A NEW CONSTRUCTION OF NONCROSSED PRODUCT ALGEBRAS

BY

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Abstract. New examples of noncrossed product division algebras are obtained, using methods different from all previous noncrossed product constructions. The examples are division algebras over intersections of \( p \)-Henselian valued fields, and they have Schur index \( p^m \) and exponent \( p^n \) for any prime number \( p \) and any integers \( m > n > 2 \) (\( n > 3 \) if \( p = 2 \)). The basic tools used in the construction are valuation theory and Galois cohomology; no generic methods are applied and there is no p.i. theory. Along the way, local-global principles are proved for central simple algebras over intersections of \( p \)-Henselian valued fields.

The first examples of central simple division algebras which are not crossed products were obtained by Amitsur in [Am] in 1972. Amitsur thereby settled a question that had been one of the outstanding open problems in the theory of algebras for at least thirty years. His examples were the generic division algebras \( UD(Q, n) \) of index \( n \) over \( Q \) (the rational numbers) for any natural number \( n \) such that \( p^2 | n \), \( p \) an odd prime, or \( 8 | n \). All subsequent constructions of noncrossed products in [SS, Sa\textsubscript{1}–Sa\textsubscript{3}, Ri, Ro, and Ti] have heretofore been based on Amitsur’s specialization argument, and they are all generic division algebras or extensions of generic division algebras. The centers of these noncrossed product algebras are not known, nor are the Brauer groups, nor the absolute Galois groups of the centers.

We present here a new method of constructing noncrossed product algebras. In our approach, the noncrossed product is realized as the underlying division algebra \( D \) of a tensor product of suitably chosen cyclic algebras over a field \( F = L_1 \otimes L_2 \), where each \( L_i \) is a \( p \)th root Henselian valued field. We prove local global principles relating the splitting fields of \( D \) to those of \( D \otimes_F L_i \), \( i = 1, 2 \). It is shown that the \( p \)-part of the Brauer group of \( F \) is completely determined by that of \( L_1 \) and \( L_2 \). Computations for central simple \( F \)-algebras thus become very tractable. For example, we not only show that \( D \) is not a crossed product, but also calculate exactly how large \( r \) must be so that the matrix ring \( M_r(D) \) is a crossed product, and how large \( s \) must be so that \( M_s(D) \) is a tensor product of cyclic algebras. Indeed, the structure of the Brauer group of \( F \) is so nice that we were somewhat surprised that noncrossed products could possibly exist over \( F \).

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The paper is organized as follows: In §1 we define terminology and describe the $p$-Galois cohomology and the $p$th root Henselian valuations that will be used throughout the paper. We develop in §§2 and 3 the “local” theory of valued division algebras and the $p$-Brauer group of fields with $p$th root Henselian valuations. The bridge between the “local” theory for $p$th root Henselian valued fields $L_1$ and the “global” theory for $L_1 \cap L_2$ is provided in §4: We prove that (under suitable hypotheses) the $p$-part of the absolute Galois group of $L_1 \cap L_2$ is the free product (in the category of pro-$p$-groups) of the $p$-parts of the absolute Galois groups of $L_1$ and $L_2$ (Theorem 4.3). Finally in §§5 and 6 we give the noncrossed product examples. At the end of §5 we indicate how the same methods yield examples of indecomposable algebras with index exceeding the exponent.

A number of results given here can be proved either by valuation theory or by cohomological methods. Both perspectives are worthwhile, and we will try to steer a middle course to give a good sampling of each approach.

1. Preliminaries from the theory of algebras, Galois cohomology and valuation theory. All algebras considered in this paper will be finite dimensional over some field $F$. If $A$ is a central simple $F$-algebra, $[A]$ denotes the class of $A$ in the Brauer group $\text{Br}(F)$ of $F$. We write $\text{exp}(A)$ for the exponent of $A$, which is the order of $[A]$ in $\text{Br}(F)$. By Wedderburn’s theorem $A \cong M_n(D)$, i.e., $n \times n$ matrices over some $F$-central division algebra $D$. The integer $\sqrt{\dim_F D}$ is the (Schur) index of $A$, denoted $\text{index}(A)$. We will need the fact (cf. [R, Theorems 29.22, 29.24]) that $\text{exp}(A) \mid \text{index}(A)$ and $\text{exp}(A)$ and $\text{index}(A)$ have the same prime factors. It is standard that every maximal subfield $K$ of $D$ splits $A$ and $[K:F] = \text{index}(A)$. More generally, we recall from [R, pp. 238–240, Theorem 28.5, Corollary 28.10]:

$$[L:F] = s \cdot \text{index}(A)$$

(1.1)

Recall that a central simple $F$-algebra $A$ is a crossed product just when $A$ has a (maximal) subfield $M$ Galois over $F$, with $[M:F]^2 = \dim_F A$. For such an algebra, the multiplication table on a base is completely determined by the multiplication in $M$, the Galois group $\mathcal{G}(M/F)$ and a 2-cocycle of $\mathcal{G}(M/F)$. It is through crossed products that one obtains the cohomological interpretation of the Brauer group: $\text{Br}(F) \cong H^2(\mathcal{G}(\hat{F}/F),\hat{F}^*)$, where $\hat{F}$ is a separable closure of $F$ (cf. [CF, pp. 125–126; R, p. 246, Theorem 29.12; or Se2, Chapter X, §§4–5]). Our strategy for constructing central simple algebras which are not crossed products is to produce an algebra $A$ with $\dim_FA = d^2$ so that $A$ has a splitting field of degree $t$ over $F$, $t|d$, but $A$ has no splitting field Galois over $F$ with degree dividing $t$. Then (1.1) shows that $A \cong M_{d/t}(A')$ for some central simple $F$-algebra $A'$, but $A'$ cannot be a crossed product, nor a matrix algebra over a crossed product.

The algebras $A$ in our example will be built from cyclic algebras, for which we will use the following notation: If $K$ is a Galois extension field of $F$ with $\mathcal{G}(K/F)$ cyclic
of order \( n \) with generator \( \sigma \), and if \( b \in F^* = F - \{0\} \), then \( A(K/F, \sigma, b) \) denotes the ring generated over \( K \) by an element \( x \) subject to the relations \( xk = \sigma(k)x \) for all \( k \in K \), and \( x^n = b \). Recall that \( A(K/F, \sigma, b) \) is a central simple \( F \)-algebra of dimension \( n^2 \) over \( F \) in which \( K \) is a maximal subfield. A very nice account of cyclic algebras is given in [R, §30].

Suppose \( F \) contains a primitive \( n \)th root of unity \( \omega \). We write \( A_{\omega}(a, b; F) \) for the "symbol" determined by \( a \) and \( b \), i.e., the central simple \( n^2 \)-dimensional \( F \)-algebra with generators \( i, j \) and relations \( i^n = a, j^n = b, ij = \omega ji \). Of course, Kummer theory shows that with \( \omega \in F \) every cyclic \( F \)-algebra of dimension \( n^2 \) is a symbol.

Fix a prime number \( p \neq \text{char} F \). Let \( p^e \cdot \text{Br}(F) \) denote the subgroup of \( \text{Br}(F) \) consisting of those \([A]\) with \( \exp(A)|p^n \), and let \( \text{Br}_p(F) = \bigcup_{n=1}^{\infty} p^n \cdot \text{Br}(F) \), the \( p \)-primary component of \( \text{Br}(F) \). Our noncrossed product examples will all have exponent (hence index) a \( p \)-power. One reason for this is that key cohomological results in §4 hold for pro-\( p \)-groups, but are not known for arbitrary profinite groups. It is easy to work from our examples to construct noncrossed products of composite exponent; we will not do so, preferring to focus attention on the more basic ideas involved in the construction.

For any profinite group \( G \) and discrete \( G \)-module \( M \), \( H^i(G, M) \) denotes the \( i \)th continuous cohomology group of \( G \) with coefficients in \( M \) (as described e.g., in [CF, Chapter V; Sh, Chapter II; Se1, Chapter I; T, §2]). In particular, if \( N \) is any closed subgroup of \( G \), \( \text{res}_{G \to N} : H^i(G, M) \to H^i(N, M) \) denotes the restriction map; if \( N \) is normal in \( G \), then \( \inf_{G/N \to G} : H^i(G/N, M^N) \to H^i(G, M) \) is the inflation map.

Given a field \( F \) with \( \text{char} F \neq p \), let \( \mu_{p^n} \) denote the group of all \( p^n \)th roots of unity in \( \tilde{F} \), a separable closure of \( F \). Then \( \mu_{p^n} \) is a discrete module for the profinite group \( G(F) := \mathcal{G}(\tilde{F}/F) \), and we recall the standard isomorphisms

\[
H^1(G(F), \mu_{p^n}) \cong F^*/F^{*p^n} \quad \text{and} \quad H^2(G(F), \mu_{p^n}) \cong p^e \cdot \text{Br}(F),
\]

which are derived the same way as (1.7) below, but with \( \tilde{F} \) replacing \( \tilde{F}_p \). For \( a \in F^* \) we write \( (a) \) (or \( (a)_F \)) for the image of \( aF^{*p^n} \) in \( H^1(G(F), \mu_{p^n}) \).

Suppose now that \( \mu_{p^n} \subseteq F \). Then we have the \( G(F) \)-module isomorphism \( \mu_{p^n} \cong \mathbb{Z}/p^n\mathbb{Z} \) (where \( \mathbb{Z}/p^n\mathbb{Z} \) is always viewed as a trivial \( G(F) \)-module). This isomorphism is not canonical, since it depends on the choice of a generator of \( \mu_{p^n} \). From the isomorphism \( \mathbb{Z}/p^n\mathbb{Z} \oplus \mathbb{Z}/p^n\mathbb{Z} \cong \mathbb{Z}/p^n\mathbb{Z} \) given by ring multiplication, we obtain a noncanonical \( G(F) \)-module mapping \( \mu_{p^n} \otimes \mu_{p^n} \to \mu_{p^n} \) which induces the cup-product pairing

\[
\cup : H^1(G(F), \mu_{p^n}) \times H^1(G(F), \mu_{p^n}) \to H^2(G(F), \mu_{p^n}).
\]

Recall (cf. [T, (4.2), p. 266]) that under the second isomorphism in (1.2) \( (a) \cup (b) \in H^2(G(F), \mu_{p^n}) \) corresponds to the Brauer class of the symbol \( A_{\omega}(a, b; F) \), where \( \omega \) is the generator of \( \mu_{p^n} \) mapped to \( 1 \) in \( \mathbb{Z}/p^n\mathbb{Z} \). We will need to use the powerful theorem of Merkurjev and Suslin [MS, Theorem 11.5]:

**Theorem 1.3 (Merkurjev - Suslin).** Let \( F \) be an field with \( \mu_{p^n} \subseteq F \) (so char \( F \neq p \)). Then there is a short exact sequence

\[
0 \to S \to H^1(G(F), \mu_{p^n}) \otimes H^1(G(F), \mu_{p^n}) \to H^2(G(F), \mu_{p^n}) \to 0,
\]

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where $S$ is the Steinberg relation group of $F$, i.e., the subgroup of $\bigotimes_{i=1}^2 H^1(G(F), \mu_{p^n})$ generated by $\{(a) \otimes (1-a) | a \in F^*, a \neq 1\}$.

In this exact sequence the map into $H^2(G(F), \mu_{p^n})$ is the cup product. Of course, the surjectivity of this map says that $\mu_{p^n} \text{Br}(F)$ is generated by cyclic algebras whenever $\mu_{p^n} \subseteq F$.

Because of the need to work with pro-$p$-groups, we will use a $p$-version of Galois cohomology, which we now describe. For any field $F$ with char $F \neq p$, let $F(p)$ denote the $p$-closure of $F$, which is the compositum in $\bar{F}$ of all the Galois extensions $K$ of $F$ with $[K:F]$ a power of $p$. Then $\mathcal{G}(F(p)/F)$ is a pro-$p$-group. Since every maximal proper subgroup of a finite $p$-group is normal of index $p$, we have,

$$\text{If } F \subseteq L \subseteq F(p) \text{ and } [L:F] < \infty, \text{ then there is a chain of fields } F = K_0 \subseteq K_1 \subseteq \cdots \subseteq K_m = L, \text{ such that } [K_i : K_{i-1}] = p \text{ and } K_i \text{ is Galois over } K_{i-1} \text{ for } i = 1, 2, \ldots, m.$$  

(1.4)

In §6 we will work with fields $F$ with $\mu_p \not\subseteq F$. When this occurs it is desirable to work with a somewhat larger extension than $F(p)$, but one which agrees with $F(p)$ when $\mu_p \subseteq F$. We define the $p$th root closure of $F$, denoted $\bar{F}_p$, to be $F(\mu_p)(p)$. From Kummer theory we see

$$\bar{F}_p = \bigcup_{i=1}^\infty K_i, \text{ where } K_0 = F \text{ and } K_{i+1} = K_i(\{e^{1/p} | c \in K_i\}).$$  

(1.5)

Clearly $\bar{F}_p$ is Galois over $F$ and $\mathcal{G}(\bar{F}_p/F)$ is pro-solvable, though not a pro-$p$-group when $\mu_p \not\subseteq F$. Since $\bar{F}_p^p = \bar{F}_p$ and $\mu_{p^n} \subseteq \bar{F}_p$, the Merkurjev-Suslin theorem shows that $\text{Br}(\bar{F}_p)$ has no $p$-primary torsion. By contrast, it is unknown whether $\text{Br}_p(F(p)) = (0)$ when $\mu_p \not\subseteq F$.

We will use the notation $G_p(F)$ for $\mathcal{G}(\bar{F}_p/F)$. For any discrete $G_p(F)$-module $M$, we write $H^n_p(F, M)$ for $H^n(\mathcal{G}(F), M)$; we call $H^n_p(F, -)$ the $p$-Galois cohomology of $F$. When $p = 2$ this coincides with the quadratic cohomology $H^q(F, -)$ considered in [AEJ]. (For whenever char $F \neq 2$, $\mu_2 \subseteq F$, so $\bar{F}_2 = F(2)$ which is the quadratic closure of $F$.)

Now, $\bar{F}_p^*$ is a discrete $G_p(F)$-module and we recall [CF, pp. 124–126] that $H^1_p(F, \bar{F}_p^*) \cong F^*$, $H^2_p(F, \bar{F}_p^*) = 0$ (the homological Hilbert Theorem 90), and $H^2_p(F, \bar{F}_p^*) \cong \text{Br}(\bar{F}_p/F) := \ker(\text{Br}(F) \to \text{Br}(\bar{F}_p))$. Following the same route that led to formulas (1.2), we consider the short exact sequence of $G_p(F)$-modules

$$1 \to \mu_{p^n} \to \bar{F}_p^* \to F^* \to 1,$$  

(1.6)

where the right-hand map is $a \to a^{p^n}$. In view of the description just given of $H^1_p(F, \bar{F}_p^*)$, the long exact sequence in cohomology obtained from (1.6) begins

$$0 \to \mu_{p^n} \to F^* \to F^* \to H^1(F, \mu_{p^n}) \to 0$$

$$\to 0 \to H^2(F, \mu_{p^n}) \to \text{Br}(\bar{F}_p/F) \to \text{Br}(F) \to \cdots.$$  

Thus, we find,

$$H^1(F, \mu_{p^n}) \cong F^*/F^*p^n \text{ and } H^2(F, \mu_{p^n}) \cong p^n \text{Br}(F).$$  

(1.7)
The second isomorphism in (1.7) uses the nontrivial fact noted above that $Br_p(\bar{F}_p) = 0$, which implies that $\rho_p Br(F) \subseteq Br(\bar{F}_p / F)$. By comparing (1.7) with (1.2) we see that the canonical inflation map $H'_i(F, \mu_p) \to H'(G(F), \mu_p)$ must be an isomorphism, $i = 1, 2$. Consequently, the Merkurjev-Suslin Theorem 1.3 remains valid when we replace $H'(G(F), \mu_p)$ by $H'_i(F, \mu_p)$, $i = 1, 2$.

We conclude this section with some valuation theory, in particular valuation theory relative to the field extension $\bar{F}_p / F$. Let $G$ be an ordered abelian group, written additively, and let $v : F^* \to G$ be a Krull valuation on the field $F$. We will use the following notation: $\Gamma_F$ for the value group of $v$; $V_F$ for the valuation ring of $v$; $M_F$ for the unique maximal ideal of $V_F$; $U_F$ for the group of units of $V_F$; and $\bar{F}$ for the residue field $V_F / M_F$ of $V_F$. For $a \in V_F$, we write $\bar{a}$ for the image of $a$ in $\bar{F}$. Usually we will be considering only one valuation at a time on a given field $F$, but when there is more than one we avoid ambiguity by writing $\Gamma_{F,v}$,$\ldots$, $U_{F,v}$, $\bar{F}_v$. Good references for valuation theory are [E and Bo2].

If $v$ is a valuation on $F$, we say that $v$ is \textit{pth root Henselian} if $\text{char} \bar{F} \neq p$ and $v$ has a unique extension to $\bar{F}_p$. (This is an example of the $\Omega$-Henselian valuations considered in [Br], with $\Omega = \bar{F}_p$. From Bröcker’s observations we have that $v$ is $p$th root Henselian just when $\text{char} \bar{F} \neq p$ and Hensel’s lemma applies to all monic polynomials $f \in V_F[X]$ which split in $\bar{F}_p$. See [Br, (1.2)].) When $\mu_p \subseteq F$ and $\text{char} \bar{F} \neq p$, a $p$th root Henselian valuation is the same as a $p$-Henselian valuation as considered in [W, §1], and we then use the terms “$p$-Henselian” and “$p$th root Henselian” interchangeably. The following easy lemma was proved in [W, (1.2), (1.4)].

