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On the sequence $n!$ mod p

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Abstract. We prove that the sequence $1!, 2!, 3!, \ldots$ produces at least $(\sqrt{2}+o(1))\sqrt{p}$ distinct residues modulo prime p. Moreover, the factorials within an interval $\mathcal{I} \subseteq \{0, 1, \ldots, p-1\}$ of length $N > p^{7/8+\varepsilon}$ produce at least $(1+o(1))\sqrt{p}$ distinct residues modulo p. As a corollary, we prove that every non-zero residue class can be expressed as a product of seven factorials $n_1! \cdots n_7!$ modulo p, where $n_i = O(p^{6/7+\varepsilon})$ for all $i = 1, \ldots, 7$, which provides a polynomial improvement upon the preceding results.

1. Introduction

Wilson's theorem represents one of the most elegant results in elementary number theory. It states that if p is a prime number, then $(p-1)! = -1 \mod p$. As one of its simple corollaries, we note that $(p-2)! = 1! \mod p$, and thus not all the residues from

$$\mathcal{A}(p) := \{i! \mod p : i \in [p-1]\}$$

are distinct. Erdős conjectured, see [16], that this is not the only coincidence, i.e., that $|\mathcal{A}(p)| < p-2$. Surprisingly, despite the long history of this natural problem, Erdős' conjecture remains widely open though verified [18] for all primes $p < 10^9$.

At the same time, it is widely believed (see [2,6] and Section F11 in [12]) that the elements of $\mathcal{A}(p)$ may be considered as more or less 'independent uniform random variables' for large p. In particular, it is conjectured that

$$|\mathcal{A}(p)| = \Big(1 - \frac{1}{e} + o(1)\Big)p$$

as $p \to \infty$. However, the best lower bound up to now is due to García [10]:

Theorem (García).

$$|\mathcal{A}(p)| \geqslant \Big(\sqrt{\frac{41}{24}} + o(1)\Big)\sqrt{p}.$$

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The strategy in [10] was to prove that $\mathcal{A}(p)\mathcal{A}(p)$ contains residues with certain properties, which forces the estimate $|\mathcal{A}(p)\mathcal{A}(p)| \geqslant (41/48 + o(1))p$ to hold; combined with the observation

$$\binom{|\mathcal{A}(p)|+1}{2} \geqslant |\mathcal{A}(p)\mathcal{A}(p)|,$$

this yields the result. We improve it to the following.

Theorem 1.1.

$$|\mathcal{A}(p)\mathcal{A}(p)| \geqslant p + O(p^{13/14}(\log p)^{4/7}).$$

Corollary 1.2.

$$|\mathcal{A}(p)| \geqslant \big(\sqrt{2} + o(1)\big)\sqrt{p}.$$

One of the natural ways to generalize this problem is to consider it in a 'short interval' setting (see [8, 9, 13, 15]). Throughout this paper, we let p be a large enough prime, and L and N will be integers such that $0 < L + 1 < L + N < p$. Following Garaev and Hernández [8], we define a 'short interval' analogue of $\mathcal{A}(p)$ as follows:

$$\mathcal{A}(L,N) := \{n! \mod p : L+1 \leqslant n \leqslant L+N\}.$$

As L will not play any role, we write $\mathcal{A}_N$ for short. To bound the cardinality of this set from below, it is usually fruitful to estimate the size of $\mathcal{A}_N/\mathcal{A}_N$, the set of pairwise fractions, since we trivially have $|\mathcal{A}_N|^2 \geqslant |\mathcal{A}_N/\mathcal{A}_N|$. The first lower bounds on the size of this set of fractions were linear on N (see [9, 13]), while Garaev and Hernández [8] found the following logarithmic improvement.

Theorem (Garaev–Hernández). *Let $p^{1/2+\varepsilon} < N < p/10$. Then, for some $c_0 = c_0(\varepsilon) > 0$,*

$$|\mathcal{A}_N/\mathcal{A}_N| \geqslant c_0 N \log\left(\frac{p}{N}\right).$$

The strategy in [8] was to observe that $\mathcal{A}_N/\mathcal{A}_N$ contains the sets $X_1, X_2, \ldots, X_M$ defined as $X_j = \{(x+1)(x+2)\cdots(x+j) : L+1 \leqslant x \leqslant L+N-M\}$, and then prove that the X_j are 'large', but their intersections $X_k \cap X_j$ are 'small', which makes the inclusion-exclusion formula applicable:

$$|\mathcal{A}_N/\mathcal{A}_N| \geqslant |X_1 \cup X_2 \cup \cdots| \geqslant \sum_j |X_j| - \sum_{k<j} |X_k \cap X_j| \gg \sum_j |X_j|.$$

In the present paper, we give the following improvement of this result.

