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ABELIAN SUBGROUPS OF PRO-2 GALOIS GROUPS

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ABSTRACT. Let $a(K)$ be the maximal cardinality $|I|$ such that $\mathbb{Z}_2^I$ is a closed subgroup of the maximal pro-2 Galois group of a field K. We prove estimates on $a(K)$ conjectured by Ware.

Let K be a field of characteristic $\neq 2$, and let $K(2)$ be its maximal pro-2 Galois extension. Thus, $K(2)$ is obtained from K by repeatedly adjoining all square roots. Let $G_K(2)$ be the Galois group $\mathrm{Gal}(K(2)/K)$. In [11] Ware defines the a-invariant $a(K)$ of K to be the maximal rank (possible ∞) of closed subgroups of $G_K(2)$ which are torsion-free and abelian. Note that by Pontryagin duality, such subgroups are of the form $\mathbb{Z}_2^I$ for some index set I. Another closely related invariant of K is its (absolute) stability index $\mathrm{st}(K)$, defined as the minimal positive integer m (∞ if no such m exists) such that $I^{m+1}(K) = 2I^m(K)$, where $I(K)$ is the fundamental ideal of the Witt ring $W(K)$ of K. In the present note we prove the following three conjectures raised in [11]:

Theorem. (I) *If K is formally real, then* $a(K) \leq \mathrm{rank}\, G_K(2) - 1$.
(II) *For every finite extension E/K of fields,* $a(K) \leq a(E)$.
(III) $a(K) \leq \mathrm{st}(K)$.

(With regard to conjecture (I), the conjecture in [11] is in fact only that $a(K) \leq \mathrm{rank}\, G_K(2)$; this slightly weaker inequality is proved in [11, Corollary 5, p. 992] for nonformally real fields.)

Our proofs are based on valuation-theoretic techniques. For convenience, we recall the following notions and facts from [2, p. 151]: A valued field (K, v) is *2-henselian* if v has a unique extension to $K(2)$. Equivalently, Hensel's lemma holds for polynomials that split completely in $K(2)$. An arbitrary valued field (K, v) has an immediate 2-extension $(\widehat{K}, \hat{v})$ which is 2-henselian and which uniquely embeds in every 2-henselian extension (L, u) of (K, v) contained in $K(2)$. In fact, $\widehat{K}$ is the decomposition field of any extension of v to $K(2)$. An extension $(\widehat{K}, \hat{v})$ as above is called a *2-henselization* of (K, v). We denote $q(K) = (K^\times : (K^\times)^2)$. To avoid notational inconsistency, we do not distinguish here and in the sequel between different infinite cardinalities.

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Lemma 1. *Let* (K, v) *be a 2-henselian field with value group* Γ *and residue field* $\overline{K}$ *of characteristic* $\neq 2$. *Then*:

(a) $G_K(2) \cong A \rtimes G_{\overline{K}}(2)$, *where* A *is a torsion-free abelian group of rank* $\dim_{\mathbb{F}_2} \Gamma/2\Gamma$.

(b) *If* $\overline{K}$ *contains all roots of unity of* 2*-power order over its prime field, then* $G_K(2) \cong A \times G_{\overline{K}}(2)$ *with* A *as above.*

(c) $q(K) = q(\overline{K})|\Gamma/2\Gamma|$.

Proof. (a) is well known (see, e.g., [4, §§19, 20]). (b) follows from (a) and from [6, Theorem 2.2(ii)]. For (c), take a subset T of $K^\times$ such that $v(t)$, $t \in T$, represent the distinct cosets of $\Gamma/2\Gamma$. By Hensel's lemma, the 1-units of v are squares. Every element $x \in K^\times$ can be written as $x = \alpha t y^2$, where α is a unit of v, $t \in T$, and $y \in K$. This induces a bijection $K^\times/(K^\times)^2 \cong \overline{K}^\times/(\overline{K}^\times)^2 \times T$, whence the assertion. □

Our main tool is the following valuation-theoretic description of the a-invariant:

Proposition 2. *Given a field* K *with* $a(K) \geq 2$ *there exists a valuation* v *on* K *whose residue field* $\overline{K}$ *and value group* Γ *satisfy*:

(i) $\operatorname{char} \overline{K} \neq 2$;

(ii) $a(K) = \log_2 |\Gamma/2\Gamma| + 1$ (*in particular,* $\Gamma \neq 2\Gamma$);

(iii) $a(\widehat{K}) = a(K)$ *for any* 2*-henselization* $\widehat{K}$ *of* K;

(iv) $\overline{K}(2)/\overline{K}(\mu)$ *is infinite, where* μ *is the group of all roots of unity of* 2*-power order over the prime field of* $\overline{K}$.