**Lemma 1.8.** Let $(F, v)$ be a valued field with $\mu_p \subseteq F$ and $\text{char} \bar{F} \neq p$. Then,

(i) $v$ is $p$-Henselian iff $1 + M_F \subseteq F^{*p}$;

(ii) if $v$ is $p$-Henselian, then $U_F / U_F^{**} = \bar{F}^* / \bar{F}^{*p}$; hence

$$F^* / F^{*p} = (\bar{F}^* / \bar{F}^{*p}) \oplus (\Gamma_F / \Gamma_F^{*p}).$$

For any valued field $(F, v)$ with $\text{char} \bar{F} \neq p$ we can construct the \textit{pth root Henselization} of $(F, v)$ by a process analogous to the construction of the usual Henselization, as in [E, pp. 131–132]: Let $w$ be any extension of $v$ to $\bar{F}_p$, and let $K$ be the fixed field of the decomposition group of $(\bar{F}_p, w)$ over $(F, v)$. The $p$th root Henselization of $(F, v)$ is defined to be $(K, w|_K)$. It is easy to see that $(K, w|_K)$ is $p$th root Henselian and is an immediate extension of $(F, v)$. Note that the $p$th root Henselization is, up to isomorphism, independent of the choice of $w$.

In analogy with the terminology of algebraic geometry we will call a valued field $(F, v)$ \textit{strictly $p$-Henselian} if it is $p$th root Henselian and $\bar{F} = \bar{F}_p$. Let $\mathbf{Z}_p = \lim_{\leftarrow n} \mathbf{Z}/p^n\mathbf{Z}$, the $p$-adic integers, which is the free abelian pro-$p$-group of rank 1.

**Lemma 1.9.** Suppose $(F, v)$ is strictly $p$-Henselian. Then

(i) $\mu_{p^n} \subseteq F$ for all $n$;

(ii) $U_F \subseteq F^{*p}$;

(iii) $F^*/F^{*p} = \Gamma_F / \Gamma_F^{*p}$;

(iv) if $\dim_{\mathbf{Z}_p} (\Gamma_F / \mathbf{p}_F \Gamma_F) = m$, then $G_p(F) \cong \bigoplus_{m} \mathbf{Z}_p$.
Proof. Because $\mu_p \subseteq \tilde{F}$ and $v$ extends uniquely to $F(\mu_p) \subseteq \tilde{F}_p$, we must have $\mu_p \subseteq F$. The rest of (i)-(iii) follow easily from Lemma 1.8. If $K \supseteq F$ is any finite degree Galois extension of $F$ with $K \subseteq \tilde{F}_p$, then $[K:F] = p^k$, $v$ extends uniquely to $K$ and $\tilde{F}_p = \tilde{F} \subseteq \tilde{K} \subseteq \tilde{F}_p = \tilde{F}_p$. So, $\tilde{K} = \tilde{F}$. Since char $\tilde{F} + \{K:F\}$, the argument of [S, p. 66] shows that $K$ is a Kummer extension of $F$. Thus, by Kummer theory,

$$\tilde{F}_p = \bigcup_{n=1}^{\infty} F_n,$$

where $F_n = F\left(\left\{c^{1/p^n} | c \in F^*\right\}\right)$.

Because $\Gamma_F$ is a torsion-free abelian group, any inverse image of a $\mathbb{Z}/p\mathbb{Z}$-base of $\Gamma_F/p\Gamma_F$ is a base of $\Gamma_F/p^n\Gamma_F$ as a free $\mathbb{Z}/p^n\mathbb{Z}$-module. By Kummer theory and (iii), $\mathcal{G}(F_n/F) \cong F^*/F^{*,p^n} \cong (\mathbb{Z}/p^n\mathbb{Z})^m$. Consequently,

$$G_p(F) = \lim_{\leftarrow} \mathcal{G}(F_n/F) \cong (\mathbb{Z}_p)^m,$$

as desired. \[\square\]

For any valued field $(F,v)$ with char $\tilde{F} \neq p$, let $w$ be an extension of $v$ to $\tilde{F}_p$. Let $L$ be the fixed field of the inertia group of $(\tilde{F}_p,w)$ over $(F,v)$. We call $(L,w|_L)$ the strict $p$-Henselization of $(F,v)$. Note $(L,w|_L)$ is strictly $p$-Henselian and is a maximal unramified extension of $(F,v)$ in $\tilde{F}_p$. The strict $p$-Henselization is unique up to isomorphism. (Similarly, we obtain a “strict Henselization” of $(F,v)$ by replacing $\tilde{F}_p$ by $\tilde{F}$ in this construction.)

2. Valuation theory of division algebras. In this section we will give a construction for obtaining valued division algebras, and we will show how a valuation on a division algebra can restrict the possible Galois groups over the center of maximal subfields.

Let $D$ be a division algebra and let $D^* = D - \{0\}$. A valuation $v$ on $D$ is a function $v: D^* \to \Gamma$ (where $\Gamma$ is a totally ordered group), such that for all $a, b \in D^*$,

(i) $v(ab) = v(a) + v(b)$;
(ii) $v(a + b) \geq \min(v(a), v(b))$ if $b \neq -a$.

We use the same notation as with fields for the objects associated to $v$: the value group of $v$ is $\Gamma_D = v(D^*)$; the valuation ring of $D$ is $V_D = \{a \in D^* | v(a) \geq 0\} \cup \{0\}$; the unique maximal left ideal and unique maximal right ideal of $V_D$ is $M_D = \{a \in D^* | v(a) > 0\} \cup \{0\}$; the residue division ring is $\overline{D} = V_D/M_D$; and the group of units of $V_D$ is $U_D = V_D - M_D$. We will consider only division algebras finite dimensional over their centers; for such a $D$, with center $F$, $\Gamma_F$ is central in $\Gamma_D$ and $\Gamma_D/\Gamma_F$ is torsion. Hence $\Gamma_D$ must be abelian, justifying our additive notation for it. The standard reference for valued division algebras is Schilling’s book [S].

Let $E$ be a subdivision algebra of the valued division algebra $(D,v)$, and suppose $[D:E] < \infty$, where $[D:E]$ denotes the dimension of $D$ as a right $E$ vector space. Then the restriction $v|_E$ of $v$ to $E^*$ is a valuation on $E$. Recall [S, p. 21] that the following version of the “fundamental inequality” holds for the extension $v$ over $v|_E$:

$$[\overline{D} : \overline{E}] \cdot |\Gamma_D : \Gamma_F| \leq [D:E].$$

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We say that \( v \) is \textit{totally ramified} over \( v|_F \) if \( |\Gamma_D: \Gamma_E| = [D:E] \). Then, of course, \( \overline{D} = \overline{E} \).

The next proposition and its corollaries provide the link between Galois groups and value groups of division algebras. The proposition is well known (cf. \([E, (20.11) (d), (20.18); S, p. 66, p. 86, \text{Remark 1}] \)), but we sketch a proof since it is vital for our examples.

\textbf{Proposition 2.2.} Let \( F \subseteq K \) be fields with \([K:F] < \infty \) and \( K \) Galois over \( F \). Suppose \( K \) has a valuation \( v \) which is totally ramified over \( v|_F \), and suppose \( \text{char } \overline{F} + [K:F] \). Then \( \mathcal{G}(K/F) \cong \Gamma_K/\Gamma_F \), and \( \overline{F} \) contains a primitive \( l \)th root of unity, where \( l \) is the exponent of the abelian group \( \Gamma_K/\Gamma_F \).

\textbf{Sketch of the proof.} Since \( \sigma(u) = u \) for \( u \in U_K \), the function \( \mathcal{G}(K/F) \times \mathcal{K}^* \to \mathcal{K}^* = \overline{F}^* \) given by \( (\sigma, a) \to \sigma(a)/a \) induces a bimultiplicative pairing \( \gamma: \mathcal{G}(K/F) \times \Gamma_K/\Gamma_F \to \mathcal{K}^* \). The proposition follows easily once it is known that \( \gamma \) is nondegenerate. Assume first that \((F,v|_F)\) is Henselian with separably closed residue field. Then \( K \) is a Kummer extension of \( F \) by \([S, p. 64, \text{Theorem 3}] \), and the nondegeneracy of \( \gamma \) follows from the nondegeneracy of the Kummer pairing.

Dropping the restrictions on \( F \), let \( L \) be a maximal unramified extension of \((F,v|_F)\) in \( \overline{F} \). Then \( L \) is Henselian with separably closed residue field, and \( L \) and \( K \) are linearly disjoint over \( F \) as \( K/F \) is totally ramified. Since \( \mathcal{G}(K \cdot L/L) \cong \mathcal{G}(K/F) \) and \( \Gamma_K \cdot L = \Gamma_K \cdot L = \Gamma_F \), the pairing \( \gamma \) for \( K/F \) coincides with the corresponding pairing of \( K \cdot L \) over \( L \), which we have seen to be nondegenerate.

\textbf{Corollary 2.3.} Let \( D \) be a division algebra finite dimensional over a field \( F \). Suppose \( D \) has a valuation \( v \) totally ramified over \( v|_F \), and suppose \( \text{char } \overline{F} \not\in [D:F] \). If \( K \supseteq F \) is any subfield of \( D \) which is Galois over \( F \), then \( \mathcal{G}(K/F) \) is isomorphic to a subgroup of \( \Gamma_D/\Gamma_F \).

\textbf{Proof.} By the fundamental inequality \((2.1)\) and the transitivity formula for ramification index, \( v|_K \) must be totally ramified over \( v|_F \). Hence, by the proposition, \( \mathcal{G}(K/F) \cong \Gamma_K/\Gamma_F \subseteq \Gamma_D/\Gamma_F \).

\textbf{Corollary 2.4.} Let \((F,v)\) be a valued field with \( \text{char } \overline{F} \neq p \) and \( \mu_p \not\subseteq \overline{F} \) for some prime \( p \). Suppose \( K \) is a Galois extension field of \( F \) with \([K:F] = p^n \), and suppose \( v \) has a unique extension to a valuation \( w \) of \( K \). Then \( K \) is an inertial extension of \( F \) (i.e., \([\overline{K}:\overline{F}] = [K:F] \)) and \( \mathcal{G}(K/F) \cong \mathcal{G}(\overline{K}/\overline{F}) \).

\textbf{Proof.} Let \( L \) be the inertia field of \( w \) over \( F \). Then as \( v \) is indecomposed in \( K \) and \( \overline{K} \) is separable over \( \overline{F} \) (since \( \text{char } \overline{F} \not\in [K:F] \) and \([\overline{K}:\overline{F}]\cong [K:F] \) we have \( L/F \) is inertial and Galois, \( \overline{L} = \overline{K} \), \( \overline{L}/\overline{F} \) is Galois, and \( \mathcal{G}(\overline{L}/\overline{F}) \cong \mathcal{G}(L/F) \) (cf. \([E, \S 19]\)). So, it suffices to see that \( K = L \). Because \( \overline{L} = \overline{K} \) and \( \overline{w}|_L \) extends uniquely to \( K \) and \( \text{char } \overline{L} \not\in [K:L] \), \( (K,w) \) must be totally ramified over \( (L,w|_L) \). Since \([K:L] \) is a \( p \)-power, if \( K \neq L \) then Proposition 2.2 implies \( \mu_p \not\subseteq L \). However, \([\overline{L}:\overline{F}] = [L:F] \) is a \( p \)-power, so \( \mu_p \not\subseteq \overline{L} \), as \( \mu_p \not\subseteq \overline{F} \). Hence, \( K = L \), as desired.

The next theorem gives the criterion we will use for the existence of a valuation on an algebra. The somewhat cumbersome hypotheses cover the examples both in \S 5 and in \S 6. Similar theorems will appear in \([W_1]\).
Theorem 2.5. Let $A$ be an algebra finite dimensional over a field, and let $L \subseteq A$ be a field. Let $v$ be a valuation on $L$, and let $\Delta$ be the divisible hull of $\Gamma_L$ (so $\Delta \equiv \Gamma_L \otimes \mathbb{Z} \mathbb{Q}$). Suppose there are elements $a_1, \ldots, a_m$ of the group of units $A^*$ of $A$ satisfying

(i) $\{a_1, \ldots, a_m\}$ is a base of $A$ as a right $L$-vector space;
(ii) for each $l \in L^*$ and each $a_i, a_ia_i^{-1} \in L$ and $v(a_ia_i^{-1}) = v(l)$;
(iii) $a_ia_ia_i^{-1}a_j^{-1} \in U_L$ (the group of units of $v$) for all $i, j$;
(iv) $\mathcal{A} := \{a_1L^*, \ldots, a_mL^*\}$ is an abelian subgroup of $N_{A^*}(L^*)/L^*$, where $N_{A^*}(L^*)$ is the normalizer of $L^*$ in $A^*$.

Then there is a well-defined group homomorphism $\overline{w}: \mathcal{A} \rightarrow \Delta/\Gamma_L$ given by $a_iL^* \mapsto \frac{1}{m}v(a_i^m) + \Gamma_L$. Suppose $\overline{w}$ is injective. Then $v$ extends to a valuation $w$ on $A$; hence $A$ is a division ring. $\Gamma_A$ is the subgroup of $\Delta$ such that $\Gamma_A/\Gamma_L = \overline{w}(\mathcal{A})$. Furthermore, $(A, w)$ is totally ramified over $(L, v)$, and $\overline{A} \equiv \overline{L}$.

Proof. Condition (iv) shows that $a_i^m \in L^*$ for each $i$. Hence, the function $\overline{w}$ is well defined. For any $a_i$ and any $c \in L^*$ we have the general identity

$$\left(a_i c\right)^m = c^a_i c^a_i \cdots c^a_i a_i^m,$$

where $c^a_i$ means $a_i c a_i^{-1}$. Hence, by (ii),

$$v\left(\left(a_i c\right)^m\right) = mv(c) + v(a_i^m).$$

Let $T$ be the subgroup of $A^*$ generated by $\{a_1, \ldots, a_m\}$, and $T'$ its commutator subgroup. By (ii), $TU_L$ is a group in which $U_L$ is a normal subgroup. By (iii), $TU_L/U_L$ is abelian, so $T' \subseteq U_L$. Since for any $i, j$, $(a_ia_j)^m = a_i^m a_j^mt$ with $t \in T' \subseteq U_L$, we have

$$v\left((a_ia_j)^m\right) = v(a_i^m) + v(a_j^m).$$

From (1) and (2) it follows that $\overline{w}$ is a group homomorphism.

Because $\Delta$ is torsion-free and $\Delta/\Gamma_L$ is torsion, the ordering on $\Gamma_L$ has a unique extension to $\Delta$ which makes $\Delta$ a totally ordered abelian group. This is the ordering on $\Delta$ we use.

Now suppose $\overline{w}$ is injective. Define a function $w: A \setminus \{0\} \rightarrow \Delta$ as follows: For any $a_i$ and any $c \in L^*$, set

$$w(a_i, c) = \frac{1}{m}v(a_i^m) + v(c).$$

Now, for any $\alpha \in A \setminus \{0\}$, $\alpha$ has a unique representation $\alpha = \sum_{i=1}^m a_i c_i$ with the $c_i \in L$, some $c_i \neq 0$; define $w(\alpha) = \inf\{w(a_i c_i)|c_i \neq 0\}$. Since $\overline{w}$ is injective, $w(a_i c_i) \neq w(a_i c_j)$ for $i \neq j$. Thus, there is a unique summand $a_i c_j$ of $\alpha$ with $w(a_i c_j) = w(\alpha)$; we call $a_i c_j$ the leading term of $\alpha$. Take any $\beta = \sum a_i d_i \in A \setminus \{0\}$ ($d_i \in L$) with $\beta \neq -\alpha$. Let $a_k(c_k + d_k)$ be the leading term of $\alpha + \beta$. We have, if $c_k \neq 0$, $d_k \neq 0$,

$$w(a_k(c_k + d_k)) = \frac{1}{m}v(a_k^m) + v(c_k + d_k) \geq \inf \left(\frac{1}{m}v(a_k^m) + v(c_k), \frac{1}{m}v(a_k^m) + v(d_k)\right) = \inf(w(a_k c_k), w(a_k d_k)) \geq \inf(w(\alpha), w(\beta)).$$

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Hence, \( w(\alpha + \beta) = w(a_k(c_k + d_k)) \geq \inf(w(\alpha), w(\beta)) \); this inequality still holds if \( c_k = 0 \) or \( d_k = 0 \). Since \( w(-\alpha) = w(\alpha) \), the usual argument shows:

\[
(3) \quad \text{if } w(\alpha) \neq w(\beta), \text{ then } w(\alpha + \beta) = \inf(w(\alpha), w(\beta)).
\]

It remains to check that \( w(\alpha \beta) = w(\alpha) + w(\beta) \). Take any \( a_i \) and \( a_j \) and write \( a_i a_j = a_k e \) with \( e \in L^* \). Then for any \( c, d \in L^* \),

\[
(4) \quad w(a_i a_j c d) = w(a_k e (a_j^{-1}c a_j) d)
\]

\[
= \frac{1}{m} w((a_k e)^m) + v(c) + v(d) \quad \text{by (1) and (ii)}
\]

\[
= \frac{1}{m} [w(a_i^m) + w(a_j^m)] + v(c) + v(d) \quad \text{by (2)}
\]

\[
= w(a_i) + w(a_j).
\]

Now, for any \( \alpha = \sum a_i c_i \) and \( \beta = \sum a_i d_i \in A \setminus \{0\} \) we have

\[
(5) \quad w(\alpha \beta) = w\left( \sum_{i,j} a_i c_i a_j d_j \right) \geq \inf_{i,j} \{ w(a_i c_i a_j d_j) | c_i, d_j \neq 0 \}
\]

\[
= \inf_{i,j} \{ w(a_i c_i) + w(a_j d_j) | c_i, d_j \neq 0 \} \geq w(\alpha) + w(\beta).
\]

Say \( a_i c_j \) is the leading term of \( \alpha \), and set \( \alpha' = \alpha - a_i c_j \). So, \( w(\alpha) = w(a_j c_j) < w(\alpha') \) (or \( \alpha' = 0 \)). Likewise, set \( \beta' = \beta - a_k d_k \), where \( a_k d_k \) is the leading term of \( \beta \). Then,

\[
\alpha \beta = (a_j c_j, a_k d_k) + \alpha'(a_k d_k) + (a_j c_j)\beta' + \alpha'\beta'.
\]

By (4) and (5) the first summand here has value strictly smaller than the other three. Hence, by (3) and (4), \( \alpha \beta \neq 0 \) and

\[
w(\alpha \beta) = w(a_j c_j a_k d_k) = w(a_j c_j) + w(a_k d_k) = w(\alpha) + w(\beta).
\]

Since we have just seen that the finite dimensional algebra \( A \) has no zero divisors, it must be a division algebra. Our calculations show that \( w: A \setminus \{0\} \to \Delta \) is a valuation on \( A \). It is easy to check that \( w|_L = v \).