Theorem 1.3. *Let N be such that $c_5\sqrt{p}(\log p)^2 \leqslant N \leqslant p$. Let $K := p/N$ and let $Q := \frac{N}{\sqrt{p}(\log p)^2}$. Then*

$$|\mathcal{A}_N/\mathcal{A}_N| \geqslant \begin{cases} p + O(p^{13/14}(\log p)^{4/7}) & \text{if } N \geqslant c_1 p^{13/14}(\log p)^{4/7}, \\ p + O(p^{5/6}K^{4/3}(\log p)^{4/3}) & \text{if } c_1 p^{13/14}(\log p)^{4/7} \geqslant N \geqslant c_2 p^{7/8}\log p, \\ cNQ^{1/3}(\log Q)^{-2/3} & \text{if } c_2 p^{7/8}\log p \geqslant N \geqslant c_3 p^{4/5}(\log p)^{8/5}, \\ cNK^{1/2} & \text{if } c_3 p^{4/5}(\log p)^{8/5} \geqslant N \geqslant c_4 p^{4/5}(\log p)^{4/5}, \\ cNQ^{1/3} & \text{if } c_4 p^{4/5}(\log p)^{4/5} \geqslant N \geqslant c_5 p^{1/2}(\log p)^2. \end{cases}$$

where $c, c_1, c_2, c_3, c_4, c_5 > 0$ are some absolute constants, whose values can be extracted from the proof.

Corollary 1.4. *For $N \gg p^{7/8}\log p$,*

$$|\mathcal{A}_N| \geqslant (1+o(1))\sqrt{p}.$$

To derive Theorem 1.3, we continue the strategy from [8] as follows: using strong results from algebraic geometry, we prove 'best possible' bounds $|X_j| \geqslant (1+o(1))N$ and $|X_k \cap X_j| \leqslant (1+o(1))N^2/p$ for prime k, j. Then we observe that bounds on sets X_j and their intersections imply they behave like independent random variables, and therefore the size of their union is at least $p+o(p)$ (see Lemma 2.1), which implies that $\mathcal{A}_N/\mathcal{A}_N$ has size at least $p+o(p)$.

This strategy turns out to be helpful when proving Theorem 1.1 as well.

One of the nice applications of these results deals with the representation of residues as a product of several factorials. It is not hard to see that the classical Wilson theorem implies the following. Any given $a \in [p-1]$ can be represented[1] as a product of three factorials,

$$a \equiv n_1!\,n_2!\,n_3! \mod p$$

for some $n_1, n_2, n_3 \in [p-1]$. The aforementioned conjecture on the 'randomness' of $\mathcal{A}(p)$ implies that even two factorials are enough. However, if we add the additional constraint that all the n_i should be of magnitude $o(p)$ as $p \to \infty$, it becomes not so clear how many factorials are required. Garaev, Luca, and Shparlinski [9] coped with seven.

Theorem (Garaev, Luca and Shparlinski). *Fix any positive $\varepsilon < 1/12$. Then for all prime p, every residue class $a \not\equiv 0 \mod p$ can be represented as a product of seven factorials,*

$$a \equiv n_1! \cdots n_7! \pmod{p},$$

such that $n_0 := \max_{1\le i\le 7} n_i = O(p^{11/12+\varepsilon})$ as $p \to \infty$.

During the last two decades, the number of factors in the last theorem was not reduced even to 6. However, there were certain improvements on the value of n_0. García [11] showed that the theorem above holds with $n_0 = O(p^{11/12}\log^{1/2} p)$, while Garaev and Hernández [8] relaxed it to $O(p^{11/12}\log^{-1/2} p)$. Since our Theorem 1.3 improves the bounds used in the latter proof, one can obtain a slight (again, *polynomial*) improvement on the value of n_0 by following the same proof.

