PERMUTATION GROUPS
WITH PROJECTIVE UNITARY SUBCONSTITUENTS

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ABSTRACT. Let \( \Gamma \) be a finite directed graph with vertex set \( V(\Gamma) \) and edge set \( E(\Gamma) \) and let \( G \) be a subgroup of \( \text{aut}(\Gamma) \) which we assume to act transitively on both \( V(\Gamma) \) and \( E(\Gamma) \). Suppose that for some prime power \( q \), the stabilizer \( G(x) \) of a vertex \( x \) induces on both \( \{ y | (x, y) \in E(\Gamma) \} \) and \( \{ w | (w, x) \in E(\Gamma) \} \) a group lying between \( \text{PSU}(3, q^2) \) and \( \text{PTU}(3, q^2) \). It is shown that if \( G \) acts primitively on \( V(\Gamma) \), then for each edge \( (x, y) \), the subgroup of \( G(x) \) fixing every vertex in \( \{ w | (x, w) \text{ or } (y, w) \in E(\Gamma) \} \) is trivial.

Let \( \Gamma \) be a directed graph with vertex set \( V(\Gamma) \) and edge set \( E(\Gamma) \) and let \( G \) be a subgroup of \( \text{aut}(\Gamma) \) which we assume to act transitively on both \( V(\Gamma) \) and \( E(\Gamma) \). Let \( x \in V(\Gamma) \) be arbitrary. We denote by \( \Gamma(x) \) the set of \( y \in V(\Gamma) \) such that \( (x, y) \in E(\Gamma) \) and by \( \Gamma'(x) \) the set of \( w \in V(\Gamma) \) such that \( (w, x) \in E(\Gamma) \). Since \( G \) acts transitively on \( E(\Gamma) \), the stabilizer \( G(x) \) of \( x \) in \( G \) acts transitively on both \( \Gamma(x) \) and \( \Gamma'(x) \) and either \( \Gamma(x) \cap \Gamma'(x) = \emptyset \) or \( \Gamma(x) = \Gamma'(x) \). In the latter case, we may identify \( \Gamma \) with the undirected graph with vertex set \( V(\Gamma) \) and edge set \( \{ (x, y) | (x, y) \in E(\Gamma) \} \) and will, in fact, simply say that \( \Gamma \) itself is undirected. Let \( G_1(x) = \{ a \in G(x) | a \in G(y) \text{ for all } y \in \Gamma(x) \} \) and \( G_1'(x) = \{ a \in G(x) | a \in G(w) \text{ for all } w \in \Gamma'(x) \} \). For \( u \in \Gamma(x) \) or \( \Gamma'(x) \), we set \( G(x, u) = G(x) \cap G(u) \) and \( G'(x, u) = G'(x) \cap G'(u) \). \( \Gamma \) is called connected if for every two vertices \( u \) and \( v \), there is a sequence \( (x_0, x_1, \ldots, x_s) \) of vertices such that \( x_0 = u \), \( x_s = v \) and \( x_i \in \Gamma(x_i) \cup \Gamma'(x_i) \) for \( 1 \leq i < s \). The following observation is easily verified.

**Lemma 1.** If \( \Gamma \) is connected and undirected and \( (x, y) \in E(\Gamma) \), then \( \langle G(x), G(y) \rangle \) acts transitively on \( E(\Gamma) \).

Note that this statement does not hold if we do not assume \( \Gamma \) to be undirected. Consider, for instance, the graph \( \Gamma \) with \( V(\Gamma) = \mathbb{Z}_k \times M \), \( M \) an arbitrary non-empty set and \( k > 3 \), and \( E(\Gamma) = \{ ((i, x), (j, y)) | i - j \equiv 1 \pmod{k} \} \) and \( G = \text{aut}(\Gamma) \).

If \( G \) is an arbitrary transitive permutation group on a set \( \Omega \) and \( \Delta \) an orbit of \( G \) on \( \Omega \times \Omega \) (called an orbital of \( G \)), then \( G \) can be considered as a vertex- and edge-transitive subgroup of \( \text{aut}(\Gamma_{\Delta}) \) where \( \Gamma_{\Delta} \) is the graph with vertex set \( \Omega \) and edge set \( \Delta \). According to [9, (4.4)], \( G \) is primitive on \( \Omega \) if and only if, for each nondiagonal orbital \( \Delta \), \( \Gamma_{\Delta} \) is connected.