Clearly the value group \( \Gamma_A \) is the subgroup of \( \Delta \) generated by \( \{w(a_1), \ldots, w(a_m)\} \) and \( \Gamma_L \); so \( \Gamma_A/\Gamma_L = \text{im}(\bar{w}) \). As \( \bar{w} \) is injective, \( |\Gamma_A/\Gamma_L| = |\mathcal{O}| = m = [A : L] \), i.e. \( A \) is totally ramified over \( L \). Take any \( \alpha = \sum a_i c_i \in A^* \) with \( w(\alpha) = 0 \). If the leading term of \( \alpha \) is \( a_j c_j \), we have \( w(a_j c_j) = w(\alpha) = 0 \). Since \( w(a_j c_j) = -w(c_j) \in \Gamma_L \), the injectivity of \( \bar{w} \) implies \( a_j \in L^* \); so \( a_j c_j \in U_L \). Hence, in \( A \), \( \bar{a} = a_j c_j \in \bar{L} \). Thus, \( A = \bar{L} \).

\[\square\]

**Corollary 2.6.** Consider the algebra

\[ A = A_{\omega_n}(b_1, c_1; F) \otimes_F \cdots \otimes_F A_{\omega_n}(b_k, c_k; F), \]

where \( \omega_n \) is a primitive \( n \)th root of unity in a field \( F \) and \( b_1, c_1, \ldots, b_k, c_k \in F^* \). Let \( n = n_1 \cdots n_k \) and \( l = \text{lcm}(n_1, \ldots, n_k) \). Let \( v \) be a valuation on \( F \). Suppose \( \{(l/n_m)v(b_m), (l/n_m)v(c_m)\mid 1 \leq m \leq k\} \) generates a subgroup of order \( n^2 \) in \( \Gamma_F/\Gamma_F \).
Then $A$ is a division algebra and $v$ extends to a valuation on $A$ totally ramified over $F$, with $\overline{A} = \overline{F}$ and with value group $\Gamma_A$ generated by $((1/n_m)v(b_m), (1/n_m)v(c_m)| 1 \leq m \leq k}$ and $\Gamma_F$. So,

$$\Gamma_A/\Gamma_F \cong \prod_{m=1}^{k} (\mathbb{Z}/n_m\mathbb{Z} \times \mathbb{Z}/n_m\mathbb{Z}).$$

**Proof.** For $1 \leq m \leq k$, let $i_m, j_m \in A$ be the standard generators of $A_{\omega_m}(b_m, c_m; F)$. We want to apply the theorem with $L = F$ and the $a_i$ all being products $i_i^i j_i^i \cdots i_k^i j_k^i$ with $0 \leq r_m < n_m$, $0 \leq s_m < n_m$, for $1 \leq m \leq k$. There are $n^2$ of the $a_i$, and they clearly form an $F$-base of $A$. Every commutator $a_i a_j a_i^{-1} a_j^{-1}$ is a product of roots of unity. Condition (iii) holds trivially since $F$ is the center of $D$. It follows easily that (i)–(iv) of the theorem all hold. We have $\overline{w}(i_m F^*) = (1/n_m)v(b_m) + \Gamma_F$ and $\overline{w}(j_m F^*) = (1/n_m)v(c_m) + \Gamma_F$. The assumption on the values of the $b_m$ and $c_m$ implies that $\overline{w}(\mathcal{O})$ is a subgroup of order $n^2$ of $(1/l)\Gamma_F/\Gamma_F$. Hence, $\overline{w}$ must be injective, and the corollary follows from the theorem. □

**Example 2.7.** Let $K$ be a field containing a primitive $p'$th root of unity $\omega$ for some prime $p$. Let $z_1, \ldots, z_{2l}$ be independent commuting indeterminates over $K$, and let $F = K(z_1, \ldots, z_{2l})$. The lexicographic ordering makes $\Gamma := \prod_{1}^{2l} \mathbb{Z}$ into a totally ordered abelian group. There is a unique valuation $v: F^* \to \Gamma$ such that $v(z_i) = (0, \ldots, 0, 1, 0, \ldots, 0)$ (the 1 in the $i$th place) for each $i$ and $v(c) = 0$ for all $c \in K^*$. Specifically, $v$ is defined first on $K[z_1, \ldots, z_{2l}] - \{0\}$ by

$$v\left( \sum_{i_1} \cdots \sum_{i_{2l}} c_{i_1 \cdots i_{2l}} z_{i_1}^i \cdots z_{i_{2l}}^i \right) = \inf\{((i_1, \ldots, i_{2l})|c_{i_1 \cdots i_{2l}} \neq 0}\}.$$ 

Then $v$ is extended to the quotient field $F$ by defining $v(a/b) = v(a) - v(b)$ for all $a, b \in K[z_1, \ldots, z_{2l}] - \{0\}$. Let $A = A_{\omega}(z_1, z_{2l}; F) \otimes_F \cdots \otimes_F A_{\omega}(z_{2l-1}, z_{2l}; F)$. By the corollary, $A$ is a division algebra and $v$ extends to a valuation on $A$ which is totally ramified over $F$, with $\overline{A}/\overline{F} \cong (\mathbb{Z}/p^l\mathbb{Z})^{2l}$ and $\overline{A} = \overline{F} = K$. Hence, by Corollary 2.3, if $K \supseteq F$ is any subfield of $A$ which is Galois over $F$, then $\mathcal{O}(K/F)$ is isomorphic to a subgroup of $(\mathbb{Z}/p^l\mathbb{Z})^{2l}$. Note also that if $L \supseteq F$ is any field which has an unramified extension of $v$, then Corollary 2.6 applies equally well to $A \otimes_F L$. So, $A \otimes_F L$ is also a valued division algebra, with $\Gamma_{A \otimes_F L}/\Gamma_L \cong \Gamma_A/\Gamma_F$.

**Remark 2.8.** For any prime $p$, let $k$ be any field with char $k \neq p$, and let $K = k(\mu_{p^n})$ for some fixed $n \geq 3$. If we let $r = 1$ and $l = n$ in the preceding example, then we obtain a division algebra $D_1$ of index $p^n$ in which every maximal subfield of $D_1$ Galois over its center has an elementary abelian Galois group of order $p^n$. If we let $r = n$ and $l = 1$ in the example we obtain another division algebra $D_2$ of index $p^n$. The Galois group over the center of $D_2$ of any Galois maximal subfield must be a subgroup of $(\mathbb{Z}/p^n\mathbb{Z}) \times (\mathbb{Z}/p^n\mathbb{Z})$ of order $p^n$. Such a group cannot be elementary abelian, as $n \geq 3$. Since no group can occur as a Galois group of a maximal subfield for both $D_1$ and $D_2$, it follows by Amitsur's argument (cf. [Am, pp. 418–419; or Ja, p. 93, Theorem 4]) that the generic division algebra...
UD(k, pⁿ) of index pⁿ (n ≥ 3) over k is not a crossed product. Amitsur proved this in his original paper (for char k = 0, and Schacher-Small [SS] did the case char k = prime ≠ p). Amitsur did not mention valued division algebras, but the valuation theory given here applies to (and perhaps clarifies) his examples, which were iterated twisted Laurent power series division algebras.

We now give one more corollary to Theorem 2.5, which will apply to the examples in §6.

**Corollary 2.9.** Let F be a field with valuation v. Let K₁, ..., Kₖ be cyclic Galois extensions of F, and let A = A(K₁/F, a₁, b₁) ⊗ₕ ⋯ ⊗ₕ A(Kₖ/F, aₖ, bₖ) for some b₁, ..., bₖ ∈ F*. Let [Kᵢ : F] = nᵢ, n = n₁ ⋯ nₖ, and l = lcm(n₁, ..., nₖ). Suppose

(i) each Kᵢ is an inertial extension of (F, v), i.e., v extends (uniquely) to a valuation vᵢ on Kᵢ with residue field Kᵢ such that [Kᵢ : F] = [Kᵢ : F];

(ii) K₁, ..., Kₖ are all linearly disjoint over F;

(iii) {((l/nᵢ)v(bᵢ)) | 1 ≤ i ≤ k} generates a subgroup of order n in Γₖ/Γ_F.

Then A is a division algebra and v extends to a valuation w on A with residue division algebra A = A₁ ⋯ Aₖ and value group Γₐ generated by {(l/nᵢ)v(bᵢ)} and Γ_F. So, [A : F] = [Γₐ : Γ_F] = n.

**Proof.** Let L be the compositum K₁ ⋯ Kₖ in F, and let u be any extension of v to L, with L the residue field of u. Since u|ₖ = vᵢ by (i), we have each Kᵢ ⊆ L. Then from (2.1), (ii), and (i),

\[ [L : F] ≥ [L : F] ≥ [K₁ ⋯ Kₖ : F] = \prod_{i=1}^{k} [Kᵢ : F] = \prod_{i=1}^{k} [Kᵢ : F] ≥ [L : F]. \]

So equality must hold throughout. Hence, L is an inertial extension of F, L = K₁ ⋯ Kₖ and K₁, ..., Kₖ are all linearly disjoint over F, so L ≅ K₁ ⊗ₕ ⋯ ⊗ₕ Kₖ.

Let xᵢ ∈ A be the standard generator of A(Kᵢ/F, aᵢ, bᵢ) over Kᵢ. We will apply Theorem 2.5, taking for the aᵢ, 1 ≤ i ≤ n, all products xᵢ¹ ⋯ xᵢᵢ with 0 ≤ rᵢ < nᵢ for each j. For L we take K₁ ⊗ₕ ⋯ ⊗ₕ Kₖ ⊆ A which we have seen has a unique extension of v to F. Clearly the aᵢ form an L-base of A. Condition (ii) of Theorem 2.5 holds since the aᵢ conjugate each Kᵢ to itself and the extension of v to L is unique. Condition (iii) holds trivially because aᵢaⱼ = aⱼaᵢ, all i, j, and (iv) also clearly holds. We have \( \bar{w}(xᵢL*) = (1/nᵢ)v(bᵢ) + Γ_L \), and \( Γ_L = Γ_F \) as L/F is inertial. Assumption (iii) implies that \( \bar{w}(σᵣ) \) is a subgroup of order n in \( (1/l)Γ_L/Γ_F \). Since \( |σᵣ| = n \), \( \bar{w} \) must be injective. The conclusions of the corollary follow from the theorem and the observations above about L. □

3. Cohomology of free abelian pro-p-groups. For any prime number p and any natural number m, let \( P_m := \bigoplus_{i=1}^{m} \mathbb{Z}_p \), which is the free abelian pro-p-group of rank m. As we saw in Lemma 1.9(iv) this group arises as \( G_p(F) \) for a strictly p-Henselian valued field if \( Γ_F/pΓ_F \) has rank m. In this section we prove a result on splitting of elements of \( H^2(P_m, \mathbb{Z}/p\mathbb{Z}) \) by subgroups of \( P_m \). We will give purely cohomological arguments, although other approaches are possible. We always consider \( \mathbb{Z}/p\mathbb{Z} \) as a trivial \( P_m \)-module. Then \( H^1(P_m, \mathbb{Z}/p\mathbb{Z}) \cong \text{Hom}(P_m, \mathbb{Z}/p\mathbb{Z}) \cong (\mathbb{Z}/p\mathbb{Z})^m \), which will be viewed as a vector space over \( \mathbb{Z}/p\mathbb{Z} \).
Lemma 3.1. Suppose \( \chi_1, \chi_2, \ldots, \chi_{2t} \) are linearly independent in \( H^1(\mathbb{P}_m, \mathbb{Z}/p\mathbb{Z}) \). Then,
\[
\chi_1 \cup \chi_2 + \chi_3 \cup \chi_4 + \cdots + \chi_{2t-1} \cup \chi_{2t} \neq 0 \quad \text{in} \quad H^2(\mathbb{P}_m, \mathbb{Z}/p\mathbb{Z}).
\]

Proof. We verify this by direct calculation, using additive notation for the group operation on \( \mathbb{P}_m \). The cohomology class in question is represented by the 2-cocycle
\[
z(r, s) = \chi_1(r)\chi_2(s) + \chi_3(r)\chi_4(s) + \cdots + \chi_{2t-1}(r)\chi_{2t}(s),
\]
as the group action is trivial (cf. [Sh, p. 38]). Clearly \( z(0, 0) = z(0, s) = 0 \). If \( z \) is a coboundary, there is a continuous function \( f: \mathbb{P}_m \to \mathbb{Z}/p\mathbb{Z} \) with \( z(r, s) = f(s) - f(r + s) + f(r) \). So \( f(0) = z(0, 0) = 0 \). Now, choose \( a_1, a_2 \in \mathbb{P}_m \) with \( \chi_i(a_j) = \delta_{ij} \) (Kronecker delta), \( i = 1, \ldots, 2t, \; j = 1, 2 \). We calculate:
\[
f(a_1) + f(-a_1) - z(a_1, -a_1) = -1 + f(a_2).
\]
This contradiction proves the lemma. \( \square \)

Remark 3.2. For an alternative proof observe that Lemma 3.1 is an immediate consequence of the isomorphism \( H^2(\mathbb{P}_m, \mathbb{Z}/p\mathbb{Z}) \cong H^1(\mathbb{P}_m, \mathbb{Z}/p\mathbb{Z}) \wedge H^1(\mathbb{P}_m, \mathbb{Z}/p\mathbb{Z}) \) (exterior product) which can be verified by induction on \( m \) using the K"{u}nneth formula. The lemma is also deducible from Corollary 2.6.

Remark 3.3. Suppose \( \Delta \subseteq \mathbb{P}_m \) is a subgroup of index \( p \). Then \( \Delta \supseteq p\mathbb{P}_m \). Using the fact that every lift of a \( \mathbb{Z}/p\mathbb{Z} \)-base of \( p\mathbb{P}_m/p\mathbb{P}_m \) is a base of \( \mathbb{P}_m \) as a free abelian pro-\( p \)-group, it is easy to see that \( \Delta \cong \mathbb{P}_m \) as profinite groups. It follows by induction that for any subgroup \( H \) of finite index in \( \mathbb{P}_m \), \( H \) is open in \( \mathbb{P}_m \) and \( H \cong \mathbb{P}_m \).

The main result of this section is needed for the study of splitting fields of the examples in \( \S 5 \). What we need is obtainable by adapting to the strictly \( p \)-Henselian situation the following theorem of Tignol and Amitsur [TA]: If \( D \) is a central simple division algebra over a field \( F \) with strictly Henselian valuation and \( \text{char} F + [D : F] \), then every splitting field of \( D \) algebraic over \( F \) contains a maximal subfield of \( D \). We prefer to give an entirely cohomological formulation and proof. For algebras of prime exponent the Tignol-Amitsur theorem is actually deducible from our next theorem.

Theorem 3.4. Suppose \( \chi_1, \chi_2, \ldots, \chi_{2t} \in H^1(\mathbb{P}_m, \mathbb{Z}/p\mathbb{Z}) \) are linearly independent, and set \( \gamma = \chi_1 \cup \chi_2 + \chi_3 \cup \chi_4 + \cdots + \chi_{2t-1} \cup \chi_{2t} \in H^2(\mathbb{P}_m, \mathbb{Z}/p\mathbb{Z}) \). Let \( N \) be an open subgroup of \( \mathbb{P}_m \) with \( \text{res}_{\mathbb{P}_m \to N}(\gamma) = 0 \). Then, there is a base \( \psi_1, \ldots, \psi_{2t} \) of \( \text{span}(\chi_1, \ldots, \chi_{2t}) \subseteq H^1(\mathbb{P}_m, \mathbb{Z}/p\mathbb{Z}) \) such that \( \gamma = \psi_1 \cup \psi_2 + \cdots + \psi_{2t-1} \cup \psi_{2t} \), and \( N \subseteq \ker(\psi_1, \ldots, \psi_{2t-1}) \). Hence, \( (\mathbb{Z}/p\mathbb{Z})^t \) is a homomorphic image of \( \mathbb{P}_m/N \).

