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A new class of permutation polynomials of $\mathbb{F}_q$

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Let $\mathbb{F}_q$ be the finite field of characteristic p containing $q = p^r$ elements. A polynomial $f(x) \in \mathbb{F}_q[x]$ is called a permutation polynomial of $\mathbb{F}_q$ if the induced map $f : \mathbb{F}_q \to \mathbb{F}_q$ is one to one. The study of permutation polynomials goes back to Hermite [2] for $\mathbb{F}_p$ and to Dickson [1] for $\mathbb{F}_q$. One of the open problems proposed by Lidl and Mullen [3], is to find new classes of permutation polynomials of $\mathbb{F}_q$. We refer to [4] or [5] for the basic results on permutation polynomials. Wan and Lidl [7], gave conditions on a polynomial of the form $x^r f(x^{(q-1)/d})$ to be a permutation polynomial. The conditions are not explicitely given in terms of q and r, and may be difficult to verify in general. In the present note, without using the characterization of Wan and Lidl [7], but using only an elementary method, we exhibit a new class of permutation polynomials. We prove the following:

Theorem 1 *Let $q = p^r$, where p is a prime number and r is a positive integer. Let u be a positive integer and let*

$$f(x) = x^u\left(x^{\frac{q-1}{2}} + x^{\frac{q-1}{4}} + 1\right). \tag{1}$$

Unter einem Permutationspolynom des kommutativen Ringes R mit Einselement versteht man ein Polynom $p \in R[x]$, für welches die durch $\pi\alpha := p(\alpha)$ definierte Abbildung von R nach R eine Permutation der Ringelemente ist. Permutationspolynome sind beliebte Studienobjekte der Zahlentheorie, der Algebra und der Kombinatorik. Am besten untersucht ist wohl der Fall, wenn R ein endlicher Körper ist. Die Autoren der vorliegenden Arbeit steuern zu dieser Theorie eine neue, einfache Klasse von Permutationspolynomen bei.

Assume that the following conditions hold:

(i) $gcd(u, q-1) = 1$.

(ii) $q \equiv 1 \pmod 8$.

(iii) $3^{\frac{q-1}{4}} \equiv 1 \pmod p$.

Then $f(x)$ is a permutation polynomial of $\mathbb{F}_q$.

Proof. We will prove that under the above conditions, the polynomial f induces a one-to-one application on $\mathbb{F}_q$. Suppose that $f(a) = f(b)$ for some elements a and b of $\mathbb{F}_q$. If one of them, say a, is 0, then $b^u\big(b^{\frac{q-1}{2}} + b^{\frac{q-1}{4}} + 1\big) = 0$. Suppose that $b \neq 0$, then $b^{\frac{q-1}{2}} + b^{\frac{q-1}{4}} + 1 = 0$. Set $c = b^{\frac{q-1}{4}}$, then $c^2 + c + 1 = 0$ and c is a cubic root of unity. Condition (iii) implies $c \neq 1$. We have $c = c^4 = b^{q-1} = 1$, which is a contradiction. It follows that $b = 0 = a$.

From now on we may suppose that $ab \neq 0$. It is clear that $a^{\frac{q-1}{2}} = \pm 1$ and $b^{\frac{q-1}{2}} = \pm 1$. By symmetry, we have to consider only the following three cases:

Case 1: If $a^{\frac{q-1}{2}} = b^{\frac{q-1}{2}} = 1$. If $a^{\frac{q-1}{4}} = b^{\frac{q-1}{4}} = 1$, then $a^u = b^u$, hence $(\frac{a}{b})^u = 1$. Therefore $a = b$ by (i). To complete Case 1, we may suppose that $a^{\frac{q-1}{4}} = 1$ and $b^{\frac{q-1}{4}} = -1$. From equation (1) we have $3a^u = b^u$ or $(\frac{b}{a})^u = 3$. We deduce that $\left(\frac{b^{\frac{q-1}{4}}}{a^{\frac{q-1}{4}}}\right) = 3^{\frac{q-1}{4}}$, hence $(-1)^u = 1$ by (iii). By (i), u is odd and we reached a contradiction.

Case 2: If $a^{\frac{q-1}{2}} = b^{\frac{q-1}{2}} = -1$. From equation (1) we get: $a^{u+\frac{q-1}{4}} = b^{u+\frac{q-1}{4}}$, hence $(b/a)^{u+\frac{q-1}{4}} = 1$. The order δ of b/a in $\mathbb{F}_q$ divides $q-1$ and $u + \frac{q-1}{4}$. Let l be a prime factor of δ. Because u is odd and by (ii), we may exclude the case $l = 2$. It follows that l is odd and $l \mid \frac{q-1}{4}$, therefore $l \mid u$, which contradicts (i).

Case 3: If $a^{\frac{q-1}{2}} = -b^{\frac{q-1}{2}} = 1$. Here we have $a^{\frac{q-1}{4}} = \pm 1$ and $b^{\frac{q-1}{4}} = \zeta$, where ζ is a primitive quartic root of unity.

- If $a^{\frac{q-1}{4}} = -1$ and $b^{\frac{q-1}{4}} = \zeta$, then by equation (1), we have $a^u = \zeta b^u$. We deduce that $(a/b)^u = \zeta$, therefore $(a/b)^{4u} = 1$. Using (i), we conclude that $(a/b)^4 = 1$. If $a/b = -1$, then $a^{\frac{q-1}{2}} = (-1)^{\frac{q-1}{2}} b^{\frac{q-1}{2}} = b^{\frac{q-1}{2}}$, which is a contradiction. Suppose next that $a/b = \pm\zeta$, then $a^{\frac{q-1}{2}} = (\pm\zeta)^{\frac{q-1}{2}} b^{\frac{q-1}{2}}$. Hence $1 = (\zeta^4)^{\frac{q-1}{8}}(-1) = -1$, which is a contradiction. We conclude that $a = b$.
- Suppose now that $a^{\frac{q-1}{4}} = 1$ and $b^{\frac{q-1}{4}} = \zeta$, then by equation (1) we have $3a^u = \zeta b^u$. By condition (iii), the characteristic of the field is $\neq 3$, hence we may write this equation in the form: $(a/b)^u = \zeta/3$. It follows that $\left(\frac{a^{\frac{q-1}{2}}}{b^{\frac{q-1}{2}}}\right)^u = \frac{\zeta^{\frac{q-1}{2}}}{3^{\frac{q-1}{2}}}$, hence $3^{\frac{q-1}{2}} = -1$, contradicting (iii). □

Remark 1 The minimal example for Theorem 1 is when $p = 7$ and $q = 7^2$.

Example 1 Let p be a prime number such that $p \equiv 1 \pmod 8$ and $p \equiv 1 \pmod 3$ and let $q = p^r$ where r is positive and even. It is clear that condition (ii) of Theorem 1 is satisfied. Euler criteria gives that $3^{\frac{p-1}{2}} = \left(\frac{3}{p}\right) = 1$ (see [6]). It follows that $3^{\frac{p-1}{4}} = \pm 1$, hence $3^{\frac{q-1}{4}} = (3^{\frac{p-1}{4}})^{(1+p+\ldots+p^{r-1})} = 1$ and condition (iii) of Theorem 1 is fulfilled. By Dirichlet's theorem (see [6]), there exist infinitely many prime numbers $p \equiv 1 \pmod 8$ and $p \equiv 1 \pmod 3$. The smallest such prime is 73. Any polynomial $f(x)$ of the form (1) such that u satisfies condition (i) of Theorem 1 induces a permutation of $\mathbb{F}_q$. We may put $u = 1$ for example.

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