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In [2] and [3], Dempwolff proved the following result.

**Theorem 2.** Let \( q \) be a prime power, \( q > 2 \). Let \( \Gamma \) be a finite graph and \((x,y) \in E(\Gamma)\) arbitrary. Suppose \( \text{aut}(\Gamma) \) contains a subgroup \( G \) acting transitively on both \( V(\Gamma) \) and \( E(\Gamma) \) such that both \( G(x)^{(x)} \) (i.e., the permutation group induced by \( G(x) \) on \( \Gamma(x) \)) and \( G(x)^{(x)} \) are isomorphic to \( \text{PSU}(3, q^2) \) in its usual 2-transitive representation of degree \( q^3 + 1 \). Suppose further that \( G \) is primitive on \( V(\Gamma) \) or that \( \Gamma \) is undirected and connected. Then \( G_1(x,y) = 1 \).

Actually, Dempwolff simply required \( G \) to be primitive on \( V(\Gamma) \). This hypothesis is used, however, only in the following way.

Suppose \( H \) is a subgroup of \( G(x,y) \) normalized by both \( G(x) \) and \( G(y) \). Since \( G \) is primitive and not regular on \( V(\Gamma) \), \( G = \langle G(x), G(y) \rangle \). Hence \( H \leq G \). Since \( H \) fixes the edge \((x,y)\), \( H \) fixes every edge. Therefore \( H = 1 \).

In light of Lemma 1, this same conclusion (i.e., \( H = 1 \)) holds if, instead of assuming \( G^{\nu(\Gamma)} \) to be primitive, we assume \( \Gamma \) to be undirected and connected.

In this paper, we prove the following improved version of Theorem 2.

**Theorem 3.** Let \( q \) be an arbitrary prime power. Let \( \Gamma \) be a finite graph and \((x,y) \in E(\Gamma)\) arbitrary. Suppose \( \text{aut}(\Gamma) \) contains a subgroup \( G \) acting transitively on both \( V(\Gamma) \) and \( E(\Gamma) \) such that \( \text{PSU}(3, q^2) \leq G(x)^{(x)} \leq \text{PGU}(3, q^2) \) and \( \text{PSU}(3, q^2) \leq G(x)^{(x)} \leq \text{PGU}(3, q^2) \). Suppose that \( G \) is primitive on \( V(\Gamma) \) or that \( \Gamma \) is undirected and connected. Then \( G_1(x,y) = 1 \).

Our proof of Theorem 3, although similar to the proof of Theorem 2 given in [2] and [3], is more elementary in that we avoid having to prove [2, (2.3)] and [3, (2.5)]. Moreover, our proof remains valid with only the most minor changes when we replace \( \text{PSU}(3, q^2) \) by \( \text{Sz}(q) \) or \( \text{Sz}(q) \) (and \( \text{PGU}(3, q^2) \) by the corresponding automorphism group) in the statement of Theorem 3 once it is shown that \( \text{Sz}(q) \) and \( \text{Sz}(q) \) have a certain elementary property. For \( \text{Sz}(q) \), this property is easily checked; for \( \text{Sz}(q) \), verification is more difficult. See the remarks at the end of our proof of Theorem 3. Of course, these versions of Theorem 3 were already proved in [1, (2.6) and (3.5)], but only by using the very deep results [4, Corollary 10] in the case \( \text{Sz}(q) \) and [5, (1.4)] in the case \( \text{Sz}(q) \).

