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DIVISION ALGEBRAS
AND THE HAUSDORFF-BANACH-TARSKI PARADOX

by Pierre DELIGNE and Dennis SULLIVAN

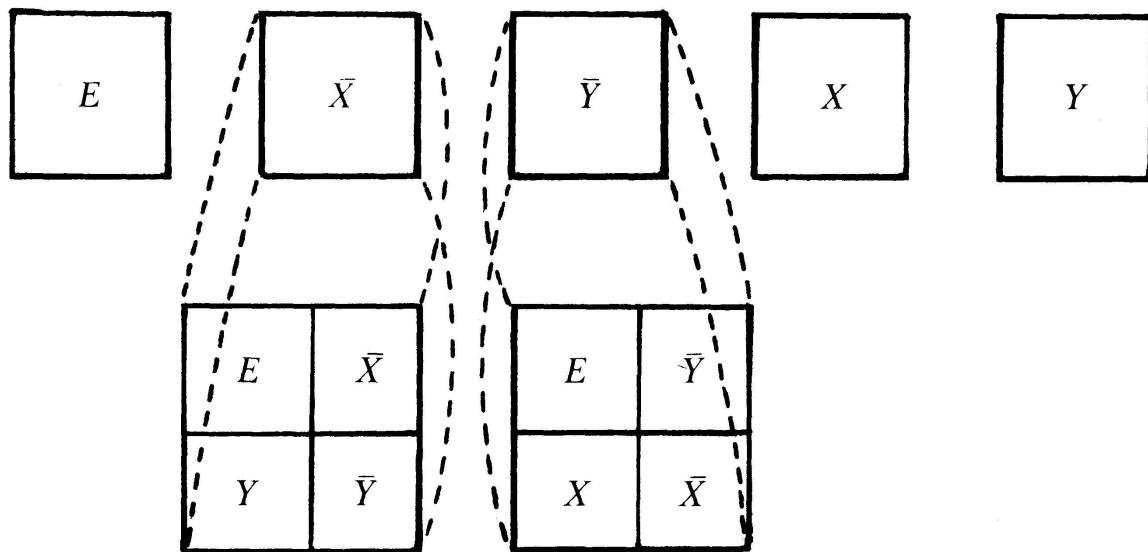
In this note we observe that a question raised by Dekker (1956) about rotations inspired by the Hausdorff-Banach-Tarski paradox can be answered using algebraic number theory. For motivation, we recall a form of the paradox.

Partition the free group in two generators F into the five sets $E, X, \bar{X}, Y, \bar{Y}$ consisting respectively of the identity and of the elements which, when written in reduced form, begin with x, x^{-1}, y or y^{-1} . If F acts freely on a sphere S , by rigid rotations, and if, using the axiom of choice, we choose a transversal T , i.e. a set with exactly one point in each orbit, the five subsets $T, XT, \bar{X}T, YT, \bar{Y}T$ form a partition of S . For economy of notation, we will write again $E, X, \bar{X}, Y, \bar{Y}$ for $T, XT, \bar{X}T, YT, \bar{Y}T$. The rotation by x moves \bar{X} onto

$$S - X = E \cup \bar{X} \cup Y \cup \bar{Y}.$$

Similarly, y moves \bar{Y} onto

$$S - Y = E \cup X \cup \bar{X} \cup \bar{Y}.$$



Thus we can reassemble from these 11 (actually 5) pieces 2 congruent spheres plus one congruent copy of the set E . This is a form of the Hausdorff-Banach-Tarski paradox which comes quickly from a free action of a free group

on two generators (see Appendix A for the more precise form). Thus we have the question of Dekker (communicated by Jan Mycielski): do such actions really exist? The sphere must be odd-dimensional for topological reasons: a fixed point free map $f : S^d \rightarrow S^d$ must have vanishing Lefschetz number

$$L(f) = \sum (-1)^i \operatorname{Trace}(f; H_i(S^d)) = 1 + (-1)^d \deg(f).$$

For a free action of a free group, the square of a non-trivial element will act by a map of degree $+1$ and this forces d odd. The dimension must be > 1 . These are the only conditions.

THEOREM. *For $n \geq 2$, there is a free non-abelian group of rigid rotations acting freely on the odd dimensional sphere S^{2n-1} .*

Remark. The corresponding orthogonal matrices can be chosen to have algebraic entries, and the group of matrices corresponds to a subgroup of the non-zero elements in a division algebra over a number field.

Remark. The theorem was proved by Dekker for n even [D].

Remark. Let $u : O(p) \times O(q) \rightarrow O(p+q)$ be the natural embedding:

$$u(A, B) = \text{matrix} \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}.$$

If $A \in O(p)$ and $B \in O(q)$ don't have any nonzero fixed vector, neither has $u(A, B)$. If $\sigma_1 : F \rightarrow O(p)$ and $\sigma_2 : F \rightarrow O(q)$ define free actions on S^{p-1} and S^{q-1} , $u(\sigma_1, \sigma_2)$ hence defines a free action of F on S^{p+q-1} . Using this remark, one could reduce the theorem to the two particular cases $n = 2$ and $n = 3$.

