the l -term addition $k + \dots + k$ because the sum has last digit 3, and l is 2 or 4.

Subcase 5.2: $n - 3$ is a power of 3 but $n - 5$ is not a power of 5.

Let $p \neq 5$ be a prime with $p \mid n - 5$. Then $p \geq 7$ and we apply the argument of subcase 5.1: an l -term sum $k + \dots + k$ cannot have last digit 5 in base p .

Subcase 5.3: $n - 3 = 3^a$ and $n - 5 = 5^b$ for some $a, b \geq 1$.

Then $3^a - 5^b = 2$, so $a = 3$ and $b = 2$ by [3, Theorem 4.06]. This contradicts $n > 30$. \square

5.3 | Intransitive subgroups

As in Section 4, G embeds in $S_u \times S_v \subset S_n$ for some $u, v \geq 1$ with $u + v = n$. Write $n = 2^s m$, where $s \geq 0$ and $2 \nmid m$. The argument in Section 4 for odd p with E_n in place of D_n and (11) in place of (8) implies $m \mid u, v$. Thus $s \geq 1$.

If $s = 1$, then $n = 2m$, so $u = v$. This case is covered in Section 5.2.

Suppose that $s \geq 2$. Then $4 \mid n$, so (11) implies that $E_n/2$ is odd. Using $\frac{a}{|G|} = \frac{E_n/2}{n!/2}$, we obtain $\nu_2(n!/2) \leq \nu_2(|G|) \leq \nu_2(u!v!) \leq \nu_2(n!)$. If the last inequality is an equality, then the same argument used in Section 4 shows that $\nu_2(u) = \nu_2(v) = \nu_2(n)$; combining this with $m \mid u, v$ shows that $n \mid u, v$, a contradiction. Therefore the first two inequalities must be equalities, so $\nu_2(u!v!) = \nu_2(n!) - 1$; equivalently, $s_2(u) + s_2(v) = s_2(n) + 1$. This means there is exactly one carry operation in $u + v$ in base 2. This is possible only when $2^{s-1} \mid u, v$. Also, $m \mid u, v$, so $n/2 \mid u, v$, so again $u = v$, and this case is covered in Section 5.2.

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