Quadric surfaces fibrations over the real projective line (joint work with Alena Pirutka)

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A basic non-closed field : $\mathbb{R}$, the reals.

Basic rational varieties over a closed field : quadrics ; total space of a family of positive dimensional quadrics over the projective line.

A basic birational invariant of smooth, projective, geometrically connected varieties X over the field $\mathbb{R}$: the number of connected components of the topological space $X(\mathbb{R})$.

Beniamino Segre (1951) : a smooth real cubic surface $X \subset \mathbb{P}^3_{\mathbb{R}}$ is $\mathbb{R}$-unirational, is $\mathbb{C}$-rational, but if $X(\mathbb{R})$ has two connected components, it is not $\mathbb{R}$-rational.

A smooth, projective, geometrically rational surface X over $\mathbb{R}$ is $\mathbb{R}$-rational if and only if $X(\mathbb{R})$ is nonempty and connected (Comessatti 1913, Silhol 1989). Proof uses birational classification.

Suppose $X(\mathbb{R})$ nonempty and connected and X is rational over $\mathbb{C}$.

Is X $\mathbb{R}$-rational ?

(Weaker)
Is X stably $\mathbb{R}$-rational ?

(Weaker)
Is X universally Chow-trivial : for any overfield $F/\mathbb{R}$, is the degree map $deg_F : CH_0(X_F) \to \mathbb{Z}$ an isomorphism ?
Enough to prove it for $F = \mathbb{R}(X)$.

Two classical problems.

$X = X_3 \subset \mathbb{P}^n_{\mathbb{R}}$, $n \geq 3$, a smooth cubic hypersurface. For $n = 4$, over $\mathbb{C}$ need not be rational ($n = 4$, Clemens–Griffiths). Rationality is known for various classes for all n odd, also over $\mathbb{R}$. Universal Chow triviality is known for some other classes (n odd or even). Just as stable rationality over $\mathbb{C}$, universal Chow triviality is an open problem for arbitrary X_3 over $\mathbb{C}$.

$X = X_{2,2} \subset \mathbb{P}^n_{\mathbb{R}}$, $n \geq 4$ a smooth complete intersection of two quadrics. Over $\mathbb{C}$, rational for all n. Over $\mathbb{R}$, for $n = 5$, works of Hassett-Tschinkel and Benoist-Wittenberg extending the Clemens-Griffiths method yield non-$\mathbb{R}$-rationality when X contains no real line (may happen with $X(\mathbb{R})$ connected), but the method gives no information on stable rationality or universal CH_0-triviality. For $n = 6$, Hassett-Kollár-Tschinkel establish $\mathbb{R}$-rationality when $X(\mathbb{R})$ is connected.

Let $X \to \mathbb{P}^1_{\mathbb{R}}$ be a family of quadrics of relative dimension $d \geq 1$. with smooth total space $X/\mathbb{R}$.

$X_{\mathbb{C}}$ is rational. If $X(\mathbb{R})$ is nonempty, X is $\mathbb{R}$-unirational.

If $X(\mathbb{R})$ is connected, is X rational over $\mathbb{R}$? Is it at least stably rational ? Is it universally CH_0-trivial ?

First negative answer

Let X be a smooth projective model of the variety given by the equation

$$x^2 + (1+u^2)y^2 - u(z^2+t^2) = 0$$

in $\mathbb{P}^3 \times \mathbb{A}^1$, coordinates $(x, y, z, t; u)$.

Real points cover exactly $u \geq 0$, real fibres are connected. This gives connectedness of the real locus. Over $u = 0$ and over $u = \infty$ the family degenerates to two conjugate planes. One computes $\mathrm{Br}(X)/\mathrm{Br}(\mathbb{R}) \neq 0$. The class $(-1, u) \in \mathrm{Br}(\mathbb{R}(X))$ is not in the image of $\mathrm{Br}(\mathbb{R})$ and is unramified.

This implies that X is not universally CH_0-trivial, hence not $\mathbb{R}$-rational and not even stably $\mathbb{R}$-rational.