Theorem 1.5. *Fix any positive $\varepsilon < 1/7$. Then for all prime p, every residue class $a \not\equiv 0$ mod p can be represented as a product of seven factorials,*

$$a \equiv n_1! \cdots n_7! \pmod{p},$$

such that $n_0 := \max_{1\le i\le 7} n_i = O(p^{6/7+\varepsilon})$ as $p \to \infty$.

The remainder of the text has the following structure. In Section 2 we introduce some notations and useful lemmas, in Section 3 we prove results on images of 'generic' polynomials, in Section 4 we apply these results to polynomials $P_j(x) = (x+1)\cdots(x+j)$, and, finally, in Sections 5 and 6 we prove Theorems 1.1 and 1.3.

[1] Indeed, one may easily verify that, depending on the 'parity' of the inverse residue $b \equiv a^{-1}$, we have either $a \equiv (b-1)!(p-1-b)!$, or $a \equiv -(b-1)!(p-1-b)! \equiv (b-1)!(p-1-b)!(p-1)!$ modulo p.

2. Conventions and preliminary results

Here and below, p denotes a large prime number.

Whenever A is a set, we identify it with its indicator function

$$A(x) = \begin{cases} 1, & x \in A, \\ 0, & x \notin A. \end{cases}$$

Throughout the paper, the standard notations $\ll$, $\gg$, and respectively O and Ω, are applied to positive quantities in the usual way. That is, $X \ll Y$, $Y \gg X$, $X = O(Y)$ and $Y = \Omega(X)$ all mean that $Y \geqslant cX$, for some absolute constant $c > 0$.

A polynomial $f \in \mathbb{F}_p[x]$ is *decomposable* if $f = g \circ h$ for some polynomials $g, h \in \mathbb{F}_p[x]$ of degrees at least 2. Otherwise, it is *indecomposable*.

We recall that for any integer $d > 0$ and $a \in \mathbb{F}_p$, the *Dickson polynomial* $D_{d,a} \in \mathbb{F}_p[x]$ is defined to be the unique polynomial such that $D_{d,a}(x + a/x) = x^d + (a/x)^d$. There is also an explicit formula for it:

$$D_{d,a}(x) = \sum_{i=0}^{\lfloor d/2 \rfloor} \frac{d}{d-i} \binom{d-i}{i} (-a)^i x^{d-2i}.$$

For a positive integer j, define the polynomial

$$P_j(x) = \prod_{i=1}^{j} (x + i).$$

Given a set A and a polynomial $P \in \mathbb{F}_p[x]$, denote by $P(A)$ the set $\{P(a) \pmod{p} : a \in A\}$.

A key lemma to estimate the union of sets is the following.

Lemma 2.1. *Let $A_1, A_2, \ldots, A_n$ be finite sets, and let $a \geqslant b$ be positive integers, such that the following properties hold*:

- $|A_i| \geqslant a$ *for all* i,
- $|A_i \cap A_j| \leqslant b$ *for all* $i \neq j$.

Let $A := A_1 \cup A_2 \cup \cdots \cup A_n$. Then

$$|A| \geqslant \frac{a^2}{b}\Big(1 - \frac{a}{nb}\Big).$$

Proof. Let $S = \sum_{i \leqslant n} \sum_{a \in A} A_i(a) \geqslant na$. Observe that

$$S^2 = \Big(\sum_{a \in A}\Big(\sum_{i \leqslant n} A_i(a)\Big)\Big)^2 \leqslant |A| \sum_{a \in A}\Big(\sum_{i \leqslant n} A_i(a)\Big)^2 = |A| \sum_{a \in A} \sum_{i,j \leqslant n} A_i(a) A_j(a)$$
$$= |A| \sum_{i,j \leqslant n} |A_i \cap A_j| \leqslant |A|\big(S + (n^2 - n)b\big),$$

which implies

$$|A| \geqslant \frac{S^2}{S + (n^2 - n)b} \geqslant \frac{(na)^2}{na + (n^2 - n)b} \geqslant \frac{na^2}{a + nb} = \frac{a^2}{b} \frac{1}{1 + \frac{a}{bn}} \geqslant \frac{a^2}{b}\Big(1 - \frac{a}{bn}\Big). \qquad \blacksquare$$

3. On images of generic polynomials

The two following results seem to be well known, yet not explicitly written in the literature (see [4,5] for more information on related questions); we prove them here for the sake of completeness.

