

# Norm equivalences and ideals of composition algebras<sup>1</sup>

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## Abstract

We show that linear bijections between quaternion algebras over a commutative ring preserving norms and identity elements are basically the same as isomorphisms or anti-isomorphisms. We also show that one-sided ideals of octonion algebras over a commutative ring are extended from the base.

**Introduction.** By a *composition algebra* over a commutative ring  $k$  we mean a non-associative  $k$ -algebra  $C$  with the following properties:  $C$  is finitely generated projective as a  $k$ -module, contains an identity element and is equipped with a quadratic form  $n_C: C \rightarrow k$  (the *norm*), uniquely determined by the condition that it is non-singular (see **2.** below for the definition) and *permits composition*:  $n_C(1_C) = 1$  and  $n_C(xy) = n_C(x)n_C(y)$  for all  $x, y \in C$ . The rank of a composition algebra (provided it has one) is known to be one of the numbers  $r = 1, 2, 4, 8$ . More precisely,  $C \cong k$  for  $r = 1$ ,  $C$  is a commutative associative *quadratic étale* algebra for  $r = 2$ , an associative but not commutative *quaternion* algebra for  $r = 4$  and an alternative but neither commutative nor associative *octonion* (or *Cayley*) algebra for  $r = 8$ . Octonion algebras, in particular, derive much of their importance from their intimate connection with the exceptional groups of type  $G_2$ ; we refer to Gille-Neher [10] for details

Over a field or, more generally, a semi-local ring, composition algebras are well understood. They can all be obtained from a (repeated) application of the Cayley-Dickson construction [21, §6] and, thanks to Witt cancellation of quadratic forms (Baeza [3, III, Corollary (4.3)]), they are classified by their norms: two composition algebras over a semi-local ring are isomorphic if and only if their norms are equivalent (Petersson-Racine [26, Theorem 26.7]), see [27, Theorem 1.7.1] for the field case. Unfortunately, however, if the base ring is arbitrary, these nice and useful properties are no longer valid. In fact, there exist octonion algebras that as quadratic spaces are either indecomposable themselves or, if the base ring contains  $\frac{1}{2}$ , their subspaces of trace-zero elements are. In any event, they cannot be realized by the Cayley-Dickson construction, the most interesting examples of this kind being provided by the Dickson-Coxeter octonions living on the  $E_8$ -lattice over the integers ( $[6, 5, 24]$ ), and by the constructions of Knus-Parimala-Sridharan [16, Theorem (7.7)] over the polynomial ring in two variables with coefficients in an appropriate field of characteristic not two; for a simplification of this construction, see Thakur [28]. Moreover, Gille [9, Theorem 3.3] has exhibited examples of octonion algebras that have isometric norms but fail to be isomorphic; see also Alsaody-Gille [2, Corollary 6.7] for a characterization of octonion algebras with equivalent norms in terms of isotopes in the sense of McCrimmon [20]. On the positive side, there is a theorem of Knus-Paques [15, Theorem (3.10)] which implies that quaternion algebras over any commutative ring are always classified by their norms. For a refinement of this result, see Knus [12, V, Corollary (4.3.2)].

Our aim in this paper is twofold. On the one hand, we will be concerned with more explicit version of the Knus-Paques theorem. More specifically, we show that unit preserving isometries of quaternion algebras over any commutative ring are basically

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the same as isomorphisms or anti-isomorphisms (Theorem 6). This result, which is well known to hold over fields (Knus-Merkurjev-Rost-Tignol [13, VIII, Exercise 2]), yields the Knus-Paques theorem at once (Corollary 7). On the other hand, we will investigate the (one- or two-sided) ideal structure of composition algebras. Our main result (Theorem 10) extends earlier ones due to Mahler [19], Van der Blij-Springer [29] and Allcock [1] from the Dickson-Coxeter octonions over the integers to arbitrary composition algebras and implies among other things that one-sided ideals of any octonion algebra over any commutative ring are always extended from the base; this fact is all the more remarkable since the analogous result for quaternion or quadratic étale algebras breaks down even if the base ring is an algebraically closed field. In particular, octonion algebras over a commutative ring are arithmetically simple in the sense of Legrand [17]. The methods we employ to establish these results are quite elementary, relying only on properties of finitely generated projective modules and composition algebras that are basically standard.

