GALOIS GROUPS OVER NONRIGID FIELDS

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Dedicated to Paulo Ribenboim

ABSTRACT. Let F be a field with $\operatorname{char} F \neq 2$. We show that there are two groups of order 32, respectively 64, such that a field F with $\operatorname{char} F \neq 2$ is nonrigid if and only if at least one of the two groups is realizable as a Galois group over F. The realizability of those groups turns out to be equivalent to the realizability of certain quotients (of order 16, respectively 32). Using known results on connections between rigidity and existence of certain valuations, we obtain new Galois-theoretic criteria for the existence of these valuations.

1. INTRODUCTION

Let F be a field with $\operatorname{char} F \neq 2$. The goal of this paper is to identify basic Galois groups that must occur if F is not a rigid field. It is well known from Galois cohomology that rigidit is a Galois-theoretic property, reflected in teh absolute Galois group of a field. Here we present, using elementary methods, explicit finite groups whose realizability is a criterion for nonrigidity. If $|\dot{F}/\dot{F}^2| \geq 8$ then it is known that F is not rigid if and only if a certain group (often denoted DC) of order 16 occurs as a Galois group over F ([MS]). It has also been shown ([LS], simplifying an earlier proof in [AGKM]) that F is rigid if and only if $F^{(3)} = F^{\{3\}}$ (all notation defined below). In this paper we identify two groups, denoted G_1 and G_2, where $|G_1| = 32$, $|G_2| = 64$, with the property that a field F is nonrigid if and only if at least one of G_1 and G_2 is realizable as a Galois group over F. In each case the corresponding Galois extension lies in $F^{\{3\}}$ but not in $F^{(3)}$. Moreover, it is shown that extensions realizing G_1 and G_2 correspond, respectively, to extensions realizing the groups $D \curlywedge C$ and $D \curlywedge D$, which lie inside $F^{(3)}$. This correspondence gives new nontrivial "automatic realizability" results for Galois groups. We also point out how to detect nonrigid elements in F using the groups G_1 and G_2. Finally, since rigidity conditions

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on field elements are known to correspond to the existence of certain valuations ([W]), we can provide a Galois-theoretic interpretation of valuation-theoretic results.

It is well known that there exist Galois-theoretic characterizations of fields which admit non-dyadic, not 2-divisible valuations. See, for example, [EN], [Ef] and [EK]. These characterizations are, however, substantially different from our characterization, as we use Galois groups of small orders while the characterizations above use the Galois groups of maximal p-extensions and their abelian subgroups.

We begin in the following section with necessary notation and terminology, as well as an explanation of the extensions $F^{(3)}$ and $F^{\{3\}}$ and properties of their Galois groups. In section 3 we examine the group $D \curlywedge C$ and its associated group G_1, and in section 4 the groups $D \curlywedge D$ and G_2 are considered. Section 5 gives the main theorems connecting nonrigidity to the realizability of the groups $D \curlywedge C$, G_1, $D \curlywedge D$ and G_2, as well as the Galois-theoretic interpretation of the existence of a nonrigid element. We conclude in section 6 with a detailed analysis of the situation when $|\dot{F}/\dot{F}^2| = 4$. This is the case where the group DC is not realizable as a Galois group over F, and yet F may be nonrigid.

2. Notation, terminology and Preliminaries

We let $\dot{F} = F\backslash\{0\}$, the group of nonzero elements of F. If $a_1, \dots, a_n \in \dot{F}$, the notation $\langle a_1, \dots, a_n\rangle$ denotes the quadratic form $a_1x_1^2 + \cdots + a_nx_n^2$. If q is a quadratic form defined over F, the notation $D_F(q)$ denotes the set of elements in $\dot{F}$ represented by q over F. Basic results on quadratic forms can be found in [La].

If G is a group and $\sigma, \tau \in G$, then $[\sigma, \tau]$ denotes the commutator $\sigma^{-1}\tau^{-1}\sigma\tau$.

The notion of a rigid field and a rigid element are important in what follows. An element $a \in \dot{F}\backslash \pm F^2$ is *rigid* if $D_F(\langle 1, a\rangle) = \dot{F}^2 \cup a\dot{F}^2$ and is *nonrigid* otherwise. An element $a \in \dot{F}\backslash \pm F^2$ is *double rigid* or *birigid* if a and $-a$ are both rigid. A field F is *rigid* if each $a \in \dot{F}\backslash \pm F^2$ is rigid and is *nonrigid* otherwise.

Lemma 2.1. *The following are equivalent.*

1. *F is nonrigid.*
2. *There exists $a \in \dot{F}\backslash F^2$ such that $|D_F(\langle 1, -a\rangle)/\dot{F}^2| \geq 4$.*
3. *There exists $a \in \dot{F}\backslash \pm F^2$ such that $|D_F(\langle 1, -a\rangle)/\dot{F}^2| \geq 4$.*

Proof. It is clear that (1) and (3) are equivalent and that (3) implies (2). Now assume that (2) holds but that each element in $\dot{F}\backslash \pm F^2$ is rigid. Then we can assume $a = -1$ in (2) and that $-1 \notin F^2$. Then there exists $b \in \dot{F} \setminus \pm F^2$ such that $b \in D_F(\langle 1, 1\rangle)$. Then $-1 \in D_F(\langle 1, -b\rangle) = \dot{F}^2 \cup -b\dot{F}^2$, which is a contradiction. $\square$

An element $a \in \dot{F}$ is *basic* if either $a \in \pm F^2$ or a is not double rigid. The set of all basic elements in F is denoted $B(F)$. Thus $\dot{F} = B(F) \cup \{\text{double rigid elements}\}$ is a disjoint union and $B(F) = \dot{F}^2 \cup -\dot{F}^2$ if and only if F is a rigid field.

Let $v : F \to \Gamma \cup \{\infty\}$ be a valuation on F with valuation ring A, maximal ideal M, residue field $k = A/M$ and value group Γ, where Γ is an ordered abelian group. Let $U = A \setminus M$ be the group of units of A. Then $\Gamma \cong \dot{F}/U$. The valuation v is called 2-henselian if v has a unique extension to the quadratic closure of F. If $\operatorname{char} F \neq 2$ and $1 + M \subseteq \dot{F}^2$, then v is 2-henselian ([W], Lemma 4.3). The valuation v is called 2-divisible if Γ is a 2-divisible group. Since $\dot{F}^2U$ is the set of elements in F whose valuation lies in 2Γ, it follows that v is 2-divisible if and only if $\dot{F} = \dot{F}^2U$.

The following theorem first appeared in [W], Theorem 4.4 (3).

Theorem 2.2. *Suppose F is nonrigid. Then there exists a valuation v on F such that $1 + M \subseteq \dot{F}^2$ and $B(F) = \dot{F}^2U$.*

Corollary 2.3. *Suppose F is nonrigid. The following are equivalent.*

1. *There exists a valuation v on F such that $1 + M \subseteq \dot{F}^2$, $B(F) = \dot{F}^2U$ and v is not 2-divisible.*
2. *F contains a double rigid element.*

In particular, if v is a valuation on F such that $1 + M \subseteq \dot{F}^2$ and $B(F) = \dot{F}^2U$, then an element $f \in F$ is double rigid if and only if $v(f) \notin 2\Gamma$.

Proof. Since F is nonrigid, there exists a valuation v on F such that $1 + M \subseteq \dot{F}^2$ and $B(F) = \dot{F}^2U$. We have v is not 2-divisible if and only if $\dot{F}^2U \subsetneq \dot{F}$, which is equivalent to $B(F) \subsetneq \dot{F}$, in other words, F contains a double rigid element. $\square$

We now define some of our main objects of study.

1. Let $F^{(2)} = F(\sqrt{F})$, the maximal multiquadratic extension of F. Then $\operatorname{Gal}(F^{(2)}/F)$ is an elementary abelian 2-group isomorphic to $\prod_I \mathbb{Z}/2\mathbb{Z}$ where $|I| = \dim_{\mathbb{Z}/2\mathbb{Z}} \dot{F}/\dot{F}^2$. We denote $\operatorname{Gal}(F^{(2)}/F)$ by $G_F^{[2]}$.
2. Let $F^{\{3\}} = F^{(2)}(\sqrt{F^{(2)}}) = (F^{(2)})^{(2)}$. Then $F^{\{3\}}$ is a Galois extension of F and we denote $\operatorname{Gal}(F^{\{3\}}/F)$ by $G_F^{\{3\}}$.

3. Let $F^{(3)}$ denote the subfield of $F^{\{3\}}$ generated by all fields $F^{(2)}(\sqrt{g})$ such that $g \in F^{(2)}$ and $F^{(2)}(\sqrt{g})/F$ is a Galois extension. Denote $\mathrm{Gal}(F^{(3)}/F)$ by $G_F^{[3]}$.

Thus $F \subseteq F^{(2)} \subseteq F^{(3)} \subseteq F^{\{3\}}$ and $F^{(2)}/F$, $F^{(3)}/F$, $F^{\{3\}}/F$ are each Galois extensions. The groups $G_F^{[3]}$, $G_F^{[2]}$ are quotients of $G_F^{\{3\}}$.

For the connection between $G_F^{[3]}$ and the Witt ring of quadratic forms over F, see [MSp].