Lemma 3.1. *Let $P \in \mathbb{F}_p[x]$ of degree d be such that $(P(x) - P(y))/(x - y)$ is absolutely irreducible over $\mathbb{F}_p$, and let $\mathcal{I}$ be an arithmetical progression in $\mathbb{F}_p$. Then*

$$|P(\mathcal{I})| = |\mathcal{I}| + O\big(|\mathcal{I}|^2 p^{-1} + d^2 \sqrt{p}\,(\log p)^2\big).$$

Lemma 3.2. *Let $P, Q \in \mathbb{F}_p[x]$ of maximal degree d be such that $P(x) - Q(y)$ is absolutely irreducible over $\mathbb{F}_p$, and let $\mathcal{I}$ be an arithmetical progression in $\mathbb{F}_p$. Then*

$$|P(\mathcal{I}) \cap Q(\mathcal{I})| \leqslant |\mathcal{I}|^2 p^{-1} + O(d^2 \sqrt{p}\,(\log p)^2).$$

We postpone their proofs until the end of the section, and formulate some helpful results, which are only to be used in this section.

Given $P, Q \in \mathbb{F}_p[x]$, let us define $\phi(P, Q) \in \mathbb{F}_p[x, y]$ as

$$\phi(P, Q)(x, y) := \begin{cases} P(x) - Q(y), & \text{if } P \neq Q, \\ \frac{P(x)-P(y)}{x-y}, & \text{if } P = Q. \end{cases}$$

Let us also define

$$J(P, Q) := \#\big\{(x, y) \in \mathbb{F}_p \times \mathbb{F}_p : \phi(P, Q)(x, y) = 0\big\}.$$

Lemma 3.3. *Given $P, Q \in \mathbb{F}_p[x]$, suppose that $\phi(P, Q)$ is absolutely irreducible over $\mathbb{F}_p$. Then*

$$J(P, Q) = p + O(d^2 \sqrt{p}),$$

where d is the degree of $\phi(P, Q)$.

Proof. We recall the modification of the classical Lang–Weil result [14], with an error term due to Aubry and Perret [1]:

Theorem (Lang–Weil). *Let $\mathbb{F}_q$ be a finite field. Let $X \subseteq \mathbb{A}^2_{\mathbb{F}_q}$ be a geometrically irreducible hypersurface of degree d. Then*

$$|X(\mathbb{F}_q) - q| \leqslant (d - 1)(d - 2)\sqrt{q} + d - 1.$$

Since $\phi(P, Q)(x, y)$ is absolutely irreducible over $\mathbb{F}_p$, its set of zeros is (by definition) a geometrically irreducible hypersurface, and therefore the Lang–Weil theorem is applicable. This proves the lemma. ∎

Given a subset $\mathcal{I} \subseteq \mathbb{F}_p$, let us define

$$J_{\mathcal{I}}(P, Q) := \#\{(x, y) \in \mathcal{I} \times \mathcal{I} : \phi(P, Q)(x, y) = 0\}.$$

We need the following lemma, whose proof is already contained in [8], but we write it down explicitly here in full generality.

Lemma 3.4. *Let $P, Q \in \mathbb{F}_p[x]$ be such that $\phi(P,Q)$ has no linear divisors. Let $\mathcal{J}$ be an arithmetical progression in $\mathbb{F}_p$. Then*

$$J_{\mathcal{J}}(P,Q) = \frac{|\mathcal{J}|^2}{p^2}\, J(P,Q) + O(d^2\sqrt{p}\,(\log p)^2),$$

where d is the degree of $\phi(P,Q)$.

Proof. We recall the statement of Lemma 1 in [8] (originated in [3]):

Theorem (Bombieri, Chalk-Smith). *Let $(b_1, b_2) \in \mathbb{F}_p \times \mathbb{F}_p$ be a nonzero vector, and let $f(x,y) \in \mathbb{F}_p[x,y]$ be a polynomial of degree $d \geqslant 1$ with the following property: there is no $c \in \mathbb{F}_p$ for which the polynomial $f(x,y)$ is divisible by $b_1x + b_2y + c$. Then*

$$\Bigg| \sum_{\substack{(x,y)\in\mathbb{F}_p\times\mathbb{F}_p:\\ f(x,y)=0}} e^{2\pi i(b_1x+b_2y)/p} \Bigg| \leqslant 2d^2p^{1/2}.$$

