ESSENTIAL DIMENSION OF FINITE GROUPS IN PRIME CHARACTERISTIC

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Abstract. Let F be a field of characteristic $p > 0$ and G be a smooth finite algebraic group over F. We compute the essential dimension $\operatorname{ed}_F(G;p)$ of G at p. That is, we show that

$$\operatorname{ed}_F(G;p) = \begin{cases} 1, \text{ if } p \text{ divides } |G|, \text{ and} \\ 0, \text{ otherwise.} \end{cases}$$

1. Introduction

Let F be a field and G be an algebraic group over F. We begin by recalling the definition of the essential dimension of G.

Let K be a field containing F and $\tau\colon T \to \operatorname{Spec}(K)$ be a G-torsor. We will say that τ descends to an intermediate subfield $F \subset K_0 \subset K$ if τ is the pull-back of some G-torsor $\tau_0\colon T_0 \to \operatorname{Spec}(K_0)$, i.e., if there exists a Cartesian diagram of the form

$$\begin{tikzcd} T \arrow[r] \arrow[d, "\tau"] & T_0 \arrow[d, "\tau_0"] & \\ \operatorname{Spec}(K) \arrow[r] & \operatorname{Spec}(K_0) \arrow[r] & \operatorname{Spec}(F). \end{tikzcd}$$

The essential dimension of τ, denoted by $\operatorname{ed}_F(\tau)$, is the smallest value of the transcendence degree $\operatorname{trdeg}(K_0/F)$ such that τ descends to K_0. The essential dimension of G, denoted by $\operatorname{ed}_F(G)$, is the maximal value of $\operatorname{ed}_F(\tau)$, as K ranges over all fields containing F and τ ranges over all G-torsors $T \to \operatorname{Spec}(K)$.

Now let p be a prime integer. A field K is called p-closed if the degree of every finite extension L/K is a power of p. Equivalently, $\operatorname{Gal}(K^s/K)$ is a pro-p-group, where K^s is a separable closure of K. For example, the field of real numbers is 2-closed. The essential dimension $\operatorname{ed}_F(G;p)$ of G at p is the maximal value of $\operatorname{ed}_F(\tau)$, where K ranges over p-closed fields K containing F, and τ ranges over the G-torsors $T \to \operatorname{Spec}(K)$.

It is easy to see that if τ is a versal torsor in the sense of [Se03, Section 5], then $\operatorname{ed}_F(\tau) = \operatorname{ed}_F(G)$. In fact, $\operatorname{ed}_F(G)$ is the minimal value of $\operatorname{trdeg}(K/F)$ such that there exists a versal G-torsor over K. Similarly, $\operatorname{ed}_F(G;p)$ is the minimal value of $\operatorname{trdeg}(K/F)$

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such that there exists a p-versal G-torsor over K; see [DR15, Section 8]. For an overview of the theory of essential dimension, we refer the reader to the surveys [Rei10] and [Me13].

The case where G is a finite group (viewed as a constant group over F) is of particular interest. A theorem of N. A. Karpenko and A. S. Merkurjev [KM08] asserts that in this case

$$\mathrm{ed}_F(G;p) = \mathrm{ed}_F(G_p;p) = \mathrm{ed}_F(G_p) = \mathrm{rdim}_F(G_p)\,, \tag{1}$$

provided that F contains a primitive p-th root of unity ζ_p. Here G_p is any Sylow p-subgroup of G, and $\mathrm{rdim}_F(G_p)$ denotes the minimal dimension of a faithful representation of G_p defined over F. For example, assuming that $\zeta_p \in F$, $\mathrm{ed}_F(G) = \mathrm{ed}(G;p) = r$, if $G = (\mathbb{Z}/p\mathbb{Z})^r$ and $\mathrm{ed}(G) = \mathrm{ed}(G;p) = p$, if G is a non-abelian group of order p^3. Further examples can be found in [MR10].

Little is known about essential dimension of finite groups over a field F of characteristic $p > 0$. A. Ledet [Led04] conjectured that

$$\mathrm{ed}_F(\mathbb{Z}/p^r\mathbb{Z}) = r \tag{2}$$

for every $r \geqslant 1$. This conjecture remains open for every $r \geqslant 3$. In this paper we will prove the following surprising result.

Theorem 1. *Let F be a field of characteristic $p > 0$ and G be a smooth finite algebraic group over F. Then*

$$\mathrm{ed}_F(G;p) = \begin{cases} 1, & \text{if } p \text{ divides } |G|, \text{ and} \\ 0, & \text{otherwise.} \end{cases}$$

In particular, Ledet's conjecture (2) fails dramatically if essential dimension is replaced by essential dimension at p.