Proof. We argue by induction on \( t \). Since \( N \cong \mathbb{P}_m \), we may apply Lemma 3.1 over \( N \) to see that \( \{ \text{res}_{\mathbb{P}_m \to N}(\chi_i) \mid 1 \leq i \leq 2t \} \) must be linearly dependent in \( H^1(N, \mathbb{Z}/p\mathbb{Z}) \). That is, for some nonzero linear combination \( \delta = a_1\chi_1 + \cdots + a_{2t}\chi_{2t} \in H^1(\mathbb{P}_m, \mathbb{Z}/p\mathbb{Z}) \), \( 0 = \sum a_i \text{res}_{\mathbb{P}_m \to N}(\chi_i) = \text{res}_{\mathbb{P}_m \to N}(\delta) \). Hence, \( N \subseteq \ker(\delta) \). After renumbering the \( \chi_i \) if necessary and replacing \( \delta \) by \( a_1^{-1}\delta \) we may
assume $a_1 = 1$; that is, $X_1 = \delta - a_2X_2 - \cdots - a_{2t}X_{2t}$. If $t = 1$, we have $\gamma = X_1 \cup X_2 = \delta \cup X_2$ (as $X_2 \cup X_2 = 0$), and the desired result follows by setting $\psi_1 = \delta$ and $\psi_2 = X_2$. Now assume $t > 1$. From the formula for $X_1$ (together with $X_2 \cup X_2 = 0$) we find
\[
\gamma = \delta \cup X_2 + (X_3 + a_4X_2) \cup (X_4 - a_3X_3) \\
+ \cdots + (X_{2t-1} + a_{2t}X_2) \cup (X_{2t} - a_{2t-1}X_2) \\
= \delta \cup X_2 + \sum_{i=2}^{t} \psi_{2i-1} \cup \psi_{2i},
\]
where $\psi_{2i-1} = X_{2i-1} + a_{2i}X_{2i}$ and $\psi_{2i} = X_{2i} - a_{2i-1}X_{2i}$. Clearly $\{\delta, X_2, \psi_3, \ldots, \psi_{2t}\}$ is a base of span\{$X_1, \ldots, X_{2t}$\}.

Let $\gamma' = \gamma - (\delta \cup X_2) = \sum_{i=2}^{t} \psi_{2i-1} \cup \psi_{2i}$. Since $N \subseteq \ker \delta$, $\text{res}_{P_m \to N}(\gamma') = \text{res}_{P_m \to N}\gamma = 0$. By induction there are $\psi_3, \psi_4, \ldots, \psi_{2t} \in H^1(P_m, \mathbb{Z}/p\mathbb{Z})$ with span\{$\psi_3, \ldots, \psi_{2t}$\} = span\{$\psi_3, \ldots, \psi_{2i}$\}, $\gamma' = \sum_{i=2}^{t} \psi_{2i-1} \cup \psi_{2i}$, and $N \subseteq \cap_{i=2}^{t} \ker \psi_{2i-1}$. Set $\psi_1 = \delta$ and $\psi_2 = X_2$. Clearly $\psi_1, \ldots, \psi_{2t}$, have all the required properties. Let $K = \cap_{i=1}^{t} \ker \psi_{2i-1} \ni N$. Then $P_m/K$ is a homomorphic image of $P_m/N$, and $P_m/K \cong (\mathbb{Z}/p\mathbb{Z})^{t}$ as $\psi_1, \psi_3, \ldots, \psi_{2t-1}$ are linearly independent. □

4. Free products of pro-$p$-groups. In this section we prove that, for certain $p$-Henselian fields $L_1$ and $L_2$, $G_p(L_1 \cap L_2)$ is the free product of $G_p(L_1)$ and $G_p(L_2)$ (Theorem 4.3). This will allow us to prove local global principles (Theorem 4.11) relating central simple $(L_1 \cap L_2)$-algebras to algebras over $L_1$ and $L_2$. Our main tools are a cohomological characterization of free products of pro-$p$-groups (Theorem 4.1) and the analogue for pro-$p$-groups of Kurosh's theorem on subgroups of free products (Theorem 4.5).

Let $\mathcal{G}_p$ denote the category of pro-$p$-groups, a subcategory of the category $\mathcal{G}$ of all groups. For $G_1, G_2 \in \mathcal{G}_p$, let $G_1 \ast_p G_2$ denote the free product (coproduct) of $G_1$ and $G_2$ in $\mathcal{G}_p$. (This is not the same as the free product of $G_1$ and $G_2$ in $\mathcal{G}$, nor even in the category of all profinite groups.) The existence of free products in $\mathcal{G}_p$ can be verified by observing that the inclusion functor $\mathcal{G}_p \to \mathcal{G}$ has a left adjoint, and free products exist in $\mathcal{G}$. More explicitly, one can construct the free product in $\mathcal{G}_p$ as follows: Let $G_1, G_2 \in \mathcal{G}_p$. Denote by $G_1 \ast G_2$ the usual free product of $G_1$ and $G_2$ in $\mathcal{G}$. Then
\[
G_1 \ast_p G_2 = \lim_{\leftarrow N} \left((G_1 \ast G_2)/N\right),
\]
as $N$ ranges over all normal subgroups of $G_1 \ast G_2$ with $|G_1 \ast G_2: N|$ a power of $p$. The easy verification that $G_1 \ast_p G_2$ has the desired universal mapping property is omitted.

3For any $\chi \in H^1(P_m, \mathbb{Z}/p\mathbb{Z})$, $\chi \cup \chi = 0$. For, there is a closed subgroup $H$ of $P_m$ with $P_m/H \cong P_1$ and a $\chi' \in H^1(P_m/H, \mathbb{Z}/p\mathbb{Z})$ with $\chi = \inf_{P_m/H \to P_m}(\chi')$. Since $P_m/H$ is a free pro-$p$-group, $H^2(P_m/H, \mathbb{Z}/p\mathbb{Z}) = 0$. Hence, $\chi \cup \chi = \inf_{P_m/H \to P_m}(\chi' \cup \chi') = 0$. License or copyright restrictions may apply to redistribution; see http://www.ams.org/journal-terms-of-use
The basic cohomological properties of free products in \( \mathcal{G}_p \) are recalled in convenient form in the next two theorems, which are due to Neukirch [N, Sätze 4.3, 4.2]. (For a version of Theorem 4.1, see also [Er, Proposition 2].) Theorem 4.2 is the pro-\( p \) analogue to a well-known result for the usual free products of groups (cf. [HS, p. 220]).

Recall that \( \mathbb{Z}/p\mathbb{Z} \) is always viewed as a trivial \( G \)-module for any \( G \in \mathcal{G}_p \).

**Theorem 4.1 (Neukirch).** Suppose \( G, G_1, \ldots, G_k \) are pro-\( p \)-groups, and \( f_j : G_j \to G \) are continuous homomorphisms, \( j = 1, 2, \ldots, k \). Then the induced map \( G_1 \ast_p G_2 \ast_p \cdots \ast_p G_k \to G \) is an isomorphism iff the map

\[
H^i(G, \mathbb{Z}/p\mathbb{Z}) \to \bigoplus_{j=1}^k H^i(G_j, \mathbb{Z}/p\mathbb{Z})
\]

induced by the \( f_j \) is an isomorphism for \( i = 1 \) and a monomorphism for \( i = 2 \).

In his version of Theorem 4.1 Neukirch assumes that the \( G_j \) are subgroups of \( G \). But his proof works in the situation described here, without initially assuming the \( f_j \) to be injective.

**Theorem 4.2 (Neukirch).** Suppose \( G_1, \ldots, G_k \) are pro-\( p \)-groups, and that \( G = G_1 \ast_p G_2 \ast_p \cdots \ast_p G_k \). Then for any finite discrete \( G \)-module \( M \) and any \( i \geq 2 \) the map

\[
\text{res}: H^i(G, M) \to \bigoplus_{j=1}^k H^i(G_j, M)
\]

(\( \text{induced by the inclusions } G_j \hookrightarrow G \)) is an isomorphism. Moreover, if \( M \) is a trivial \( G \)-module, \( \text{res} \) is an isomorphism for \( i = 1 \), as well.

The crucial observation needed for our examples is that free products of very nice groups can occur as \( G_p(F) \) for suitable fields \( F \). This is the conclusion of the next key theorem. (A special case of this theorem was proved by a different method in [J, Lemma 9′].)

Two valuations \( v_1 \) and \( v_2 \) on a field \( F \) are said to be independent if no proper subring of \( F \) contains both valuation rings \( V_{F,v_1} \) and \( V_{F,v_2} \). Recall that the approximation theorem [E, (11.16); or Bo2, §7, No. 2, Theorem 1] holds between any two independent valuations \( v_1 \) and \( v_2 \).

**Theorem 4.3.** Let \( (L_i, v_i) \) be \( p \)-Henselian valued fields with \( \mu_p \subseteq L_i \) and \( \text{char } L_i \neq p \), \( i = 1, 2 \). Let \( F = L_1 \cap L_2 \). Suppose that the valuations \( v_1|_F \) and \( v_2|_F \) on \( F \) are independent and that the maps \( \Gamma_{F,v_i}/p\Gamma_{F,v_i} \to \Gamma_{L_i}/p\Gamma_{L_i} \) and \( F_{v_i} \to L_{v_i} \) are surjective, \( i = 1, 2 \). Then,

\[
G_p(F) \cong G_p(L_1) \ast_p G_p(L_2).
\]

**Proof.** For short we denote the unit group \( U_{F,v_i} \) by \( U_i \), the value group \( \Gamma_{F,v_i} \) by \( \Gamma_i \), the residue field \( \bar{F}_{v_i} \) by \( \bar{F}_i \), and \( H^i_p(K, \mu_p) \equiv H^i_p(K, \mathbb{Z}/p\mathbb{Z}) \) by \( H^i(K) \) for \( K = F \) or \( L_1 \) or \( L_2 \). Let \( \text{res}_{F \to L_i} : H^i(F) \to H^i(L_i) \) denote the map induced by the restriction homomorphism \( G_p(L_i) \to G_p(F) \). Set \( B_1 = L_2^p \cap F^* \) and \( B_2 = L_1^p \cap F^* \).
Consider the commutative diagram:

$$0 \to (U_1 \cap U_2)/(U_1 \cap U_2)^p \to \frac{F^*}{F^{*p}} \to \frac{\Gamma_1/p\Gamma_1 \oplus \Gamma_2/p\Gamma_2}{\to 0}$$

(*)

$$0 \to \frac{U_{\ell_1}/U_{\ell_1}^p \oplus U_{\ell_2}/U_{\ell_2}^p}{\to L_{\ell_1}^*/L_{\ell_1}^{*p} \oplus L_{\ell_2}^*/L_{\ell_2}^{*p}} \to \frac{\Gamma_{\ell_1}/p\Gamma_{\ell_1} \oplus \Gamma_{\ell_2}/p\Gamma_{\ell_2}}{\to 0}$$

The middle map $\beta$ is injective as $\mu_p \subseteq F$ and $F = L_1 \cap L_2$; that is, $B_1 \cap B_2 = F^{*p}$. Clearly the bottom row of (*) is exact. Since $v_1|_F$ and $v_2|_F$ are independent, the approximation theorem shows $F^*$ maps onto $\Gamma_1 \oplus \Gamma_2$; hence, the top row of (*) is exact. Because $(L_i, v_i)$ is $p$-Henselian we have $U_i/U_i^p \cong L_i^*/L_i^{*p}$ (see Lemma 1.8(ii)). It follows that $\alpha$ is surjective by the approximation theorem and the hypothesis that $\bar{F}_i \cong \bar{L}_i$. By hypothesis, $\gamma$ is also surjective. Thus, the snake lemma [Bo1, §1, Proposition 2] implies that $\beta$ and $\gamma$ are isomorphisms. Hence, $B_i/F_i^{*p} \cong L_i^*/L_i^{*p}$, $i = 1, 2$, $B_1 \cdot B_2 = F^*$, and $p\Gamma_{\ell_i} \cap \Gamma_i = \Gamma_{\ell_i}$, $i = 1, 2$. In cohomological terms, the isomorphism $\beta$ reads: $H^1(F) \cong H^1(L_1) \oplus H^1(L_2)$.

Let $C_{ij}$ denote the subgroup of $H^2(F)$ generated by the cup products $\{(a) \cup (b) | a \in B_i, b \in B_j\}$ for $i = 1, 2, j = 1, 2$. Since $B_1 \cdot B_2 = F^*$ the Merkurjev-Suslin Theorem 1.3 and the remarks after (1.7) show that $H^2(F) = C_{11} + C_{12} + C_{22}$. We will prove that $C_{12} = 0$ and $H^2(F) = C_{11} \oplus C_{22}$, with $C_{ii} \cong H^2(L_i)$ via the restriction map. Since clearly $\text{res}_{F \to L_i}(C_{22}) = \text{res}_{F \to L_i}(C_{11}) = 0$ it follows that $\text{res}: H^2(F) \to H^2(L_1) \oplus H^2(L_2)$ is an isomorphism. Then the desired conclusion $G_p(F) \cong G_p(L_1) \oplus G_p(L_2)$ follows by Neukirch’s Theorem 4.1.

Consider any generator $(a) \cup (b)$ of $C_{12}$ with $a \in B_1, b \in B_2$ as $a \in L_2^p$ using $p\Gamma_{\ell_2} \cap \Gamma_2 = p\Gamma_2$, the surjectivity of $\bar{F}_2 \to \bar{L}_2$, and the approximation theorem we may find an $a' \in F^*$ with $a' \equiv a \mod F^{*p}$, $v_2(a') = 0, a' = 1 \mod \bar{F}_2$, and $v_1(a') > 0$. Likewise, there is a $b' \equiv b \mod F^{*p}$ with $v_1(b') = 0, b' = 1 \mod \bar{F}_1$, and $v_2(b') > 0$. Consequently $v_i(a' + b') = 0$ and $a' + b' = 1 \mod \bar{L}_i$ for $i = 1$ and $i = 2$. Since the $L_i$ are $p$-Henselian it follows by Lemma 1.8(i) that $a' + b' \in L_2^p \cap L_2^\infty \cap F = F^{*p}$. Thus, $(a') \otimes (b')$ lies in the Steinberg relation subgroup of $H^1(F) \otimes H^1(F)$ (cf. Theorem 1.3). From this we see that $(a) \cup (b) = (a') \cup (b') = 0$ in $H^2(F)$. Thus, $C_{12} = 0$.

To complete the proof we must show $H^2(F) = C_{11} \oplus C_{22} \equiv H^2(L_1) \oplus H^2(L_2)$. This is immediate from the following

CLAIM. There exist homomorphisms $\epsilon_i: H^2(L_i) \to H^2(F)$, with $\text{im}(\epsilon_i) = C_{ii}$ and $\text{res}_{F \to L_i} \circ \epsilon_i: H^2(L_i) \to H^2(L_i)$ the identity map, $i = 1, 2$.

To prove the claim, observe first that the isomorphism $B_i/F_i^{*p} \equiv L_i^*/L_i^{*p}$ yields an injection $\hat{\epsilon}_i: H^1(L_i) \to H^1(F)$ which is the composite of

$$H^1(L_i) \overset{\approx}{\to} L_i^*/L_i^{*p} \overset{\approx}{\to} B_i/F_i^{*p} \hookrightarrow F^*/F_i^{*p} \overset{\approx}{\to} H^1(F).$$

Note that $\hat{\epsilon}_i((a)_{\ell_i}) = (a)$, for every $a \in B_i$. The map $\hat{\epsilon}_i \otimes \hat{\epsilon}_i$ composed with the cup product yields a homomorphism

$$\epsilon_i': H^1(L_i) \otimes H^1(L_i) \to H^2(F)$$
defined on generators by \( e'_i((a)_{L_i} \otimes (b)_{L_i}) = (a)_{F} \cup (b)_{F} \) for all \( a, b \in B_i \). Since \( \text{im}(e'_i) = C_{i,i} \) and the composition \( \text{res}_{F \to L_i} \circ e'_i : H^1(L_i) \to H^1(L_i) \) is identity, to prove the claim it suffices to show that \( e'_i \) induces a well-defined homomorphism \( e'_i : H^2(L_i) \to H^2(F) \). In view of the Merkurjev-Suslin Theorem 1.3 we must show that \( S_i \subseteq \ker e'_i \), where \( S_i \) is the Steinberg relation subgroup of \( H^1(L_i) \otimes H^1(L_i) \). That is, Steinberg relations can be “lifted” from \( L_i \) to \( F \).