Proof. Let $k \subset \mathbf{R}$ be a real algebraic number field, and $k' \subset \mathbf{C}$ be a quadratic extension of k . We assume that $k' \not\subset \mathbf{R}$, i.e. that $k' \otimes_k \mathbf{R} = \mathbf{C}$. Let D be a division algebra of dimension n^2 over its center k' , equipped with an anti-involution $*$ inducing on k' the complex conjugation. The \mathbf{R} -algebra $D \otimes_k \mathbf{R}$ is a simple algebra over its center $k' \otimes_k \mathbf{R} = \mathbf{C}$, hence isomorphic to $M(n, \mathbf{C})$. We assume that, for a suitable isomorphism between $D \otimes_k \mathbf{R}$ and $M(n, \mathbf{C})$, $*$ becomes transpose conjugate.

In term of an isomorphism as above, the elements u of D satisfying $uu^* = 1$ become unitary matrices. They operate on the unit sphere in \mathbf{C}^n . Furthermore, if $u \neq 1$, $u - 1$ is invertible in D so that the corresponding matrix does not have 1 as an eigenvalue. It hence acts without fixed point on the sphere.

The group $\Gamma := \{u \in D \mid uu^* = 1\}$ is the group of k -rational points of a k -form of the real algebraic group $U(n)$. For $n > 1$, the perfect subgroup $SU(n)$

of $U(n)$ is not trivial, and $U(n)$ is not solvable. The group Γ is dense in $U(n)$: skew adjoints elements of D are dense in the skew adjoint matrices in $M(n, \mathbf{C})$, and the Cayley transform $t \mapsto \frac{t-1}{t+1}$ is an homeomorphism from the space of skew-adjoint matrices in $M(n, \mathbf{C})$ to an open dense subset of $U(n)$, carrying skew adjoint elements of D into Γ . From this density, it results that, if $n > 1$, the linear group Γ is not solvable. By [Tits], it contains a non abelian free subgroup.

It remains to construct pairs $(D, *)$. A division algebra D with center k' admits an anti-involution $*$ inducing on k' the non trivial element $\text{Gal}(k'/k)$, if and only if its class $\text{cl}(D)$ in the Brauer group $\text{Br}(k')$ of k' has a trivial image by the norm map $N_{k'/k} : \text{Br}(k') \rightarrow \text{Br}(k)$ —see Appendix B. Class field theory provides an explicit computation of $\text{Br}(k)$, and of $N_{k'/k}$, and tells which elements of $\text{Br}(k')$ come from division algebras. From the explicit description it provides, existence of such D follows. A direct construction is given in Appendix C. When we choose an isomorphism of $D \otimes_k \mathbf{R}$ with $M(n, \mathbf{C})$, the involution $*$ becomes adjunction with respect to some hermitian form ϕ on \mathbf{C}^n , not necessarily positive definite: $\phi(ax, y) = \phi(x, a^*y)$. If h is self adjoint in D , $\text{int}(h^{-1}) \circ *$ is adjunction, with respect to the form $\phi_h(x, y) = \phi(hx, y)$. For suitable h , ϕ_h is positive definite and $(D, \text{int}(h^{-1}) \circ *)$ is of the type sought.

APPENDIX A

Consider $\phi : S' \cup S'' \rightarrow S - E$ as in the introduction, with S' and S'' two copies of the sphere S , and $\psi : S \rightarrow S'$ the obvious bijection. Consider as in the Schröder-Bernstein theorem the set S_e of points p in S with an even number of ancestors, namely for which there exists an integer $n \geq 0$ with $p \in \text{Im}(\phi \circ \psi)^n$ and $p \notin \text{Im}(\psi \circ (\phi \circ \psi)^n)$. Consider also the set S_0 of those p in S for which there exists $n \geq 0$ with $p \in \text{Im}(\psi \circ (\phi \circ \psi)^n)$ and $p \notin \text{Im}(\phi \circ \psi)^{n+1}$, and finally the set S_∞ of those p such that $p \in \text{Im}(\phi \circ \psi)^n$ for any $n \geq 0$. Consider similarly

$$S' \cup S'' = (S' \cup S'')_e \cup (S' \cup S'')_0 \cup (S' \cup S'')_\infty.$$

Then ψ induces a bijection from $S_e \cup S_\infty$ onto $(S' \cup S'')_0 \cup (S' \cup S'')_\infty$ and ϕ^{-1} from S_0 onto $(S' \cup S'')_e$. Combining these two we have a bijection $\chi : S \rightarrow S' \cup S''$ and a partition of S into finitely many pieces, the restriction of χ to each of these being a rotation.