Proof. We first observe that $\operatorname{char} K \neq 2$. For otherwise $\operatorname{cd}(G_K(2)) \leq 1$ [9, II-4, Proposition 3]. Since $\operatorname{cd}(\mathbb{Z}_2^I) = |I|$ (use, e.g., [9, I-32, Proposition 22]), this implies that $a(K) \leq 1$, contrary to the assumption.

Now let L be the fixed field of a torsion-free abelian closed subgroup of $G_K(2)$ of maximal rank. Write $G_L(2) \cong \mathbb{Z}_2^I \times \mathbb{Z}_2$ with $|I| \geq 1$. By [6, Theorem 2.5] (and its proof), L has a 2-henselian valuation u whose residue field $\overline{L}$ satisfies $\operatorname{char} \overline{L} \neq 2$ and $G_{\overline{L}}(2) \cong \mathbb{Z}_2$. By [10, Theorem 3.6], L contains all roots of unity of 2-power order over its prime field. Hence, so does $\overline{L}$. Let v be the restriction of u to K, and let $(\widehat{K}, \hat{v})$ be a 2-henselization of (K, v). We may take $\widehat{K} \subseteq L$. Let $v(2)$ be the unique extension of $\hat{v}$ to $K(2)$, and let $\overline{K}$, $\overline{K(2)}$ be the residue fields of (K, v) and $(K(2), v(2))$, respectively. Since $\overline{L}/\overline{K}$ is an algebraic extension, $\operatorname{char} \overline{K} \neq 2$. Therefore, the 2-extension $\overline{K(2)}/\overline{K}$ is separable. Clearly, $\overline{K(2)}$ is quadratically closed. Thus $\overline{K(2)} = \overline{K}(2)$. Denoting the inertia field of $(K(2), v(2))/(\widehat{K}, \hat{v})$ by K^T we obtain from [4, Theorem 19.6] that

$$\operatorname{Gal}(K^T/\widehat{K}) \cong \operatorname{Aut}(\overline{K(2)}/\overline{K}) = G_{\overline{K}}(2).$$

Next let $E = L \cap K^T$. It is 2-henselian with respect to the unique extension of $\hat{v}$ [2, Proposition 1.6] and has value group Γ and residue field $\overline{L}$. By Lemma 1(b), $G_E(2)$ is a torsion-free abelian pro-2 group of rank $\log_2 |\Gamma/2\Gamma| + 1$. As $K \subseteq \widehat{K} \subseteq E \subseteq L$ and $a(K) = a(L)$, we have

$$a(K) = a(\widehat{K}) = a(E) = \log_2 |\Gamma/2\Gamma| + 1,$$

proving (ii) and (iii).

Finally, (iv) follows from the fact that $\overline{K}(\mu) \subseteq \overline{L} \subset \overline{K}(2)$, and $G_{\overline{L}}(2) \cong \mathbb{Z}_2$. □

Remarks. (1) Given a field K, with $a(K) \geq 2$, one in general does not have a valuation on K with value group Γ satisfying $a(K) = \log_2|\Gamma/2\Gamma|$. For example, let $\mathbb{Q}_{ab}$ be the maximal pro-abelian extension of $\mathbb{Q}$ and let E be any algebraic extension of $\mathbb{Q}_{ab}$ with absolute Galois group $\mathbb{Z}_2$. The field $K = E((t))$ is henselian with respect to its natural valuation u. By Lemma 1(b), $G_K(2) \cong \mathbb{Z}_2 \times \mathbb{Z}_2$, hence $a(K) = 2$. We show that for every nontrivial valuation v on K with value group Γ, $|\Gamma/2\Gamma| \leq 2$. Indeed, if v and u are independent, then the (ordinary) henselization of K with respect to u is the algebraic closure $\widetilde{K}$ [5, Corollary 2.4], so Γ is in this case divisible. Suppose on the other hand that v and u are dependent and distinct. Since the value group $\mathbb{Z}$ of u has no nontrivial isolated subgroups, there are no proper nontrivial coarsenings of u [1, Chapter VI, §4.3, Proposition 4]. Therefore, v is finer then u. Let v^0 be the valuation induced by v on the residue field E of u, and let Γ_0 be its value group. One has a short exact sequence:

$$0 \to \Gamma_0 \to \Gamma \to \mathbb{Z} \to 0$$

[1, Chapter VI, §4.3, Remark]. The restriction of v_0 to $\mathbb{Q}$ is p-adic for some prime p. Since $\sqrt[n]{p} \in \mathbb{Q}_{ab} \subseteq E$ for all $n \geq 1$, the group Γ_0 is divisible. Therefore, $\Gamma/2\Gamma \cong \mathbb{Z}/2\mathbb{Z}$, as desired.