Lemma 2.4. 1. *The group $G_F^{\{3\}}$ has exponent dividing 4.*
2. *For each $\sigma, \tau \in G_F^{\{3\}}$, the commutator $[\sigma,\tau]$ has order dividing 2, and $[\sigma,\tau] = [\tau,\sigma]$.*
3. *All commutators and squares in $G_F^{\{3\}}$ commute with each other.*

Proof. Let $\sigma, \tau \in G_F^{\{3\}}$. Then $\sigma^2|_{F^{(2)}} = 1$ since $G_F^{[2]}$ has exponent dividing 2 and $[\sigma,\tau]|_{F^{(2)}} = 1$ since $G_F^{[2]}$ is abelian. Thus $\sigma^2, [\sigma,\tau] \in \mathrm{Gal}(F^{\{3\}}/F^{(2)})$, a group of exponent dividing 2. Therefore $\sigma^4 = 1$ and $[\sigma,\tau]^2 = 1$. Note that $[\tau,\sigma] = [\sigma,\tau]^{-1} = [\sigma,\tau]$ This proves (1) and (2).

For (3), we have from above that each commutator and square in $G_F^{\{3\}}$ lies in $\mathrm{Gal}(F^{\{3\}}/F^{(2)})$, which is an abelian group of exponent dividing 2. □

Lemma 2.5. *For every $\sigma, \tau \in G_F^{\{3\}}$, the commutator $[\,[\sigma,\tau],\,\sigma]$ commutes with both σ and τ.*

Proof. In any group, we have the identity

$$[a, bc] = [a,c][a,b][\,[a,b],\,c].$$

Let $b = c$ and assume that $a, b \in G_F^{\{3\}}$. Then $[a, b^2] = [\,[a,b],\,b]$ by Lemma 2.4. Let $a = [\sigma,\tau]$ and $b = \sigma$. We have $[\,[\sigma,\tau],\,\sigma^2] = 1$ by Lemma 2.4. Therefore, $[\,[\,[\sigma,\tau],\,\sigma],\,\sigma] = 1$. This implies $[\,[\sigma,\tau],\,\sigma]$ commutes with σ.

Now let $a = \sigma^2$ and $b = \tau$. Since $[\sigma^2,\tau^2] = 1$ by Lemma 2.4, we have $[\,[\sigma^2,\tau],\,\tau] = 1$ and so $[\sigma^2,\tau]$ commutes with τ. But $[\sigma^2,\tau] = [\,[\sigma,\tau],\,\sigma]$ by the following argument. Let $a = \tau$ and $b = \sigma$ in the identity to see

$$[\sigma^2,\tau] = [\tau,\sigma^2] = [\,[\tau,\sigma],\,\sigma] = [\,[\sigma,\tau],\,\sigma].$$

□

Remark 1. The results in Lemmas 2.4, 2.5 hold in any homomorphic image of $G_F^{\{3\}}$.

Proposition 2.6. *Every square and commutator of elements in $G_F^{[3]}$ lies in $Z(G_F^{[3]})$, the center of $G_F^{[3]}$.*

Proof. Let $\sigma, \tau, \psi \in G_F^{[3]}$. We must show σ^2 and $[\sigma, \tau]$ commute with ψ. Since $F^{(3)}$ is the compositum of all fields $F^{(2)}(\sqrt{g})$ where $g \in F^{(2)}$ and $F^{(2)}(\sqrt{g})/F$ is a Galois extension, it is sufficient to prove the result for elements of the group $\mathrm{Gal}(F^{(2)}(\sqrt{g})/F)$ whenever $F^{(2)}(\sqrt{g})/F$ is a Galois extension. Since $G_F^{[2]}$ is an abelian group of exponent dividing 2, it follows σ^2 and $[\sigma, \tau]$ both lie in $\mathrm{Gal}(F^{(2)}(\sqrt{g})/F^{(2)})$, a group of order dividing 2. As $F^{(2)}(\sqrt{g})/F$ is a Galois extension, the group $\mathrm{Gal}(F^{(2)}(\sqrt{g})/F^{(2)})$ is a normal subgroup of $\mathrm{Gal}(F^{(2)}(\sqrt{g})/F)$ of order 1 or 2 and thus lies in the center of $\mathrm{Gal}(F^{(2)}(\sqrt{g})/F)$. Therefore σ^2 and $[\sigma, \tau]$ lie in $Z(\mathrm{Gal}(F^{(2)}(\sqrt{g})/F))$. $\square$

Remark 2. In Lemma 2.4(3) and Proposition 2.6, the result for commutators is a consequence of the result for squares since the identity $[\sigma, \tau] = (\sigma^{-1})^2(\sigma\tau^{-1})^2\tau^2$ shows that a commutator is a product of three squares.

Proposition 2.7. *Let G_0 be a group with generators x, y and assume*

1. $x^4 = y^4 = 1$,
2. $[x, y]^2 = [\,[x, y], x\,]^2 = [\,[x, y], y\,]^2 = 1$,
3. $[\,[x, y], x\,]$ *and* $[\,[x, y], y\,]$ *each commute with* x *and* y.

Then the following identities hold in G_0, and $|G_0| \le 128$.

(a) $yx = xy[x, y]$,
(b) $[x, y]x = x[x, y][\,[x, y], x\,]$,
(c) $[x, y]y = y[x, y][\,[x, y], y\,]$.

If in addition one assumes

4. $y^2 = 1$,

then $[\,[x, y], y\,] = 1$ *and* $|G_0| \le 32$.

Proof. Since $[x, y] = [x, y]^{-1} = [y, x]$, we have $yx = xy[y, x] = xy[x, y]$, which is (a). For (b), let $z = [x, y]$ in the identity $zx = xz[z, x]$ and prove (c) similarly.

We will next show that each element $g \in G_0$ can be written in the form

$$g = x^{e_1}y^{e_2}[x, y]^{e_3}[\,[x, y], x\,]^{e_4}[\,[x, y], y\,]^{e_5},$$

where $e_1, e_2 \in \{0, 1, 2, 3\}$ and $e_3, e_4, e_5 \in \{0, 1\}$. This will show $|G_0| \le 4 \cdot 4 \cdot 2 \cdot 2 \cdot 2 = 128$. Let $g \in G_0$. Since $x^4 = 1$ and $[\,[x, y], x\,]$ commutes with x, (a) and (b) allow us to write g in the form $g = x^{e_1}z$ where $e_1 \in \{0, 1, 2, 3\}$ and z involves factors of the type $y, [x, y], [\,[x, y], x\,]$. Since $y^4 = 1$ and $[\,[x, y], x\,]$ and $[\,[x, y], y\,]$ both commute with y, (c) allows us to write $g = x^{e_1}y^{e_2}w$ where $e_2 \in \{0, 1, 2, 3\}$ and w involves factors of the type $[x,y], [\,[x,y],x\,], [\,[x,y],y\,]$. We now use (2) and (3) to show g has the required form.

Now assume (4) also holds. Then

$$[x,y]y = x^{-1}y^{-1}xy^2 = x^{-1}yx = x^{-1}(xy[x,y]) = y[x,y]$$

and so $[\,[x,y],y\,] = 1$. In this case we may assume $e_2 \in \{0,1\}$ and $e_5 = 0$, and therefore $|G_0| \leq 4 \cdot 2 \cdot 2 \cdot 2 \cdot 1 = 32$. $\square$

Remark 3. The proof that $[\,[x,y],y\,] = 1$ in (4) holds in any group where $y^2 = [x,y]^2 = 1$.

Corollary 2.8. 1. *Any subgroup of $G_F^{\{3\}}$ or any subgroup of a homomorphic image of $G_F^{\{3\}}$ that is generated by two elements x,y satisfies (1)-(3) of Proposition 2.7.*

2. *Any subgroup of $G_F^{[3]}$ or any subgroup of a homomorphic image of $G_F^{[3]}$ that is generated by two elements x,y has order at most* 32.

Proof. (1). Lemmas 2.4, 2.5 imply (1)-(3) hold in $G_F^{\{3\}}$, and these properties are preserved in any homomorphic image of $G_F^{\{3\}}$.

(2). As $G_F^{[3]}$ is a homomorphic image of $G_F^{\{3\}}$, we know (1)-(3) hold. Since $[x,y] \in Z(G_F^{[3]})$ by Proposition 2.6, it follows $[\,[x,y],x\,] = [\,[x,y],y\,] = 1$. Therefore the subgroup has order at most $4\cdot 4\cdot 2\cdot 1\cdot 1 = 32$. $\square$

The next proposition and corollary are needed in section 4.

Proposition 2.9. *Let G be a metabelian group. If $x,y,z \in G$ then*

$$[\,[x,y],\ z][\,[y,z],\ x][\,[z,x],\ y] = 1.$$

Proof. Since G is metabelian, there is a normal subgroup H such that H and G/H are abelian. Thus every commutator of G lies in H and any two commutators commute.

After completely expanding $[\,[x,y],\ z][\,[y,z],\ x][\,[z,x],\ y]$ and making obvious cancellations, one is left with

$$y^{-1}x^{-1}yxz^{-1}x^{-1}y^{-1}(xzyx^{-1}y^{-1}z^{-1})(yxzy^{-1}z^{-1}x^{-1})zxy.$$

The two expressions in parentheses commute since they are the commutators $[x^{-1},y^{-1}z^{-1}]$ and $[y^{-1},z^{-1}x^{-1}]$. After transposing these expressions and cancelling the remaining terms, one is left with the identity. $\square$

Corollary 2.10. *Let $\sigma,\tau,\psi \in G_F^{\{3\}}$ and assume $[\tau,\psi] = 1$. Then* $[\tau,\ [\sigma,\psi]\,] = [\psi,\ [\sigma,\tau]\,]$.