In what follows, we will need a bit of discrete Fourier transform in $\mathbb{F}_p$. Given a function $f\colon \mathbb{F}_p \to \mathbb{C}$, we define its discrete Fourier transform $\hat{f}\colon \mathbb{F}_p \to \mathbb{C}$ by

$$\hat{f}(r) = \sum_{x\in\mathbb{F}_p} f(x)\, e^{-2\pi i\, rx/p}.$$

One can easily verify the inverse Fourier transform formula:

$$f(x) = \frac{1}{p}\sum_{r\in\mathbb{F}_p} \hat{f}(r)\, e^{2\pi i\, rx/p}.$$

We also need the following well-known result. Let $\mathcal{J}$ be a (finite) arithmetic progression in $\mathbb{F}_p$. Then

$$\sum_{r\in\mathbb{F}_p} |\hat{\mathcal{J}}(r)| \ll p\log p,$$

where $\mathcal{J}\colon \mathbb{F}_p \to \mathbb{C}$ is interpreted as the characteristic function of the set $\mathcal{J} \subseteq \mathbb{F}_p$.

Let us consider $\mathcal{J}$ as a characteristic function of a set. Then

$$\begin{aligned} J_{\mathcal{J}}(P,Q) &= \sum_{\substack{(x,y)\in\mathbb{F}_p\times\mathbb{F}_p:\\ \phi(P,Q)(x,y)=0}} \mathcal{J}(x)\,\mathcal{J}(y) = \sum_{\substack{(x,y)\in\mathbb{F}_p\times\mathbb{F}_p:\\ \phi(P,Q)(x,y)=0}} \frac{1}{p^2}\sum_{r_1,r_2\in\mathbb{F}_p} \hat{\mathcal{J}}(r_1)\,\hat{\mathcal{J}}(r_2)\, e^{2\pi\frac{(r_1x+r_2y)}{p}} \\ &= \frac{|\mathcal{J}|\,|\mathcal{J}|}{p^2} J(P,Q) + \frac{1}{p^2}\sum_{(r_1,r_2)\neq(0,0)} \hat{\mathcal{J}}(r_1)\,\hat{\mathcal{J}}(r_2) \sum_{\substack{(x,y)\in\mathbb{F}_p\times\mathbb{F}_p\\ \phi(P,Q)(x,y)=0}} e^{2\pi i\frac{(r_1x+r_2y)}{p}}. \end{aligned}$$

The last summand can be bounded as

$$\frac{1}{p^2}\sum_{r_1\in\mathbb{F}_p} |\hat{\mathcal{J}}(r_1)| \sum_{r_2\in\mathbb{F}_p} |\hat{\mathcal{J}}(r_2)| \max_{(r_1,r_2)\neq 0} \Bigg| \sum_{\substack{(x,y)\in\mathbb{F}_p\times\mathbb{F}_p:\\ \phi(P,Q)(x,y)=0}} e^{2\pi i\frac{r_1x+r_2y}{p}} \Bigg| \ll (\log p)^2\sqrt{p}d^2.$$

This completes the proof. ∎

Now, let us turn to the proof of Lemma 3.1.

Proof. Clearly, $|P(\mathcal{I})| \leqslant |\mathcal{I}|$. Let us obtain a lower bound. The Cauchy–Bunyakovsky–Schwarz inequality implies

$$\#\{(x,y) \in \mathcal{I} \times \mathcal{I} : P(x) = P(y)\}|P(\mathcal{I})| \geqslant |\mathcal{I}|^2,$$

Clearly,

$$\#\{(x,y) \in \mathcal{I} \times \mathcal{I} : P(x) = P(y)\} = |\mathcal{I}| + J_{\mathcal{I}}(P,P) \leqslant |\mathcal{I}| + |\mathcal{I}|^2 p^{-1} + O(d^2\sqrt{p}\log^2 p),$$

where we applied Lemmas 3.4 and 3.3. Deriving the lower bound on $|P(\mathcal{I})|$ completes the proof. ∎

Now we prove Lemma 3.2.

Proof. By Lemmas 3.4 and 3.3,

$$\begin{aligned} |P(\mathcal{I}) \cap Q(\mathcal{I})| \leqslant J_{\mathcal{I}}(P,Q) &= \frac{|\mathcal{I}|^2}{p^2} J(P,Q) + O(d^2\sqrt{p}\log^2 p) \\ &\leqslant \frac{|\mathcal{I}|^2}{p} + O(d^2\sqrt{p}\log^2 p). \end{aligned}$$ ∎

4. Properties of the polynomials P_j

Let us start with the following simple lemma.