(2) For every valuation v on K with value group Γ and residue characteristic $\neq 2$, $\log_2|\Gamma/2\Gamma| \leq a(K)$ [11, Corollary 2(i), p. 990].

Proof of (I). By Kummer theory and [9, I-38, Corollary],

$$\log_2 q(K) = \dim_{\mathbb{F}_2} \operatorname{Hom}(G_K(2), \mathbb{Z}/2\mathbb{Z}) = \operatorname{rank} G_K(2).$$

We therefore need to show that $a(K) \leq \log_2 q(K) - 1$ for K formally real. This is trivial when $q(K) = \infty$. Suppose then that $q(K) < \infty$. We prove the assertion by induction on $q(K)$. The case $a(K) = 0$ is clear. If $a(K) = 1$, then $q(K) \geq 4$ by [11, Example (1)], as required. We may therefore assume that $a(K) \geq 2$. Let v, $\overline{K}$, and Γ be as in Proposition 2, and let $(\widehat{K}, \hat{v})$ be a 2-henselization of (K, v). Then $\widehat{K} = K\widehat{K}^2$ (see, e.g., [3, Lemma 2.4(a)]). Therefore, the natural homomorphism

$$\Lambda: K^\times/(K^\times)^2 \to \widehat{K}^\times/(\widehat{K}^\times)^2$$

is surjective, so one of the following holds:

Case (1): Λ *is not injective.* Then $2q(\widehat{K}) \leq q(K)$. If $\widehat{K}$ is formally real, we may therefore apply the induction hypothesis to obtain that $a(\widehat{K}) \leq \log_2 q(\widehat{K}) - 1$. If $\widehat{K}$ is not formally real, then we still have $a(\widehat{K}) \leq \log_2 q(\widehat{K})$, by [11, Corollary 5, p. 992]. As $a(K) = a(\widehat{K})$, we conclude that $a(K) \leq \log_2(\widehat{K}) \leq \log_2 q(K) - 1$, as required.

Case (2): Λ *is an isomorphism.* Let M be the maximal ideal of the valuation ring of v. By Hensel's Lemma, $1+M \subseteq \widehat{K}^2 \cap K = K^2$. This implies that (K, v) is 2-henselian [7, Lemma 3.14], i.e., $\widehat{K} = K$. We have $q(\overline{K}) < (\Gamma : 2\Gamma)q(\overline{K}) = q(K)$, by Lemma 1(c). Moreover, $\overline{K}$ is formally real [7, Lemma 3.15]. From the induction hypothesis we therefore get $a(\overline{K}) \leq \log_2 q(\overline{K}) - 1$. Conclude from [11, Corollary 1, p. 990] that

$$a(K) \leq \log_2 |\Gamma/2\Gamma| + a(\overline{K}) \leq \log_2 |\Gamma/2\Gamma| + \log_2 q(\overline{K}) - 1 = \log_2 q(K) - 1,$$

completing the induction. □

Remarks. (1) Ware [11, Remark, p. 992] proves (I) for K (real-)pythagorean and shows that in general $a(K) \leq 2\log_2(K) - 2$.

(2) The bound $a(K) \leq \log_2 q(K) - 1$ for K formally real is sharp. For example, a repeated application of Lemma 1(a) shows that $K = \mathbb{R}((t_1))\cdots((t_n))$ has $G_K(2) \cong \mathbb{Z}_2^n \rtimes (\mathbb{Z}/2\mathbb{Z})$, hence $a(K) = \log_2 q(K) - 1 = n$.

(3) If K is not formally real, then in general one cannot improve the bound $a(K) \leq \log_2 q(K)$ given in [11, Corollary 5, p. 992]. E.g., $K = \widetilde{\mathbb{Q}}((t_1))\cdots((t_n))$ has $a(K) = \log_2 q(K) = n$.

(4) Denote the maximal rank of torsion-free abelian closed subgroups of a pro-2 group G by $a(G)$. The inequality $a(G) \leq \operatorname{rank} G$, although valid for maximal pro-2 Galois groups of fields (by (I) and [11, Corollary 5, p. 992]), does not hold for arbitrary pro-2 groups. For example, the wreath product $G = \mathbb{Z}_2 \wr (\mathbb{Z}/4\mathbb{Z})$ has rank 2, yet it has $\mathbb{Z}_2^4$ as an open subgroup.

For the next proof we need an almost trivial yet important observation:

Lemma 3. *Let Γ be a subgroup of a finite index of a torsion-free abelian group Δ. Then* $(\Delta\colon 2\Delta) = (\Gamma\colon 2\Gamma)$.