Proof. Since $G_F^{\{3\}}$ is metabelian, Proposition 2.9 implies

$$1 = [\ [\sigma,\tau],\ \psi][\ [\tau,\psi],\ \sigma][\ [\psi,\sigma],\ \tau] = [\ [\sigma,\tau],\ \psi][\ [\psi,\sigma],\ \tau].$$

Since all commutators have order dividing 2 by Lemma 2.4, the last expression equals $[\psi,\ [\sigma,\tau]\,][\tau,\ [\sigma,\psi]\,]$ and the result follows. ☐

3. The groups $D \curlywedge C$ and G_1 as Galois groups

Let D denote the dihedral group of order 8 and let C denote the cyclic group of order 4. Let $\lambda : D \to \mathbb{Z}/2\mathbb{Z}$ be a group homomorphism with $\ker(\lambda) \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ and let $\eta : C \to \mathbb{Z}/2\mathbb{Z}$ be the unique nontrivial group homomorphism. We let $D \curlywedge C$ denote the pullback of this pair of homomorphisms. Thus $D \curlywedge C$ is the subgroup of $D \times C$ of order 16 consisting of elements (u, v) such that $\lambda(u) = \eta(v)$. Note that the subgroup $D \curlywedge C$ projects onto both D and C with maps $\pi_1 : D \curlywedge C \to D$ and $\pi_2 : D \curlywedge C \to C$ such that $\lambda \circ \pi_1 = \eta \circ \pi_2$.

Let $a, b \in F$ and let $E = F(\sqrt{a}, \sqrt{b})$. Assume $[E : F] = 4$. We let $D^{a,b}$ denote a Galois extension of F (if one exists) such that $F \subseteq E \subseteq D^{a,b}$, $\mathrm{Gal}(D^{a,b}/F) \cong D$, and $\mathrm{Gal}(D^{a,b}/F(\sqrt{ab})) \cong C$.

We let C^a denote a cyclic quartic extension of F (if one exists) such that $F \subseteq F(\sqrt{a}) \subseteq C^a$.

It is known that $D^{a,b}$ exists if and only if the quaternion algebra $(a, b)_F = 0$ in the Brauer group $Br(F)$, and this is equivalent to $a \in \mathrm{im}(N_{F(\sqrt{b})/F})$ where $N_{F(\sqrt{b})/F}$ is the norm map from $F(\sqrt{b})$ to F. The field C^a exists if and only if the quaternion algebra $(a, a)_F = 0$, which is equivalent to $a \in \mathrm{im}(N_{F(\sqrt{a})/F})$ and also equivalent to a being a sum of two squares in F.

Now assume C^a and $D^{a,b}$ exist, and let K denote a composite of C^a and $D^{a,b}$. We have $F(\sqrt{a}) = C^a \cap D^{a,b}$ since D does not admit C as a quotient group. Thus K/F is a Galois extension and $[K : F] = 16$.

Proposition 3.1. $\mathrm{Gal}(K/F) \cong D \curlywedge C$.

Proof. Let $r : \mathrm{Gal}(K/F) \longrightarrow D \times C$ be the group homomorphism defined by $r(\sigma) = (\sigma|_{D^{a,b}}, \sigma|_{C^a})$. Then r is injective since $K = D^{a,b}C^a$. Since $F(\sqrt{a}) = C^a \cap D^{a,b}$ and $\mathrm{Gal}(D^{a,b}/F(\sqrt{a})) \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$, it follows that $r(\sigma) \in D \curlywedge C$. Since $|\,\mathrm{Gal}(K/F)| = 16 = |D \curlywedge C|$, it follows that r maps $\mathrm{Gal}(K/F)$ isomorphically onto $D \curlywedge C$. ☐

Proposition 3.2. *The following statements are equivalent.*

1. *There is a Galois extension K/F such that* $\mathrm{Gal}(K/F) \cong D \curlywedge C$.
2. *There exist elements $a, b \in F$ such that $[F(\sqrt{a}, \sqrt{b}) : F] = 4$ and $(a, a)_F = (a, b)_F = 0$ in the Brauer group $Br(F)$.*

Proof. We have that (2) implies (1) by Proposition 3.1 since (2) implies that $D^{a,b}$ and C^a exist. Now suppose (1) holds and let $\mathrm{Gal}(K/F) \cong D \curlywedge C$. The kernel of $\lambda \circ \pi_1 = \eta \circ \pi_2$ has order 8 and thus the subfield of K corresponding to $\ker(\lambda \circ \pi_1)$ is a quadratic extension of F that we denote $F(\sqrt{a})$. It follows that $\ker(\pi_1)$ is a subgroup of $D \curlywedge C$ of order 2 which corresponds to a subfield of K of the form $D^{a,b}$ for some $b \in F$ and $\ker(\pi_2)$ is a subgroup of $D \curlywedge C$ of order 4 which corresponds to a subfield of K of the form C^a. The existence of both $D^{a,b}$ and C^a implies (2). □

See [GSS] and [GS] for more information on the realizability of $D \curlywedge C$ as a Galois group.

Corollary 3.3. *Let K/F be a Galois extension with* $\mathrm{Gal}(K/F) \cong D \curlywedge C$. *Then K contains a unique quadratic extension of F that imbeds into a cyclic quartic extension contained in K/F. This quadratic extension imbeds into two different cyclic quartic extensions contained in K/F.*

Proof. This follows from the observation that $D \curlywedge C$ has just two normal subgroups N_1, N_2 with the property that $(D \curlywedge C)/N_i$ is a cyclic group of order 4 and that $|N_1 \cap N_2| = 2$. Indeed if $D \curlywedge C/N \cong C$, then N contains the commutator subgroup $(D \curlywedge C)'$. Since $(D \times C)'$ has order 2, it follows that $(D \curlywedge C)'$ has order 2 and $D \curlywedge C/(D \curlywedge C)' \cong C \times \mathbb{Z}/2\mathbb{Z}$. One checks that $C \times \mathbb{Z}/2\mathbb{Z}$ has exactly two subgroups M of order 2 such that $(C \times \mathbb{Z}/2\mathbb{Z})/M \cong C$. Then N is one of the two inverse images of M in $D \curlywedge C$. Since $|N_1 \cap N_2| = |(D \curlywedge C)'| = 2$, the subfields corresponding to N_i do not generate K, and so they must intersect in a quadratic extension of F. □

Now we consider a group G_1 (defined below) of order 32 and study how to contruct a Galois extension with Galois group isomorphic to G_1.

Definition 3.4. *Let G_1 be the group generated by two symbols x, y subject to the relations*

1. $x^4 = y^2 = 1,\ [x, y]^2 = 1,\ [\,[x, y], x\,]^2 = 1.$
2. $[[x, y], x]$ *commutes with x and y.*

Proposition 3.5. $|G_1| \leq 32$.

Proof. Since $[\,[x, y], y\,] = 1$ by Remark 3 after Proposition 2.7, the result now follows from Proposition 2.7. □

We now give a construction of a Galois extension L/F with $[L : F] = 32$ and $\mathrm{Gal}(L/F) \cong G_1$. So, in particular, $|G_1| = 32$. Let $a, b \in F$, let $E = F(\sqrt{a}, \sqrt{b})$ and assume $[E : F] = 4$. Assume in addition that $D^{a,b}$

and C^a exist. Then $a \in \operatorname{im}(N_{F(\sqrt{b})/F}) \cap \operatorname{im}(N_{F(\sqrt{a})/F})$ and so there exist $\alpha \in F(\sqrt{a})$ and $\beta \in F(\sqrt{b})$ such that $N_{F(\sqrt{a})/F}(\alpha) = N_{F(\sqrt{b})/F}(\beta) = a$. Then [Wd], Lemma 2.14, implies there exist $\gamma \in E$ and $d \in F$ such that $N_{E/F(\sqrt{a})}(\gamma) = \alpha d$ and $N_{E/F(\sqrt{b})}(\gamma) = \beta d$. Let $L = E(\sqrt{\alpha d}, \sqrt{\beta d}, \sqrt{\gamma})$ and $K = E(\sqrt{\alpha d}, \sqrt{\beta d})$.

Proposition 3.6. 1. *K/F is a Galois extension with* $\operatorname{Gal}(K/F) \cong D \curlywedge C$.
2. *L/F is a Galois extension with* $\operatorname{Gal}(L/F) \cong G_1$.
3. *$K \subseteq F^{(3)}$, $L \subseteq F^{\{3\}}$, $L \nsubseteq F^{(3)}$.*

Proof. The extensions $F(\sqrt{\alpha d})/F$ and $E(\sqrt{\beta d})/F$ are Galois with

$$\operatorname{Gal}(F(\sqrt{\alpha d})/F) \cong C, \quad \operatorname{Gal}(E(\sqrt{\beta d})/F) \cong D,$$

because $N_{F(\sqrt{a})/F}(\alpha d) = ad^2$ and $N_{F(\sqrt{b})/F}(\beta d) = ad^2$. We also note that $\operatorname{Gal}(E(\sqrt{\beta d})/F(\sqrt{ab})) \cong C$ because $F(\sqrt{ab}) \subseteq F(\sqrt{ab})(\sqrt{a}) = E \subseteq E(\sqrt{\beta d})$ and $N_{E/F(\sqrt{ab})}(\beta d) = N_{F(\sqrt{b})/F}(\beta d) = ad^2$. We see that K is the composite of $F(\sqrt{\alpha d})$ and $E(\sqrt{\beta d})$, so K/F is Galois and Proposition 3.1 implies $\operatorname{Gal}(K/F) \cong D \curlywedge C$.

We have $K \subseteq F^{(3)}$ since $F(\sqrt{\alpha d}) = F(\sqrt{a})(\sqrt{\alpha d}) \subseteq F^{(3)}$ and $E(\sqrt{\beta d}) \subseteq F^{(3)}$. This proves (1) and the first part of (3).