Take any generator \( (a)_{L_i} \otimes (b)_{L_i} \) of \( S_i \), \( a, b \in B_i \). Then there exist \( r, s \in L_i^* \) such that

\[
(\dagger) \quad ar^p + bs^p = 1.
\]

In showing \( (a)_{F} \cup (b)_{F} = 0 \) there are four cases to consider:

First, suppose \( v_i(ar^p) \neq 0 \) and \( v_i(bs^p) \neq 0 \). Then valuation theory and equation \((\dagger)\) show that \( v_i(ar^p) = v_i(bs^p) < 0 \) and \(-ar^p(bs^p)^{-1} \in 1 + M_{L_i} \). This yields \(-ab^{-1} \in L_i^p \) since \( L_i \) is \( p \)-Henselian. As \( L_i^p \cap B_i = F*_{p} \) we find \(-ab^{-1} \in F*_{p} \), i.e., \( (b)_{F} = -(a)_{F} \) in \( H^1(F) \). So \( e'_i((a)_{L_i} \otimes (b)_{L_i}) = (a)_{F} \cup (b)_{F} = (a)_{F} \cup (-a)_{F} = 0 \) in \( H^2(F) \) (cf. [Mi, p. 319]).

For the next case suppose \( v_i(ar^p) = 0 \) but \( v_i(bs^p) \neq 0 \). Then from \((\dagger)\) we have \( v_i(bs^p) > 0 \) and \( ar^p \in 1 + M_{L_i} \subseteq L_i^p \). Thus, \( a \in L_i^p \cap B_i = F*_{p} \). So, \( (a)_{F} = 0 \) in \( H^1(F) \), which assures \( (a)_{F} \cup (b)_{F} = 0 \) in \( H^2(F) \). The case where \( v_i(ar^p) \neq 0 \) but \( v_i(bs^p) = 0 \) is handled analogously.

In the final case, we have \( v_i(ar^p) = v_i(bs^p) = 0 \). So, \( v_i(a), v_i(b) \in p\Gamma_i \) by the injectivity of the map \( \gamma \) of diagram \((*)\). Modifying \( a \) and \( b \) by \( p \)th powers from \( F \), we may assume that each of \( a, b, r, s \) lies in \( U_{L_i} \). Recall that \( a \in B_i \subseteq L_i^p \), where \( j = 3 - i \). So \( v_j(a) \in p\Gamma_{L_j} \cap \Gamma_j = p\Gamma_j \). Applying the approximation theorem and the isomorphism \( F_i \cong \bar{L}_i \), we can choose \( r', s' \in F^* \) with \( v_i(r') = 0, \bar{r}' = \bar{r} \in \bar{L}_i, v_i(r'^p) = -v_i(a), \) and \( v_i(s') = 0, \bar{s}' = \bar{s} \) in \( \bar{L}_i \). \( v_i(s'^p) > v_i(b) \). Then \( ar'^p + bs'^p = 1 \) in \( \bar{L}_i \) and \( ar'^p + bs'^p = ar'^p \) in \( L_i^p \). Since \( L_1 \) and \( L_2 \) are each \( p \)-Henselian, it follows that \( ar'^p + bs'^p \in L_i^p \cap L_2^p \cap F = F^p \). Hence, \( (a)_{F} \otimes (b)_{F} \) lies in the Steinberg relation group of \( H^1(F) \otimes H^1(F) \). Thus, \( (a)_{F} \cup (b)_{F} = 0 \) in \( H^2(F) \). This establishes the claim and completes the proof of Theorem 4.3. □

Remark 4.4. Suppose \((L_i, v_i)\) are \( p \)-Henselian valued fields, \( i = 1, 2 \), with \( \mu_p \subseteq L_i \) and \( \text{char } L_i \neq p \) for each \( i \). Let \( F = L_1 \cap L_2 \), and suppose \( v_1|_F \) and \( v_2|_F \) are independent valuations. In each of the following two situations we can see that each \((L_i, v_i)\) is an immediate extension of \((F, v_i)\), so the hypotheses of Theorem 4.3 are satisfied:

(i) Each \( L_i \) is unramified over \( F, \bar{L}_i \) is Galois over \( \bar{F}_{v_i} \) and \((L_i, v_i)\) is Henselian.

(ii) Each \( L_i \) is unramified over \( F \) and \( L_i \subseteq \bar{F}_{v_i} \), the \( p \)th root closure of \( F \).

In either case, it suffices to check that \( \bar{F} = \bar{F}_{v_i} \) maps onto \( \bar{L}_i \). In case (i) take any \( \bar{c} \in \bar{L}_i \), and let \( \bar{f}_i \in \bar{F}_{v_i}[X] \) be the minimal polynomial of \( \bar{c} \) over \( \bar{F}_i \). Then \( \bar{f}_i \) splits completely over \( \bar{L}_i \), as \( \bar{L}_i \) is Galois over \( \bar{F}_i \). For \( j = 3 - i \), pick any monic \( \bar{f}_j \in \bar{F}_j[X] \) with \( \text{deg } \bar{f}_j = \text{deg } \bar{f}_i \), and such that \( \bar{f}_j \) splits completely in \( \bar{F}_j[X] \) with no repeated roots. By the approximation theorem applied to the corresponding coefficients of \( \bar{f}_i \) and \( \bar{f}_j \) there is a monic \( f \in V_{\bar{F}_{v_i}}[X] \cap V_{\bar{F}_{v_j}}[X] \) with \( \bar{f}_i = \bar{f}_j \) in \( \bar{F}_{v_i}[X] \).
and \(\tilde{f} = \tilde{f}_2\) in \(\overline{F}_2[X]\). The Henselian assumption implies that \(f\) splits in \(L_1\) and \(L_2\). Hence, \(f\) splits in \(L_1 \cap L_2 = F\). So, \(\tilde{c} \in \overline{F}_j\) which shows that \(\overline{L}_j = \overline{F}_j\). In case (ii) we have \(\mu_p \subseteq \overline{F}_i\) and \(\overline{L}_j \subseteq \overline{F}_p\). From the theory of \(p\)-groups (cf. (1.4)) if \(\overline{F}_i \neq \overline{L}_i\), then there is a \(d \in \overline{L}_i - \overline{F}_i\) with \(d^p \in \overline{F}_i\). Pick any \(\tilde{e} \in \overline{F}_j^*, \ j = 3 - i. By the approximation theorem there is a \(b \in F^*\) with \(v_i(b) = v_2(b) = 0\) and \(\tilde{b} = \tilde{d}^p\) in \(\overline{F}_i\) and \(\tilde{b} = \tilde{e}^p\)

in \(\overline{F}_j\). Since \(L_1\) and \(L_2\) are \(p\)-Henselian, we have \(b \in L_1^p \cap L_2^p \cap F = F^p\). Hence \(\tilde{d}^p = \tilde{b} \in \overline{F}_p^p\), contradicting the choice of \(d\).

We will exploit Theorem 4.3 below to obtain local global principles relating algebras over \(F\) to their extensions over \(L_1\) and \(L_2\). The key to moving from cohomological data to information about algebras is provided by some index computations which are consequences of the pro-\(p\) version of the famous Kurosch subgroup theorem. This theorem is due to Binz, Neukirch, and Wenzel [BNW]—in a more general form than given here. In what follows, we write \(H^G\) for the conjugate \(gHg^{-1}\) of a group \(H\).

**Theorem 4.5 (Binz, Neukirch, Wenzel).** Suppose \(G, G_1, \ldots, G_k\) are pro-\(p\)-groups with \(G = G_1 \ast_p G_2 \ast_p \cdots \ast_p G_k\). Let \(H\) be an open subgroup of \(G\). Then,

\[
H = \bigast_p \left( \bigast_{i=1}^k G_i^{g_i/H} \cap H \right) \ast_p \mathcal{F},
\]

where for each \(i\) the \(g_i, 1, \ldots, g_i, n_i\) are a full set of representatives for the double cosets \(Hg_i\) of \(H\) and \(G_i\) in \(G\), and \(\mathcal{F}\) is a free pro-\(p\)-group.

Before turning to central simple algebras we consider the notion of index in a purely cohomological setting:

**Definition 4.6.** Let \(G\) be a pro-\(p\)-group and let \(\gamma \in H^i(G, M), \ i \geq 2,\) for some discrete \(G\)-module \(M\). The \(p\)-index of \(\gamma\) is

\[
p-ind(\gamma) := \min \{|G : H| \mid H\ is an open subgroup of \ G\ and \ \res_{G \rightarrow H}(\gamma) = 0 \text{ in } H^i(H, M)\}.
\]

**Remarks 4.7.** (i) \(p\)-ind(\(\gamma\)) is always finite. For, as \(M\) is discrete and \(\gamma\) is a continuous cohomology class, there is an open normal subgroup \(N\) of \(G\) with \(\gamma \in \text{im}(\inf_{G/N \rightarrow G}).\) Hence, \(\res_{G \rightarrow N}(\gamma) = 0\).

(ii) If \(K\) is a closed subgroup of \(G\), then \(p\)-ind(\(\res_{G \rightarrow K}(\gamma)\)) \(\leq\) \(p\)-ind(\(\gamma\)).

(iii) If \(\res_{G \rightarrow H}(\gamma) = 0\), we say that \(H\) splits \(\gamma\). Note that if \(H\) splits \(\gamma\), then every conjugate \(H^g\) of \(H\) in \(G\) also splits \(\gamma\). For, the conjugation map \(H \rightarrow H^g\) induces a function \(c_{g, H^g} : H^i(H, M) \rightarrow H^i(H^g, M)\). Since \(c_{g, H^g}\) is the identity map on \(H^i(G, M)\) (cf. [Se2, p. 116, Proposition 3; or We, p. 65, Proposition 2-3-1]), we have

\[
\res_{G \rightarrow H^g}(\gamma) = (\res_{G \rightarrow H^g} \circ c_{g, H^g})(\gamma) = (c_{g, H^g} \circ \res_{G \rightarrow H})(\gamma) = 0.
\]

**Theorem 4.8.** Suppose \(H_1, \ldots, H_k\) are closed subgroups of a pro-\(p\)-group \(G\), and suppose \(G = H_1 \ast_p \cdots \ast_p H_k\). Then, for any discrete \(G\)-module \(M\) and any \(\gamma \in H^i(G, M), i \geq 2,\)

\[
p\text{-ind}(\gamma) = \max_{1 \leq j \leq k} \{p\text{-ind}(\res_{G \rightarrow H_j}(\gamma))\}.
\]
Proof. Let $p^m = \max_{1 \leq j \leq k} \{ p\text{-ind}(\text{res}_{G \to H_j}(\gamma)) \}$. By Remark 4.7(ii), $p\text{-ind}(\gamma) \geq p^m$. To prove the reverse inequality we proceed by induction on $m$. If $m = 0$, each $H_j$ splits $\gamma$, so as $H'(G, M) \cong \bigoplus_{j=1}^k H'(H_j, M)$ by Theorem 4.2, we find that $G$ splits $\gamma$, i.e., $p\text{-ind}(\gamma) = 1 = p^0$.

Now, suppose $m \geq 1$. For each $j$, choose an open subgroup $K_j$ of $H_j$ such that $K_j$ splits $\gamma$ and $|H_j : K_j| = p\text{-ind}(\text{res}_{G \to H_j}(\gamma))$. If $K_j \neq H_j$, let $N_j$ be a maximal proper subgroup of $H_j$ containing $K_j$; so $N_j$ is normal in $H_j$ and $H_j/N_j \cong \mathbb{Z}/p\mathbb{Z}$, as $H_j$ is a pro-$p$-group. If $K_j = H_j$, let $N_j = H_j$. Then for each $j$ there is a homomorphism $\pi_j : H_j \to \mathbb{Z}/p\mathbb{Z}$ with $\pi_j|_{H_j} = \pi_j$ for each $j$. Set $N = \ker(\pi)$. Then $N$ is a normal subgroup of $G$, $|G : N| = p$, and $N \cap H_j = N_j \supseteq K_j$ for $j = 1, 2, \ldots, k$.

Applying Theorem 4.5 we have

$$N = L_1 \ast_p \cdots \ast_p L_k \ast_p \mathcal{F},$$

where $\mathcal{F}$ is a free pro-$p$-group and each $L_i = N \cap H_{j(i)} \cong (N \cap H_{j(i)})^{\pi_i}$ for some $g_i \in G$ and $j(i) \in \{1, 2, \ldots, k\}$. Set $K'_i = K_{j(i)}^{\pi_i} \subseteq L_i$ and set $\delta = \text{res}_{G \to L_i}(\gamma)$. Since $K_{j(i)}$ splits $\gamma$, $K'_i$ must also split $\gamma$ (hence $\delta$), by Remark 4.7(iii). Consequently,

$$p\text{-ind}(\text{res}_{G \to L_i}(\delta)) \leq |L_i : K'_i| = |N_{j(i)} : K_{j(i)}| \leq p^{m-1}.$$  

Also, $p\text{-ind}(\text{res}_{G \to \mathcal{F}}(\delta)) = p^0$ as $H'(\mathcal{F}, M) = 0$, $i \geq 2$. Thus, by induction, $p\text{-ind}(\delta) \leq p^{m-1}$, so that

$$p\text{-ind}(\gamma) \leq |G : N| \cdot p\text{-ind}(\text{res}_{G \to N}(\gamma)) \leq p \cdot p^{m-1} = p^m.$$  

This proves the theorem. □

Definition 4.9. Let $A$ be a central simple $F$-algebra with $[A] \in \text{Br}_p(F)$. The $p$-index of $A$ is

$$p\text{-ind}(A) := \min \{ \left[ L : F \right] \mid L \text{ is a field}, F \subseteq L \subseteq \tilde{F}_p, \text{ and } L \text{ splits } A \}.$$  

Remarks 4.10. (i) For every $A$ with $[A] \in \text{Br}_p(F)$, $p\text{-ind}(A)$ is necessarily finite. For, as we observed in §1, every such $A$ is split by $\tilde{F}_p$, so by some finite degree subextension.

(ii) If $\mu_p \subseteq F$, then $G_p(F)$ is a pro-$p$-group. If $[A]$ has exponent $p^n$ there is a corresponding element $\gamma$ of $H_p^2(F, \mu_p^n)$. Then for any field $M \supseteq F$, $\text{res}_{F \to M}(\gamma)$ is the element of $H_p^2(M, \mu_p^n)$ corresponding to $[M \otimes_F A]$ in $\text{Br}_p(M)$. From this it is clear that $p\text{-ind}(A) = p\text{-ind}(\gamma)$, which is a power of $p$. However, if $\mu_p \not\subseteq F$, it is unknown whether $p\text{-ind}(A)$ is always a $p$-power.

(iii) For any $A$ with $[A] \in \text{Br}_p(F)$, clearly index$(A) \leq p\text{-ind}(A)$, but it is an open question whether equality always holds. (Equality means that the underlying division algebra of $A$ has a maximal subfield in $\tilde{F}_p$.) Indeed, if $\mu_p \not\subseteq F$ and index$(A) = p$, then $p\text{-ind}(A) = p$ iff the underlying division algebra of $A$ is a cyclic algebra. But for $p \geq 5$ ($p$ prime) it is unknown whether every division algebra of index $p$ is cyclic.
Theorem 4.11 (Local-Global Principles). Let $L_1$ and $L_2$ be fields with $\mu_p \subseteq L_i$, $i = 1, 2$, and let $F = L_1 \cap L_2$. Suppose the natural map $G_p(L_1) \ast_p G_p(L_2) \to G_p(F)$ is an isomorphism. Then for any central simple $F$-algebra $A$ with $[A] \in Br_p(F)$,

(i) $F$ splits $A$ iff $L_1$ and $L_2$ each split $A$;

(ii) $\text{index}(A) \leq p\text{-ind}(A) = \max\{p\text{-ind}(A \otimes_F L_i)|i = 1, 2\}$;

(iii) if $\text{index}(A \otimes_F L_i) = p\text{-ind}(A \otimes_F L_i), i = 1, 2$, then $\text{index}(A) = p\text{-ind}(A)$;

(iv) for any field $K$ with $F \subseteq K \subseteq F_p$ and $[K : F] < \infty$, $K$ splits $A$ iff $K \otimes_F L_i$ splits $A, i = 1, 2$;

(v) suppose there are finite degree Galois $p$-extensions $M_i$ of $L_i$ which split $A$, and suppose $G$ is a finite $p$-group generated by isomorphic copies of $\mathcal{G}(M_i/L_i), i = 1, 2$; then there is a Galois extension $M$ of $F$ for which $\mathcal{G}(M/F) \cong G, M$ splits $A$ and $M \cdot L_i = M_i, i = 1, 2$.

Note that for $K$ as in (iv), $K$ is separable over $F$, so $K \otimes_F L_i$ is a direct sum of fields. “$K \otimes_F L_i$ splits $A$” means each summand splits $A$.

Proof. Suppose $[A]$ has exponent $p^n$, let $\gamma \in H^2_p(F, \mu_{p^n})$ be the element corresponding to $[A]$ in $\rho_n\text{-Br}(F)$.

Part (i) is immediate from the isomorphism $H^2_p(F, \mu_{p^n}) \cong H^2_p(L_1, \mu_{p^n}) \oplus H^2_p(L_2, \mu_{p^n})$ given by Theorem 4.2. Part (ii) follows from Theorem 4.8 and Remarks 4.10(h), (iii). Since $\text{index}(A) \geq \max\{\text{index}(A \otimes_F L_i)|i = 1, 2\}$, (iii) is immediate from (ii).