**1. Notation.** Let  $k$  be a commutative ring remaining fixed throughout this paper. We denote by  $\text{Spec}(k)$  the prime spectrum of  $k$ , i.e., the totality of prime ideals in  $k$  equipped with the Zariski topology. Recall that a basis for this topology is furnished by the principal open sets  $D(f)$ ,  $f \in k$ , which consist of all prime ideals in  $k$  not containing  $f$ . For  $\mathfrak{p} \in \text{Spec}(k)$ , we denote by  $k_{\mathfrak{p}}$  the local ring of  $k$  at  $\mathfrak{p}$ , with maximal ideal  $\mathfrak{p}_{\mathfrak{p}}$  and residue field  $\kappa(\mathfrak{p}) = k_{\mathfrak{p}}/\mathfrak{p}_{\mathfrak{p}} = \text{Quot}(k/\mathfrak{p})$ . The category of unital commutative associative  $k$ -algebras will be denoted by  $k\text{-alg}$ , its morphisms being  $k$ -algebra homomorphisms taking 1 into 1. If  $M$  is a (left)  $k$ -module, then its base change or scalar extension from  $k$  to  $R \in k\text{-alg}$  will be denoted by  $M_R := M \otimes R$ , unadorned tensor products always being taken over  $k$ ; ditto for (non-associative) algebras instead of modules. For  $\mathfrak{p} \in \text{Spec}(k)$ , we abbreviate  $M_{\mathfrak{p}} := M_{k_{\mathfrak{p}}}$ ,  $M(\mathfrak{p}) := M_{\kappa(\mathfrak{p})}$ .

**2. Quadratic forms.** Let  $M$  be a  $k$ -module and  $q: M \rightarrow k$  a quadratic form, so  $q$  is homogeneous of degree 2 and the map  $M \times M \rightarrow k$ ,  $(x, y) \mapsto q(x, y) := q(x + y) - q(x) - q(y)$  is (symmetric) bilinear, called the *bilinearization* of  $q$ . We say that  $q$  is *non-singular* if  $M$  is finitely generated projective and the linear map from  $M$  to its dual canonically induced by the bilinearization of  $q$  is an isomorphism. The property of a quadratic form to be non-singular is stable under base change, so if  $q: M \rightarrow k$  is a non-singular quadratic form over  $k$ , its scalar extension  $q_R: M_R \rightarrow R$  is a non-singular quadratic form over  $R$ , for any  $R \in k\text{-alg}$ .

**3. Basic properties of composition algebras.** Recall that a composition algebra over  $k$  is a (non-associative)  $k$ -algebra  $C$  that is unital (i.e., contains an identity element), finitely generated projective as a  $k$ -module, and equipped with its norm  $n_C: C \rightarrow k$ , a non-singular quadratic form permitting composition:

$$n_C(1_C) = 1, \quad n_C(xy) = n_C(x)n_C(y) \quad (x, y \in C).$$

Note that the non-singularity condition prevents the base ring from being counted as a composition algebra unless it contains  $\frac{1}{2}$ . In order to avoid this awkward phenomenon, the notion of a composition algebra has to be modified: rather than insisting that the norm be non-singular, one should merely require that it be separable in the sense of Loos [18, 3.2]. This approach has been worked out in [26, Chap. 4], with a summary given in [25, §4]. It should also be noted that what we call non-singular (resp. separable) quadratic forms are called regular (resp. non-singular) ones in [2].

Now let  $C$  be a composition algebra over  $k$ . Referring to [12, V, (7.1)], [21, 22] for details, we collect a few properties of  $C$  that will be used frequently later on.