APPENDIX B

Let K be a separable quadratic extension of a field k . We denote $x \mapsto \bar{x}$ the non trivial element $\text{Gal}(K/k)$. Let D be a simple algebra with dimension n^2 over its center K . We will check the criterion of the text, for the existence of an involution of the second kind on D , i.e. of an anti-involution $*$ of D , inducing $x \mapsto \bar{x}$ on K . The criterion is that $N_{K/k} \text{cl}(D) = 0$ in $\text{Br}(k)$.

Let us localize, for the étale topology, over $\text{Spec}(k)$. This means making large enough étale extensions of scalars $\otimes_k k'$, and keeping track of the functoriality in k' . The field K becomes the separable quadratic extension $K' = K \otimes_k k'$ of k' . The algebra D becomes $D' = D \otimes_k k'$, and is of the form $D' = \text{End}_{K'}(V')$, for V' a free module K' . The module V' is not determined uniquely by D' , only up to homotheties (the corresponding projective space is uniquely determined).

For any K -module M , let M^- be the module deduced from M by the extension of scalars $\bar{}: K \rightarrow K$, i.e. the module, unique up to unique isomorphism, provided with an anti-linear isomorphism $x \mapsto \bar{x}: M \xrightarrow{\sim} M^-$. Similarly for K' -modules. If $D' = \text{End}(V')$, then $D'^- = \text{End}(V'^-)$, and

$$(D \otimes_K D^-)' = \text{End}(V' \otimes V'^-).$$

Let W' be the fixed subspace of the anti-linear automorphism of $V' \otimes V'^-$ defined by $v \otimes \bar{w} \mapsto w \otimes \bar{v}$. It is the space of Hermitian forms on the dual of V' . One has $W' \otimes_{k'} K' = V' \otimes V'^-$. If $D_1 \subset D \otimes_K D^-$ is the fixed subspace of the anti-linear automorphism of $D \otimes_K D^-$ defined by $x \otimes \bar{y} \mapsto y \otimes \bar{x}$, then D'_1 is the k' -form of the K' -algebra $(D \otimes_K D^-)' = \text{End}(V' \otimes V'^-)$ deduced from the k' -form W' of the K' -module $V' \otimes V'^-$: $D'_1 = \text{End}_{k'}(W')$.

Involutions of the second kind on D' correspond one to one to non degenerate Hermitian forms on V' , taken up to a factor (in k'^*). Those, in turn, by the “dual form” construction, correspond to “non degenerate” elements of W' . Again, one has to take them up to a factor. The projective space $\mathbf{P}(W')$ over k' is determined up to unique isomorphism by D' . It is hence (this is the point of localisation) defined over k : $\mathbf{P}(W') = P \otimes_k k'$, functorially in k' . The k -points of P (rather, the non degenerate points) parametrize the involutions of the second kind on D .

The functorial isomorphism $D'_1 = \text{End}_{k'}(W')$ shows that P is the form of projective space (Severi-Brauer variety) attached to D_1 . It has a rational point, and is then the ordinary projective space, if and only if D_1 is a matrix algebra.

This shows that D has involutions of the second kind if and only if the class of D_1 in $\text{Br}(k)$ is trivial. This class is the required norm $N_{K/k}(\text{cl}(D))$. In the localization spirit, this can be deduced from the fact that the homothety by $\lambda \in K'^*$ of V' induces on W' the homothety by $N_{K'/k'}(\lambda) \in k'^*$.

APPENDIX C

For $n \geq 3$, examples can be obtained as follows: take $k' = \mathbf{Q}[\zeta]$, with $\zeta = \exp(2\pi i/n)$, and $k = k' \cap \mathbf{R}$. Fix $a, b \in k^*$ and let D be the k' -algebra generated by X, Y , subject to

$$\begin{aligned} X^n &= a, & Y^n &= b \\ XY &= \zeta YX. \end{aligned}$$

It admits the anti-involution $*$, inducing complex conjugation on k' , defined by $\zeta^* = \zeta^{-1}$, $X^* = X$, $Y^* = Y$. The algebra D is of the type we require, provided it is a division algebra. This happens already with $a, b \in \mathbf{Z}$: take for a a prime congruent to 1 mod n , and for b an integer whose residue mod a has in the cyclic group of order n $(\mathbf{Z}/(a))^*/(\mathbf{Z}/(a))^{*n}$ an image of exact order n . For instance $n = 3$, $a = 7$, $b = 2$. For $n = 2$, one proceeds similarly with $k' = \mathbf{Q}[i]$, $\zeta = -1$, a congruent to 1 mod 4 and b not a square mod a . For instance, $a = 5$, and $b = 2$. In each case, the assumption on a ensures that k' embed in the a -adic completion \mathbf{Q}_a of \mathbf{Q} , and the fact that D is a division algebra can be seen locally at a : $D \otimes_{k'} \mathbf{Q}_a$ is a division algebra with center \mathbf{Q}_a .

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