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A Few More Functions That Are Not APN Infinitely Often

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Abstract

We consider exceptional APN functions on \mathbb{F}_{2^m} , which by definition are functions that are APN on infinitely many extensions of \mathbb{F}_{2^m} . Our main result is that polynomial functions of odd degree are not exceptional, provided the degree is not a Gold number ($2^k + 1$) or a Kasami-Welch number ($4^k - 2^k + 1$). We also have partial results on functions of even degree, and functions that have degree $2^k + 1$.

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1 Introduction

Let $L = \mathbb{F}_q$ with $q = 2^n$ for some positive integer n . A function $f : L \rightarrow L$ is said to be *almost perfect nonlinear* (APN) on L if the number of solutions in L of the equation

$$f(x+a) + f(x) = b$$

is at most 2, for all $a, b \in L$, $a \neq 0$. Equivalently, f is APN if the set $\{f(x+a) + f(x) : x \in L\}$ has size at least 2^{n-1} for each $a \in L^*$. Because L has characteristic 2, the number of solutions to the above equation must be an even number, for any function f on L .

This kind of function is very useful in cryptography because of its good resistance to differential cryptanalysis as was proved by Nyberg in [4].

The best known examples of APN functions are the Gold functions x^{2^k+1} and the Kasami-Welch functions $x^{4^k-2^k+1}$. These functions are defined over \mathbb{F}_2 , and are APN on any field \mathbb{F}_{2^m} where $\gcd(k, m) = 1$.

If f is APN on L , then f is APN on any subfield of L as well. We will consider going in the opposite direction. This means we will study functions f which are APN on L , and we ask whether f can be APN on an extension field of L . More specifically, we consider functions that are APN on infinitely many extensions of L . We call a function $f : L \rightarrow L$ *exceptional* if f is APN on L and is also APN on infinitely many extension fields of L . The Gold and Kasami-Welch functions are exceptional.

We make the following conjecture.

Conjecture: The Gold and Kasami-Welch functions are the only exceptional APN functions.

We will prove some cases of this conjecture. It was proved in Hernando-McGuire [1] that the conjecture is true among the class of monomial functions. Some cases for f of small degree have been proved by Rodier [5].

We define

$$\phi(x, y, z) = \frac{f(x) + f(y) + f(z) + f(x+y+z)}{(x+y)(x+z)(y+z)}$$

which is a polynomial in $\mathbb{F}_q[x, y, z]$. This polynomial defines a surface X in the three dimensional affine space \mathbb{A}^3 .

If X is absolutely irreducible (or has an absolutely irreducible component defined over \mathbb{F}_q) then f is not APN on \mathbb{F}_{q^n} for all n sufficiently large. As shown in [5], this follows from the Lang-Weil bound for surfaces, which

guarantees many \mathbb{F}_{q^n} -rational points on the surface for all n sufficiently large.

Let \overline{X} denote the projective closure of X in the three dimensional projective space \mathbb{P}^3 . If H is a another projective hypersurface in \mathbb{P}^3 , the idea of this paper is to apply the following lemma.

Lemma 1.1 *If $\overline{X} \cap H$ is a reduced (no repeated component) absolutely irreducible curve, then \overline{X} is absolutely irreducible.*

Proof: If \overline{X} is not absolutely irreducible then every irreducible component of \overline{X} intersects H in a variety of dimension at least 1 (see Shafarevich [6, Chap. I, 6.2, Corollary 5]). So $\overline{X} \cap H$ is reduced or reducible. □

In particular, we will apply this when H is a hyperplane. In Section 2 we study functions whose degree is not a Gold number ($2^k + 1$) or a Kasami-Welch number ($4^k - 2^k + 1$). In Section 3 we study functions whose degree is a Gold number - this case is more subtle.

The equation of \overline{X} is the homogenization of $\phi(x, y, z) = 0$, which is $\overline{\phi}(x, y, z, t) = 0$ say. If $f(x) = \sum_{j=0}^d a_j x^j$ write this as

$$\overline{\phi}(x, y, z, t) = \sum_{j=3}^d a_j \phi_j(x, y, z) t^{d-3-j}$$

where

$$\phi_j(x, y, z) = \frac{x^{j+3} + y^{j+3} + z^{j+3} + (x + y + z)^{j+3}}{(x + y)(x + z)(y + z)}$$

is homogeneous of degree j . We will later consider the intersection of \overline{X} with the hyperplane $z = 0$, and this intersection is a curve in a two dimensional projective space with equation $\overline{\phi}(x, y, 0, t) = 0$. An affine equation of this surface \overline{X} is $\overline{\phi}(x, y, z, 1) = \phi(x, y, z) = 0$.