(a)  $C$  is alternative, so its associator  $[x, y, z] := (xy)z - x(yz)$  is alternating in  $x, y, z \in C$ . Hence the expression  $xyx$  is unambiguous and the Moufang identities hold.

$$x(y(xz)) = (xyx)z, \quad (xy)(zx) = x(yz)x, \quad ((zx)y)x = z(xy)x. \quad (1)$$

Writing

$$t_C: C \longrightarrow k, \quad x \longmapsto t_C(x) := n_C(1_C, x),$$

for the *trace* of  $C$  (a linear form) and

$$\iota_C: C \longrightarrow C, \quad x \longmapsto \bar{x} := t_C(x)1_C - x$$

for its *conjugation* (an algebra involution), the following identities hold, for all  $x, y, z \in C$ .

$$x^2 = t_C(x)x - n_C(x)1_C, \tag{2}$$

$$x\bar{x} = n_C(x)1_C = \bar{x}x, \tag{3}$$

$$n_C(x, \bar{y}) = t_C(x)t_C(y) - n_C(x, y) = t_C(xy). \tag{4}$$

In particular, we conclude from (3) that  $x$  is invertible in  $C$  if and only if  $n_C(x)$  is invertible in  $k$ , in which case  $x^{-1} = n_C(x)^{-1}\bar{x}$ . The set of invertible elements in  $C$  (resp.  $k$ ) will be denoted by  $C^\times$  (resp.  $k^\times$ ).

(b) Composition algebras are stable under base change:  $C_R$  is a composition algebra over  $R$ , for any  $R \in k\text{-alg}$ , the norm of  $C_R$  being the  $R$ -quadratic extension of the norm of  $C$ .

(c) The trace  $t_C$  is an *associative* linear form in the sense that  $t_C([x, y]) = t_C([x, y, z]) = 0$  for all  $x, y, z \in C$ , where  $[x, y] := xy - yx$  is the commutator of  $x$  and  $y$ .

(d)  $1_C \in C$  is *unimodular* in the sense that some linear form  $\lambda: C \rightarrow k$  has  $\lambda(1_C) = 1$ , making  $C$  a faithful  $k$ -module and  $k1_C$  a free  $k$ -module of rank 1.

(e) If  $C$  has rank  $r > 2$ , then  $C$  is *central* in the sense that its *centre*, i.e.,

$$\text{Cent}(C) := \{x \in C \mid [x, C] = [x, C, C] = \{0\}\}$$

satisfies  $\text{Cent}(C) = k1_C$ . Similarly, if  $C$  is an octonion algebra, then  $C$  is *nuclear* in the sense that its *nucleus*, i.e.,

$$\text{Nuc}(C) := \{x \in C \mid [x, C, C] = \{0\}\}$$

satisfies  $\text{Nuc}(C) = k1_C$  [2, Lemma 2.8].

**4. The Cayley-Dickson construction.** Let  $B$  be an associative composition algebra over  $k$  and  $\mu \in k$  an invertible element. Then the  $k$ -algebra  $C$  defined on the direct sum  $B \oplus Bj$  of two copies of  $B$  as a  $k$ -module by the multiplication

$$(u_1 \oplus v_1j)(u_2 \oplus v_2j) = (u_1u_2 + \mu\bar{v}_2v_1) \oplus (v_2u_1 + v_1\bar{u}_2)j \tag{5}$$

for  $u_i, v_i \in B$ ,  $i = 1, 2$ , is a composition algebra whose unit element, norm and conjugation for  $u, v \in B$  are respectively given by

$$1_C = 1_B \oplus 0 \cdot j, \quad n_C(u \oplus vj) = n_B(u) - \mu n_B(v), \quad \overline{u \oplus vj} = \bar{u} \oplus (-vj) \tag{6}$$

in terms of the corresponding data for  $B$ . We write  $C =: \text{Cay}(B, \mu)$  and call it the composition algebra arising from  $B, \mu$  by the *Cayley-Dickson construction*. The assignment  $u \mapsto u \oplus 0 \cdot j$  gives an embedding, i.e., an injective homomorphism of unital  $k$ -algebras, allowing us to identify  $B \subseteq C$  as a unital subalgebra. We then have  $u + vj = u \oplus vj$  for all  $u, v \in B$ , and  $B^\perp = Bj$  is the orthogonal complement of  $B$  in  $C$  relative to the bilinearized norm. By (6) and **3.** (a), therefore,  $j \in B^\perp$  is invertible in  $C$ .