For (iv) the “only if” part is clear. For the reverse implication assume that (each summand of) each $K \otimes_F L_i$ splits $A$. Let $N = G_p(K)$, an open subgroup of $G_p(F).$ Let $H_i = G_p(L_i)$, which we identify with its image in $G_p(F).$ (The free product hypothesis assures that the map $H_i \to G_p(L_i)$ is injective.) Let

$$N = N_{11} \ast_p \cdots \ast_p N_{1n_1} \ast_p \cdots \ast_p N_{2n_2} \ast_p \mathcal{F}$$

be the free product decomposition of $N$ given by Theorem 4.5, where $N_{ij} = H^p \cap N$ for suitable $g_{ij} \in G_p(F)$ and $\mathcal{F}$ is a free pro-$p$-group. For each $i, j, H_j \cap N^{g_{ij}}$ is (isomorphic to) $G_p(g_{ij}^{-1}(K) \cdot L_i).$ Since the compositum $g_{ij}^{-1}(K) \cdot L_i$ is isomorphic to a summand of $K \otimes_F L_i$, it splits $A$. Thus, $\text{res}_{G \to (H \cap N^{g_{ij}})}(\gamma) = 0$. Let $\delta = \text{res}_{G \to N}(\gamma).$ Since $H_i \cap N^{g_{ij}} = N^{g_{ij}}$, we have $0 = \text{res}_{G \to N}(\gamma) = \text{res}_{G \to N}(\delta)$ (cf. Remark 4.7(iii)). Because $\mathcal{F}$ is free, $\text{res}_{G \to \mathcal{F}}(\delta) = 0$. Therefore, by Theorem 4.2 $\delta = 0$ in $H^2(N, \mu_{p^n}),$ i.e., $K$ splits $A$, as desired.

(v) Let $f_i$ be the composite homomorphism $G_p(L_i) \to \mathcal{G}(M_i/L_i) \to G$, with kernel $G_p(M_i)$; we have an induced epimorphism $f: G_p(F) \to G_p(L_1) \ast_p G_p(L_2) \to G$. Let $M$ be the fixed field of $\ker f$. Then $M$ is Galois over $F$ and $\mathcal{G}(M/F) \cong G_p(F)/\ker f \cong G$. When we identify $G_p(F)$ with $G_p(L_1) \ast_p G_p(L_2)$, $\ker f \cap G_p(L_i) = \ker f_i = G_p(M_i)$. Consequently, $M \cdot L_i = M_i$. Since $M$ is Galois over $F$ every summand of $M \otimes_F L_i$ is isomorphic to $M \cdot L_i$. Hence, $M \otimes_F L_i$ splits $A$. By (iv) $M$ splits $A$, as desired. □

Remark. Theorems 4.3 and 4.11 which were stated for $F = L_1 \cap L_2$ clearly hold as well for $F = L_1 \cap L_2 \cap \cdots \cap L_k$ for any integer $k \geq 2$. License or copyright restrictions may apply to redistribution; see http://www.ams.org/journal-terms-of-use
5. Noncrossed products of exponent $p^n$, $n \geq 3$. Fix a prime number $p$ and integers $m \geq n \geq 3$. In this section we will construct a noncrossed product division algebra $D$ of exponent $p^n$ and index $p^m$ over a field $F$ of any characteristic $\neq p$.

To begin, fix any field $k$ containing $p$ distinct $p$th roots of unity (so $\text{char } k \neq p$). Set $F_0 = k(x_1, x_2, y_1, y_2, y_3, \ldots, y_{2m})$, where $x_1, x_2, y_1, \ldots, y_{2m}$ are algebraically independent over $k$. Let $v_1$ be the valuation on $F_0$ with residue field $k(y_1, \ldots, y_{2m})$ and value group $\mathbb{Z} \times \mathbb{Z}$, ordered lexicographically, with $v_1(x_1) = (1,0)$ and $v_1(x_2) = (0,1)$. (This is the valuation described in Example 2.7, viewing $F_0 = K(x_1, x_2)$, with $K = k(y_1, \ldots, y_{2m})$.) Let $v_2$ be the valuation on $F_0$ with residue field $k(x_1, x_2)$ and value group $\prod_{i=1}^{2m} \mathbb{Z}$, ordered lexicographically, with $v_2(y_i) = (0, \ldots, 0, 1, 0, \ldots, 0)$ (the 1 in the $i$th place). (This is another case of Example 2.7, viewing $F_0 = K(y_1, \ldots, y_{2m})$ with $K = k(x_1, x_2)$.) Clearly $v_1$ and $v_2$ are independent valuations on $F_0$. Within some fixed algebraic closure of $F_0$ let $(L_1, v_1)$ be a strict $p$-Henselization of $(F_0, v_1)$ and let $(L_2, v_2)$ be a strict $p$-Henselization of $(F_0, v_2)$, as described in §1.

Let $F = L_1 \cap L_2$. Note that $F$ contains a primitive $p^n$th root of unity $\omega$ as $\mu_{p^l} \subseteq L_i$ for all $l, i = 1, 2$. Let $\rho = \omega^{p^{n-1}}$, a primitive $p$th root of unity. Using the notation of §1 we define central simple $F$-algebras $A_1$ and $A_2$ by

$$A_1 = A_\omega(x_1, x_2; F) \quad \text{and} \quad A_2 = \bigotimes_{j=1}^{m} A_\rho(y_{2j-1}, y_{2j}; F).$$

Set $A = A_1 \otimes_F A_2$. By Wedderburn’s theorem $A \cong M_r(D)$, where $D$ is a division algebra with center $F$. The notation defined here will remain fixed throughout this section. We will show in Theorem 5.4 that $D$ is not a crossed product. But first we summarize the nice properties of $F$ given by our earlier theorems.

**Theorem 5.1.** With $F$, $L_1$, $L_2$, and $p$ as above, we have

(i) $G_p(L_1) \cong \hat{L}_p \oplus \hat{L}_p$ and $G_p(L_2) \cong (\hat{L}_p)^m$;

(ii) $G_p(F) \cong G_p(L_1) \ast_p G_p(L_2)$;

(iii) $\text{Br}_p(F) \cong \text{Br}_p(L_1) \oplus \text{Br}_p(L_2)$;

(iv) the local global principles (Theorem 4.11) apply from $L_1$ and $L_2$ to $F$.

**Proof.** Since the value group $\Gamma_L = \Gamma_{F_0,v_i}$, (i) follows from Lemma 1.9(iv). The valuations $v_1$ and $v_2$ are independent on $F$ since they are independent on $F_0$ and $F$ is algebraic over $F_0$. Thus, (ii) follows from Remark 4.4(ii) and Theorem 4.3. Then (iii) follows by Theorem 4.2, taking $M = \mu_{p^l}$, $l = 1, 2, \ldots$. Finally, (ii) implies (iv).

**Remark 5.2.** It can be shown (though we will not) that over a strictly $p$-Henselian field $L$ every central simple division algebra $B$ with $[B] \in \text{Br}_p(L)$ is isomorphic to a tensor product of cyclic algebras. Hence, $\text{index}(B) = p\text{-ind}(B)$. Using this and Theorem 4.11(iii) we can add the following properties of $F$ to the list in 5.1: Let $C$ be any central simple $F$-algebra with $[C] \in \text{Br}_p(F)$; then

(v) $\text{index}(C) = p\text{-ind}(C) = \max\{ p\text{-ind}(C \otimes_F L_i) | i = 1, 2 \}$;

(vi) if $C$ is a division algebra, then $C \otimes_F L_1$ is a division algebra or $C \otimes_F L_2$ is a division algebra.
**Lemma 5.3.** (i) $A_1 \otimes_F L_1$ is a division algebra of exponent, index, and $p$-index $p^n$, while $L_2$ splits $A_1$.

(ii) $A_2 \otimes_F L_2$ is a division algebra of index and $p$-index $p^m$, while $L_1$ splits $A_2$. If $M$ is a Galois extension of $L_2$ which splits $A_2$ and $[M : L_2]$ is a power of $p$, then $(\mathbb{Z}/p\mathbb{Z})^m$ is a homomorphic image of $\mathcal{G}(M/L_2)$.

**Proof.** (i) Note that $A_1 \otimes_F L_1 \equiv A_\omega(x_1, x_2; L_1) \equiv A'_1 \otimes_{F_0} L_1$, where $A'_1 = A_\omega(x_1, x_2; F_0)$. Example 2.7 with the valuation $v_1$ on $F_0$ shows that $A'_1$ is a division algebra, and that $A'_1 \otimes_{F_0} L_1$ is also a division algebra, as $(L_1, v_1)$ is unramified over $(F_0, v_1)$. Since $A_1 \otimes_F L_1$ is a crossed product division algebra, $p$-ind$(A \otimes_F L_1) = \text{index}(A \otimes_F L_1) = p^n$. The valuation $v_1$ on $L_1$ extends uniquely to $L'_1 := L_1(x_1^{1/p^n})$ with value group $p^{-n}\mathbb{Z} \times \mathbb{Z}$. So, $v_1$ maps the norm group $N_{L_1/L_1}(L_1^*)$ into $\mathbb{Z} \times p^n\mathbb{Z}$. Since $v_1(x_2) = (0, 1)$, $x_2^l$ is not a norm from $L_1$ for $l < p^n$; hence the cyclic algebra $A_1 \otimes_F L_1$ has exponent at least $p^n$ (cf. [R, p. 261, Corollary 30.7]). The exponent divides the index, so equals $p^n$. Turning to $L_2$, we have $x_1 \in L_2^{*p^n}$ by Lemma 1.9(ii) since $x_1$ is a unit of $(L_2, v_2)$ which is strictly $p$-Henselian; hence $L_2$ splits $A_1$.

(ii) The arguments of (i) for $A_1$ apply to $A_2$ with the valuations reversed, yielding the first part of (ii). Now, $A_2 \otimes_F L_2$ corresponds to $(y_1) + \cdots + (y_{2m-1}) + (y_{2m})$ in $H^2(L_2, \mu_p) \cong H^2(P_{2m}, \mathbb{Z}/p\mathbb{Z})$. Thus, Theorem 3.4 establishes the final assertion of (ii). □

**Theorem 5.4.** Let $D$ be the $F$-central division algebra defined at the beginning of this section. Then $D$ has exponent $p^n$ and index $p^m$ where $m \geq n \geq 3$. Further,

(i) $D$ is not a crossed product.

(ii) The matrix algebra $M_{p^r}(D)$ is not a crossed product for all integers $r \leq n - 3$.

(iii) $M_{p^{n-1}}(D)$ is a crossed product but is not isomorphic to a tensor product of cyclic algebras.

(iv) $M_{p^{n-1}}(D)$ is isomorphic to the tensor product of a cyclic algebra of index $p^n$ and $(m - 1)$ cyclic algebras of index $p$.

(v) $D$ has a maximal subfield whose normal closure over $F$ is of degree a power of $p$.

**Proof.** Recall that $D$ is the underlying division algebra of $A = A_1 \otimes_F A_2$. So, in $\text{Br}(L_i)$, $[D \otimes_F L_i] = [A \otimes_F L_i] = [A_i \otimes_F L_i]$, $i = 1, 2$, by Lemma 5.3. We have $\exp(D) \leq p^n$ by the construction of the $A_i$, and $\exp(D) \geq \exp(A_i \otimes_F L_i) = p^n$, by Lemma 5.3. Applying 5.3 and the local global principles Theorem 4.11(iii), (ii), we have $\text{index}(D \otimes_F L_i) = p$-ind$(D \otimes_F L_i)$, $i = 1, 2$, hence $\text{index}(D) = p$-ind$(D) = \max\{p$-ind$(D \otimes_F L_i)|i = 1, 2\} = p^m$. Part (v) is a restatement of the equality $\text{index}(D) = p$-ind$(D)$.

Part (i) is a special case of (ii), so we prove (ii). Suppose $M_{p^r}(D)$ is a crossed product for $0 \leq r \leq n - 3$. This means that there is a splitting field $K$ of $D$ with $K$ Galois over $F$ and $[K : F] = p^{m-r}$. Then $K \cdot L_i$ is Galois over $L_i$ and $[K \cdot L_i : L_i][K : F]$, so $K \cdot L_i \subseteq (L_i)_p$. Let $G_i = \mathcal{G}(K \cdot L_i/L_i)$. Then $G_1$ is a homomorphic image of $G_p(L_1) \equiv (\hat{\mathbb{Z}}_p)^2$, so $G_1$ is abelian of rank $(:= \text{minimum number of generators}) \leq 2$. Hence, the $p$-torsion group $G_1$ of $G_1$ has order equal to $|G_1/G_1^p| \leq p^2$. Also, since $K \cdot L_1$ splits $D$ and hence splits $A_1 \otimes_F L_1$, we have $|G_1| = [K \cdot L_1 : L_1] \geq \text{index}(A_1 \otimes_F L_1) = p^n$ (cf. (1.1)). On the other hand, as $K \cdot L_2$
splits $A_2 \otimes_F L_2$, the last part of Lemma 5.3 says $G_2$ has $(\mathbb{Z}/p\mathbb{Z})^m$ as a homomorphic image. Therefore, the abelian group $G_2$ has a subgroup $G_3$ with $G_3 \cong (\mathbb{Z}/p\mathbb{Z})^m$. Both $G_1$ and $G_3$ may be viewed as subgroups of $\mathcal{G}(K/F)$. Since $|\mathcal{G}(K/F)| = p^{m+r} \leq p^{m+n-3}$ while $|G_1| \geq p^n$ and $|G_3| = p^m$, we find $|G_1 \cap G_3| \geq p^3 > |G_1|$. But $G_1 \cap G_3 \leq pG_1$. This contradiction proves (ii).

(iii) $A_1 \otimes_F L_1$ has a splitting field $M_1 = L_1(x_1/p^{n-1}, x_2/p)$ which is Galois over $L_1$ with $\mathcal{G}(M_1/L_1) \cong \mathbb{Z}/p^{n-1}\mathbb{Z} \oplus \mathbb{Z}/p\mathbb{Z}$. Likewise $A_2 \otimes_F L_2$ has a splitting field $M_2 = L_2(y_1/p, y_3/p, \ldots, y_{2m-1}/p)$ which is Galois over $L_2$ with $\mathcal{G}(M_2/L_2) \cong (\mathbb{Z}/p\mathbb{Z})^m$. Since each $M_j$ splits $D$, the local global principle (Theorem 4.11) (v) says that there is a splitting field $M$ of $D$ with $M$ Galois over $F$ and $\mathcal{G}(M/F) \cong \mathbb{Z}/p^{m-1}\mathbb{Z} \oplus (\mathbb{Z}/p\mathbb{Z})^{m-1}$. Thus $M$ is a maximal subfield of $M_p^{n-1}(D)$, which must therefore be a crossed product.

Suppose $M_{p^{n-1}}(D) = C_1 \otimes_F C_2 \otimes_F \cdots \otimes_F C_r$, with each $C_i$ a cyclic algebra. Let $N$ be a compositum of $t$ maximal subfields cyclic over $F$, one from each $C_i$. Then $\mathcal{G}(N/F)$ is an abelian $p$-group, and $t \geq \text{rank}(\mathcal{G}(N/F)) \geq \text{rank} \mathcal{G}(N \cdot L_2/L_2) \geq m$; the last inequality comes from Lemma 5.3 as $N \cdot L_2$ splits $A_2 \otimes_F L_2$. However, at least one of the $C_i$ has exponent (hence index) at least $\exp(D) = p^n$. Thus, $\dim_F(C_1 \otimes_F \cdots \otimes_F C_r) \geq (p^n \cdot p^{m-1})^2 > \dim_F M_{p^{n-1}}(D)$, and this contradiction finishes (iii).

For (iv) note that $A_\omega(x_1, y_2^{p^{n-1}}; F)$ and $A_\omega(y_1, x_2; F)$ are split, by Theorem 5.1(iii), since the argument of Lemma 5.3 shows that they are each split by $L_1$ and by $L_2$. Also, in $\text{Br}_p(F), [A_\omega(y_1, y_2^{p^{n-1}}; F)] = [A_\rho(y_1, y_2; F)]$ by [R, p. 262, Theorem 30.10] as $\rho = \omega^{p^{n-1}}$. Thus, in $\text{Br}_p(F)$, $D$ is similar to $A_1 \otimes_F A_2$ which is similar to

$$A_\omega(x_1y_1, x_2y_2^{p^{n-1}}; F) \otimes_F A_\rho(y_3, y_4; F) \otimes_F \cdots \otimes_F A_\rho(y_{2m-1}, y_{2m}; F).$$

This yields (iv), completing the proof of the theorem. □

Remarks 5.5. (i) In case $m = n$ we can see that $D$ is not a crossed product using the valuation theory in §2 without invoking the cohomological machinery in §3. (Indeed, §3 is needed only for working with matrix algebras in proving Theorem 5.4(ii), (iii).) For, suppose $K$ is a maximal subfield of $D$ with $K$ Galois over $F$. Let $G = \mathcal{G}(K/F)$. Because $D \otimes_F L_i \cong A_1 \otimes_F L_i$ is a division algebra by Lemma 5.3 and Example 2.7, $K$ is linearly disjoint to $L_i$ over $F$, so that $G \cong \mathcal{G}(K \cdot L_i/L_i)$. By 2.7, $\mathcal{G}(K \cdot L_i/L_i)$ is isomorphic to a subgroup of $\Gamma_{A_i \otimes_F L_i}/\Gamma_{L_i}$: but this group is $(\mathbb{Z}/p\mathbb{Z})^2$ if $i = 1$ and $(\mathbb{Z}/p\mathbb{Z})^{2m}$ if $i = 2$. Clearly these two groups have no common subgroup of order $p^m$, as $m \geq 3$, so $D$ cannot be a crossed product.