Before proceeding with the proof of Theorem 1, we remark that the condition that G is smooth cannot be dropped. Indeed, it is well known that $\mathrm{ed}_F(\mu_p^r;p) = r$ for any $r \geqslant 0$. More generally, if G is a group scheme of finite type over a field F of characteristic p (not necessarily finite or smooth), then $\mathrm{ed}_F(G;p) \geqslant \dim(\mathcal{G}) - \dim(G)$, where $\mathcal{G}$ is the Lie algebra of G; see [TV13, Theorem 1.2].

2. Proof of Theorem 1

By [MR10, Lemma 4.1], if the index $[G : G']$ of a subgroup of $G' \subset G$ is prime to p, then

$$\mathrm{ed}_F(G;p) = \mathrm{ed}_F(G';p). \tag{3}$$

In particular, if p does not divide $|G|$, then taking $G' = \{1\}$, we conclude that $\mathrm{ed}_F(G;p) = 0$. On the other hand, if p divides $|G|$, then $\mathrm{ed}_F(G;p) \geqslant 1$; see [Me09, Proposition 4.4] or [LMMR13, Lemma 10.1].

Our goal is thus to show that $\mathrm{ed}_F(G;p) \leqslant 1$. First let us consider the case where G is a finite group, viewed as a constant algebraic group over F. By (3), we may replace G by a Sylow subgroup G_p. In other words, we may assume without loss of generality that G is a p-group. Moreover, since $\mathbb{F}_p \subset F$, $\mathrm{ed}_F(G;p) \leqslant \mathrm{ed}_{\mathbb{F}_p}(G;p)$. Thus, for the purpose of proving the inequality $\mathrm{ed}_F(G;p) \leqslant 1$, we may assume that $F = \mathbb{F}_p$.

Recall that the Nottingham group $\mathrm{Aut}_0(F[[t]])$ is the group of automorphisms σ of the algebra $F[[t]]$ of formal power series such that $\sigma(t) = t + a_2t^2 + a_2t^3 + \ldots$, for some $a_2, a_3, \ldots \in F$. By a theorem of of Leedham-Green and Weiss [C97, Theorem 3], every finite p-group G embeds into $\mathrm{Aut}_0(F[[t]])$. Fix an embedding $\phi\colon G \hookrightarrow \mathrm{Aut}_0(F[[t]])$. By a theorem of D. Harbater [Ha80, Section 2], there exists a smooth curve X with a G-action defined over F, and an F-point $x \in X$ fixed by G, such that the G-action in the formal neighborhood of x is given by ϕ; see also [Ka86, Theorem 1.4.1] and [BCPS17, Theorem 4.8]. Since ϕ is injective, the G-action on X is faithful. By [DR15, Corollary 8.6(b)], the G-action on X is p-versal. Since $\mathrm{ed}_F(G;p)$ is the minimal dimension of an F-variety Y with a faithful p-versal G-action, we conclude that $\mathrm{ed}_F(G;p) \leqslant 1$. This completes the proof of Theorem 1 in the case where G is a constant group.

Now consider the general case, where G is a smooth finite algebraic group over F. In other words, $G = {}^{\tau}\Gamma$, where Γ is a constant finite group, $A = \mathrm{Aut}_{\mathrm{grp}}(\Gamma)$ is the group of automorphisms of Γ and τ is a cocycle representing a class in $H^1(F, A)$.

Lemma 2. (a) $\mathrm{ed}_F(G) \leqslant \mathrm{ed}_F(\Gamma \rtimes A)$, (b) $\mathrm{ed}_F(G;p) \leqslant \mathrm{ed}(\Gamma \rtimes A; p)$.

The semidirect product $\Gamma \rtimes A$ is a constant finite group. Hence, as we showed above, $\mathrm{ed}_F(\Gamma \rtimes A; p) \leqslant 1$. Theorem 1 now follows from Lemma 2(b). It thus remains to prove Lemma 2.

3. Proof of Lemma 2

We will make use of the following description of $\mathrm{ed}_F(G)$ and $\mathrm{ed}_F(G;p)$ in the case, where G is a finite algebraic group over F. Let $G \to \mathrm{GL}(V)$ be a faitful representation. A compression (respectively, a p-compression) of V is a dominant G-equivariant rational map $V \dashrightarrow X$ (respectively, a dominant G-equivariant correspondence $V \rightsquigarrow X$ of degree prime to p), where G acts faithfully on X. Recall that $\mathrm{ed}_F(G)$ (respectively, $\mathrm{ed}_F(G;p)$) equals the minimal value of $\dim(X)$ taken over all compressions $V \dashrightarrow X$ (respectively all p-compressions $V \rightsquigarrow X$). In particular, these numbers depend only on G and F and not on the choice of the generically free representation V. For details, see [Rei10].