Conversely, let  $C$  be a composition algebra over  $k$  and  $B \subset C$  a proper composition subalgebra. Then  $B$  is associative and for any  $l \in B^\perp \cap C^\times$  (which always exists if  $k$  is a semi-local ring), the inclusion  $B \hookrightarrow C$  has a unique extension to an embedding from the Cayley-Dickson construction  $\text{Cay}(B, \mu)$ ,  $\mu := -n_C(l) \in k^\times$ , into  $C$  that sends  $j$  to  $l$ . This embedding is an isomorphism provided  $C, B$  have rank  $r, \frac{r}{2}$ , respectively.

**5. The Knus-Paques theorem.** Let  $B, B'$  be quaternion algebras over  $k$ . Using the theory of Clifford algebras, Knus-Paques [15, Theorem (3.10)] have shown that  $B$  and  $B'$  are isomorphic if and only if, for some  $\beta \in k^\times$ , the quadratic forms  $\beta n_B$  and  $n_{B'}$  are isometric. In the present paper, we give this equivalence an explicit form. More specifically, calling an isometry from  $n_B$  to  $n_{B'}$  that preserves identity elements a *unital norm equivalence*, and guided by [13, VIII, Exercice 2], we will establish the following result.

**6. Theorem.** *Let  $B, B'$  be quaternion algebras over  $k$ . A map  $f: B \rightarrow B'$  is a unital norm equivalence if and only if there exists a decomposition  $k = k_+ \oplus k_-$  of  $k$  as a direct sum of ideals such that the induced decompositions*

$$\begin{aligned} B &= B_+ \oplus B_-, & B_\pm &:= B_{k_\pm}, & B' &= B'_+ \oplus B'_-, & B'_\pm &:= B'_{k_\pm}, \\ f &= f_+ \oplus f_-, & f_\pm &:= f_{k_\pm} \end{aligned} \quad (7)$$

make  $f_+: B_+ \rightarrow B'_+$  an isomorphism of quaternion algebras over  $k_+$  and  $f_-: B_- \rightarrow B'_-$  an anti-isomorphism of quaternion algebras over  $k_-$ .

*Proof.* If such a decomposition exists,  $f$  is clearly a unital norm equivalence. Conversely, let this be so. We put  $X := \text{Spec}(k)$  and conclude that the subsets

$$\begin{aligned} X_+ &:= \{\mathfrak{p} \in X \mid f_{\mathfrak{p}}: B_{\mathfrak{p}} \rightarrow B'_{\mathfrak{p}} \text{ is an isomorphism}\}, \\ X_- &:= \{\mathfrak{p} \in X \mid f_{\mathfrak{p}}: B_{\mathfrak{p}} \rightarrow B'_{\mathfrak{p}} \text{ is an anti-isomorphism}\} \end{aligned}$$

of  $X$  are Zariski-open (since  $B$  is finitely generated as a  $k$ -module, so the conditions imposed on  $X_\pm$  may be characterized by finitely many equations) and disjoint (since quaternion algebras are not commutative). Suppose we can show that they cover  $X$ . Then Bourbaki [4, II, §4, Proposition 15] yields a complete orthogonal system  $(\varepsilon_+, \varepsilon_-)$  of idempotents in  $k$  satisfying  $X_\pm = D(\varepsilon_\pm)$ . Now it suffices to put  $k_\pm = k\varepsilon_\pm$ , which implies for any  $\mathfrak{p}_\pm \in \text{Spec}(k_\pm)$  that  $\mathfrak{p} := \mathfrak{p}_\pm \oplus k_\mp \in D(\varepsilon_\pm)$  makes  $f_{\mathfrak{p}_\pm} = (f_{\mathfrak{p}})_{k_\pm \mathfrak{p}_\pm}$  an isomorphism in case of the plus-sign and an anti-isomorphism in case of the minus-sign. Hence  $f_+$  is an isomorphism and  $f_-$  is an anti-isomorphism.