(ii) An explicit example (for any $m \geq n \geq 3$) of a maximal subfield of $D$ is given by $K = F(\alpha_1, \alpha_2, \ldots, \alpha_m)$, where

$$\alpha_1 = \sqrt[p]{(x_1 + y_2m)^{p-1}x_1y_2m},$$

$$\alpha_j = \sqrt[p]{(\alpha_{j-1} + y_{2(m-j+1)})^{p-1}\alpha_{j-1}y_{2(m-j+1)}}, \quad j = 2, 3, \ldots, m.$$ 

One can check that $K \cdot L_1 = L_1(x_1^{1/p^n})$ and $K \cdot L_2 = L_2(y_2/p, y_4/p, \ldots, y_{2m}/p)$. Since $K \cdot L_i (\cong K \otimes_F L_i)$ splits $A_i$, hence $D$, Theorem 4.11(iv) shows $K$ splits $D$.

This gives a more concrete verification of the index of $D$ and of (v) of the theorem.
(iii) We have focussed here on a single prime $p$. But if we take the $L_i$ to be strict Henselizations of $(F_0, v_i)$ (not just strict $p$-Henselizations) and assume $k$ has enough roots of unity, it is clear that we can find over $F = L_1 \cap L_2$ noncrossed products $D_q$ of index $q^m$ and exponent $q^n$ ($m \geq n \geq 3$) for every prime $q \neq \text{char } k$. It can be shown that $M_i(D_q)$ is a crossed product iff $q^{n-2}|t$. Furthermore, noncrossed products of composite index can be constructed over such an $F$.

**Remark 5.6.** When $m > n$ the noncrossed product $D$ of Theorem 5.4 is decomposable—one can check that $D \cong D_0 \otimes_F D_1 \otimes_F \cdots \otimes_F D_{m-n}$, where $D_0$ is a noncrossed product of exponent and index $p^n$, while $D_1, \ldots, D_{m-n}$ are cyclic of exponent and index $p$. However, the methods used in constructing $D$ can also be extended to obtain examples of indecomposable division algebras with index exceeding the exponent. Here is a sketch for the case index $= p^4$, exponent $= p^3$ (which is inspired by the examples in [Sa3, §2]): Construct fields and valuations $(L_1, v_1)$, $(L_2, v_2)$, and $F = L_1 \cap L_2$ exactly as at the beginning of this section except with four $x_i$ instead of two and four $y_j$. Let $\omega_j$ be a primitive $p^j$th root of unity in $F$, $j = 1, 2, 3$, let

$$A_1 = A_\omega(x_1, x_2; F) \otimes_F A_\omega(x_3, x_4; F),$$

$$A_2 = A_\omega(y_1, y_2; F) \otimes_F A_\omega(y_3, y_4; F),$$

and let $D$ be the underlying division algebra of $A_1 \otimes_F A_2$. One checks as in Lemma 5.3 and Theorem 5.4 that $\text{index}(D) = p^4$, $\exp(D) = p^3$, and that $D_i = D_i \otimes_F L_i$, $i = 1, 2$. Furthermore, by Corollary 2.6 the valuation $v_i$ on $L_i$ extends to $D_i$, so $D_i$ is a division algebra totally ramified over $L_i$, and $\Gamma_{D_i}/\Gamma_{L_i} \cong (\mathbb{Z}/p^2\mathbb{Z})^2 \times (\mathbb{Z}/p\mathbb{Z})^2$ and $\Gamma_{D_2}/\Gamma_{L_2} \cong (\mathbb{Z}/p^2\mathbb{Z})^4$. Suppose $D_i = D_a \otimes_{L_i} D_\beta$. We claim that $\Gamma_{D_a} \cap \Gamma_{D_\beta} = \Gamma_{L_i}$. For, otherwise $(\Gamma_{D_a} \cap \Gamma_{D_\beta})/\Gamma_{L_i}$ would have a nontrivial cyclic subgroup $H$, and $D_a$ and $D_\beta$ would each contain a copy of the unique totally ramified field extension $K$ of $L_i$ with $\Gamma_K/\Gamma_{L_i} = H$. But then $D_a \otimes_F D_\beta$ would have zero divisors, contradicting the fact that $D_i$ is a division algebra. This shows that $\Gamma_{D_i}/\Gamma_{L_i} = (\Gamma_{D_a}/\Gamma_{L_i}) \times (\Gamma_{D_\beta}/\Gamma_{L_i})$. Note also that the invariant factors of the finite abelian groups $\Gamma_{D_i}/\Gamma_{L_i}$ occur with even multiplicity, $\gamma = \alpha, \beta$. (For this “local” information, proofs will appear in [W2].) Thus, in a nontrivial decomposition of $D_i$ one of the tensor factors has index $p^3$ and the other has index $p$; likewise in a decomposition of $D_2$ each factor has index $p^2$. Since the decompositions of $D_1$ and $D_2$ are incompatible, $D$ must be indecomposable. This $D$ is a crossed product, since by Theorem 4.11(v) it is split by a Galois extension $M$ of $F$ with $\mathcal{O}(M/F) \cong (\mathbb{Z}/p^2\mathbb{Z}) \times (\mathbb{Z}/p\mathbb{Z})^2$. However, with suitable modifications in the construction, by using three valuations, one can obtain examples of noncrossed product division algebras which are indecomposable of degree $p^m$ and exponent $p^n$ for any of the $p^m$ and $p^n$ given in Saltman’s theorem [Sa3, p. 811, Theorem 2.6].

**6. Noncrossed products of exponent $p^2$.** We will now show that our basic method can be used to construct noncrossed product division algebras of exponent $p^2$ ($p \neq 2$) and index $p^m$ for any $m \geq 2$. The construction is more delicate than the one in §5, as we must work with a field $F$ not containing $p$th roots of unity, and must take care to control what happens when $\mu_p$ is adjoined to $F$. (We need to
assure that the local global principles of Theorem 4.11 apply to $F(\mu_p)$, even though they do not apply directly to $F$ itself.) It is still an open question whether there exists a noncrossed product division algebra of index $p^2$ over a field containing $\mu_p$.

We now fix a prime $p \neq 2$ and an integer $m \geq 2$. Fix also a field $k$, char $k \neq p$, satisfying

(i) $[k(\mu_p):k] = 2$;

(ii) $k$ has $m + 1$ linearly disjoint cyclic Galois extensions $\mathcal{L}, \mathcal{L}_1, \mathcal{L}_2, \ldots, \mathcal{L}_m$, with $[\mathcal{L}:k] = p^2$ and $[\mathcal{L}_j:k] = p$,

$j = 1, 2, \ldots, m$.

For example, one could set $k_1 = \mathbb{R}(w_1, \ldots, w_{p^2}, z_{ij}, 1 \leq i \leq p, 1 \leq j \leq p)$ where all the $w_i$ and $z_{ij}$ are algebraically independent over the real numbers $\mathbb{R}$; then let $k$ be the fixed field of the group $\mathbb{Z}/p^2 \mathbb{Z} \times (\mathbb{Z}/p \mathbb{Z})^m$ acting on $k_1$ by permuting the indeterminates, cf. [Ri, §2]. Fields $k$ satisfying (6.1) exist in characteristic 0 and in those prime characteristics $q \neq p$ such that the order of the residue of $q$ in the multiplicative group of the ring $\mathbb{Z}/p \mathbb{Z}$ is even.

Let $F_0 = k(x_1, \ldots, x_m, y_1, \ldots, y_m)$, where $x_1, \ldots, x_m, y_1, \ldots, y_m$ are algebraically independent over $k$. Let $v_1$ be the valuation on $F_0$ as described in Example 2.7, viewing $F_0 = K(x_1, \ldots, x_m)$, where $K = k(y_1, \ldots, y_m)$. So, the value group of $(F_0, v_1)$ is $(\mathbb{Z})^m$ ordered lexicographically and $v_1(x_i) = (0, \ldots, 0, 1, 0, \ldots, 0)$ (the 1 in the $i$th position) while $v_1(y_i) = 0$, all $i$. The residue field $F_{0v_1}$ is $k(\bar{y}_1, \ldots, \bar{y}_m)$ (where $\bar{y}_i$ is the image of $y_i$), which is isomorphic to $k(y_1, \ldots, y_m)$. Let $v_2$ be the same type of valuation on $F_0$ but with the $x_i$ and $y_i$ interchanged. So, $\Gamma_{F_0, v_2} = (\mathbb{Z})^m$, $v_2(y_i) = (0, \ldots, 0, 1, 0, \ldots, 0)$ (the 1 in the $i$th position) while $v_2(x_i) = 0$, and $F_{0v_2} = k(\bar{x}_1, \ldots, \bar{x}_m) \cong k(x_1, \ldots, x_m)$. It is easy to see that $v_1$ and $v_2$ are independent valuations. Next set

$$F_1 = F_0\left(\sqrt[p]{x_1 + y_1}, \sqrt[p]{x_2 + y_2}, \ldots, \sqrt[p]{x_m + y_m}\right).$$

Any extension of $v_1$ to $F_1$ has residue field containing $k(\bar{y}_1^{1/p^2}, \bar{y}_2^{1/p}, \ldots, \bar{y}_m^{1/p})$, an extension of $F_{0v_1}$ of degree $p^{m+1}$. From the fundamental inequality $\Sigma_{e,f}j_i \leq [F_1:F_0] = p^{m+1}$ we see that $v_1$ has a unique extension (also called $v_1$) to $F_1$ which is inertial, hence unramified, with residue field $k(\bar{y}_1^{1/p^2}, \bar{y}_2^{1/p}, \ldots, \bar{y}_m^{1/p})$. Likewise $v_2$ has a unique inertial extension to $F_1$, with residue field $F_0(\bar{x}_1^{1/p^2}, \bar{x}_2^{1/p}, \ldots, \bar{x}_m^{1/p})$.

Now, let $F$ be an algebraic extension of $F_1$ which is maximal with respect to the property that both valuations $v_1$ and $v_2$ have immediate extensions from $F_1$ to $F$; these valuations on $F$ are again denoted $v_1$ and $v_2$. The existence of such an $F$ follows by Zorn’s lemma. This $F$ is the field over which our example will be constructed. Within the $p$th root closure $F_p$ of $F$ let $(L_i, v_i)$ be a $p$th root Henselization of $(F, v_i)$, $i = 1, 2$, as described in §1. Since $F \subseteq L_1 \cap L_2$ and each $v_i$ has an immediate extension to $L_1 \cap L_2$, the definition of $F$ guarantees that $F = L_1 \cap L_2$.

Let $F' = F(\mu_p)$ and $L'_i = L_i(\mu_p)$, $i = 1, 2$. Note that $[F':F] = [L'_i:L_i] = 2$ by (6.1)(i) since the residue fields of the $L_i$ are purely transcendental over $k$. Furthermore $v_i$ has a unique inertial extension from $L_i$ to $L_i'$ and from $F$ to $F'$, $i = 1, 2$. Licensing or copyright restrictions may apply to redistribution; see http://www.ams.org/journal-terms-of-use
The goal of the next few lemmas is to prove that $F' = L_1' \cap L_2'$, so that the machinery of §4 can be invoked. The notation defined thus far will be held fixed throughout this section.

**Lemma 6.2.** $F \cap L_1' \cap L_2' = F'$.

**Proof.** Take any $a \in F \cap L_1' \cap L_2'$, and suppose $a \notin F'$. Pick $\alpha_i \in L_i$ with $\alpha_i^p = a$, $i = 1, 2$. The $p$th root Henselization $(L_i, v_i)$ is an immediate extension of $(F, v_i)$, so $v_i|_{F(\alpha_i)}$ is an immediate extension of $(F, v_i)$ to $F(\alpha_i)$. Now, the polynomial $X^p - a \in F[X]$ is irreducible since it has no roots in $F$ and $p$ is prime (cf. [K, p. 62]). Therefore, $F(\alpha_1) = F(\alpha_2)$. Hence both $v_1$ and $v_2$ have immediate extensions to $F(\alpha_1)$, contradicting the maximality of $F$. Thus, we must have $a \in F'$.

**Lemma 6.3.** Pick any $\gamma \in G_p(L_i) = \mathcal{G}(\tilde{L}_p/L_i)$ such that $\gamma$ restricts to the nontrivial $L_i$-automorphism of $L_i' = L_i(\mu_p)$. Take any $b \in F' \cap L_1' \cap L_2'$ and any $\beta \in L_1' \cap L_2'$ with $\beta^p = b$. Then $\gamma(\beta) = \gamma(\beta)$.

**Proof.** We have $\gamma(\beta) = N_{L_i'/L_i}(\beta) \in L_i$, $i = 1, 2$. Thus, $(\beta\gamma(\beta))^p = b\gamma(\beta) = N_{F'/F}(b) \in F \cap L_1' \cap L_2'$. The preceding lemma says there is a $c \in F$ with $c^p = (\beta\gamma(\beta))^p$; then $\beta\gamma(\beta) = \omega_ic$ for some $\omega_i \in \mu_p$, $i = 1, 2$. So $\omega_i = \beta\gamma(\beta)c^{-1} \in L_i$. Since $L_i(\mu_p) \neq L_i$ we must have $\omega_1 = \omega_2 = 1$. Therefore, $\gamma(\beta) = c\beta^{-1} = \gamma(\beta)$, as desired.

**Lemma 6.4.** Let $G$ be a profinite group which is generated topologically by closed subgroups $G_1$ and $G_2$. Let $H$ be an open subgroup of $G$ with $|G:H| = |G_1:G_1 \cap H| = |G_2:G_2 \cap H| = 2$. If $\gamma \in G_1 \cap H$, then $G$ is generated topologically by its closed subgroups $G_1 \cap H$, $G_2 \cap H$, and $\langle \gamma \gamma_2 \rangle$.

**Proof.** Let $H_0$ be the closed subgroup of $H$ generated topologically by $G_1 \cap H$ and $G_2 \cap H$ and by $\langle \gamma \gamma_2 \rangle$ (which is the closed subgroup of $H$ generated by $\gamma \gamma_2$). We must show that $H_0 = H$. Assume first that $G$ is finite. Then, as $G$ is generated by $G_1$ and $G_2$ we may express any $h \in H$ as $h = r_1s_1r_2s_2 \cdots r_ns_n$, with $r_1, \ldots, r_n \in G_1$ and $s_1, \ldots, s_n \in G_2$. We show by induction on $n$ that $h \in H_0$. For $n = 1$, if $r_1 \in H$, then also $s_1 \in H$, so $r_1s_1 \in H_0$. If $r_1 \notin H$, then $s_1 \notin H$, so that $r_1\gamma_1 \in G_1 \cap H$, $\gamma_2s_1 \in G_2 \cap H$, and $h = (r_1\gamma_1)(\gamma_2s_1) \in H_0$. Now assume $n > 1$. If $r_1s_1 \in H$, then $r_1s_1 \in H_0$ and $r_2s_2 \cdots r_ns_n \in H_0$ by induction, and we are done. If $r_1s_1 \notin H$, then $r_1(s_1\gamma_1) \in H$ and $(\gamma_2r_1)s_2r_2s_3 \cdots r_ns_n \in H$. By induction both these terms lie in $H_0$, whence $h = (r_1s_1\gamma_2)(\gamma_2s_2r_2s_3 \cdots r_ns_n) \in H_0$. This proves the lemma if $G$ is finite.