Since $L = K(\sqrt{\gamma})$, in order to show L/F is Galois, it is sufficient to show $\gamma\sigma(\gamma) \in K^2$ for all $\sigma \in \operatorname{Gal}(K/F)$. Since $\gamma \in E$, we need only consider $\sigma \in \operatorname{Gal}(E/F)$. This is clear for $\sigma = 1$, and the others follow from the calculations $N_{E/F(\sqrt{a})}(\gamma) = \alpha d \in K^2$, $N_{E/F(\sqrt{b})}(\gamma) = \beta d \in K^2$ and

$$N_{E/F(\sqrt{ab})}(\gamma) = \frac{N_{E/F}(\gamma)\gamma^2}{N_{E/F(\sqrt{a})}(\gamma) N_{E/F(\sqrt{b})}(\gamma)} = \frac{ad^2\gamma^2}{\alpha d \beta d} \in K^2.$$

Therefore L/F is a Galois extension.

We have $L \subseteq F^{\{3\}}$ since αd, βd, $\gamma \in E \subseteq F^{(2)}$. To show $L \nsubseteq F^{(3)}$ it is sufficient to show $F^{(2)}(\sqrt{\gamma})/F$ is not a Galois extension. There exists $\sigma \in \operatorname{Gal}(F^{(2)}/F)$ such that $\gamma\sigma(\gamma) = N_{E/F(\sqrt{a})}(\gamma) = \alpha d$. But $\alpha d \notin (F^{(2)})^2$ since $\operatorname{Gal}(F(\sqrt{\alpha d})/F) \cong C$, and thus $F^{(2)}(\sqrt{\gamma})/F$ is not a Galois extension. This finishes the proof of (3).

We now show $\operatorname{Gal}(L/F) \cong G_1$. We have $[L : F] = 32$ since $[K : F] = 16$ and $K \subsetneq L$ by (3). There exist $\sigma_a, \sigma_b \in \operatorname{Gal}(L/F)$ such that $\sigma_a(\sqrt{a}) = -\sqrt{a}$, $\sigma_a(\sqrt{b}) = \sqrt{b}$, $\sigma_b(\sqrt{a}) = \sqrt{a}$, $\sigma_b(\sqrt{b}) = -\sqrt{b}$ and $\sigma_b(\sqrt{\alpha d}) = \sqrt{\alpha d}$. (To see that σ_b exists, note that an automorphism with this property lies in $\operatorname{Gal}(K/F)$ and that it can be extended to $\operatorname{Gal}(L/F)$.) The group generated by σ_a and σ_b equals $\operatorname{Gal}(L/F)$, otherwise the fixed field of this subgroup would contain a quadratic extension of F, but none of $\sqrt{a}, \sqrt{b}, \sqrt{ab}$ is fixed by both σ_a and σ_b. We will now show that σ_a and σ_b satisfy the relations in Definition 3.4. Since the group generated by σ_a and σ_b has order 32 and $|G_1| \leq 32$, this will imply that $\mathrm{Gal}(L/F) \cong G_1$.

Lemmas 2.4, 2.5 and Remark 1 following these lemmas, along with the fact that σ_a and σ_b generate $\mathrm{Gal}(L/F)$, imply that $\sigma_a^4 = [\sigma_a, \sigma_b]^2 = [[\sigma_a, \sigma_b], \sigma_a]^2 = 1$, and $[[\sigma_a, \sigma_b], \sigma_a] \in Z(G_1)$. It remains to prove $\sigma_b^2 = 1$.

Since we know $\mathrm{Gal}(E(\sqrt{\beta d})/F) \cong D$, $\mathrm{Gal}(E(\sqrt{\beta d})/F(\sqrt{ab})) \cong C$ and $\sigma_b(\sqrt{ab}) = -\sqrt{ab}$, it follows that $\sigma_b|_{E(\sqrt{\beta d})}$ has order 2. Thus $\sigma_b|_K$ has order 2. We now show $\sigma_b^2(\sqrt{\gamma}) = \sqrt{\gamma}$. We have $\gamma\sigma_b(\gamma) = \alpha d$ and thus $\sqrt{\gamma}\sigma_b(\sqrt{\gamma}) = (-1)^\epsilon\sqrt{\alpha d}$, where $\epsilon \in \{0, 1\}$. Then $\sigma_b(\sqrt{\gamma})\sigma_b^2(\sqrt{\gamma}) = \sigma_b((-1)^\epsilon\sqrt{\alpha d}) = (-1)^\epsilon\sqrt{\alpha d}$. These equations imply $\sigma_b^2(\sqrt{\gamma}) = \sqrt{\gamma}$.

It follows that $\mathrm{Gal}(L/F) \cong G_1$ since the relations in Definition 3.4 hold and $[L : F] = 32$. □

Theorem 3.7. *The following statements are equivalent.*

1. *There is a Galois extension K/F such that* $\mathrm{Gal}(K/F) \cong D \curlywedge C$.
2. *There is a Galois extension L/F such that* $\mathrm{Gal}(L/F) \cong G_1$.
3. *There exist $a, b \in F$ such that $[F(\sqrt{a}, \sqrt{b}) : F] = 4$ and $(a, a)_F = (a, b)_F = 0$.*
4. *There exists $a \in D_F(\langle 1, 1\rangle)\backslash \dot{F}^2$ such that $|D_F(\langle 1, -a\rangle)| \geq 4$.*
5. *F is not rigid and $D_F(\langle 1, 1\rangle) \nsubseteq F^2 \cup -F^2$.*
6. *Either $-1 \in F^2$ and F is not rigid or $-1 \notin F^2$ and $D_F(\langle 1, 1\rangle) \nsubseteq F^2 \cup -F^2$.*

If F is formally real, then statements (1)-(6) hold if and only if F is not a Pythagorean field.

Proof. We have already seen in Proposition 3.2 and the proof of Proposition 3.6 that (1)-(3) are equivalent. Note that (2) implies (1) because $D \curlywedge C$ is a quotient of G_1. The equivalence of (3) and (4) is easy to check. It is clear that (5) implies (6).

(6) $\Rightarrow$ (3): First assume $-1 \in F^2$ and F is not rigid. Then there exists $a \in F$ with $a \notin \pm F^2$ such that $b \in D_F(\langle 1, a\rangle)$ and $b \notin F^2 \cup aF^2$. Then (3) holds since $(a, b)_F = 0$ and $-1 \in F^2$ implies $(a, a)_F = (a, -a)_F = 0$. Now assume $-1 \notin F^2$ and $D_F(\langle 1, 1\rangle) \nsubseteq F^2 \cup -F^2$. Let $a \in D_F(\langle 1, 1\rangle)$ with $a \notin \pm F^2$. Then $[F(\sqrt{a}, \sqrt{-1}) : F] = 4$ and $(a, a)_F = 0$. Now (3) holds with $b = -a$.

(3) $\Rightarrow$ (5): Suppose $D_F(\langle 1, 1\rangle) \subseteq F^2 \cup -F^2$. We have $a \in D_F(\langle 1, 1\rangle)$ since $(a, a)_F = 0$. Since $a \notin F^2$, we have $a \in -F^2$. Then $(-1, b)_F = 0$ and thus $b \in D_F(\langle 1, 1\rangle)$. This is a contradiction since $b \notin F^2 \cup aF^2 = F^2 \cup -F^2$. Therefore $D_F(\langle 1, 1\rangle) \nsubseteq F^2 \cup -F^2$. Since $(a, a)_F = (a, b)_F =$

0 implies $a, b \in D_F(\langle 1, -a\rangle)$, we have $1, a, b, ab \in D_F(\langle 1, -a\rangle)$ and so $D_F(\langle 1, -a\rangle)$ contains at least four square classes. Thus F is not rigid by Lemma 2.1.

Now assume F is formally real. If (6) holds, then $-1 \notin F^2$ and $D_F(\langle 1, 1\rangle) \nsubseteq F^2 \cup -F^2$. Thus F is not a Pythagorean field. If F is not a Pythagorean field, then $D_F(\langle 1, 1\rangle) \nsubseteq F^2 \cup -F^2$, since F is formally real. Thus (6) holds. $\square$

Nondyadic local fields are rigid. Every dyadic local field F satisfies conditions (1)-(6). In fact, a can be chosen as any nonsquare element in $D_F(\langle 1, 1\rangle)$. All global fields (of characteristic different from 2) also satisfy conditions (1)-(6).

Proposition 3.8. *Suppose* $\mathrm{Gal}(L/F) \cong G_1$. *Then there is a unique quadratic extension* $F(\sqrt{a})$ *of* F *such that*

$$F \subseteq F(\sqrt{a}) \subseteq E \subseteq L,$$

for some subfield E *of* L *where* $\mathrm{Gal}(E/F) \cong C$. *The element* $-a$ *is not rigid.*

Proof. Let $K = F^{(3)} \cap L$. Then $\mathrm{Gal}(K/F) \cong D \curlywedge C$. Corollary 3.3 implies there is a unique quadratic extension $F(\sqrt{a})$ of F in K such that F is contained in a cyclic quartic extension E lying in K. The construction in Proposition 3.1 along with Proposition 3.2 and Theorem 3.7 imply $-a$ is not rigid. $\square$

In the notation of this section, the two cyclic quartic extensions that appear in Corollary 3.3 are easily seen to be $F(\sqrt{a}, \sqrt{\alpha d})$ and $F(\sqrt{a}, \sqrt{\alpha db})$.