We begin the proof of Theorem 3 by gathering the properties of \( \text{PSU}(3, q^2) \) which will be needed. The reader unacquainted with these groups is referred to [7] (in particular, pp. 242–244). Let \( \Pi \) be the desarguesian plane \( \text{PG}(2, q^2) \) over the field \( GF(q^2) \), \( \delta \) the unitary polarity of \( \Pi \) corresponding to a nondegenerate hermitian form on the underlying vector space and \( X \) the set of absolute points (i.e., those \( x \) in \( \Pi \) incident with \( x^\delta \)). \( \text{PSU}(3, q^2) \) is the subgroup of \( \text{PSL}(3, q^2) \) consisting of those elements which commute with \( \delta \). Let \( H = \text{PSU}(3, q^2) \). \( H \) acts 2-transitively on \( X \) and \( |X| = q^3 + 1 \). Let \( x \in X \) be arbitrary. Let \( q = p^n \), \( p \) prime. Then \( O_p H(x) \) (i.e., the largest normal \( p \)-subgroup of the stabilizer \( H(x) \)) acts regularly on \( X - \{ x \} \) and its center \( ZO_p H(x) \), which is of order \( q \), consists of precisely those elements of \( H(x) \) fixing all the \( q^2 \) nonabsolute lines (i.e., those lines \( L \) of \( \Pi \) not incident with \( L^\delta \)) passing through \( x \). It is straightforward to check by calculating with the elements denoted by \( Q(a, b) \) and \( T \) in [7, pp. 243–244] that if
$x_1, x_2$ and $x_3 \in X$ are noncollinear, then $\langle ZO_\rho H(x_i) \vert 1 < i < 3 \rangle$ acts transitively on $X$ and hence $\langle ZO_\rho H(x_i) \vert 1 < i < 3 \rangle = \langle ZO_\rho H(x) \vert x \in X \rangle$. If $q > 2$, we have $\langle ZO_\rho H(x) \vert x \in X \rangle = H$ since $H$ is simple; when $q = 2$, $\langle ZO_\rho H(x) \vert x \in X \rangle = H'$.  

Lemma 4. Let $P_1$ be a nontrivial subgroup of $ZO_\rho H(x)$ for some $x \in X$ and let $C$ be the set of subgroups conjugate to $P_1$ in $H$. If $\vert P_1 \vert > 2$ or $q = 2$, there exist $P_2$ and $P_3 \in C$ such that $\langle P_1, P_2, P_3 \rangle = H'$ (where $H = H'$ if $q > 2$). If $\vert P_1 \vert = 2$ and $q > 2$, there exist $P_2, P_3$ and $P_4 \in C$ such that $\langle P_1, P_2, P_3, P_4 \rangle = H$. 

Proof. Let $Y$ be the set of absolute points on some nonabsolute line through $x$. $H_Y$ induces $PGL(2, q)$ on $Y$. If $q$ is even, there exists, according to [7, (8.8.27)], a subgroup $P_2 \subseteq C$ such that $\langle P_1, P_2 \rangle_Y$ contains a dihedral group of order $2(q + 1)$ which is maximal in $H_Y \cong PSL(2, q)$. If $\vert P_1 \vert > 2$ or $q = 2$, we have $\langle P_1, P_2 \rangle_Y \cong PSL(2, q)$. If $\vert P_1 \vert = 2$ but $q > 2$, there is a subgroup $P_4 \subseteq C$, $P_4 < H(x)$, distinct from $P_1$, we have $\langle P_1, P_2, P_4 \rangle_Y \cong PSL(2, q)$. If $q$ is odd, it follows from [6, (2.8.4)] if $q \neq 9$ and from $PSL(2, 9) \cong A_6$ when $q = 9$ that there exists a $P_2 \subseteq C$ such that $\langle P_1, P_2 \rangle_Y \cong PSL(2, q)$ since any two $\rho$-elements of $PSL(2, q)$ are conjugate in $PGL(2, q)$ and $A_6$ can be generated by two of its 3-elements. 

Now suppose that for some subgroup $A$ of $H_Y$, $A_Y \cong PSL(2, q)$, $q$ even or odd. Then $ZO_\rho H(y) < A$ for every $y \in Y$. If $P_3$ is any subgroup in $C$ whose absolute fixed point does not lie on $Y$, then $g(Y) \neq Y$ for every nontrivial element $g$ in $P_3$ and so $\langle A, P_3 \rangle$ contains $ZO_\rho H(z)$ for at least three noncollinear points $z \in X$.  

In the proof of Theorem 3 we will need to deal with an arbitrary elementary abelian subgroup of $O_\rho H(x)$. If $p = 2$, every such subgroup is contained in $ZO_\rho H(x)$. For odd $p$, this is not so. 