We are thus reduced to showing  $X = X_+ \cup X_-$ . Equivalently, we may assume that  $k$  is a local ring and must show that  $f$  is either an isomorphism or an anti-isomorphism. Writing  $\mathfrak{m}$  for the maximal ideal of  $k$ , the quaternion algebra  $B(\mathfrak{m})$  over the field  $\kappa(\mathfrak{m})$  contains a quadratic étale subalgebra generated by an element of trace 1, which in turn lifts to a quadratic étale subalgebra  $D = k[u] \subseteq B$ , for some trace-one element  $u \in B$ . Since units, norms, and traces are preserved by  $f$ , so are squares (by (2)), and we conclude that  $D' := f(D) = k[u']$ ,  $u' := f(u)$ , is a quadratic étale subalgebra of  $B'$ , making  $f|_D: D \rightarrow D'$  an isomorphism. Now apply 4. to reach  $B$  from  $D$  by means of the Cayley-Dickson construction: there exists a unit  $\mu \in k^\times$  such that the inclusion  $D \hookrightarrow B$  extends to an identification  $B = \text{Cay}(D, \mu) = D \oplus Dj$ ,  $j \in D^\perp$ ,  $n_B(j) = -\mu$ . Moreover, setting  $j' := f(j) \in D'^\perp \subseteq B'$ , we obtain  $n_{B'}(j') = -\mu$ , and conclude that  $f|_D$  extends to an isomorphism  $g: B \rightarrow B'$  satisfying  $g(j) = j'$ . Hence  $f_1 := g^{-1} \circ f: B \rightarrow B$  is a unital norm equivalence inducing the identity on  $D$  and satisfying  $f_1(j) = j$ . Since  $f_1$  stabilizes  $D^\perp = Dj$ , we find a  $k$ -linear bijection  $\varphi: D \rightarrow D$  such that  $f_1(vj) = \varphi(v)j$  for all  $v \in D$ . Then  $\varphi(1_D) = 1_D$ , and since  $n_B$  permits composition,  $\varphi$  leaves  $n_D$  invariant and is thus a unital norm equivalence of  $D$ , hence an automorphism. By [12, III, Lemma (4.1.1)], therefore, we are left with the following cases.

*Case 1.*  $\varphi = 1_D$ . Then  $f_1 = 1_B$ , and  $f = g: B \rightarrow B'$  is an isomorphism.

*Case 2.*  $\varphi = \iota_D$ . One checks easily that the *reflection in  $D$*  (Jacobson [11, p. 12]), i.e., the map  $\psi: B \rightarrow B$  defined by  $\psi(v + wj) := v - wj$  for all  $v, w \in D$  is an automorphism satisfying  $f_1 = \psi \circ \text{Int}(j) \circ \iota_B$ , where  $\text{Int}(j)$  stands for the inner automorphism  $x \mapsto jxj^{-1}$  of  $B$  affected by  $j$ . Hence  $f = g \circ \psi \circ \text{Int}(j) \circ \iota_B: B \rightarrow B'$  is an anti-isomorphism.  $\square$

**7. Corollary** (Knus-Paques [15, Theorem (3.10)]). *For quaternion algebras  $B, B'$  over  $k$ , the following conditions are equivalent.*

- (i)  $B$  and  $B'$  are isomorphic.
- (ii)  $B$  and  $B'$  are norm-equivalent, i.e., their norms are isometric.
- (iii)  $B$  and  $B'$  are norm-similar, i.e., there exists a scalar  $\beta \in k^\times$  such that  $\beta n_B$  and  $n_{B'}$  are isometric.

*Proof.* The implications (i)  $\Rightarrow$  (ii)  $\Rightarrow$  (iii) being obvious, it remains to establish the implication (iii)  $\Rightarrow$  (i), so let us assume for some  $\beta \in k^\times$  that  $g: B \rightarrow B'$  is an isometry from  $\beta n_B$  to  $n_{B'}$ . Then  $u := g^{-1}(1_{B'}) \in B$  has  $n_B(u) = \beta^{-1}$  and hence is invertible. Thus, since  $n_B$  permits composition, the assignment  $x \mapsto g(ux)$  defines a unital norm equivalence  $f: B \rightarrow B'$ , and we obtain a decomposition  $k = k_+ \oplus k_-$  as a direct sum of ideals such that the induced decompositions (7) enjoy the properties spelled out in Theorem 6. Hence  $f_+ \oplus (f_- \circ \iota_B): B \rightarrow B'$  is an isomorphism of quaternion algebras.  $\square$

**8. Remarks.** (a) Another proof of Theorem 6 using group schemes may be found in a forthcoming monograph by Gille-Neher [10]. A scheme-theoretic proof of Corollary 7 is due to Gille [9, Theorem 2.4].