A reminder on quadric surface fibrations

Given a field k, say of char. zero, and a quadric surface fibration $X \to \mathbb{P}^1_k$ the generic fibre is a smooth quadric $Y \subset \mathbb{P}^3_K$ where $K = k(\mathbb{P}^1)$. Let L/K be the discriminant quadratic extension. Thus $L = k(\Delta)$ for Δ a smooth projective curve over k. There is an associated quaternion class $\beta \in \mathrm{Br}(L)$. For any smooth plane (conic) section Z/K of Y, we have $Y \simeq R_{L/K}(Z_L)$.
The Brauer class $\beta \in \mathrm{Br}(L)$ is the image under $\mathrm{Br}(K) \to \mathrm{Br}(L)$ of the Brauer class of the conic Z/K in $\mathrm{Br}(K)$.
If $X/\mathbb{P}^1_k$ is a good fibration, we have $\beta \in \mathrm{Br}(\Delta)$.

Back to the problem : Second negative answer

What about "good fibrations", i.e. those $p : X \to \mathbb{P}^1_{\mathbb{R}}$ with X smooth and *all* geometric fibres irreducible quadric surfaces ? For these, $\mathrm{Br}(X/\mathrm{Br}(\mathbb{R}) = 0$.

In the 2021 paper by Hassett and Tschinkel, one finds examples of smooth $Y_{2,2} \subset \mathbb{P}^5_{\mathbb{R}}$ with $Y(\mathbb{R})$ connected and Y not $\mathbb{R}$-rational because of the extended Clemens–Griffiths obstruction.

One may birationally transform this into a good fibration into quadrics $X \to \mathbb{P}^1_{\mathbb{R}}$ with 6 geometric singular fibres. Here the quotient $\mathrm{Br}(X)/\mathrm{Br}(\mathbb{R}) = 0$, $X(\mathbb{R})$ is connected and X is not rational over $\mathbb{R}$.

Under the
Additional assumption : the class of $\beta \in \mathrm{Br}(\Delta) \subset \mathrm{Br}(k(\Delta))$ is not in the image of $\mathrm{Br}(k) \to \mathrm{Br}(k(\Delta))$
Wittenberg (2023) has a general non-rationality result along these lines for good quadric surface fibrations $X/\mathbb{P}^1_k$ with at least 6 geometric singular fibres, with application to the problem over the reals.
For instance $X/\mathbb{P}^1_{\mathbb{R}}$ given by the affine equation

$$(u^2-1)x^2+(u^2-2)y^2+(u^2-3)z^2=1$$

is not rational over $\mathbb{R}$ but $X(\mathbb{R})$ is connected.

The following problems remain :

Suppose $p : X \to \mathbb{P}^1_{\mathbb{R}}$ is a *good fibration*, i.e. X is smooth and all geometric fibres of p are irreducible quadrics (at worse simple cones), in which case there is no Brauer obstruction to rationality. Suppose $X(\mathbb{R})$ is connected.

(1) Is $X/\mathbb{R}$ stably rational ? Is it universally CH_0-trivial ?

(2) If the *additional assumption* fails, is X rational over $\mathbb{R}$?

In this talk, we shall concentrate on a very concrete case.
Let $p(u) \in \mathbb{R}[u]$ *a monic, nonconstant, even degree, separable, polynomial, strictly positive on* $\mathbb{R}$. One easily constructs a good family of quadric surfaces $X/\mathbb{P}^1_{\mathbb{R}}$ which is a birational model of the affine variety with equation

$$x^2 + y^2 + z^2 = u.p(u),$$

with the projection given by the u coordinate. For the purpose of this talk, we shall call such a fibration a "special quadric fibration". The space $X(\mathbb{R})$ is connected. The curve Δ is given by $w^2 = v.p(-v)$. The additional assumption fails. Indeed β is given by $(-1, -1)$.
One may show $H^i(\mathbb{R}, \mathbb{Z}/2)) \simeq H^i_{nr}(\mathbb{R}(X)/\mathbb{R}, \mathbb{Z}/2)$ for all $i \geq 0$.
Is X rational over $\mathbb{R}$? is X stably rational over $\mathbb{R}$? Is it universally CH_0-trivial ?