Proof. Since Δ is torsion-free, $\Delta/\Gamma \cong 2\Delta/2\Gamma$ naturally. The assertion therefore follows from the equalities

$$(\Delta\colon 2\Delta)(2\Delta\colon 2\Gamma) = (\Delta\colon 2\Gamma) = (\Delta\colon \Gamma)(\Gamma\colon 2\Gamma). \quad \square$$

Proof of (II). If $a(E) = 0$, then $[E(2)\colon E] \leq 2$ by [11, Example (1)], whence $[K(2)\colon K] < \infty$ and we get $a(K) = 0$. We may therefore assume that $a(K) \geq 2$. Let v, Γ, $\overline{K}$, and μ be as in Proposition 2. Also let u be an extension of v to E, let $\overline{E}$ be the residue field of (E, u), and let Δ be its value group. Fix a 2-henselization $\widehat{E}$ of (E, u). Since $\overline{E}/\overline{K}$ and, hence, $\overline{E}(\mu)/\overline{K}(\mu)$ are finite extensions and since $\overline{E}(2)/\overline{K}(\mu)$ is infinite, $\overline{E}(\mu) \neq \overline{E}(2)$. By [11, Theorem 1(i)], $a(\widehat{E}) = \log_2 |\Delta/2\Delta| + a(\overline{E})$. Since $\overline{K}(2)/\overline{K}$ is an infinite extension, so is $\overline{E}(2)/\overline{K}$, hence so is $\overline{E}(2)/\overline{E}$. In particular, $1 \leq a(\overline{E})$, by [11, Example (1)), p. 985] again. From this and from Lemma 3 we deduce:

$$a(K) = \log_2 |\Gamma/2\Gamma| + 1 \leq \log_2 |\Delta/2\Delta| + a(\overline{E}) = a(\widehat{E}) \leq a(E). \quad \square$$

Remark. The inequality (II) holds also when $\operatorname{char} K = 2$. Indeed, as observed at the beginning of the proof of Proposition 2, this implies that $a(K) \leq 1$. Moreover, $a(E) = 0$ if and only if E is quadratically closed. But in this case we obviously have $a(K) = 0$ as well.

Proof of (III). If $\operatorname{st}(K) = 0$, then K is quadratically closed and we are done. We may therefore assume that $a(K) \geq 2$. Let v, Γ, and $\overline{K}$ be as in Proposition 2, and choose a subset T of $K^\times$ such that the cosets of $v(t)$, $t \in T$, form a linear basis of $\Gamma/2\Gamma$ over $\mathbb{F}_2$. Thus, $a(K) = \log_2 |\Gamma/2\Gamma| + 1 = |T| + 1$. Since $\overline{K}$ is not quadratically closed, there exists a v-unit α in K whose residue $\overline{\alpha}$

is not in $\overline{K}^2$. For any finite subset T_0 of T having m elements, consider the $(m+1)$-Pfister form $\varphi_{T_0} = \langle\langle \alpha \rangle\rangle \otimes \bigotimes_{t\in T_0} \langle\langle t \rangle\rangle$. Its similarity class is in $I^{m+1}(K)$. But all its nonzero residue forms (cf. [8, p. 136]) are $\langle\langle \overline{\alpha} \rangle\rangle$ and, hence, are not in $2W(\overline{K})$. It follows that $\varphi_{T_0} \notin 2I^m(K)$, so $m < \mathrm{st}(K)$. Conclude that $a(K) = |T| + 1 \leq \mathrm{st}(K)$. □

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References

1. N. Bourbaki, *Commutative algebra*, Hermann, Paris, 1972.
2. L. Bröcker, *Characterization of fans and herditarily pythagorean fields*, Math. Z. **151** (1976), 149–163.
3. I. Efrat, *Free product decompositions of Galois groups over pythagorean fields*, Comm. Algebra **21** (1993), 4495–4511.
4. O. Endler, *Valuation theory*, Springer, Berlin, 1972.
5. A. Engler, *Fields with two incomparable henselian valuation rings*, Manuscripta Math. **23** (1977), 373–385.
6. B. Jacob and R. Ware, *A recursive description of the maximal pro-2 Galois group via Witt rings*, Math. Z. **200** (1989), 379–396.
7. T. Y. Lam, *Orderings, valuations and quadratic forms*, Conf. Board Math. Sci., vol. 52, Amer. Math. Soc., Providence, RI, 1983.
8. W. Scharlau, *Quadratic and Hermitian forms*, Springer, Berlin, 1985.
9. J. P. Serre, *Cohomologie Galoisienne*, Lecture Notes in Math., vol. 5, Springer, Berlin, 1965.
10. R. Ware, *When are Witt rings groups rings*? II, Pacific J. Math. **76** (1978), 541–564.
11. ——, *Stability in Witt rings and abelian subgroups of pro-2-Galois groups*, Rocky Mountain J. Math. **19** (1989), 985–995.

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