Lemma 4.1. *For a given integer j, $5 \leqslant j < p$, the polynomial $P_j(x) \in \mathbb{F}_p[x]$ is not equal to $\alpha D_{j,a}(x+b) + c$ for $\alpha, a, b, c \in \mathbb{F}_p$. Moreover, if j is prime, then $P_j(x)$ is indecomposable.*

Proof. The second assertion is clear since $\deg P_j = j$. The first assertion can be proved by a straightforward comparison of the first five leading coefficients of these two polynomials. ∎

For given k, j (possibly equal), we define the polynomial $Q_{kj}(x,y)$ as $P_k(x) - P_j(y)$ divided by all possible linear factors. If $k = j$, we denote this polynomial by $Q_j(x,y)$. One can show that, for $k, j < p-2$,

$$Q_{kj}(x,y) = \begin{cases} P_k(x) - P_j(y) & \text{if } j \neq k, \\ \frac{P_j(x)-P_j(y)}{x-y} & \text{if } k = j,\ j \text{ is odd}, \\ \frac{P_j(x)-P_j(y)}{(x-y)(x+y-j-1)} & \text{if } k = j,\ j \text{ is even}. \end{cases}$$

Lemma 4.2. *The polynomial $Q_{kj}(x,y)$ is absolutely irreducible over $\mathbb{F}_p$ for (possibly equal) primes $2 < j, k < p-2$.*

Proof. First, consider the case $j = k$. Recall the following theorem of Fried [7], later modified by Turnwald [19]. We adapt it for the field $\mathbb{F}_p$ and for polynomials f of degree less than p.

Theorem (Fried–Turnwald). *Let $f \in \mathbb{F}_p[x]$ be a polynomial of degree n, $4 < n < p$. Consider the polynomial*

$$\phi(x, y) := \frac{f(x) - f(y)}{x - y}.$$

If f is indecomposable, and it is not equal $\alpha D_{n,a}(x + b) + c$ for some $\alpha, a, b, c \in \mathbb{F}_p$, then $\phi(x, y)$ is absolutely irreducible.

The application of this result to the polynomial P_j (along with the Lemma 4.1), with the explicit check for $j = 3$, gives the result.

Next, consider the case $j \neq k$. Recall the statement of Theorem 1B in [17]:

Theorem (Schmidt). *Let*

$$f(x, y) = g_0 y^d + g_1(x) y^{d-1} + \cdots + g_d(x)$$

be a polynomial in $\mathbb{K}[x, y]$ for some field $\mathbb{K}$, where g_0 is a non-zero constant. Denote

$$\psi(f) = \max_{1 \le i \le d} \frac{\deg g_i}{i}$$

and suppose $\psi(f) = m/d$, where m is coprime to d. Then $f(x, y)$ is absolutely irreducible.

Noticing that $\psi(Q_{kj}) = k/j$ gives the result. ∎

Clearly, if $j > k$ are odd primes, Lemma 4.2 is applicable, and Lemmas 3.1 and 3.2 imply the following:

$$|P_j(\mathcal{I})| = |\mathcal{I}| + O\big(|\mathcal{I}|^2 p^{-1} + j^2 \sqrt{p} (\log p)^2\big), \tag{4.1}$$

$$|P_j(\mathcal{I}) \cap P_k(\mathcal{I})| \leqslant |\mathcal{I}|^2 p^{-1} + O(j^2 \sqrt{p} (\log p)^2), \tag{4.2}$$

where $\mathcal{I}$ is a finite arithmetic progression in $\mathbb{F}_p$.

5. On the inequality $|\mathcal{A}(p)\mathcal{A}(p)| \geqslant p + o(p)$

Now we prove Theorem 1.1.