Theorem *Let* $X/\mathbb{P}^1_{\mathbb{R}}$ *be a special quadric fibration with affine equation*

$$x^2 + y^2 + z^2 = u.p(u).$$

Let $\Delta/\mathbb{R}$ *be the smooth projective curve with affine equation*

$$w^2 = v.p(-v).$$

Let W *the fourfold given by* $W := X \times_{\mathbb{R}} \Delta$.
(1) The cup-product $(u+v, -1, -1) \in H^3(\mathbb{R}(W), \mathbb{Z}/2)$ *is unramified over* $\mathbb{R}$. *It vanishes if and only if the rational function* $u + v \in \mathbb{R}(W)$ *(a sum of 6 squares) is a sum of 4 squares in* $\mathbb{R}(W)$.
(2) The following conditions are equivalent :
(2a) The variety X *is universally* CH_0*-trivial.*
(2b) For $F = \mathbb{R}(\Delta)$, *the map* $H^3(F, \mathbb{Z}/2) \to H^3_{nr}(F(X)/F, \mathbb{Z}/2)$ *is an isomorphism.*
(2c) The rational function $u + v \in \mathbb{R}(W)$ *is a sum of 4 squares.*

Ingredients of the proof. Results in algebraic K-theory and quadratic forms (Arason, Merkurjev, Suslin, Kahn-Rost-Sujatha).
[CTSk] CT-Skorobogatov, J. K-Theory 7 (1993).
Let $A_0(X) \subset CH_0(X)$ the group of degree zero cycle classes. Let $X/\mathbb{P}^1_k$ be a good nonconstant quadric surface fibration $X/\mathbb{P}^1_k$. Let $\Delta/\mathbb{P}^1_k$ and $\beta \in \mathrm{Br}(\Delta)[2] \subset H^2(k(\Delta, \mathbb{Z}/2)$ as above.
[CTSk] gives an injection
$\Phi : A_0(X) \hookrightarrow H^3_{nr}(k(\Delta)/k, \mathbb{Z}/2)/[H^1(k, \mathbb{Z}/2) \cup (\beta)]$.
For "special quadric fibrations", $\beta = (-1,-1)_k$ and $\Delta(k) \neq \emptyset$ (the *additional assumption* fails). Using precisely this, taking $k = \mathbb{R}(X)$, using [CTSk], we prove : **the image under Φ of the difference between the generic point of X and an $\mathbb{R}$-rational point above $u = \infty$ vanishes if and only if $(u+v, -1, -1) = 0 \in H^3(\mathbb{R}(W), \mathbb{Z}/2)$, if and only if $u+v$ is a sum of 4 squares in $\mathbb{R}(W)$.**

Universal CH_0-triviality via (2c) : hypotheses on $p(u)$ ensuring $u+v \in \mathbb{R}(W)$ is a sum of 4 squares

CH_0-triviality via sums of 4 squares, $p(u)$ of degree 2

Theorem. *Let* $p(u) = x^2 + au + b \in \mathbb{R}[u]$ *be separable and nonnegative. Let* $X/\mathbb{P}^1_{\mathbb{R}}$ *be a special quadric fibration with affine equation*

$$x^2 + y^2 + z^2 = u.p(u).$$

If $b \geq a^2/3$*, then* X *is universally* CH_0*-trivial.*

This covers the case $p(u) = u.(u^2 + 1)$ but does not cover the range $a^2/3 > b > a^2/4$.

Proof. Recall that Δ is defined by $w^2 = v.p(-v)$, and $W = X \times_{\mathbb{R}} \Delta$. In $\mathbb{R}(u, v)$,

$$up(u) + vp(-v) = (u+v)(u^2 - uv + v^2 + au - av + b) =$$

$$= (u+v)\left(\left(u + \frac{a-v}{2}\right)^2 + \frac{3}{4}\left(v - \frac{a}{3}\right)^2 + b - \frac{a^2}{3}\right).$$

Since $b - \frac{a^2}{3} \geq 0$.

$$r(u,v) = \frac{up(u) + vp(-v)}{u+v} = \left(u + \frac{a-v}{2}\right)^2 + \frac{3}{4}\left(v - \frac{a}{3}\right)^2 + b - \frac{a^2}{3}$$

is a sum of 3 squares in $\mathbb{R}(u, v)$. In $\mathbb{R}(W)$, we have

$$x^2 + y^2 + z^2 + w^2 = up(u) + vp(-v) = (u+v).r(u,v).$$

Thus $u + v$ is a sum of 4 squares in $\mathbb{R}(W)$.

CH_0-triviality via sums of 4 squares, $p(u)$ of higher degree

Theorem. *Let $X/\mathbb{P}^1_{\mathbb{R}}$ be a special quadric fibration with affine equation*

$$x^2 + y^2 + z^2 = u.p(u).$$

Let $p(u) = u^{2n} + \sum_{i=0}^{n-1} a_{2i} u^{2i}$. If $a_0 > 0$ and $a_{2i} \geq 0$ for all $0 < i < n$, then X is universally CH_0-trivial.