A fact we will use is that if $f(x) = x^{2^k+1}$ then

$$\phi(x, y, z) = \prod_{\alpha \in \mathbb{F}_{2^k} - \mathbb{F}_2} (x + \alpha y + (\alpha + 1)z). \tag{1}$$

This can be shown by elementary manipulations (see Janwa, Wilson, [2, Theorem 4]).

Our definition of exceptional APN functions is motivated by the definition of exceptional permutation polynomials. A permutation polynomial $f : \mathbb{F}_q \rightarrow \mathbb{F}_q$ is said to be exceptional if f is a permutation polynomial on infinitely many extensions of \mathbb{F}_q . One technique for proving that a polynomial is not exceptional is to prove that the curve $\phi(x, y) = (f(y) - f(x))/(y - x)$ has an absolutely irreducible factor over \mathbb{F}_q . Then the Weil bound applied to this factor guarantees many \mathbb{F}_{q^n} -rational points on the curve for all n sufficiently large. In particular there are points with $x \neq y$, which means that f cannot be a permutation.

2 Degree not Gold or Kasami-Welch

If the degree of f is not a Gold number $2^k + 1$, or a Kasami-Welch number $4^k - 2^k + 1$, then we will apply results of Rodier [5] and Hernando-McGuire [1] to prove our results.

Lemma 2.1 *Let H be a projective hypersurface. If $\overline{X} \cap H$ has a reduced absolutely irreducible component defined over \mathbb{F}_q then \overline{X} has an absolutely irreducible component defined over \mathbb{F}_q .*

Proof: Let Y_H be a reduced absolutely irreducible component of $\overline{X} \cap H$ defined over \mathbb{F}_q . Let Y be an absolutely irreducible component of \overline{X} that contains Y_H . Suppose for the sake of contradiction that Y is not defined over \mathbb{F}_q . Then Y is defined over \mathbb{F}_{q^t} for some t . Let σ be a generator for the Galois group $\text{Gal}(\mathbb{F}_{q^t}/\mathbb{F}_q)$ of \mathbb{F}_{q^t} over \mathbb{F}_q . Then $\sigma(Y)$ is an absolutely irreducible component of \overline{X} that is distinct from Y . However, $\sigma(Y) \supseteq \sigma(Y_H) = Y_H$, which implies that Y_H is contained in two distinct absolutely irreducible components of \overline{X} . This means that a double copy of Y_H is a component of \overline{X} , which contradicts the assumption that Y_H is reduced. \square

Lemma 2.2 *Let H be the hyperplane at infinity. Let d be the degree of f . Then $\overline{X} \cap H$ is not reduced if d is even, and $\overline{X} \cap H$ is reduced if d is odd and f is not a Gold or Kasami-Welch monomial function.*

Proof: Let $\phi_d(x, y, z)$ denote the ϕ corresponding to the function x^d . In $\overline{X} \cap H$ we may assume $\phi = \phi_d$.

If d is odd then the singularities of $\overline{X} \cap H$ were classified by Janwa-Wilson [2]. They show that the singularities are isolated (the coordinates must be $(d-1)$ -th roots of unity) and so the dimension of the singular locus of $\overline{X} \cap H$ is 0.

Suppose d is even and write $d = 2^j e$ where e is odd. In $\overline{X} \cap H$ we have

$$\begin{aligned} (x+y)(x+z)(y+z)\phi_d(x,y,z) &= x^d + y^d + z^d + (x+y+z)^d \\ &= (x^e + y^e + z^e + (x+y+z)^e)^{2^j} \\ &= ((x+y)(x+z)(y+z)\phi_e(x,y,z))^{2^j}. \end{aligned}$$

Therefore

$$\phi_d(x,y,z) = \phi_e(x,y,z)^{2^j} ((x+y)(x+z)(y+z))^{2^j-1}$$

and is not reduced. □

Here is the main result of this section.