(b) It is easy to see that a unital norm equivalence between quadratic étale algebras is an isomorphism. More precisely, given a unital norm equivalence  $f: D \rightarrow D'$  of quadratic étale algebras, and arguing as in the proof of Theorem 6, one obtains decompositions as in the theorem such that  $f_+ = \mathbf{1}_{D_+}$  is the identity of  $D_+$  and  $f_- = \iota_{D_-}$  is the conjugation of  $D_-$ . This result is well known [12, Proposition (4.1.2)].

(c) At the other extreme, Theorem 6 breaks down for octonion algebras, even if the base ring is an algebraically closed field. In order to illuminate this well-known phenomenon, we refer to McCrimmon's notion of isotopy [20], a special case of which may be described as follows.

Let  $C$  be an octonion algebra over  $k$ , an arbitrary commutative ring. For  $p \in C^\times$ , the  $k$ -module  $C$  together with the multiplication  $(xp^{-1})(py)$  is again an octonion algebra over  $k$ , denoted by  $C^p$  and called the  $p$ -isotope of  $C$ ; it has the same identity element, norm, trace, and conjugation as  $C$ . For another invertible element  $q \in C^\times$ , the Moufang identities (1) imply  $(C^p)^q = C^{pq}$  and, using **3.** (e), one checks that  $C^p = C^q$  if and only if  $q = \alpha p$  for some  $\alpha \in k^\times$ . Now suppose  $B \subseteq C$  is a quaternion subalgebra and let  $p \in B^\times$ . Then  $C = B \oplus B^\perp$  as  $k$ -modules and, localizing if necessary, a straightforward verification shows that

$$f: C \xrightarrow{\sim} C^p, \quad f(u + v) := p^{-1}up + v$$

for  $u \in B$ ,  $v \in B^\perp$  is an isomorphism. In particular,  $f$  is a unital norm equivalence but not an automorphism of  $C$  unless  $p \in k1_C$ . It follows from Gille [9, Theorem 3.3] and Alsaody-Gille [2, Corollary 6.7] that, if  $C$  is split and  $k$  is chosen judiciously, some  $p \in C^\times$  has  $C^p \not\cong C$ . Such a  $p$ , therefore, cannot be embedded into a quaternion subalgebra of  $C$ , in stark contrast to the general situation over fields (Springer-Veldkamp [27, Proposition 1.6.4]).

The preceding examples are in some sense typical: it follows from the principle of triality [27, Theorem 3.2.1] combined with the formalism of [23] that, if  $k$  is a field, any rotation (resp. reflection) of the quadratic space  $(C, n_C)$  fixing the identity element is an isomorphism (resp. anti-isomorphism) from  $C$  to  $C^p$ , for some  $p \in C^\times$ . Whether the same conclusion holds over any commutative ring seems to be an open problem.

**9. Ideals.** In order to put our approach to ideals of octonion algebras in perspective, it seems appropriate to discuss them in the broader context of arbitrary composition algebras. We begin by distinguishing three types of ideals in a composition algebra  $C$ : the *general type*, i.e., one-sided ideals, the *middle ground*, i.e., arbitrary two-sided ideals, and the *special type*, i.e., ideals of  $(C, \iota_C)$  as an algebra with involution, equivalently, ideals stable under conjugation.

The final result of this paper basically says that, if  $C$  has rank  $r > 1$ , all its ideals of the right type are extended from the base ring provided as  $r$  increases so does the generality of the type. More precisely, we can prove:

**10. Theorem.** *Let  $C$  be a composition algebra of rank  $r > 1$  over  $k$  and identify  $k = k1_C \subseteq C$  canonically via **3.** (d). Then the assignment*

$$\mathfrak{a} \longmapsto \mathfrak{a}C$$

*defines an inclusion-preserving bijection from the ideals of  $k$  to*

- (i) *the one-sided ideals of  $C$  for  $r = 8$ ,*
- (ii) *the two-sided ideals of  $C$  for  $r = 4$ ,*
- (iii) *the ideals of  $(C, \iota_C)$  as an algebra with involution for  $r = 2$ .*

*The inverse of this map is given by the assignment*

$$I \longmapsto I \cap k.$$

*Proof.* We proceed in several steps by proving the following intermediate assertions.