4. The groups $D \curlywedge D$ and G_2 as Galois groups

Let $\lambda_1 : D \to \mathbb{Z}/2\mathbb{Z}$ be a group homomorphism with $\ker(\lambda_1) \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ and let $\lambda_2 : D \to \mathbb{Z}/2\mathbb{Z}$ be another group homomorphism with $\ker(\lambda_2) \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$. Let $D \curlywedge D$ denote the pullback of this pair of homomorphisms. Thus $D \curlywedge D$ is the subgroup of $D \times D$ of order 32 consisting of elements (u, v) such that $\lambda_1(u) = \lambda_2(v)$. Note that the subgroup $D \curlywedge D$ projects onto D with maps $\pi_1 : D \curlywedge D \to D$ and $\pi_2 : D \curlywedge D \to D$ such that $\lambda_1 \circ \pi_1 = \lambda_2 \circ \pi_2$.

Proposition 4.1. *The following statements are equivalent.*

1. *There is a Galois extension* K/F *such that* $\mathrm{Gal}(K/F) \cong D \curlywedge D$.
2. *There exist elements* $a, b, c \in F$ *such that* $[F(\sqrt{a}, \sqrt{b}, \sqrt{c}) : F] = 8$ *and* $(a, b)_F = (a, c)_F = 0$ *in the Brauer group* $Br(F)$.

Proof. First assume that (2) holds. Then there exist Galois extensions $D^{a,b}$ and $D^{a,c}$ of F. Let K denote a composite of $D^{a,b}$ and $D^{a,c}$. Then $D^{a,b} \cap D^{a,c} = F(\sqrt{a})$ since the intersection is a Galois extension of F and the only Galois subextension of $D^{a,b}$ of degree 4 over F is $F(\sqrt{a}, \sqrt{b})$. Therefore, K/F is a Galois extension of F with $[K : F] = 32$. Now a proof that is very similar to the proof of Proposition 3.1 shows that $\mathrm{Gal}(K/F) \cong D \curlywedge D$.

Now assume that (1) holds and let $\mathrm{Gal}(K/F) \cong D \curlywedge D$. The kernel of $\lambda_1 \circ \pi_1 = \lambda_2 \circ \pi_2$ has order 16 and thus the subfield of K corresponding to this kernel is a quadratic extension of F which we denote $F(\sqrt{a})$. Since both π_1 and π_2 are surjective, it follows that $\ker(\pi_1)$ and $\ker(\pi_2)$ are each normal subgroups of $D \curlywedge D$ of order 4 which correspond to subfields E_1, E_2 of K which are Galois over F with $\mathrm{Gal}(E_1/F) \cong D \cong \mathrm{Gal}(E_2/F)$. Since $\ker(\pi_1) \cap \ker(\pi_2) = 1$, it follows that $\ker(\pi_1)$ and $\ker(\pi_2)$ generate a subgroup of order 16. This subgroup is $\ker(\lambda_1 \circ \pi_1)$ since $\ker(\pi_i) \subseteq \ker(\lambda_1 \circ \pi_1) = \ker(\lambda_2 \circ \pi_2)$. Thus $E_1 \cap E_2 = F(\sqrt{a})$. Since $\ker(\lambda_i) \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$, it follows E_1 has the form $D^{a,b}$ and E_2 has the form $D^{a,c}$ for some $b, c \in \dot{F}$. Thus $(a, b)_F = (a, c)_F = 0$. We have $[F(\sqrt{a}, \sqrt{b}, \sqrt{c}) : F] = 8$ since $D^{a,b} \cap D^{a,c} = F(\sqrt{a})$. □

Proposition 4.2. *The group $D \curlywedge D$ contains a unique abelian subgroup of order 16. This subgroup equals $\ker(\lambda_1) \times \ker(\lambda_2)$ and is isomorphic to $(\mathbb{Z}/2\mathbb{Z})^4$.*

Proof. We have that $\ker(\lambda_1) \times \ker(\lambda_2)$ is an abelian subgroup of $D \curlywedge D$ of order 16 that is isomorphic to $(\mathbb{Z}/2\mathbb{Z})^4$. Now let H be any abelian subgroup of $D \curlywedge D$ of order 16. Since $\pi_i(H)$ is an abelian subgroup of D, we have $\pi_i(H)$ is a subgroup of order at most 4. Since $H \subseteq \pi_1(H) \times \pi_2(H)$ and H has order 16, it follows $H = \pi_1(H) \times \pi_2(H)$. Since $\pi_1(H) \times \pi_2(H) \subseteq D \curlywedge D$, it follows $\pi_1(H) = \ker(\lambda_1)$ and $\pi_2(H) = \ker(\lambda_2)$. □

Corollary 4.3. *In the notation of Proposition 4.1,*

$$\mathrm{Gal}(K/F(\sqrt{a})) = \ker(\lambda_1 \circ \pi_1) = \ker(\lambda_1) \times \ker(\lambda_2) \cong (\mathbb{Z}/2\mathbb{Z})^4.$$

Proof. The first equality follows from the proof of Proposition 4.1. Since $\ker(\lambda_1) \times \ker(\lambda_2) \subseteq \ker(\lambda_1 \circ \pi_1)$ and each has order 16, we have equality. □

Now we consider a group G_2 (defined below) of order 64 and study how to construct a Galois extension over a field F with Galois group isomorphic to G_2.

Definition 4.4. *Let G_2 be the group generated by three symbols x, y, z subject to the relations*

1. $x^2 = y^2 = z^2 = 1$, $[x, y]^2 = [x, z]^2 = [y, z] = 1$.
2. $[y, [x, z]] = [z, [x, y]]$ *has order dividing 2 and commutes with* x, y *and* z.

Lemma 4.5. *The following identities hold in* G_2 *and* $|G_2| \leq 64$.

1. $yx = xy[x, y]$, $zx = xz[x, z]$.
2. $[x, y]$ *commutes with both* x *and* y *and* $[x, z]$ *commutes with both* x *and* z.
3. $[x, z]y = y[x, z][y,\, [x, z]\,]$ *and* $[x, y]z = z[x, y][z,\, [x, y]\,]$.
4. $[x, z][x, y] = [x, y][x, z]$.

Proof. Statements (1)-(3) are proved as in Proposition 2.7. (See Remark 3 following the proof of Proposition 2.7.) Since $[x, y] = xyxy$, and $[y, [x, z]]$ is in the center, we have

$$\begin{aligned}[x, z][x, y] &= [x, z]xyxy = x[x, z]yxy = xy[x, z][y,\, [x, z]\,]xy \\ &= xy[x, z]xy[y,\, [x, z]\,] = xyxy[x, z][y,\, [x, z]\,]^2 \\ &= [x, y][x, z],\end{aligned}$$

which proves (4).

To show $|G_2| \leq 64$, it is sufficient to show that each element of G_2 can be written in the form

$$x^{e_1}y^{e_2}z^{e_3}[x, y]^{e_4}[x, z]^{e_5}[y,\, [x, z]\,]^{e_6},$$

where each $e_i \in \{0, 1\}$, $1 \leq i \leq 6$. The relations defining G_2 and statements (1)-(4) allow exactly this. □

We now give a construction of a Galois extension L/F with $[L : F] = 64$ and $\mathrm{Gal}(L/F) \cong G_2$.

Assume $a, b, c \in F$ such that $[F(\sqrt{a}, \sqrt{b}, \sqrt{c}) : F] = 8$ and $(a, b)_F = (a, c)_F = 0$ in the Brauer group $Br(F)$. Then $a \in \mathrm{im}(N_{F(\sqrt{b})/F}) \cap \mathrm{im}(N_{F(\sqrt{c})/F})$ and so there exist $\beta \in F(\sqrt{b})$ and $\gamma \in F(\sqrt{c})$ such that $N_{F(\sqrt{b})/F}(\beta) = N_{F(\sqrt{c})/F}(\gamma) = a$. Let $E = F(\sqrt{b}, \sqrt{c})$. Then [Wd], Lemma 2.14, implies there exist $\delta \in E$ and $d \in F$ such that $N_{E/F(\sqrt{b})}(\delta) = \beta d$ and $N_{E/F(\sqrt{c})}(\delta) = \gamma d$.

Let $E' = E(\sqrt{a})$, $K = E'(\sqrt{\beta d}, \sqrt{\gamma d})$, and $L = K(\sqrt{\delta})$.

Proposition 4.6. 1. K/F *is a Galois extension with* $\mathrm{Gal}(K/F) \cong D \curlywedge D$.
2. L/F *is a Galois extension with* $\mathrm{Gal}(L/F) \cong G_2$.
3. $K \subseteq F^{(3)}$, $L \subseteq F^{\{3\}}$, $L \nsubseteq F^{(3)}$.

Proof. We have $F(\sqrt{a}, \sqrt{b}, \sqrt{\beta d}) = D^{a,b}$ and $F(\sqrt{a}, \sqrt{c}, \sqrt{\gamma d}) = D^{a,c}$. Since $D^{a,b}$ and $D^{a,c}$ are each Galois extensions of F, it follows that

$K = D^{a,b}D^{a,c}$ is a Galois extension of F. The reasoning in the proof of Proposition 4.1 lets us conclude $\mathrm{Gal}(K/F) \cong D \curlywedge D$. This proves (1).