Theorem 2.3 *If the degree of the polynomial function f is odd and not a Gold or a Kasami-Welch number then f is not APN over \mathbb{F}_{q^n} for all n sufficiently large.*

Proof: By Lemma 2.2, $\overline{X} \cap H$ is reduced. Furthermore, we know by [1] that $\overline{X} \cap H$ has an absolutely irreducible component defined over \mathbb{F}_q , which is also reduced. Thus, by Lemma 2.1, we obtain that \overline{X} has an absolutely irreducible component defined over \mathbb{F}_q . As discussed in the introduction, this enables us to conclude that f is not APN on \mathbb{F}_{q^n} for all n sufficiently large. □

In the even degree case, we can state the result when half of the degree is odd, with an extra minor condition.

Theorem 2.4 *If the degree of the polynomial function f is $2e$ with e odd, and if f contains a term of odd degree, then f is not APN over \mathbb{F}_{q^n} for all n sufficiently large.*

Proof: As shown in the proof of Lemma 2.2 in the particular case where $d = 2^j e$ with e odd and $j = 1$, we can write

$$\phi_d(x,y,z) = \phi_e(x,y,z)^2 (x+y)(x+z)(y+z).$$

Hence, $x+y=0$ is the equation of a reduced component of the curve $X_\infty = \overline{X} \cap H$ with equation $\phi_d = 0$ where H is the hyperplane at infinity. The only absolutely irreducible component X_0 of the surface \overline{X} containing the line $x+y=0$ in H is reduced and defined over \mathbb{F}_q . We have to show that this component doesn't contain the plane $x+y=0$.

The function $x + y$ doesn't divide $\phi(x, y, z)$ if and only if the function $(x + y)^2$ doesn't divide $f(x) + f(y) + f(z) + f(x + y + z)$. Let x^r be a term of odd degree of the function f . We show easily that $(x + y)^2$ doesn't divide $x^r + y^r + z^r + (x + y + z)^r$ by using the change of variables $s = x + y$ which gives:

$$x^r + y^r + z^r + (x + y + z)^r = s(x^{r-1} + z^{r-1}) + s^2 P$$

where P is a polynomial.

Hence \overline{X} has an absolutely irreducible component defined over \mathbb{F}_q and then f is not APN on \mathbb{F}_{q^n} for all n sufficiently large. □

3 Gold Degree

Suppose the degree of f is a Gold number $d = 2^k + 1$. Set d to be this value for this section. Then the degree of ϕ is $d - 3 = 2^k - 2$.

3.1 First Case

We will prove the absolute irreducibility for a certain type of f .

Theorem 3.1 *Suppose $f(x) = x^d + g(x)$ where $\deg(g) \leq 2^{k-1} + 1$. Let $g(x) = \sum_{j=0}^{2^{k-1}+1} a_j x^j$. Suppose moreover that there exists a nonzero coefficient a_j of g such that $\phi_j(x, y, z)$ is absolutely irreducible. Then $\phi(x, y, z)$ is absolutely irreducible.*

Proof: We must show that $\phi(x, y, z)$ is absolutely irreducible. Suppose $\phi(x, y, z) = P(x, y, z)Q(x, y, z)$. Write each polynomial as a sum of homogeneous parts:

$$\sum_{j=3}^d a_j \phi_j(x, y, z) = (P_s + P_{s-1} + \cdots + P_0)(Q_t + Q_{t-1} + \cdots + Q_0) \quad (2)$$

where P_j, Q_j are homogeneous of degree j . Then from (1) we get

$$P_s Q_t = \prod_{\alpha \in \mathbb{F}_{2^k} \setminus \mathbb{F}_2} (x + \alpha y + (\alpha + 1)z).$$

In particular this implies that P_s and Q_t are relatively prime as the product is made of distinct irreducible factors.