$1^0$ . *For  $r = 8$ , i.e., if  $C$  is an octonion algebra, its one-sided ideals are two-sided ones.* In order to see this, let  $I \subseteq C$  be a one-sided ideal. Replacing  $I$  by  $\bar{I}$  if necessary, we may assume that  $I$  is a right ideal in  $C$ . Since the assertion is local on  $k$ , we may further assume that  $k$  is a local ring. From **4.** we conclude  $C = \text{Cay}(B, \mu) = B \oplus Bj$  for some quaternion algebra  $B$  over  $k$  and some invertible scalar  $\mu \in k$ . For  $l = 1, 2$ , let  $\pi_l: C \rightarrow B$  be the  $l$ -th projection defined by  $x = \pi_1(x) + \pi_2(x)j$  for  $x \in C$ . Then  $I_l := \pi_l(I)$  is a  $k$ -submodule of  $B$  satisfying  $I \subseteq I_1 \oplus I_2j$ . From **(5)** we deduce

$$(u + vj)w = uw + (v\bar{w})j, \quad (u + vj)(wj) = \mu\bar{w}v + (wu)j$$

for all  $u, v, w \in B$ . Assuming  $u + vj \in I$ , the first equation shows that  $I_l$  is a right ideal in  $B$ , while the second one gives  $CI_2 \subseteq I_1$ ,  $CI_1 \subseteq I_2$ . Hence  $I_1 = 1_C I_1 \subseteq I_2 = 1_C I_2 \subseteq I_1$ , so  $I_0 := I_1 = I_2$  is a two-sided ideal in  $B$  such that  $I \subseteq I_0 \oplus I_0j$ . Now let  $u, v, w_1, w_2 \in B$  and assume again  $u + vj \in I$ . Then  $I$  contains the quantity

$$((u + vj)w_1)w_2 - (u + vj)(w_2w_1) = uw_1w_2 + (v\bar{w}_1\bar{w}_2)j - u(w_2w_1) - (v\bar{w}_2\bar{w}_1)j = u[w_1, w_2].$$

Let  $\mathfrak{m}$  be the maximal ideal of  $k$  and  $\kappa := k/\mathfrak{m}$  its residue field. Since  $[B(\mathfrak{m}), B(\mathfrak{m})]$ , being the space of trace-zero elements in the quaternion algebra  $B(\mathfrak{m})$  over the field  $\kappa$ , contains invertible elements, so does  $[B, B]$ , and we conclude  $u, v \in I$ . Thus  $I = I_0 \oplus I_0j$  is a two-sided ideal in  $C$ .

$2^0$ . *Let  $I$  be a two-sided ideal in  $C$ . Then  $I \cap k = \{0\}$  implies  $I = \{0\}$  provided  $r > 2$  or  $I$  is stable under conjugation.* Suppose first  $I$  is stable under conjugation and let  $x \in I$ . Then  $t_C(x) = x + \bar{x} \in I \cap k = \{0\}$ . But  $I \subseteq C$  is an ideal, so  $x\bar{z} \in I$  for all  $z \in C$ , and from **(4)** we conclude  $n_C(x, z) = t_C(x\bar{z}) = 0$ , hence  $x = 0$  by non-singularity.

Next consider the case  $r > 2$ . Since  $I \cap \bar{I} \subseteq C$  is a two-sided ideal stable under conjugation and satisfying  $I \cap \bar{I} \cap k \subseteq I \cap k = \{0\}$ , the previous case yields  $I \cap \bar{I} = \{0\}$ .