Lemma 5. Let $p \neq 2$, let $P_1$ be a nontrivial elementary abelian subgroup of $O_\rho H(x)$ for some $x \in X$ and let $C$ be the set of subgroups conjugate to $P_1$ in $H$. Then $\vert P_1 \vert < q^2$. If $P_1 \cap ZO_\rho H(x) = 1$ then $\vert P_1 \vert < q$ and there exist $P_2, P_3$ and $P_4 \in C$ such that $\langle P_1, P_2, P_3, P_4 \rangle = H$. If $\vert P_1 \vert > q$ then there exists a single subgroup $P_2$ such that $\langle P_1, P_2 \rangle = H$. 

Proof. It is easily checked that $\vert P_1 \vert < q^2$ and $\vert P_1 \vert < q$ if $P_1 \cap ZO_\rho H(x) = 1$. Suppose first that $\vert P_1 \vert > q$ so that $P_1 \cap ZO_\rho H(x) \neq 1$. Given any nonabsolute line $L$ through $x$, we may choose $P_2 \subseteq C$ such that $\langle P_1, P_2 \rangle$ induces $PSL(2, q)$ on $Y$, where $Y = X \cap L$. Since $\vert P_1 \vert > q$, $P_1 \subseteq ZO_\rho H(x)$ and so $P_1$ contains elements which do not map $Y$ to itself. Hence $\langle P_1, P_2 \rangle$ contains $ZO_\rho H(z)$ for at least three noncollinear points $z \in X$. Thus $\langle P_1, P_2 \rangle = H$. Now suppose $P_1 \cap ZO_\rho H(x) = 1$. Choose any nontrivial element $a \in P_1$. There exists an homology $h \in H(x)$ such that $a$ and $a^h$ do not commute. Let $P_2 = P_1^h$. Then $1 \neq [a, a^h] \in (O_\rho H(x))' = ZO_\rho H(x)$; thus $\langle P_1, P_2 \rangle \cap ZO_\rho H(x) \neq 1$. It follows now just as in the previous case that there exists a subgroup $P$ conjugate to $\langle P_1, P_2 \rangle$ in $H$ such that $\langle P_1, P_2, P \rangle = H$.  

$PGL(3, q^2)$ is the subgroup of $PGL(3, q^2)$ consisting of those elements which commute with the polarity $\delta$. Let $K = PGL(3, q^2)$. Then $K = \text{aut}(H)$ and for each $x \in X$, $O_\rho H(x) = O_\rho K(x)$. If $H < L < K$, then $p$ is the only local prime of $L(x)$, i.e., the only prime such that $O_\rho L(x) \neq 1$. 

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We now begin the actual proof of Theorem 3. Suppose $\Gamma$ and $G$ fulfill the hypotheses. According to [8, (4.9)] if $q = 2$ and [8, (3.5), condition (1)] if $q > 2$, $G_t(x) = G_t(x)$. Suppose that $G_t(x, y) \neq 1$. Recalling our previous remarks, we note that [8, (4.11)] continues to hold when $G^{\Gamma(x)}$ is imprimitive if $\Gamma$ is assumed to be undirected and connected. Thus $G_t(x, y)$ is a $p$-group since $p$ is the only local prime of $(G(x, y))^{\Gamma(x)}$.

Let $u \in \Gamma(x)$ or $\Gamma(x)$ be arbitrary. We claim that $Z_{O_p}G(x, u)$ is contained in $Z_{O_p}G(x)$. Suppose the contrary. Since $O_p(G(x))^{\Gamma(x)} = 1$, $O_p(G(x)) = O_pG(x) = O_pG(x) \cap G_t(x)$. It follows that $Z_{O_p}G(x, u) \not< G_t(x)$. Since $G_t(x) = G_t(x)$, we can find $a \in Z_{O_p}G(x, u)$, $z \in \Gamma(x)$ and $w \in \Gamma(x)$ such that $a \not\in G(z)$ and $a \not\in G(w)$. Since $G_t(x, z) \not< G_t(x)$, $G_t(x, z) \not< O_pG(x) \not< O_pG(x, u)$ and hence $G_t(x, z) = aG_t(x, z)a^{-1} = G_t(x, a(z))$. Therefore $G_t(x, z) \not< \langle G_t(x, z), G_t(x, a(z)) \rangle$. Since $G_t(x)^{\Gamma(x)}$ is primitive but not regular and $a(z) \not= z$, $\langle G_t(x, z), G_t(x, a(z)) \rangle = G_t(x)$. Thus $G_t(x, z) \not< G_t(x)$. Similarly, $G_t(w, x) \not< G_t(x)$. If $b \in G$ is an element mapping $(w, x)$ to $(x, z)$ then $G_t(x, z) = bG_t(w, x)b^{-1} \not< bG(x)b^{-1} = G_t(x)$. It follows that $G_t(x, z) \not< \langle G_t(x), G_t(z) \rangle$ although $G_t(x, z) \not= 1$, a contradiction. Thus $Z_{O_p}G(x, u) < Z_{O_p}G(x)$ as claimed.