We are now ready to proceed with the proof of Lemma 2. To prove part (a), let V be a generically free representation of $\Gamma \rtimes A$ and let $f\colon V \dashrightarrow X$ be a $\Gamma \rtimes A$-compression, with X of minimal possible dimension. That is, $\dim_F(X) = \mathrm{ed}_F(\Gamma \rtimes A)$. Twisting by τ, we obtain a $G = {}^{\tau}\Gamma$-equivariant map ${}^{\tau}f\colon {}^{\tau}V \dashrightarrow {}^{\tau}X$; see e.g., [FR17, Proposition 2.6(a)]. Now observe that by Hilbert's Theorem 90, ${}^{\tau}V$ is a vector space with a linear action of $G = {}^{\tau}\Gamma$ and ${}^{\tau}f\colon {}^{\tau}V \dashrightarrow {}^{\tau}X$ is a compression. (To see that the G-action on ${}^{\tau}V$ and ${}^{\tau}X$ are faithful, we may pass to the algebraic closure $\overline{F}$ of F. Over $\overline{F}$, τ is split, so that $G = \Gamma$, ${}^{\tau}V = V$, ${}^{\tau}X = X$ and ${}^{\tau}f = f$, and it becomes obvious that the G-actions on ${}^{\tau}V$ and ${}^{\tau}X$ are faithful.) We conclude that $\mathrm{ed}_F(G) \leqslant \dim_F({}^{\tau}X) = \dim_F(X) = \mathrm{ed}_F(\Gamma \rtimes A)$, as desired.

The proof of part (b) proceeds along the same lines. The starting point is a p-compression $f\colon V \rightsquigarrow X$ with X of minimal possible dimension, $\dim_F(X) = \mathrm{ed}_F(\Gamma \rtimes A; p)$. We twist f by τ to obtain a p-compression ${}^{\tau}f\colon {}^{\tau}V \rightsquigarrow {}^{\tau}X$ of the linear action of $G = {}^{\tau}\Gamma$ on ${}^{\tau}V$. The rest of the argument is the same as in part (a). This completes the proof of Lemma 2 and thus of Theorem 1. ♠

4. An application

In this section G will denote a connected reductive linear algebraic group over a field F. It is shown in [CGR06, Theorem 1.1(c)] that there exists a finite F-subgroup $S \subset G$ such that every Γ-torsor over every field K/F admits reduction of structure to S; see also [CGR08, Corollary 1.4]. In other words, the map $H^1(K, S) \to H^1(K, G)$ is surjective for every field K containing F. If this happens, we will say that "G admits reduction of structure to S".

We will now use Theorem 1 to show that if $\mathrm{char}(F) = p > 0$ and p is a torsion prime for G, then S cannot be smooth. For the definition of torsion primes, a discussion of their properties and further references, see [Se00]. Note, in particular, that by a theorem of A. Grothendieck [Gr58], if G is not special (i.e., if $H^1(K, G) \neq \{1\}$ for some field K containing F), then G has at least one torsion prime; see also [Se00, 1.5.1].

Corollary 3. *Let G be a connected linear algebraic group over an algebraically closed field F of characteristic $p > 0$.*

(a) If S is a smooth finite subgroup of G defined over F, then the natural map

$$f_K \colon H^1(K, S) \to H^1(K, G)$$

is trivial for any p-closed field K containing F. In other words, f_K sends every $\alpha \in H^1(K, S)$ to $1 \in H^1(K, G)$.

(b) If p is a torsion prime for G, then G does not admit reduction of structure to any smooth finite subgroup.

Proof. (a) Let $\alpha \in H^1(K, S)$ and $\beta = f_K(\alpha) \in H^1(K, G)$. By Theorem 1, α descents to $\alpha_0 \in H^1(K_0, S)$ for some intermediate field $F \subset K_0 \subset K$, where $\mathrm{trdeg}(K_0/F) \leqslant 1$. It now suffices to show that $H^1(K_0, G) = \{1\}$. If we can do this, then the diagram

$$\begin{tikzcd}
H^1(K_0, S) \arrow[rrr, "f_{K_0}"] \arrow[ddd] & & & H^1(K_0, G) \arrow[ddd] \\
& \alpha_0 \arrow[r, mapsto] \arrow[d, mapsto] & 1 \arrow[d, mapsto] & \\
& \alpha \arrow[r, mapsto] & \beta & \\
H^1(K, S) \arrow[rrr, "f_K"] & & & H^1(K, G)
\end{tikzcd}$$

shows that $\beta = 1$. Since F is algebraically closed and $\mathrm{trdeg}(K_0/F) \leqslant 1$, the cohomological dimension of K_0 is $\leqslant 1$; see [Se97, §II.3.2]. By Serre's Conjecture I,

$$H^1(K_0, G) = \{1\}, \tag{4}$$

as desired. Note that (4) was proved by R. Steinberg [St65] in the case where K_0 is perfect, and by A. Borel and T. A. Springer [BS68, §8.6] for general K.

(b) If p is a torsion prime for G, then $H^1(K, G) \neq \{1\}$ for some p-closed field K containing F; see [Me09, Proposition 4.4]. In view of part (a), this implies that f_K is not surjective. ♠

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