The homogeneous terms of degree less than $d - 3$ and greater than 2^{k-1} are 0. Equating terms of degree $s + t - 1$ in the equation (2) gives $P_s Q_{t-1} + P_{s-1} Q_t = 0$. Hence P_s divides $P_{s-1} Q_t$ which implies P_s divides P_{s-1} because $\gcd(P_s, Q_t) = 1$, and we conclude $P_{s-1} = 0$ as $\deg P_{s-1} < \deg P_s$. Then we also get $Q_{t-1} = 0$. Similarly, $P_{s-2} = 0 = Q_{t-2}$, $P_{s-3} = 0 = Q_{t-3}$, and so on until we get the equation

$$P_s Q_0 + P_{s-t} Q_t = 0$$

where we suppose wlog that $s \geq t$. This equation implies P_s divides $P_{s-t} Q_t$, which implies P_s divides P_{s-t} , which implies $P_{s-t} = 0$. Since $P_s \neq 0$ we must have $Q_0 = 0$.

We now have shown that $Q = Q_t$ is homogeneous. In particular, this means that $\phi_j(x, y, z)$ is divisible by $x + \alpha y + (\alpha + 1)z$ for some $\alpha \in \mathbb{F}_{2^k} \setminus \mathbb{F}_2$ and for all j such that $a_j \neq 0$. One is done if there exists such a j with $\phi_j(x, y, z)$ irreducible. □

Remark: The hypothesis that there should exist a j with $\phi_j(x, y, z)$ is absolutely irreducible is not a strong hypothesis. This is true in many cases (see the next remarks). However, some hypothesis is needed, because the theorem is false without it. One counterexample is with $g(x) = x^5$ and $k \geq 4$ and even.

Remark: It is known that ϕ_j is irreducible in the following cases (see [3]):

- $j \equiv 3 \pmod{4}$;
- $j \equiv 5 \pmod{8}$ and $j > 13$.

Remark: The theorem is true with the weaker hypothesis that there exists a nonzero coefficient a_j such that $\phi_j(x, y, z)$ is prime to ϕ_d (recall $d = 2^k + 1$). This is the case for

- $j = 2^r + 1$ is a Gold exponent with r prime to k ;
- j is a Kasami exponent (see [2, Theorem 5]);
- $j = 2^j e$ with e odd and e is in one of the previous cases.

Example: This applies to $x^{33} + g(x)$ where $g(x)$ is any polynomial of degree ≤ 17 .

Remark: The proof did not use the fact that f is APN. This is simply a result about polynomials.

Remark: The bound $\deg(g) \leq 2^{k-1} + 1$ is best possible, in the sense that there is an example with $\deg(g) = 2^{k-1} + 2$ in Rodier [5] where ϕ is not absolutely irreducible. The counterexample has $k = 3$, and $f(x) = x^9 + ax^6 + a^2x^3$.

3.2 On the Boundary of the First Case

As we said in the previous section, when $f(x) = x^{2^k+1} + g(x)$ with $\deg(g) = 2^{k-1} + 2$, it is false that ϕ is always absolutely irreducible. However, the polynomial ϕ corresponding to the counterexample $f(x) = x^9 + ax^6 + a^2x^3$ where $a \in \mathbb{F}_q$ factors into two irreducible factors over \mathbb{F}_q . We generalize this to the following theorem.

Theorem 3.2 *Let $q = 2^n$. Suppose $f(x) = x^d + g(x)$ where $g(x) \in \mathbb{F}_q[x]$ and $\deg(g) = 2^{k-1} + 2$. Let k be odd and relatively prime to n . If $g(x)$ does not have the form $ax^{2^{k-1}+2} + a^2x^3$ then ϕ is absolutely irreducible, while if $g(x)$ does have the form $ax^{2^{k-1}+2} + a^2x^3$ then either ϕ is irreducible or ϕ splits into two absolutely irreducible factors which are both defined over \mathbb{F}_q .*

Proof: Suppose $\phi(x, y, z) = P(x, y, z)Q(x, y, z)$ and let

$$g(x) = \sum_{j=0}^{2^{k-1}+2} a_j x^j.$$

Write each polynomial as a sum of homogeneous parts:

$$\sum_{j=3}^d a_j \phi_j(x, y, z) = (P_s + P_{s-1} + \cdots + P_0)(Q_t + Q_{t-1} + \cdots + Q_0).$$

Then

$$P_s Q_t = \prod_{\alpha \in \mathbb{F}_{2^k} - \mathbb{F}_2} (x + \alpha y + (1 + \alpha)z).$$