Let $\Omega_t$ be the functor which assigns to a $p$-group the subgroup generated by its elements of order $p$. Let $V = \{u \in \Omega_tZ_{O_p}G(x, u) \cap \Gamma(x) \cap \Gamma(x)\}$. By the previous paragraph, $V, \Omega_tZ_{O_p}G(x)$. Let $C(V) = C_{G(x)}(V)$, the centralizer of $V$ in $G(x)$, and suppose that $C(V) \not< G_t(x)$. Since $G_t(x) = G_t(x)$, we can find $a \in C(V)$, $z \in \Gamma(x)$ and $w \in \Gamma(x)$ such that $a \not\in G(z)$ and $a \not\in G(w)$. Since $\Omega_tZ_{O_p}G(x, z) \not< V$, $\Omega_tZ_{O_p}G(x, z) = a\Omega_tZ_{O_p}G(x, z)a^{-1} = \Omega_tZ_{O_p}G(x, a(z))$ and thus $\Omega_tZ_{O_p}G(x, z) \not< \langle G_t(x, z), G_t(x, a(z)) \rangle = G_t(x)$. Similarly, $\Omega_tZ_{O_p}G(w, x) \not< G_t(x)$. Conjugating $\Omega_tZ_{O_p}G(x, z)$ by an element mapping $(w, x)$ to $(x, z)$, we conclude that $\Omega_tZ_{O_p}G(x, z) \not< G_t(x)$. Thus $\Omega_tZ_{O_p}G(x, z) \not< \langle G_t(x), G_t(z) \rangle$ and so $\Omega_tZ_{O_p}G(x, z) = 1$ although $1 \not= G_t(x, z) \not< O_pG(x, z)$, a contradiction. It follows that $C(V) < G_t(x)$.

Let $n$ denote the functor which assigns to a $p$-group the maximal order of an elementary abelian subgroup and $J_t$ the functor which assigns to a $p$-group the subgroup generated by all its elementary abelian subgroups of this order. Suppose $J_tO_pG(x, y) < G_t(x)$. Then $J_tO_pG(x, y) < O_pG(x, y) \cap G_t(x) = O_pG(x)$ and hence $mO_pG(x, y) = mO_pG(x)$ and $J_tO_pG(x, y) = J_tO_pG(x)$. Let $w \in \Gamma(x)$ be arbitrary. Since $G$ acts transitively on $K(\Gamma)$, $mO_pG(w, x) = mO_pG(x, y) = mO_pG(x)$. Since $O_pG(x) \not< O_pG(w, x)$, $J_tO_pG(x) \not< J_tO_pG(w, x)$. Since $|J_tO_pG(x)| = |J_tO_pG(w, x)|$, $J_tO_pG(x) = J_tO_pG(w, x)$. Conjugating $J_tO_pG(w, x)$ by an element mapping $(w, x)$ to $(x, y)$, we see that $J_tO_pG(x, y) \not< G_t(y)$ and thus $J_tO_pG(x, y) \not< \langle G_t(x, y) \rangle$ and so $J_tO_pG(x, y) = 1$ although $O_pG(x, y) \not= 1$, a contradiction. It follows that $J_tO_pG(x, y) \not< G_t(x)$.