Proof. Let $\varepsilon_1, \varepsilon_2 > 0$ be dependent on p, but separated from zero. Set

$$N := \lfloor p^{1-\varepsilon_1} \rfloor, \quad M := \lfloor p^{\varepsilon_2} \rfloor, \quad \kappa := \log\log p / \log p,$$
$$\delta := \min(\varepsilon_1, 1/2 - 2\varepsilon_1 - 2\varepsilon_2 - 2\kappa, \varepsilon_2 - \varepsilon_1 - \kappa) > 0.$$

Let $\mathcal{I}$ be the set of odd numbers not exceeding $2N - M$, and let $Y_j := P_j(\mathcal{I})$. Clearly, $|\mathcal{I}| = N + O(M)$. Set

$$\mathcal{A} := \{1!, 2!, \ldots, (2N)!\} \cup \{(p - 2N)!, \ldots, (p - 2)!, (p - 1)!\} \mod p.$$

Clearly, $\mathcal{A}\mathcal{A} \subseteq \mathcal{A}(p)\mathcal{A}(p)$, and from now on we work with $\mathcal{A}\mathcal{A}$.

From Wilson's theorem, it follows that $y!(p-1-y)! = (-1)^{y+1} \mod p$. Therefore, y being odd implies $1/(p-1-y)! = y! \mod p$. Let $j \leqslant M$. Then

$$\begin{aligned}\mathcal{A}\mathcal{A} &\supseteq \{(y+j)!(p-1-y)! \mid y+j < 2N, y \text{ is odd}\}\\ &= \{(y+j)!/y! \mid y+j < 2N, y \text{ is odd}\} = \{P_j(y) \mid y+j < 2N, y \text{ is odd}\}.\end{aligned}$$

This implies $Y_j \subseteq \mathcal{A}\mathcal{A}$ for all $j \leqslant M$.

By equations (4.1) and (4.2), implied by Lemmas 3.1 and 3.2, we obtain the following (note that $\delta \leqslant \varepsilon_1, 1/2 - 2\varepsilon_1 - 2\varepsilon_2 - 2\kappa$ now plays a role):

$$|Y_j| \geqslant N + O(Np^{-\delta}), \quad |Y_k \cap Y_j| \leqslant \frac{N^2}{p} + O(N^2 p^{-1-\delta}), \quad k \neq j \text{ odd primes below } M.$$

Set

$$A := \bigcup_j Y_j \quad \text{for primes } j \leqslant M.$$

We have reduced the problem to showing that $|A| \geqslant p + o(p)$.

Let us apply Lemma 2.1 with

$$a := N(1 + O(p^{-\delta})), \quad b := \frac{N^2}{p}(1 + O(p^{-\delta})), \quad n \gg M/\log M \gg p^{\varepsilon_2 - \kappa}.$$

Notice that by definition of δ, which includes $\delta \leqslant \varepsilon_2 - \varepsilon_1 - \kappa$, the inequality $a/bn \ll p^{-\delta}$ holds, and therefore

$$|A| \geqslant \frac{a^2}{b}\Big(1 - \frac{a}{bn}\Big) \geqslant p(1 + O(p^{-\delta})) = p + O(p^{1-\delta}).$$

Now our goal is to maximize δ subject to

$$\delta \leqslant \begin{cases} \varepsilon_1, \\ 1/2 - 2\varepsilon_1 - 2\varepsilon_2 - 2\kappa, \\ \varepsilon_2 - \varepsilon_1 - \kappa. \end{cases} \tag{5.1}$$

Solving this system, we obtain optimal parameters $\varepsilon_1 := 1/14 - 4\kappa/7$ and $\varepsilon_2 := 1/7 - \kappa/7$, giving $\delta = 1/14 - 4\kappa/7$. This completes the proof. ■

6. On the inequality $|\mathcal{A}_N/\mathcal{A}_N| \geqslant p + o(p)$

We turn now to the proof of Theorem 1.3.

Proof. Let $\mathcal{J} := \{L+1, \ldots, L+N-M\}$, and $X_j := P_j(\mathcal{J})$, $j \leqslant M$, with parameters N and M depending on the case.

Case 1. $N \gg p^{13/14}(\log p)^{4/7}$.

For this case, one can apply the same argument as in the proof of Theorem 1.1 to obtain the desired bound.

Case 2. $p^{13/14}(\log p)^{4/7} \gg N \gg p^{7/8}\log p$.

As in the proof above, we write $N = p^{1-\varepsilon_1}$ and set $M = \lfloor p^{\varepsilon_2} \rfloor$ for $\varepsilon_2 > 0$. Observe that now ε_1 is fixed, but ε_2 is not.