In particular this means P_s and Q_t are relatively prime as in the previous theorem. We suppose wlog that $s \geq t$, which implies $s \geq 2^{k-1} - 1$. Comparing each degree gives $P_{s-1} = 0 = Q_{t-1}$, $P_{s-2} = 0 = Q_{t-2}$, and so on until we get the equation of degree $s + 1$

$$P_s Q_1 + P_{s-t+1} Q_t = 0$$

which implies $P_{s-t+1} = 0 = Q_1$. If $s \neq t$ then $s \geq 2^{k-1}$. Note then that $a_{s+3}\phi_{s+3} = 0$. The equation of degree s is

$$P_s Q_0 + P_{s-t} Q_t = a_{s+3} \phi_{s+3} = 0.$$

This means that $P_{s-t} = 0$, so $Q_0 = 0$. We now have shown that $Q = Q_t$ is homogeneous. In particular, this means that $\phi(x, y, z)$ is divisible by $x + \alpha y + (1 + \alpha)z$ for some $\alpha \in \mathbb{F}_{2^k} \setminus \mathbb{F}_2$, which is impossible. Indeed, since the leading coefficient of g is not 0, the polynomial $\phi_{2^{k-1}+2}$ occurs in ϕ ; as $\phi_{2^{k-1}+2} = \phi_{2^{k-2}+1}^2(x+y)(y+z)(z+x)$, this polynomial is prime to ϕ , because if $x + \alpha y + (1 + \alpha)z$ occurs in the two polynomials $\phi_{2^{k-1}+2}$ and $\phi_{2^{k-1}+1}$, then α would be an element of $\mathbb{F}_{2^k} \cap \mathbb{F}_{2^{k-2}} = \mathbb{F}_2$ because k is odd.

Suppose next that $s = t = 2^{k-1} - 1$ in which case the degree s equation is

$$P_s Q_0 + P_0 Q_s = a_{s+3} \phi_{s+3}.$$

If $Q_0 = 0$, then

$$\phi(x, y, z) = \sum_{j=3}^d a_j \phi_j(x, y, z) = (P_s + P_0) Q_t$$

which implies that

$$\phi(x, y, z) = a_d \phi_d(x, y, z) + a_{2^{k-1}+2} \phi_{2^{k-1}+2}(x, y, z) = P_s Q_t + P_0 Q_t$$

and $P_0 \neq 0$, since $g \neq 0$. So one has $\phi_{2^{k-1}+2}$ divides $\phi_d(x, y, z)$ which is impossible as

$$\phi_{2^{k-1}+2} = \phi_{2^{k-2}+1}^2(x+y)(y+z)(z+x).$$

We may assume then that $P_0 = Q_0$, and we have $\phi_{2^{k-1}+2} = 0$. Then we have

$$\phi(x, y, z) = (P_s + P_0)(Q_s + Q_0) = P_s Q_s + P_0(P_s + Q_s) + P_0^2. \quad (3)$$

Note that this implies $a_j = 0$ for all j except $j = 3$ and $j = s + 3$. This means

$$f(x) = x^d + a_{s+3} x^{s+3} + a_3 x^3.$$

So if $f(x)$ does not have this form, this shows that ϕ is absolutely irreducible.

If on the contrary ϕ splits as $(P_s + P_0)(Q_s + Q_0)$, the factors $P_s + P_0$ and $Q_s + Q_0$ are irreducible, as can be shown by using the same argument.

Assume from now on that $f(x) = x^d + a_{s+3}x^{s+3} + a_3x^3$ and that (3) holds. Then $a_3 = P_0^2$, so clearly $P_0 = \sqrt{a_3}$ is defined over \mathbb{F}_q . We claim that P_s and Q_s are actually defined over \mathbb{F}_2 .

We know from (1) that P_sQ_s is defined over \mathbb{F}_2 .

Also $P_0(P_s + Q_s) = a_{s+3}\phi_{s+3}$, so $P_s + Q_s = (a_{s+3}/\sqrt{a_3})\phi_{s+3}$. On the one hand, $P_s + Q_s$ is defined over \mathbb{F}_{2^k} by (1). On the other hand, since ϕ_{s+3} is defined over \mathbb{F}_2 we may say that $P_s + Q_s$ is defined over \mathbb{F}_q . Because $(k, n) = 1$ we may conclude that $P_s + Q_s$ is defined over \mathbb{F}_2 . Note that the leading coefficient of $P_s + Q_s$ is 1, so $a_{s+3}^2 = a_3$. Whence if this condition is not true, then ϕ is absolutely irreducible.