Recall that Δ is defined by $w^2 = v.p(-v)$, and $W = X \times_{\mathbb{R}} \Delta$. Under the hypothesis on the a_i's, one checks that the rational function $r(u,v) := (up(u) + vp(-v))/(u+v)$ in the variables (u,v) is sum of squares in $\mathbb{R}(u,v)$, hence is a sum of 4 squares in $\mathbb{R}(u,v)$ (Pfister, 1967). In the field $\mathbb{R}(W)$, one has

$$(u+v).r(u,v) = x^2 + y^2 + z^2 + w^2.$$

Thus $u + v$ is a sum of 4 squares in $\mathbb{R}(W)$.

Theorem. *Let* $X/\mathbb{P}^1_{\mathbb{R}}$ *be a special quadric fibration with affine equation*

$$x^2 + y^2 + z^2 = u.p(u).$$

Let $p(u) = u^{2n} + \sum_{i=0}^{2n-1} a_i u^{2i}$. *There exists a nonempty open set* $U \subset \mathbb{A}^{2n}(\mathbb{R})$ *such that for any* $(a_0, \ldots, a_{2n-1}) \in U$, *the associated variety* X *is universally* CH_0*-trivial.*

Universal Chow triviality via (2b) for $deg(p) = 2$.

Theorem. Let $p(u) \in \mathbb{R}[u]$ be a positive polynomial of degree 2. Let $X/\mathbb{P}^1_{\mathbb{R}}$ be a special quadric fibration with affine equation

$$x^2 + y^2 + z^2 = u.p(u).$$

Assume that the elliptic curve $E/\mathbb{R}$ defined by $z^2 = u.p(u)$ has "odd" complex multiplication, namely $End_{\mathbb{C}}E = \mathbb{Z}[\omega]$, with $\omega^2 - d\omega + c = 0$, $c, d \in \mathbb{Z}$ and d odd. Let Δ be defined by $w^2 = v.p(-v)$. Let $F = \mathbb{R}(\Delta)$. Then the map $H^3(F, \mathbb{Z}/2) \to H^3_{nr}(F(X)/F, \mathbb{Z}/2)$ is an isomorphism, and the variety X is universally CH_0-trivial.

Let F be any overfield of $\mathbb{R}$. We consider the birational conic bundle fibration $X_F \to \mathbb{P}^2_F$ induced by the projection map

$$(x, y, z, u) \mapsto (z, u) \in \mathbb{A}^2 \subset \mathbb{P}^2.$$

The fibration is ramified along the elliptic curve $E_F \subset \mathbb{P}^2_F$ with affine equation $z^2 = u.p(u)$ and possibly along the line at infinity. By general K-theory results on conics, and a standard analysis of residues and their functoriality, one shows that any class $\beta \in H^3_{nr}(F(X)/F, \mathbb{Z}/2)$ trivial at an F-point is the image of a class $\alpha \in H^3(F(\mathbb{P}^2), \mathbb{Z}/2)$ whose residues aways from E_F and the line at infinity of $\mathbb{P}^2_F$ are zero, and whose residue at E_F belongs to $\mathrm{Ker}[\mathrm{Br}(E_F) \to \mathrm{Br}(E_{F'})]$, where $F' := F(\sqrt{-1})$.

Let $G = \mathbb{Z}/2 = Gal(F'/F)$. We have a standard exact sequence

$$0 \to H^2(G, F') \to \mathrm{Ker}[\mathrm{Br}(E_F) \to \mathrm{Br}(E_{F'})] \to H^1(G, Pic(E_{F'})) \to 0.$$

Key technical result :

Proposition. *Assume that the elliptic curve $E/\mathbb{R}$ defined by $z^2 = u.p(u)$ has "odd" complex multiplication, namely $End_{\mathbb{C}} E = \mathbb{Z}[\omega]$, with $\omega^2 - d\omega + c = 0$, $c, d \in \mathbb{Z}$ and d odd. Let Δ be defined by $w^2 = v.p(-v)$. Let $F = \mathbb{R}(\Delta)$ and $F' = F(\sqrt{-1})$. Then $H^1(G, Pic(E_{F'})) = 0$.*