We have $D^{a,b}$ and $D^{a,c}$ contained in $F^{(3)}$ and thus $K \subseteq F^{(3)}$. Since $L = E'(\sqrt{\beta d}, \sqrt{\gamma d}, \sqrt{\delta})$ and $\beta d,\ \gamma d,\ \delta \in F^{(2)}$, it follows $L \subseteq F^{\{3\}}$. If $L \subseteq F^{(3)}$, then $F^{(2)}(\sqrt{\delta})/F$ is a Galois extension. This implies $N_{E/F(\sqrt{b})}(\delta) = \beta d \in (F^{(2)})^2$. But this is impossible since $D^{a,b} \not\subseteq F^{(2)}$. This proves (3).

Since $[L : K] = 2$ by (3) and $[K : F] = 32$ by (1), it follows $[L : F] = 64$. Since $\delta \in E$ and K/F is a Galois extension, in order to show L/F is a Galois extension, it is sufficient to show $\sigma(\delta)\delta \in K^2$ for all $\sigma \in \mathrm{Gal}(E/F)$. This is accomplished as in the proof of Proposition 3.6.

Now we begin to show $\mathrm{Gal}(L/F) \cong G_2$. There exist automorphisms $\sigma_a, \sigma_b, \sigma_c \in \mathrm{Gal}(L/F)$ such that σ_a fixes $\sqrt{b}, \sqrt{c}$ and $\sigma_a(\sqrt{a}) = -\sqrt{a}$, and similarly σ_b fixes $\sqrt{a}, \sqrt{c}$, but not $\sqrt{b}$, and σ_c fixes $\sqrt{a}, \sqrt{b}$, but not $\sqrt{c}$.

We want to choose σ_b, σ_c more carefully as follows. Choose $\sigma_b \in \mathrm{Gal}(L/F)$ such that

$$\sigma_b|_{F(\sqrt{a},\sqrt{c},\sqrt{\gamma d})} = 1, \quad \sigma_b^2|_{F(\sqrt{a},\sqrt{b},\sqrt{\beta d})} = 1, \quad \sqrt{\beta d}\,\sigma_b(\sqrt{\beta d}) = \sqrt{a}d.$$

To see this is possible, observe that $\mathrm{Gal}(F(\sqrt{a}, \sqrt{b}, \sqrt{\beta d})/F) \cong D$ and hence there exists σ_b such that the second and third conditions hold. Since $K = F(\sqrt{a}, \sqrt{b}, \sqrt{\beta d})F(\sqrt{a}, \sqrt{c}, \sqrt{\gamma d})$, $\mathrm{Gal}(K/F) \cong D \curlywedge D$ and $\sigma_b|_{F(\sqrt{a})} = 1$, the first condition can be arranged simultaneously with the second and third.

Similarly we can choose $\sigma_c \in \mathrm{Gal}(L/F)$ such that

$$\sigma_c|_{F(\sqrt{a},\sqrt{b},\sqrt{\beta d})} = 1, \quad \sigma_c^2|_{F(\sqrt{a},\sqrt{c},\sqrt{\gamma d})} = 1, \quad \sqrt{\gamma d}\,\sigma_c(\sqrt{\gamma d}) = \sqrt{a}d.$$

We now show $\sigma_a, \sigma_b, \sigma_c$ satisfy the relations in Definition 4.4. Since σ_a fixes each element of E and $\delta \in E$, it follows that $\sigma_a^2(\sqrt{\delta}) = \sqrt{\delta}$. Similar reasoning shows that σ_a^2 fixes E' and K elementwise and hence $\sigma_a^2 = 1$.

We have that $\sigma_b^2|_K = \sigma_c^2|_K = 1$. To show $\sigma_b^2 = \sigma_c^2 = 1$, it is enough to show $\sigma_b^2(\sqrt{\delta}) = \sqrt{\delta}$ and $\sigma_c^2(\sqrt{\delta}) = \sqrt{\delta}$. Since

$$\delta\,\sigma_b(\delta) = N_{E/F(\sqrt{c})}(\delta) = \gamma d,$$

we have $\sqrt{\delta}\,\sigma_b(\sqrt{\delta}) = (-1)^\epsilon\sqrt{\gamma d}$ and thus

$$\sigma_b(\sqrt{\delta})\,\sigma_b^2(\sqrt{\delta}) = (-1)^\epsilon\sigma_b(\sqrt{\gamma d}) = (-1)^\epsilon\sqrt{\gamma d}.$$

This implies $\sigma_b^2(\sqrt{\delta}) = \sqrt{\delta}$. Since $\delta\,\sigma_c(\delta) = N_{E/F(\sqrt{b})}(\delta) = \beta d$, we have $\sqrt{\delta}\,\sigma_c(\sqrt{\delta}) = (-1)^{\epsilon'}\sqrt{\beta d}$, and a similar proof gives $\sigma_c^2(\sqrt{\delta}) = \sqrt{\delta}$.

We have $[\sigma_a, \sigma_b]^2 = [\sigma_a, \sigma_c]^2 = 1$ since $\mathrm{Gal}(L/F)$ is a homomorphic image of $G_F^{\{3\}}$. We have $[\sigma_b, \sigma_c]|_K = 1$ because $\sigma_b\sigma_c = \sigma_c\sigma_b$ on each subfield $F(\sqrt{a}, \sqrt{b}, \sqrt{\beta d})$ and $F(\sqrt{a}, \sqrt{c}, \sqrt{\gamma d})$. To show $[\sigma_b, \sigma_c] = 1$, it is enough to show $\sigma_b\sigma_c(\sqrt{\delta}) = \sigma_c\sigma_b(\sqrt{\delta})$.

The equation $\sqrt{\delta}\,\sigma_b(\sqrt{\delta}) = (-1)^{\epsilon}\sqrt{\gamma d}$ gives

$$\sigma_c(\sqrt{\delta})\,\sigma_c\,\sigma_b(\sqrt{\delta}) = (-1)^{\epsilon}\sigma_c(\sqrt{\gamma d}),$$

and the equation $\sqrt{\delta}\,\sigma_c(\sqrt{\delta}) = (-1)^{\epsilon'}\sqrt{\beta d}$ gives

$$\sigma_b(\sqrt{\delta})\,\sigma_b\,\sigma_c(\sqrt{\delta}) = (-1)^{\epsilon'}\sigma_b(\sqrt{\beta d}).$$

Since $\sqrt{\beta d}\,\sigma_b(\sqrt{\beta d}) = \sqrt{\gamma d}\,\sigma_c(\sqrt{\gamma d})$, some routine manipulation gives $\sigma_b\sigma_c(\sqrt{\delta}) = \sigma_c\sigma_b(\sqrt{\delta})$.

We now show $[\sigma_b,\ [\sigma_a, \sigma_c]\,] = [\sigma_c,\ [\sigma_a, \sigma_b]\,]$ has order dividing 2 and commutes with $\sigma_a, \sigma_b, \sigma_c$. The two expressions are equal by Corollary 2.10. The order divides 2 by Lemma 2.4. We have $[\sigma_a, \sigma_b]$ in the center of $\mathrm{Gal}(F(\sqrt{a}, \sqrt{b}, \sqrt{\beta d})/F)$ by Proposition 2.6 and thus $[\sigma_c,\ [\sigma_a, \sigma_b]\,]|_{F(\sqrt{a},\sqrt{b},\sqrt{\beta d})} = 1$. Similarly, $[\sigma_a, \sigma_c]$ is in the center of $\mathrm{Gal}(F(\sqrt{a}, \sqrt{c}, \sqrt{\gamma d})/F)$ and thus $[\sigma_b,\ [\sigma_a, \sigma_c]\,]|_{F(\sqrt{a},\sqrt{c},\sqrt{\gamma d})} = 1$. Thus, $[\sigma_b,\ [\sigma_a, \sigma_c]\,]|_K = 1$ and so

$$[\sigma_b,\ [\sigma_a, \sigma_c]\,] \in \mathrm{Gal}(L/K) \subseteq Z(\mathrm{Gal}(L/F)).$$

Therefore $[\sigma_b,\ [\sigma_a, \sigma_c]\,]$ commutes with $\sigma_a, \sigma_b, \sigma_c$.

We have now shown that $\sigma_a, \sigma_b, \sigma_c$ satisfy the relations in Definition 4.4. Next we show $\sigma_a, \sigma_b, \sigma_c$ generate $\mathrm{Gal}(L/F)$.

Let $H = \langle \sigma_a, \sigma_b, \sigma_c \rangle$. If $H \subsetneq \mathrm{Gal}(L/F)$, then there exists a quadratic extension $F(\sqrt{e})$ of F in the fixed field of H and $F(\sqrt{e}) \subseteq F^{(3)} \cap L = K$. An easy check shows that no quadratic extension of F inside $F(\sqrt{a}, \sqrt{b}, \sqrt{c})$ is in the fixed field of H. Then $F(\sqrt{a}, \sqrt{b}, \sqrt{c}, \sqrt{e}) \subseteq K$ and $(\mathbb{Z}/2\mathbb{Z})^4$ is a quotient of $\mathrm{Gal}(K/F) \cong D \curlywedge D$ by a normal subgroup N of order 2. This implies the commutator subgroup of $D \curlywedge D$ is contained in N and this is impossible since the commutator subgroup of $D \curlywedge D$ has order 4. Thus $(\mathbb{Z}/2\mathbb{Z})^4$ is not a quotient of $D \curlywedge D$ and therefore $H = \mathrm{Gal}(L/F)$. Since $\sigma_a, \sigma_b, \sigma_c$ generate $\mathrm{Gal}(L/F)$ and satisfy the relations in Definition 4.4, it follows that $\mathrm{Gal}(L/F) \cong G_2$. □

Theorem 4.7. *The following statements are equivalent.*

1. *There is a Galois extension K/F such that* $\mathrm{Gal}(K/F) \cong D \curlywedge D$.
2. *There is a Galois extension L/F such that* $\mathrm{Gal}(L/F) \cong G_2$.
3. *There exist $a, b, c \in F$ such that $[F(\sqrt{a}, \sqrt{b}, \sqrt{c}) : F] = 8$ and $(a, b)_F = (a, c)_F = 0$.*

4. *There exist* $a, b, c \in \dot{F}\backslash\dot{F}^2$ *such that* a, b, c *are independent mod squares and* $b, c \in D_F(\langle 1, -a\rangle)$.
5. *There exists* $a \in \dot{F}\backslash\dot{F}^2$ *such that either* $|D_F(\langle 1, -a\rangle)| \geq 8$ *or both* $|D_F(\langle 1, -a\rangle)| = 4$ *and* $a \notin D_F(\langle 1, 1\rangle)$.