Now drop the assumption that $G$ is finite. If $H_0 \neq H$, then $H - H_0$ is a nonempty open subset of $H$. Since a base of open sets of $H$ is given by cosets of open normal subgroups of $H$, there is an $h \in H$ and an open normal subgroup $U$ of $H$ with $hU \cap H_0 = \emptyset$. We may assume that $U$ is actually normal in $G$ (replacing $U$ if necessary by the finite intersection of conjugates of $U$). Because $U$ is open, $|G:U| < \infty$. Let $\pi: G \to G/U$ be the canonical projection. It is easy to check that the hypotheses relating $G$, $G_1$, $G_2$, $H$, $\gamma_1$, $\gamma_2$ all carry over to $\pi(G)$, $\pi(G_1)$, $\pi(G_2)$, $\pi(H)$, $\pi(\gamma_1)$, $\pi(\gamma_2)$. Clearly $\pi(H_0)$ contains the subgroup of $\pi(H)$ generated by
\[\pi(H) \cap \pi(G_1), \pi(H) \cap \pi(G_2), \text{ and } \langle \pi(\tau_1) \pi(\tau_2)^{-1} \rangle.\] But \(\pi(h) \in \pi(H) - \pi(H_0)\)
which contradicts the finite case of the lemma proved above. Thus, \(H_0 = H\), and the lemma is proved in general. \(\square\)

**Lemma 6.5.** \(F' \cap L_i^{p,p} \cap L_j^{p,p} = F'^p.\) Consequently, \(F' = L_1' \cap L_2', \ G_p(F') = G_p(L_1') \ast_p G_p(L_2'),\) and the local-global principles of Theorem 4.11 hold from \(L_1'\) and \(L_2'\) to \(F'.\)

**Proof.** We have \(F \subseteq L_i \subseteq \tilde{F}_p, \ i = 1, 2,\) and \(F = L_1 \cap L_2.\) So, \(G_p(F) = \mathcal{G}(\tilde{F}_p/F)\)
is generated topologically by its closed subgroups \(G_p(L_1)\) and \(G_p(L_2).\) We have \(|G_p(F) : G_p(F') = [F':F] = 2\) and \(G_p(F') \cap G_p(L_i) = G_p(L_i'),\) which has index 2 in \(G_p(L_i).\) Thus, Lemma 6.4 says \(G_p(F')\) is generated topologically by \(G_p(L_1), G_p(L_2),\) and \(\langle \tau_1 \tau_2^{-1} \rangle\) for any \(\tau \in G_p(L_i)\) which restricts to the nontrivial \(L_i\)-automorphism of \(L_i'.\)

Now pick any \(b \in F' \cap L_i^{p,p} \cap L_j^{p,p},\) and any \(\beta \in \tilde{F}_p\) with \(\beta^p = b.\) Let \(N = G_p(F')\), a closed subgroup of \(G_p(F')\). Since \(L_i'\) contains one, hence all \(p\)th roots of \(b, \) \(\beta \in L_i',\) so \(G_p(L_i') \subseteq N, \ i = 1, 2.\) But Lemma 6.3 shows \(\tau \in \mathbb{Z}/p^2\mathbb{Z}\) also. Since a topological generating set of \(G_p(F')\) lies in \(N,\) \(N = G_p(F')\) which shows that \(\beta \in F'.\) Thus \(F' \cap L_i^{p,p} \cap L_j^{p,p} = F'^p.\)

Since \(F' \subseteq L' \cap L_2' \subseteq \tilde{F}_p,\) \(L_1' \cap L_2'\) is obtainable from \(F'\) by successive adjunctions of \(p\)th roots (cf. (1.4)). Thus, the equality proved in the previous paragraph implies \(F' = L_1' \cap L_2'.\) Because \(L_i\) is a \(p\)th root Henselization of \((F, \nu_i),\) the unique extension of \(\nu_i\) to \(L_i'\) is \(p\)-Henselian and is an immediate extension of \((F', \nu_i).\) Also, \(\nu_1\) and \(\nu_2\) are independent valuations on \(F'\) since they are independent on \(F_0\) and \(F'\) is algebraic over \(F_0.\) Therefore, Theorem 4.3 shows that \(G_p(F') = G_p(L_1') \ast_p G_p(L_2'),\) completing the proof. \(\square\)

For each \(i\) the residue field \(\overline{F}_{\nu_i}\) of \(F\) with respect to \(\nu_i\) is the same as that of \(F_1;\) so \(\overline{F}_{\nu_i}\) is a purely transcendental extension of our original ground field \(k.\) Hence, for the fields \(\mathcal{L}, \mathcal{L}_1, \mathcal{L}_2, \ldots, \mathcal{L}_m\) posited in (6.1)(ii), the valuation \(\nu_i\) on \(F\) has a unique inertial extension to \(\mathcal{L} \cdot F\) (resp. to each \(\mathcal{L}_j \cdot F\)) with residue field \(\mathcal{L} \cdot \overline{F}_{\nu_i}\) (resp \(\mathcal{L}_j \cdot \overline{F}_{\nu_i}\)). So, \(\mathcal{L} \cdot F, \mathcal{L}_1 \cdot F, \ldots, \mathcal{L}_m \cdot F\) are linearly disjoint cyclic Galois extensions of \(F.\) We fix a generator \(\sigma\) of \(\mathcal{G} (\mathcal{L} \cdot F/F) = \mathbb{Z}/p^2\mathbb{Z},\) and generators \(\sigma_j\) of \(\mathcal{G} (\mathcal{L}_j \cdot F/F) = \mathbb{Z}/p\mathbb{Z}, \ j = 1, 2, \ldots, m.\) Using the cyclic algebra notation described in §1 we set

\[A_1 := A (\mathcal{L} \cdot F/F, a, x_1)\quad \text{and}\quad A_2 := \bigotimes_{j=1}^m A (\mathcal{L}_j \cdot F/F, \sigma_j, y_j).\]

The underlying division algebra \(D = A_1 \otimes_F A_2\) will provide the counterexample of this section. We first consider the local properties of the \(A_i.\)

**Lemma 6.6.** (i) \(A_1 \otimes_F L_1\) is a division algebra of index and exponent \(p^2,\) while \(L_2\) splits \(A_1.\)

(ii) \(A_2 \otimes_F L_2\) is a division algebra of index \(p^m\) and exponent \(p,\) while \(L_1\) splits \(A_2.\)

(iii) \(A_i \otimes_F L_i'\) has the same index and exponent as \(A_i \otimes_F L_i, i = 1, 2.\)
Proof. (i) Since $(L_1, v_1)$ has the same residue field as $(F, v_1)$, the same argument as given just above shows $v_1$ has a unique inertial (hence unramified) extension to $\mathcal{L} \cdot L_1$; so $\mathcal{L} \cdot F$ and $L_1$ are linearly disjoint over $F$. Hence, $\mathcal{G}(\mathcal{L} \cdot L_1/L_1) \cong \mathcal{G}(\mathcal{L} \cdot F/F) \cong \mathbb{Z}/p^2\mathbb{Z}$ and $A_1 \otimes_F L_1 \cong A(\mathcal{L} \cdot L_1/L_1, \sigma, x_1)$. Since $v_1(x_1) = (1, 0, \ldots, 0)$ in the value group $\Gamma_{L_1}$ of $L_1$, the image of $v_1(x_1)$ in $\Gamma_{L_1}/p^2\Gamma_{L_1}$ has order $p^2$. Therefore, Corollary 2.9 with $k = 1$ and $n_1 = l = p^2$ shows that $A_1 \otimes_F L_1$ is a valued division algebra; its index is clearly $p^2$. Because $v_1$ extends uniquely to $\mathcal{L} \cdot L_1$ without ramification, $v_1$ maps the norm group $N_{\mathcal{L} \cdot L_1/L_1}(\mathcal{L} \cdot L_1)$ into $p^2\Gamma_{L_1}$. Thus, $x_1'$ cannot be a norm from $\mathcal{L} \cdot L_1$ to $L_1$ for $1 < r < p^2$; this shows that $A_1 \otimes_F L_1$ has exponent $p^2$ by [R, p. 261, Corollary 30.7].

Now consider $A_1 \otimes_F L_2$. We have again that $\mathcal{L} \cdot F$ is linearly disjoint to $L_2$ over $F$, so $A_1 \otimes_F L_2 \cong A(\mathcal{L} \cdot L_2/L_2, \sigma, x_1)$. But $\tilde{x}_1$ has a $p^2$-root in $\tilde{L}_2$. Thus, the polynomial $f(X) = X^{p^2} - x_1 \in V_{L_2}[X]$, which splits over $\tilde{F}_p$, has image $\tilde{f}$ in $\tilde{L}_2[X]$ with a nonrepeated linear factor. Because $(L_2, v_2)$ is $p$th root Henselian, $f$ must have a linear factor in $V_{L_2}[X]$, i.e., $x_1$ has a $p^2$-root in $L_2$. Therefore, $x_1$ lies in the norm group $N_{\mathcal{L} \cdot L_1/L_1}(\mathcal{L} \cdot L_1')$, which shows that $A_1 \otimes_F L_2$ is split.

(ii) As in (i), but with the valuations reversed, we see that $v_2$ has a unique inertial extension to $\mathcal{L} \cdot L_2$ for $j = 1, 2, \ldots, m$, with residue field $\mathcal{L} \cdot \tilde{L}_j$. Hence, $A(\mathcal{L} \cdot F/F, \sigma_j, y_j) \otimes_F L_2 \cong A(\mathcal{L} \cdot L_2/L_2, \sigma_j, y_j)$. Corollary 2.9 applies to the tensor product of these algebras with $k = m$, $n_1 = n_2 = \cdots = n_k = l = p$, showing that $A_2 \otimes_F L_2 \cong \otimes_{j=1}^m A(\mathcal{L} \cdot L_2/L_2, \sigma_j, y_j)$ is a valued division algebra with residue ring $\mathcal{L}_1 \cdot \cdots \cdot \mathcal{L}_m \cdot L_2$. Clearly the exponent of $A_2 \otimes_F L_2$ is $p$ and the index is $p^m$. Switching to $L_1$, we find that $A_2 \otimes_F L_1 \cong \otimes_{j=1}^m A(\mathcal{L} \cdot L_1/L_1, \sigma_j, y_j)$. But as each $y_j$ has a $p$th root in $\tilde{L}_1$ an argument like that in (i) shows that each $y_j$ has a $p$th root in $L_1$. Hence, $L_1$ splits $A_2$ as it splits each of the cyclic factors.

(iii) The same arguments just given for $A_i \otimes_F L_i$ apply to $A_i \otimes_F L_i'$. Alternatively, note that $[L_i': L_i] = [L_i(\mu_p^s) : L_i] = 2$. Hence, the index reduction formula [P, p. 243] shows that for any central simple $L_i$-algebra $B$ of odd index, $\text{index}(B \otimes_{L_i} L_i') = \text{index}(B)$. So, in particular, the map $\text{Br}_p(L_i) \to \text{Br}_p(L_i')$ is injective.

Let $A = A_1 \otimes_F A_2$ with the $A_i$ as defined before Lemma 6.6 and the $F$ defined at the beginning of §6. Write $A \cong M_s(D)$, where $D$ is an $F$-central division algebra.

Theorem 6.7. The division algebra $D$ just defined has index $p^m$ and exponent $p^2$. $D$ is not a crossed product. The $F(\mu_p)$-division algebra $D \otimes F(\mu_p)$, with the same index and exponent as $D$, is a crossed product.

Proof. Observe that Lemma 6.6 shows that $[D \otimes_F L_i'] = [A_i \otimes_F L_i']$ in $\text{Br}_p(L_i')$ and $[D \otimes_F L_i'] = [A_i \otimes_F L_i']$ in $\text{Br}_p(L_i)$. The construction of the $A_i$ shows that $\exp(D) = p^2$. Then $\exp(D) = p^2$ since $\exp(D \otimes_F L_i) = p^2$ by Lemma 6.6(i). Hence, $\text{index}(D) = p^s$ for some $s \geq 2$. By the index reduction formula [P, p. 243], $\text{index}(D) = \text{index}(D \otimes_F F')$ as $[F' : F] = 2$ is prime to $p$. We compute the index of $D \otimes F'$ using the local global principles of Theorem 4.11. Since $A_i \otimes_F L_i'$ is a crossed product division algebra, $\text{index}(A_i \otimes_F L_i') = p - \text{ind}(A_i \otimes_F L_i')$. Therefore, by Lemmas 6.6(iii) and 6.5, and Theorem 4.11(ii), (iii),
\[ p^m = \max \{ \text{index}(A_i \otimes_F L_i') | i = 1, 2 \} = \max \{ \text{index}(D \otimes_F L_i') | i = 1, 2 \} = \text{index}(D \otimes_F F') = \text{index}(D). \]

By comparing indices we see that \( D \otimes_F L_2 \cong A_2 \otimes_F L_2 \).

Suppose \( D \) is a crossed product. Then there exists a maximal subfield \( K \) of \( D \) with \( [K : F] = p^m \) and \( K \) Galois over \( F \). Let \( K_i = K \cdot L_i, i = 1, 2 \). Then each \( K_i \) is Galois over \( L_i \), and we view \( \mathcal{B}(K_i/L_i) \subseteq \mathcal{B}(K/L) \) by restriction. In particular, \( [K_i : L_i] \) is a power of \( p \). Since \( (L_i, \psi_i) \) is \( p \)-Henselian, \( \psi_i \) has a unique extension to a valuation of \( K_i \). According to Corollary 2.4, \( K_i \) is an inertial extension of \( L_i \) with \( \mathcal{B}(K_i/L_i) \cong \mathcal{B}(\overline{K_i}/\overline{L_i}), i = 1, 2 \).

Since \( D \otimes_F L_2 \cong A_2 \otimes_F L_2 \) is a division algebra, \( K_2 \cong K \otimes_F L_2 \), which is isomorphic to a maximal subfield \( K_3 \) of \( A_2 \otimes_F L_2 \). Hence \( [K_3 : L_2] = p^m \) and \( \mathcal{B}(K/F) \cong \mathcal{B}(K_3/L_2) \cong \mathcal{B}(\overline{K_3}/\overline{L_2}) \). As we saw in proving Lemma 6.6(ii) \( A_2 \otimes_F L_2 \) is a valued division algebra with residue ring \( \mathcal{L}_1 \cdots \mathcal{L}_m \cdot L_2 \). Thus \( K_3 \subseteq \mathcal{L}_1 \cdots \mathcal{L}_m \cdot L_2 \), and equality must hold by comparing degrees over \( L_2 \). Since each \( \mathcal{L}_i \) was a cyclic extension of \( k \) of degree \( p \), \( \mathcal{B}(\overline{K_3}/\overline{L_2}) \cong (\mathbb{Z}/p^m \mathbb{Z})^m \). Putting these isomorphisms together, we have \( \mathcal{B}(K/F) \cong (\mathbb{Z}/p^m \mathbb{Z})^m \). Hence, the subgroup \( \mathcal{B}(K_i/L_i) \) is elementary abelian.

Recall now from the proof of Lemma 6.6 that \( A_i \otimes_F L_1 \cong A(\mathcal{L}_i \cdot L_1/L_1, \sigma, x_1) \), where \( \mathcal{L}_i \cdot L_1 \) is a cyclic Galois and inertial extension of \( L_1 \) with \( \mathcal{B}(\mathcal{L}_i \cdot L_1/L_1) \cong \mathbb{Z}/p^2 \mathbb{Z} \). Because \( \mathcal{B}(K_i/L_i) \) is elementary abelian, \( \mathcal{L}_i \cdot L_1 \nsubseteq K_1 \). Therefore, \( \mathcal{L}_i \cdot K_1 \), which is a cyclic Galois extension of \( K_1 \), has degree \( p \) or \( p^2 \) over \( K_1 \). By [R, p. 261, Theorem 30.8], \( A_i \otimes_F K_1 \) is similar to \( A(\mathcal{L}_i \cdot K_1/K_1, \tau, x_1) \) in \( \text{Br}(K_1) \), where \( \tau = \sigma \) if \( [\mathcal{L}_i \cdot K_1 : K_1] = p^2 \) and \( \tau = \sigma^p \) if \( [\mathcal{L}_i \cdot K_1 : K_1] = p \). In either case, \( \mathcal{L}_i \cdot K_1 \) is an inertial extension of \( K_1 \) by Corollary 2.4. \( (\mu_p, \nsubseteq K_1 \), as \( [K_1 : L_1] \) is a power of \( p \). Therefore, since \( K_1 \) has the same value group as \( L_1 \) and \( \psi_1(x_1) = (1, 0, \ldots, 0) \) we see from Corollary 2.9 with \( k = 1 \) and \( l = n_1 = p^2 \) or \( p \) that \( A(\mathcal{L}_i \cdot K_1/K_1, \tau, x_1) \) is a division algebra of index \( p^2 \) or \( p \). So, \( K_1 \) does not split \( A_1 \). Since \( [A_i \otimes_F L_1] = [D \otimes_F L_1] \), \( K_1 \) cannot split \( D \). But \( K_1 \) contains the maximal subfield \( K \) of \( D \). This contradiction shows \( D \) cannot be a crossed product.

To see that \( D \otimes_F F' \) is a crossed product, where \( F' = F(\mu_p) \), we first work locally. We have \( \mathcal{L}_i \cdot L_1' \) is cyclic Galois over \( L_1' \). Hence by Kummer theory there is a cyclic subextension \( L_1' \otimes_F (\overline{\mathbb{Q}_p}) \) of degree \( p \) over \( L_1' \). By [R, p. 261, Theorem 30.8], \( A_i \otimes_F L_i' \otimes_F (\overline{\mathbb{Q}_p}) \) is similar to \( A(\mathcal{L}_i \cdot L_1'/(\overline{\mathbb{Q}_p})/L_1', \sigma^p, x_1) \) in \( \text{Br}(L_1'/\mathbb{Q}_p) \), and this algebra is split by \( \mathcal{M}_1 := L_1' \otimes_F (\overline{\mathbb{Q}_p})x_1) \). Invoking Lemma 6.6(i) we see that \( D \) is split by \( \mathcal{M}_1 \). But \( A_2 \), and hence \( D \), is split by \( M_2 := L_2' \otimes_F (\overline{\mathbb{Q}_p}y_1, \ldots, \overline{\mathbb{Q}_p}y_n) \). Each \( M_i \) is Galois over \( L_i' \) and \( \mathcal{B}(M_i/L_i') \cong (\mathbb{Z}/p^m \mathbb{Z})^2 \) while \( \mathcal{B}(M_2/L_2') \cong (\mathbb{Z}/p^m \mathbb{Z})^m \). By Lemma 6.5 and the local global principle Theorem 4.11(v) there is a field \( M \) Galois over \( F' \) such that \( M \) splits \( D \) and \( \mathcal{B}(M/F') \cong (\mathbb{Z}/p^m \mathbb{Z})^m \). By dimension count \( M \) is a maximal subfield of \( D \otimes_F F' \); hence \( D \otimes_F F' \) is a crossed product. \( \Box \)

Remark 6.8. One can show that the \( p \)-index of \( D \), as defined in §4, is \( p^m \), the same as its index.
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