Under this hypothesis, the residue of α at E_F is of the shape $(\delta, -1)$ with $\delta \in F^*$. Over $\mathbb{A}^2_F$ the classes α and $(\delta, z^2 - up(u), -1)$ have the same residues. Their difference is thus in $H^3(F, \mathbb{Z}/2)$. Since $-(z^2 - up(u) = x^2 + y^2$ in $\mathbb{R}(X)$, the image of $(\delta, z^2 - up(u), -1)$ in $H^3(F(X), \mathbb{Z}/2)$ is $(\delta, -1, -1)$ hence comes from $H^3(F, \mathbb{Z}/2)$.

Note : If E has no complex multiplication, one computes $H^1(G, Pic(E_{F'})) = \mathbb{Z}/2$ and one proves $H^3_{nr}(F(X)/F, \mathbb{Z}/2))/H^3(F, \mathbb{Z}/2) = \mathbb{Z}/2(u+v, -1, -1)$. Whether this is zero or not remains an open question.

Comparing the two methods for $deg(p) = 2$

Let $E/\mathbb{R}$ be the elliptic curve with equation $z^2 = u.(u^2 + au + b)$, $a, b \in \mathbb{R}$. We assume $b > 0$ and $0 \leq a^2/b < 4$.
One computes

$$j(E) = 256[3 - (a^2/b)]^3/[4 - (a^2/b)] \in \mathbb{R}.$$

$0 \leq a^2/b \leq 3$ if and only if $j(E) \geq 0$, and then $0 \leq j(E) \leq 1728$.
$3 \leq a^2/b < 4$ if and only if $j(E) \leq 0$.
$a^2/b = 3$ corresponds to $j(E) = 0$ and $a^2/b = 0$ to $j(E) = 1728$

Chow triviality for $x^2 + y^2 + z^2 = u.(u^2 + au + b)$

First method (sum of squares)
This corresponds to any $0 \leq a^2/b \leq 3$, i.e. any $j(E) \geq 0$. Here $j(E)$ takes all values in $[0, 1728]$.

Second method (conic bundle fibration and E had odd complex multiplication). For $3 < a^2/b < 4$, i.e. $j(E) < 0$, this is the only method we have.
For E with odd complex multiplication, the invariant $j(E) \in \mathbb{R}$ is algebraic, the values it takes are in $[-\infty, 1728]$.
Theorem (Yu. Zarhin) : *these values are dense in* $[-\infty, 1728]$.
In a recent paper, Zarhin systematically analyzes odd versus even complex multiplication.

Examples for which we can prove X is universally CH_0-trivial

$p(u) = u^2 - 3u + 3$
E is given by $z^2 = (u-1)^3 + 1$. It has complex multiplication by ω with $\omega^2 + \omega + 1 = 0$. This it has odd CM. Here $j(E) = 0$. Both methods apply.

$p(u) = u^2 + 1$
E is given by $z^2 = u(u^2 + 1)$. It has $j(E) = 1728$. The first method applies. The curve E has CM by $\omega = \sqrt{-1}$, but $\omega^2 + 1 = 0$ hence it is not odd CM. The second method does not apply.

$p(u) = u^2 - 21u + 112$. Here $j(E) < 0$, the first method does not apply. The curve has complex multiplication by $\mathbb{Z}[\omega]$ with $\omega = (1 + \sqrt{-7})/2$. Here $\omega^2 - \omega + 2 = 0$, thus is odd CM, the second method applies.

Open problems

Let $X/\mathbb{R}$ be a smooth projective model of the variety with affine equation $x^2 + y^2 + z^2 = u.p(u)$, with $p(u)$ monic, separable, positive on $\mathbb{R}$, of degree at least 2. Let $\Delta/\mathbb{R}$ be the curve with affine equation $w^2 = v.p(-v)$.

Are the following equivalent conditions always satisfied ?

(a) The variety X is universally CH_0-trivial.

(b) The rational function $u + v \in \mathbb{R}(X \times_{\mathbb{R}} \Delta)$ (a sum of 6 squares) is a sum of 4 squares.

- Are there examples for which X is rational over $\mathbb{R}$?
- Are there examples for which X is not rational over $\mathbb{R}$?
- What about $deg(p) = 2$?
- What about $x^2 + y^2 + z^2 = u.(u^2 + 1)$?