Proof. (1) and (3) are equivalent by Proposition 4.1. The construction in Proposition 4.6 shows (3) implies (2). (2) implies (1) since $D \curlywedge D$ is a quotient of G_2 (as the construction in Proposition 4.6 shows). It is straightforward to check that (3)-(5) are equivalent using the observation $a \in D_F(\langle 1, -a\rangle)$ if and only if $a \in D_F(\langle 1, 1\rangle)$. $\square$

In the following proposition, DD denotes the central product of two copies of the dihedral group D. That is, if g denotes the nontrivial element in the center of D, then $DD \cong (D \times D)/\{1, (g, g)\}$. Thus DD is obtained from the direct product $D \times D$ by identifying the centers of the two copies of D.

Proposition 4.8. *Suppose* $\mathrm{Gal}(L/F) \cong G_2$. *Let* $K = F^{(3)} \cap L$, *so that* $\mathrm{Gal}(K/F) \cong D \curlywedge D$. *Then there is a unique quadratic extension* $F(\sqrt{a})$ *of* F *such that* $\mathrm{Gal}(K/F(\sqrt{a}))$ *is an abelian group of order* 16. *In addition the following hold.*

1. *There is a unique subgroup* N *of* G_2 *of order* 2 *such that* $G_2/N \cong D \curlywedge D$.
2. $\mathrm{Gal}(L/F(\sqrt{a})) \cong DD$.
3. $\mathrm{Gal}(L/F(\sqrt{a}))$ *is the unique subgroup of* G_2 *isomorphic to* DD.
4. *The element* $-a$ *is nonrigid.*

Proof. Using Proposition 4.2, let $F(\sqrt{a})$ be the quadratic extension of F that corresponds to the unique abelian subgroup of $\mathrm{Gal}(K/F)$ of order 16. Any extension K' of F that lies in L with $\mathrm{Gal}(K'/F) \cong D \curlywedge D$ must lie in $F^{(3)}$. Thus K is uniquely determined, so this proves (1).

In the notation of Proposition 4.6, let $D_1 = \langle \sigma_b, [\sigma_a, \sigma_c]\rangle$, let $D_2 = \langle \sigma_c, [\sigma_a, \sigma_b]\rangle$ and let $H = \langle \sigma_b, \sigma_c, [\sigma_a, \sigma_c], [\sigma_a, \sigma_b]\rangle$. Note that $D_1 \cong D_2 \cong D$ since σ_b and $[\sigma_a, \sigma_c]$ have order 2 and $[\sigma_b,\ [\sigma_a, \sigma_c]\,]$ is central of order 2. A similar argument holds for D_2. We have $|H| = 32$, by observing the representation of elements of G_2 at the end of the proof of Lemma 4.5. We show $\mathrm{Gal}(L/F(\sqrt{a})) \cong D_1 D_2 \cong DD$. The groups D_1 and D_2 commute elementwise by Definition 4.4 and Lemma 4.5. Therefore the injections $D_1 \mapsto H$ and $D_2 \mapsto H$ induce a surjective homomorphism $D_1 \times D_2 \mapsto H$. The element

$$([\sigma_b,\ [\sigma_a, \sigma_c]\,],\ [\sigma_c,\ [\sigma_a, \sigma_b]\,])$$

lies in the kernel of the map $D_1 \times D_2 \mapsto H$. Since $[\sigma_b,\ [\sigma_a, \sigma_c]\,]$ and $[\sigma_c,\ [\sigma_a, \sigma_b]\,]$ are the nontrivial elements in the center of D_1 and D_2, it follows that H is isomorphic to the central product $D_1D_2 \cong DD$. It is clear that $H \subseteq \mathrm{Gal}(L/F(\sqrt{a}))$ and therefore $\mathrm{Gal}(L/F(\sqrt{a})) = H \cong DD$. This proves (2).

Suppose E is a quadratic extension of F such that $\mathrm{Gal}(L/E) \cong DD$. Then there is a subfield M of L such that $[L : M] = 2$ and $\mathrm{Gal}(M/E) \cong (\mathbb{Z}/2\mathbb{Z})^4$. (Note that $D \times D/(\{1, g\} \times \{1, g\}) \cong (\mathbb{Z}/2\mathbb{Z})^4$.) Thus $M = E(\sqrt{\alpha_1}, \dots, \sqrt{\alpha_4})$, where $\alpha_i \in E$. The Galois closure of $E(\sqrt{\alpha_i})/F$ lies in $F^{(3)}$ for each i and hence the Galois closure of M/F lies in $F^{(3)}$. Thus M lies in $F^{(3)}$ and it follows $M = K$. Thus $\mathrm{Gal}(M/F) = \mathrm{Gal}(K/F) \cong D \curlywedge D$. Since $D \curlywedge D$ contains a unique abelian subgroup of order 16, it follows $E = F(\sqrt{a})$ and this proves (3).

We have from before that $(a, b)_F = (a, c)_F = 0$ and this implies $-a$ is not rigid by Lemma 2.1. □

5. Main Theorems

Theorem 5.1. *F is not a rigid field if and only if either G_1 or G_2 occurs as a Galois group over F.*

Proof. First assume that F is not a rigid field. Then Lemma 2.1 implies there exists $a \in \dot{F}\backslash F^2$ such that $|D_F(\langle 1, -a\rangle)/\dot{F}^2| \geq 4$. Then either the statement in Theorem 3.7(4) holds or the statement in Theorem 4.7(5) holds. Therefore, either G_1 or G_2 occurs as a Galois group over F.

Now assume that either G_1 or G_2 occurs as a Galois group over F. Then by Theorems 3.7 and 4.7, there exists an element $a \in \dot{F}\backslash F^2$ such that $D_F(\langle 1, -a\rangle)$ contains at least four square classes. Then F is nonrigid by Lemma 2.1. □

Theorem 5.2. *Let $a \in \dot{F}\backslash(F^2 \cup -F^2)$. Then the element $-a$ is not rigid in F if and only if at least one of the following two statements holds.*

1. *An imbedding $F \subseteq F(\sqrt{a}) \subseteq E \subseteq L$ exists such that $\mathrm{Gal}(E/F) \cong C$ and $\mathrm{Gal}(L/F) \cong G_1$.*
2. *An imbedding $F \subseteq F(\sqrt{a}) \subseteq L$ exists such that $\mathrm{Gal}(L/F(\sqrt{a})) \cong DD$ and $\mathrm{Gal}(L/F) \cong G_2$.*

Proof. This follows from Proposition 3.8, Proposition 4.8, the construction in Proposition 3.6 and the construction in Proposition 4.6. □

Corollary 5.3. *Assume F is nonrigid. Let v be a valuation on F satisfying $1+M \subseteq \dot{F}^2$ and $B(F) = \dot{F}^2U$. Then the following statements are equivalent.*

1. *v is not 2-divisible.*

2. *There exists an element $a \in \dot{F}\backslash \pm F^2$ such that the two imbedding problems in Theorem 5.2 have no solutions for both $F(\sqrt{a})$ and $F(\sqrt{-a})$.*

Proof. If v is not 2-divisible, then Corollary 2.3 implies there exists an element $a \in \dot{F}\backslash \pm F^2$ such that a is double rigid. Now Theorem 5.2 implies that both statements in Theorem 5.2 fail for both $F(\sqrt{a})$ and $F(\sqrt{-a})$. Conversely, if both statements in Theorem 5.2 fail for both $F(\sqrt{a})$ and $F(\sqrt{-a})$, then a and $-a$ are rigid. Thus v is not 2-divisible by Corollary 2.3. □

6. The case $|\dot{F}/(\dot{F})^2| = 4$

Proposition 6.1. *Assume $|\dot{F}/(\dot{F})^2| = 4$.*

1. *The group G_1 occurs as a Galois group over F if and only if F is nonrigid.*
2. *If F is nonreal, then G_1 occurs as a Galois group over F if and only if $Br_2(F) = 0$ (i.e., $(a,b)_F = 0$ for all $a, b \in F$).*
3. *If F is formally real, then G_1 occurs as a Galois group over F if and only if F is uniquely ordered, which in this case is equivalent to F not being Pythagorean.*

Proof. (1). If G_1 occurs as a Galois group over F, then F is nonrigid by Theorem 3.7. Now assume F is nonrigid. Then Lemma 2.1 implies there exists $a \in \dot{F}\backslash F^2$ such that $|D_F(\langle 1, -a\rangle)/\dot{F}^2| \geq 4$. Thus $D_F(\langle 1, -a\rangle) = \dot{F}$. There exists $b \in F$ such that $\dot{F} = \{1, a, b, ab\}\dot{F}^2$ and so statement (3) of Theorem 3.7 holds and G_1 occurs as a Galois group over F.