Arguing as before, we obtain $|\mathcal{A}_N/\mathcal{A}_N| \geqslant p + O(p^{1-\delta})$, where

$$\delta \leqslant \begin{cases} \varepsilon_1, \\ 1/2 - 2\varepsilon_1 - 2\varepsilon_2 - 2\kappa, \\ \varepsilon_2 - \varepsilon_1 - \kappa. \end{cases} \tag{6.1}$$

Let us set $\varepsilon_2 := 1/6 - \varepsilon_1/3 - \kappa/3$. Observe that $\varepsilon_2 > 0$, since $\varepsilon_1 \leqslant 1/2 - \kappa$. From here we obtain that $\delta = \min(\varepsilon_1, 1/6 - 4\varepsilon_1/3 - 4\kappa/3) = 1/6 - 4\varepsilon_1/3 - 4\kappa/3$ works. Notice that $\delta > 0$ as long as $\varepsilon_1 < 1/8 - \kappa$.

This concludes the proof in the case $N \gg p^{7/8}\log p$.

Case 3. $p^{7/8}\log p \gg N \gg p^{4/5}(\log p)^{8/5}$.

Let R be a positive integer, to be chosen later. Let M be a number with exactly R odd primes below it. Clearly, $M \approx R\log R$.

Applying Lemma 3.1 to P_j for an odd prime j below M, we have

$$|X_j| \geqslant N + O(N^2 p^{-1} + j^2\sqrt{p}(\log p)^2) \gg N \quad \text{if } M^2 \ll Q.$$

Therefore, summing $|X_k \cap X_j|$ and applying Lemma 3.2 to P_k, P_j for odd prime k below j, we obtain

$$\sum_{k<j} |X_k \cap X_j| \ll \frac{N^2}{p} R + RM^2\sqrt{p}(\log p)^2 \ll N \quad \text{if } R \ll K, R^3(\log R)^2 \ll Q.$$

Therefore, setting $R := Q^{1/3}(\log Q)^{-2/3}$, we obtain

$$|\mathcal{A}_N/\mathcal{A}_N| \geqslant \underbrace{|X_3 \cup X_5 \cup \cdots|}_{\text{first } R \text{ odd primes}} - \sum_{k<j,\text{odd primes}} |X_k \cap X_j| \gg \underbrace{|X_3| + |X_5| + \cdots}_{\text{first } R \text{ odd primes}} \gg NR,$$

which completes the proof in this case.

Case 4. $p^{4/5}(\log p)^{8/5} \gg N \gg p^{1/2}(\log p)^2$.

We follow the same line of argumentation as in [8], but with modified bounds on the sets X_j and their intersections.

From now on we work with all j, not just primes. Clearly, $J(j), J(k,j) \leqslant pj$, and therefore the estimates

$$J_N(j), J_N(k,j) \leqslant \frac{N^2}{p^2} pj + O(j^2\sqrt{p}(\log p)^2)$$

hold, as in [8].

As in the proof of Lemma 3.1, we apply the Cauchy–Bunyakovskii–Shwarz inequality:

$$\#\{(x,y) : P_j(x) = P_j(y), 1 \leqslant x, y \leqslant N - M\}|X_j| \geqslant (N-M)^2,$$

from where we obtain

$$|X_j| \geqslant \frac{N^2}{N + J_N(j)} \geqslant N + O\Big(\frac{N^2 j}{p} + j^2 \sqrt{p} (\log p)^2\Big) \quad \forall j \leqslant M.$$

For $X_k \cap X_j$, we have the bound

$$|X_k \cap X_j| \leqslant J_N(k, j) \leqslant \frac{N^2}{p} j + O(j^2 \sqrt{p} (\log p)^2) \quad \forall k < j \leqslant M,$$

as in [8].

Clearly, we have $|X_j| \gg N$ as long as $M \ll K, M^2 \ll Q$.

Clearly, we have $\sum_{k<j} |X_k \cap X_j| \ll N \ll |X_j|$ as long as $M^2 \ll K, M^3 \ll Q$.

Therefore, similarly to [8], we conclude that

$$|\mathcal{A}_N / \mathcal{A}_N| \geqslant \sum_{j \leqslant M} \Big(|X_j| - \sum_{k<j} |X_k \cap X_j|\Big) \gg \sum_{j \leqslant M} |X_j| \gg MN,$$

where we set $M := \min(\sqrt{K}, \sqrt[3]{Q})$, which gives the desired bound. ∎

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