Now let  $x \in I$  be non-zero. Then  $\bar{x} = t_C(x) - x$  does not belong to  $I$ , forcing  $t_C(x) \neq 0$ . Thus the linear map  $t_C: I \rightarrow k$  is injective. From **3.** (c) we deduce the relations

$$t_C([x, y]) = t_C([x, y, z]) = 0$$

for  $y, z \in C$ , which therefore imply  $[x, y] = [x, y, z] = 0$ , so  $x$  belongs to the centre of  $C$ , which by **3.** (e) is  $k$ . Hence  $I \subseteq I \cap k = \{0\}$ , which proves our claim.

$3^0$ . *There is a  $k$ -submodule  $M \subseteq C$  such that*

$$C = k \oplus M \tag{8}$$

and  $(\mathfrak{a}C) \cap k = \mathfrak{a}$  for all ideals  $\mathfrak{a} \subseteq k$ . Indeed, the first part follows immediately from  $1_C$  being unimodular (cf. **3.** (d)) and implies  $(\mathfrak{a}C) \cap k = (\mathfrak{a} \oplus \mathfrak{a}M) \cap k = \mathfrak{a}$ . Thus  $3^0$  holds.

It remains to establish

$4^0$ . *Let  $I$  be a two-sided ideal in  $C$  and assume  $r > 2$  or that  $I$  is stable under conjugation. Then  $I = (I \cap k)C$ . The right-hand side being contained in the left, it suffices to show*

$$I \subseteq (I \cap k)C. \tag{9}$$

Setting  $\mathfrak{a} := I \cap k$ , we pass to the base change  $k' := k/\mathfrak{a} \in k\text{-alg}$  and consider the composition algebra  $C' := C \otimes k' = C/\mathfrak{a}C$  over  $k'$ , denote by  $I' = I/\mathfrak{a}C$  the image of  $I$  under the canonical map  $x \mapsto x'$  from  $C$  to  $C'$  and claim that  $\mathfrak{a}' := I' \cap k' = \{0\}$ . To see this, we first note that (8) implies

$$C' = k' \oplus M', \quad M' := M \otimes k' = M/\mathfrak{a}M.$$

Given  $\alpha_1 \in \mathfrak{a}' \subseteq I'$ , we can therefore find elements  $\xi \in k, y \in M$  satisfying  $x := \xi + y \in I$  and  $x' = \alpha_1$ . This yields  $\xi' = \alpha_1, y' = 0$ , hence  $y \in \mathfrak{a}M \subseteq \mathfrak{a}C \subseteq I$  and  $\xi = x - y \in I \cap k = \mathfrak{a}$ . But then  $\alpha_1 = \xi' = 0$ , and we have arrived at the desired conclusion  $\mathfrak{a}' = \{0\}$ . Now  $2^0$  implies  $I' = \{0\}$ , hence  $I \subseteq \mathfrak{a}C$ , as claimed in (9). Thus the proof of  $4^0$  is complete.  $\square$

**11. Concluding remarks.** (a) Since quaternion algebras by [12, III, Theorem (5.1.1)] are Azumaya algebras, part (ii) of Theorem 10 is not new [14, III, Corollaire 5.2]. Neither is part (iii), of course, since a quadratic étale  $D$  over  $k$  by [12, V, (4.1)] is a Galois extension with Galois group the constant group scheme  $\mathbb{Z}/2\mathbb{Z}$ , so the assertion follows from Ford [8, 12.2.2 (7)].

(b) Part (i) of Theorem 10 breaks down for quaternion algebras since even the split quaternions (of  $2 \times 2$ -matrices with entries in  $k$ ) allow one-sided ideals not extended from the base ring. Similarly, part (ii) breaks down for quadratic étale algebras since even the split one (direct sum of two copies of  $k$ ) allows (two-sided) ideals not extended from  $k$ .

(c) Step  $1^0$  in our proof of Theorem 10 is devoted to showing that one-sided ideals of octonion algebras are, in fact, two-sided. After localizing, we do so by appealing to the Cayley-Dickson construction. This seems to be in keeping with the final remark 6.10 of [21] and also relates to an earlier result of Erdmann [7, Korollar 1 of Satz 7], who showed over fields of characteristic not 2 that algebras arising from the base field by a more than two-fold iteration of the Cayley-Dickson construction fail to admit non-trivial one-sided ideals.

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