(2). Let $F = F^2 \cup aF^2 \cup bF^2 \cup abF^2$. Then $[F(\sqrt{a}, \sqrt{b}) : F] = 4$. If $Br_2(F) = 0$, then $(a,a)_F = (a,b)_F = 0$. Thus G_1 occurs as a Galois group over F by Theorem 3.7.

Now assume G_1 occurs as a Galois group over F. Then there exist $a, b \in F$ such that $[F(\sqrt{a}, \sqrt{b}) : F] = 4$ and $(a,a)_F = (a,b)_F = 0$. It follows that $F = F^2 \cup aF^2 \cup bF^2 \cup abF^2$ and thus $(a, \dot{F})_F = 0$. Suppose first that either $-1 \in F^2$ or $a \in -F^2$. Then $(-1, \dot{F})_F = 0$. This implies $(b,b)_F = (-1,b)_F = 0$. Then $(b, \dot{F})_F = 0$ (since $(b,a)_F = 0$ and $(b,b)_F = 0$) and so $(ab, \dot{F})_F = 0$. Therefore $Br_2(F) = 0$.

Now assume $-1 \notin F^2$ and $a \notin -F^2$. Then we can assume $b = -1$ (since we also have $(a, ab)_F = 0$) and so $F = F^2 \cup -F^2 \cup aF^2 \cup -aF^2$. It is clear that $F^2 \cup aF^2 \subseteq D_F(\langle 1, a\rangle)$ and we have $F^2 \cup aF^2 \subseteq D_F(\langle 1, 1\rangle)$ since $(-1, a)_F = 0$. Since $F^2 \cup aF^2$ is not an ordering of F, we must have either $F^2 \cup aF^2 \subsetneq D_F(\langle 1, a\rangle)$ or $F^2 \cup aF^2 \subsetneq D_F(\langle 1, 1\rangle)$. In the first case we have $(-a, \dot{F})_F = 0$ and in the second case we have $(-1, \dot{F})_F = 0$. Each case implies $Br_2(F) = 0$.

(3). Since F is formally real and $|\dot{F}/(\dot{F})^2| = 4$, there is an ordering such that a is positive in this ordering and $F = F^2 \cup -F^2 \cup aF^2 \cup -aF^2$. If F is not Pythagorean then $a \in D_F(\langle 1, 1\rangle)$, and thus F is uniquely ordered since $F^2 \cup aF^2$ is contained in the positive cone of any ordering of F. If F is Pythagorean, then one checks that $-1, a \notin D_F(\langle 1, -a\rangle)$ and so $F^2 \cup -aF^2$ is also the positive cone of an ordering. Thus F is not uniquely ordered. The result now follows from Theorem 3.7. ☐

Proposition 6.2. *Assume* $|\dot{F}/(\dot{F})^2| = 4$*, F is formally real and not Pythagorean. Then* $[F^{(3)} : F] = 16$ *with* $\mathrm{Gal}(F^{(3)}/F) \cong D \curlywedge C$*, and* $[F^{\{3\}} : F] = 32$ *with* $\mathrm{Gal}(F^{\{3\}}/F) \cong G_1$.

Proof. We have $F = F^2 \cup -F^2 \cup aF^2 \cup -aF^2$ and $D_F(\langle 1, 1\rangle) = F^2 \cup aF^2$ where $F^2 \cup aF^2$ is the positive cone of the unique ordering on F. Let $E = F(\sqrt{-1})$. Then the square class exact sequence ([La], p. 202) applied to E/F gives $|\dot{E}/(\dot{E})^2| = 4$ since $D_F(\langle 1, 1\rangle)$ contains exactly two square classes. Since $F^{(2)} = E(\sqrt{a})$, the square class exact sequence applied to $F^{(2)}/E$ gives $|\dot{F}^{(2)}/(\dot{F}^{(2)})^2| \le \frac{1}{2}|\dot{E}/(\dot{E})^2| = 8$. Therefore $[F^{\{3\}} : F^{(2)}] = |\dot{F}^{(2)}/(\dot{F}^{(2)})^2| \le 8$ and so $[F^{\{3\}} : F] \le 32$. Since G_1 occurs as a Galois group for some extension in $F^{\{3\}}$, it follows $[F^{\{3\}} : F] = 32$ and $\mathrm{Gal}(F^{\{3\}}/F) \cong G_1$. Since $D \curlywedge C$ occurs as a Galois group over F and $F^{(3)} \subsetneq F^{\{3\}}$, it follows $\mathrm{Gal}(F^{(3)}/F) \cong D \curlywedge C$. ☐

Proposition 6.3. *Assume* $|\dot{F}/(\dot{F})^2| = 4$*, F is nonreal and* $Br_2(F) = 0$ *(so that G_1 occurs as a Galois group over F). Then* $[F^{(3)} : F] = 32$ *and* $[F^{\{3\}} : F] = 128$.

Proof. We have $F^{(2)} = F(\sqrt{a}, \sqrt{b})$ for some $a, b \in F$. Let $E = F(\sqrt{a})$. The square class exact sequence applied to E/F gives $|\dot{E}/(\dot{E})^2| = \frac{1}{2}|\dot{F}/(\dot{F})^2| = 8$, since $u(F) = 2$ and so binary quadratic forms over F are universal. Since F is nonreal, it is known that $u(E) = 2$ also and thus the square class exact sequence applied to $F^{(2)}/E$ gives $|\dot{F}^{(2)}/(\dot{F}^{(2)})^2| = \frac{1}{2} \cdot 8^2 = 32$. Thus $[F^{\{3\}} : F^{(2)}] = |\dot{F}^{(2)}/(\dot{F}^{(2)})^2| = 32$ and so $[F^{\{3\}} : F] = 128$.

An argument in the proof of Proposition 3.6 shows that $\mathrm{Gal}(F^{(3)}/F)$ is generated by any two automorphisms σ_a, σ_b that satisfy $\sigma_a(\sqrt{a}) = -\sqrt{a}$, $\sigma_a(\sqrt{b}) = \sqrt{b}$, $\sigma_b(\sqrt{a}) = \sqrt{a}$, $\sigma_b(\sqrt{b}) = -\sqrt{b}$. Then Corollary 2.8(2) implies $|\mathrm{Gal}(F^{(3)}/F)| \le 32$. One can check that $C^aC^b \subseteq F^{(3)}$ and $D^{a,b} \subseteq F^{(3)}$. Since $[C^aC^b : F] = 16$, $\mathrm{Gal}(C^aC^b/F)$ is abelian and $\mathrm{Gal}(D^{a,b}/F)$ is nonabelian, it follows $[F^{(3)} : F] = 32$. ☐

Generators and relations for $\mathrm{Gal}(F^{\{3\}}/F)$ and $\mathrm{Gal}(F^{(3)}/F)$ can be found using Proposition 2.7 and Corollary 2.8.

We now briefly consider the case when $|\dot{F}/(\dot{F})^2| = 4$ and F is a rigid field. Then $F^{(3)} = F^{\{3\}}$ by [LS], although when $|\dot{F}/(\dot{F})^2| = 4$, this is easily obtained by direct calculation. In the proposition below, $Q_8 \curlywedge C$ denotes the pullback of the system of nontrivial homomorphisms $Q_8 \mapsto \mathbb{Z}/2\mathbb{Z}$ and $C \mapsto \mathbb{Z}/2\mathbb{Z}$, where Q_8 is the quaternion group of order 8. The group $Q_8 \curlywedge C$ is also the pullback of the system $D \mapsto \mathbb{Z}/2\mathbb{Z}$ and $C \mapsto \mathbb{Z}/2\mathbb{Z}$, where the kernel of $D \mapsto \mathbb{Z}/2\mathbb{Z}$ is the cyclic group of order 4. See [GSS] for more details.

Proposition 6.4. *Assume $|\dot{F}/(\dot{F})^2| = 4$ and F is a rigid field.*

1. *If F is formally real, then $[F^{\{3\}} : F] = 8$ and $\mathrm{Gal}(F^{\{3\}}/F) \cong D$.*
2. *If F is nonreal, then $[F^{\{3\}} : F] = 16$.*
   (a) *If $-1 \in F^2$, then $\mathrm{Gal}(F^{\{3\}}/F) \cong C \times C$.*
   (b) *If $-1 \notin F^2$, then $\mathrm{Gal}(F^{\{3\}}/F) \cong Q_8 \curlywedge C$.*

Proof. (1). We have F is Pythagorean by Proposition 6.1 and $F^{(2)} = F(\sqrt{-1}, \sqrt{a})$ for some $a \in F$. Two applications of the square class exact sequence give $|F(\dot{\sqrt{-1}})/F(\dot{\sqrt{-1}})^2| = 2$ and $|\dot{F^{(2)}}/(\dot{F^{(2)}})^2| = 2$. Thus $[F^{\{3\}} : F^{(2)}] = 2$ and $[F^{\{3\}} : F] = 8$. We have $\mathrm{Gal}(F^{\{3\}}/F) \cong D$ since $D^{a,-a}$ is a dihedral extension of F.

(2). When F is nonreal, two applications of the square class exact sequence give $|\dot{F^{(2)}}/(\dot{F^{(2)}})^2| = 4$ and thus $[F^{\{3\}} : F] = 16$. Part (a) follows since each quadratic extension of F can be imbedded in a cyclic quartic extension of F. One way to show (b) is to see that C^{-1} and $D^{a,-a}$ are extensions of F and that $\mathrm{Gal}(D^{a,-a}/F(\sqrt{-1})) \cong C$. Then $\mathrm{Gal}(F^{\{3\}}/F) \cong Q_8 \curlywedge C$. □

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