Choose $P_1$ among those elementary abelian subgroups of $O_pG(x, y)$ of order $mO_pG(x, y)$ not contained in $G_t(x)$ and let $P_0 = P_1 \cap G_t(x)$. Since $V, \Omega_tZ_{O_p}G(x)$ and $P_0 \not< O_pG(x, y) \cap G_t(x) = O_pG(x)$, $P_0V$ is elementary abelian. Hence $|P_0V| < |P_1|$. Since $P_1$ is abelian, $P_0 \cap V < C_{P_1}(P_1)$. Therefore $|P_1|/|P_0| > |P_0V|/|P_0| = |V/V \cap V| > |V/C_{P_1}(P_1)|$. $P_1/|P_0|$ is isomorphic to a nontrivial elementary abelian group of $O_pG(x, y)$ of order $m$. Let $|P_1/|P_0| = p^m$. Let $t$ be an
integer such that there exist subgroups $P_2, \ldots, P_t$ conjugate to $P_1$ in $G(x)$ such that, with $A = \langle P_1, \ldots, P_t \rangle$, $A^{G(x)} \cong \text{PSU}(3, q^2)'$. Since $P_i$ is conjugate to $P_1$, $|V/C_V(P_i)| = |V/C_V(P_1)|$ for $2 \leq i < t$; hence $|V/C_V(A)| < |V/C_V(P_i)'| < |P_i/P_0| = p^{m_i}$. Let $W = V/C_V(A)$ and $D = C_4(W)$. $D$ is normal in $A$. If $D \not\triangleleft G_1(x)$, $|G_1(x)| = |C_V(P_1)|$ for $2 \leq i < V$, hence $|K/\text{Core}_K(P_1)| < |F/C^P_0| < |P_0/P_0| = p^m$. Let $H = F/\text{Core}_K(P_1)$ and $D = \text{Core}_W$. $D$ is normal in $G_1(x)$, $D$ contains elements of order prime to $p$ not in $G_1(x)$. By [6, (5.3.2)], these elements lie in $C(V)$. This contradicts $C(V) < G_1(x)$. Hence $D < G_1(x)$. Since $|A/D|$ is faithfully represented on $W$, we have $|A/D| < |\text{GL}(W)|$ and thus $q^3 + 1 | |A^{G(x)}|| |A/D|| |\text{GL}(W)|$ and so $q^3 + 1$ divides $(p^m - 1)(p^m - 1)(p - 1)$.

Since $p^m$ is the order of a group isomorphic to an elementary abelian $p$-subgroup of $\text{PSU}(3, q^2)$, $p^m < q$ if $q$ is even and $p^m < q^2$ if $q$ is odd. If $q = 2$ (and thus $p^m = 2$), then according to Lemma 4 we can take $t = 3$. This implies that $2^3 + 1$ divides $(2^3 - 1)(2^3 - 1)$ which is not true. Thus $q > 2$. By [11, p. 283], there exists a prime $\pi$ dividing $q^6 - 1$ but not $p^v - 1$ for any $v < 6n$ where $q = p^n$. In particular, $\pi$ divides $q^3 + 1 = (q^6 - 1)/(q^3 - 1)$. Hence $\pi$ divides $(p^m - 1)(p^{m-1} - 1) \cdots (p - 1)$ and so $6n < m$. If $p^m > q$ then according to Lemma 5 we can take $t = 2$ and so $6n < 2m$. Thus $p^{3n} < p^m$. This contradicts $p^m < q^2$. It follows that $p^m < q$, i.e., $m < n$. According to Lemmas 4 and 5, we can take $t < 4$. Thus $6n < mt < 4m < 4n$. With this contradiction, the proof of Theorem 3 is complete.

In conclusion, we note that to show that our proof of Theorem 3 remains valid if $\text{PSU}(3, q^2)$ is replaced by $Sz(q)$ or $2G_2(q)$, it is necessary only to prove an appropriate version of Lemmas 4 and 5. I leave the case $2G_2(q)$ as a problem. For the Suzuki groups, the following result, a corollary of [10, Theorem 9], is easily seen to suffice.

**Lemma 6.** Let $P_1$ be a nontrivial elementary abelian 2-subgroup of $Sz(q)$. Then there exists a subgroup $P_2$ conjugate to $P_1$ such that $\langle P_1, P_2 \rangle$ contains a dihedral group of order $2(q - 1)$ if $q > 2$, or order 10 if $q = 2$, which is maximal in $Sz(q)$ (so that $\langle P_1, P_2 \rangle = Sz(q)$ if $|P_1| > 2$).

**References**


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