Let σ denote the Galois automorphism $x \mapsto x^2$. Then $P_sQ_s = \sigma(P_sQ_s) = \sigma(P_s)\sigma(Q_s)$, and $P_s + Q_s = \sigma(P_s + Q_s) = \sigma(P_s) + \sigma(Q_s)$. This means σ either fixes both P_s and Q_s , in which case we are done, or else σ interchanges them. In the latter case, σ^2 fixes both P_s and Q_s , so they are defined over \mathbb{F}_4 . Because they are certainly defined over \mathbb{F}_{2^k} by (1), and k is odd, they are defined over $\mathbb{F}_{2^k} \cap \mathbb{F}_4 = \mathbb{F}_2$.

Finally, we have now shown that \overline{X} either is irreducible, or splits into two absolutely irreducible factors defined over \mathbb{F}_q . \square

3.3 Using the Hyperplane $y = z$

We study the intersection of $\phi(x, y, z) = 0$ with the hyperplane $y = z$.

Lemma 3.3 *$\phi(x, y, y)$ is always a square.*

Proof: It suffices to prove the result for $f(x) = x^d$. This is equivalent to proving that $\phi_d(x, 1, 1)$ is a square. This is equivalent to showing that its derivative with respect to x is identically 0. This is again equivalent to showing that the partial derivative with respect to x of $\phi_d(x, y, 1)$, evaluated at $y = 1$, is 0. In Lemma 4.1 of [5] Rodier proves that $y + z$ divides the partial derivative of $\phi_d(x, y, z)$ with respect to x , which is exactly what is required. \square

Lemma 3.4 *Let H be the hyperplane $y = z$. If $\overline{X} \cap H$ is the square of an absolutely irreducible component defined over \mathbb{F}_q then \overline{X} is absolutely irreducible.*

Proof: We claim that for any nonsingular point $P \in \overline{X} \cap H$, the tangent plane to the curve $\overline{X} \cap H$ at P is H . The equation of the tangent plane is

$$(x - x_0)\phi'_x(P) + (y - y_0)\phi'_y(P) + (z - z_0)\phi'_z(P) = 0$$

where $P = (x_0, y_0, z_0)$. Since $P \in H$ we have $y_0 = z_0$. It is straightforward to show that $\phi'_x(P) = 0$ and $\phi'_y(P) = \phi'_z(P)$, so this equation becomes

$$(y + z)\phi'_y(P) = 0.$$

But $y + z = 0$ is the equation of H . □

Corollary 3.1 *If $f(x) = x^d + g(x)$, and $d = 2^k + 1$ is a Gold exponent, and $\phi(x, y, y)$ is the square of an irreducible, then \overline{X} is absolutely irreducible.*

Note that any term x^d in $g(x)$ where d is even will drop out when we calculate $\phi(x, y, y)$, because if $d = 2e$ then

$$\begin{aligned} \phi_d(x, y, z) &= \frac{x^d + y^d + z^d + (x + y + z)^d}{(x + y)(x + z)(y + z)} \\ &= \frac{(x^e + y^e + z^e + (x + y + z)^e)^2}{(x + y)(x + z)(y + z)} \\ &= \phi_e(x, y, z)(x^e + y^e + z^e + (x + y + z)^e) \\ &= 0 \quad \text{on } H \end{aligned}$$

because the right factor vanishes on H .

In order to find examples of where we can apply this Corollary, if we write

$$\phi(x, y, y) = (x + y)^{2^k - 2} + h(x, y)^2$$

then to apply this result we want to show that

$$(x + y)^{2^{k-1} - 1} + h(x, y)$$

is irreducible. Of course the degree of h is smaller than $2^{k-1} - 1$. Letting $t = x + y$ we want an example of h with $t^{2^{k-1} - 1} + h(x, x + t)$ is irreducible.

Example: Choose any h so that $h(x, x + t)$ is a monomial, and then $t^{2^{k-1} - 1} + h(x, x + t)$ is irreducible.

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