

RATIONALITY OF FORMS OF $\overline{\mathcal{M}}_{0,n}$

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ABSTRACT. We study equivariant geometry and rationality of moduli spaces of points on the projective line, for twists associated with permutations of the points.

1. INTRODUCTION

In this note, we strengthen a theorem of Florence–Reichstein [FR18] concerning rationality of moduli spaces. They consider *forms* of $\overline{\mathcal{M}}_{0,n}$, i.e., varieties over nonclosed fields F which are isomorphic to the moduli space of n points on $\mathbb{P}^1$ over an algebraic closure of F . These forms are obtained by twisting via Galois actions permuting the points over F . The main results of [FR18] are:

- if $n \geq 5$ is odd, and F is infinite of characteristic $\neq 2$, then every form over F is rational;
- if $n \geq 6$ is even, and F has nontrivial 2-torsion in its Brauer group and contains fourth roots of unity, then there exists a form X of $\overline{\mathcal{M}}_{0,n}$ over F such that X is not retract rational over F .

These were inspired by a classical theorem of Enriques, Manin, and Swinnerton-Dyer concerning rationality of twists of $\overline{\mathcal{M}}_{0,5}$, a del Pezzo surface of degree 5, over any field F . The proof for $n \geq 5$ uses (a twisted form of) the Gelfand-MacPherson correspondence, and techniques developed in connection with Noether’s problem for twisted forms of the groups in question.

By [FR18], every form over an infinite field F is unirational over F . It is known that every form of $\overline{\mathcal{M}}_{0,6}$ over $\mathbb{R}$ is rational [Avi20, Proposition 2.9]; see Corollary 21 for generalizations.

Here, we strengthen their conclusions in two directions: we prove rationality in several situations not addressed in [FR18]. On the other hand, we show failure of rationality via Galois cohomology in instances not covered by [FR18], e.g., where the Brauer group of F is trivial.

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An important ingredient throughout is a theorem of [BM13]:

$$\mathrm{Aut}(\overline{\mathcal{M}}_{0,n}) = \mathfrak{S}_n, \quad n \geq 5,$$

acting via permutations of the n points on $\mathbb{P}^1$. In particular, Galois twists of $\overline{\mathcal{M}}_{0,n}$ factor through subgroups of $\mathfrak{S}_n$, and there is a close link between rationality of twists and linearizability of G -actions on $\overline{\mathcal{M}}_{0,n}$; see [DR15] for a general discussion of such connections. In both situations, there is an action of a finite group on the geometric Picard group

$$\mathrm{Pic}(\overline{\mathcal{M}}_{0,n}),$$

via a subgroup of $\mathfrak{S}_n$.

We present several stable rationality and linearizability results, including Propositions 3 and 5 (based on the Kapranov construction) and Theorem 24 (using torsors and quotients). Section 3 focuses on geometric constructions. One rationality construction uses Schubert calculus and the geometry of Grassmannians; Theorem 14 extends results of [FR18] to small fields (Corollary 16) and some point configurations in higher-dimensional projective spaces (Corollary 17). Another relies on fibration structures; see Theorem 20. We close with a comprehensive discussion of the $n = 6$ case (Theorem 34).

For nonrationality/nonlinearizability, we focus on situations where the twisted moduli spaces are toric via the Losev-Manin construction [LM00]. We utilize cohomological **(H1)** and **(SP)**-obstructions (see Section 5): In the arithmetic context, the group is replaced by the absolute Galois group of the ground field F and the Picard module by the geometric Picard module. We focus on *even* n :

Theorem 1 (Corollary 29 and Theorem 30). *For every even $n \geq 6$ there exists a subgroup $G = C_2^2 \subset \mathfrak{S}_n$ such that*

$$H^1(G, \mathrm{Pic}(\overline{\mathcal{M}}_{0,n})) = \mathbb{Z}/2.$$

In particular,

- *for all subgroups of $\mathfrak{S}_n$ containing G , the corresponding action is not stably linearizable,*
- *for all fields F admitting a Galois extension L/F with Galois group $\mathrm{Gal}(L/F) \simeq G$ there exists a form X of $\overline{\mathcal{M}}_{0,n}$ over F such that X is not retract rational over F .*

Indeed, nonvanishing group cohomology is an obstruction to (stable) linearizability, see, e.g., [BP13, Corollary 2.5.2.]. In the context of nonclosed fields, one can find a twist X of $\overline{\mathcal{M}}_{0,n}$ over F so that the

corresponding Galois action on the geometric Picard group of X factors through the prescribed action of G . This yields nontrivial Galois cohomology, which in turn obstructs retract rationality of X over F . In particular, our result applies to fields F with *trivial* Brauer group, e.g., $F = \mathbb{C}(t)$.

Remark 2. Florence and Reichstein have pointed out that the proof of [FR18, Theorem 1.2(b)] – giving forms of $\overline{\mathcal{M}}_{0,n}$ that are not retract rational – implicitly assumes that the base field contains fourth roots of unity. These are needed to harmonize sign choices in the quaternion algebras constructed in [FR18, Section 7]. Indeed, the field $\mathbb{R}$ has Brauer group $\mathbb{Z}/2\mathbb{Z}$ but real forms of $\overline{\mathcal{M}}_{0,n}$ are rational (see Corollary 21).

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2. $\mathfrak{S}_n$ -EQUIVARIANT GEOMETRY

We recall some terminology: Let G be a finite group acting regularly on a projective variety X . Assume the action is generically free. The action is *linearizable* if X is equivariantly birational to the projectivization $\mathbb{P}(V)$ of a linear representation V of G on a vector space. It is *stably linearizable* if $X \times \mathbb{P}^r$ – where G acts trivially on the second factor – is linearizable. By the No-Name Lemma, this is equivalent to saying that $X \times V$ is linearizable for some linear representation V of G , or that the total space of a G -equivariant vector bundle $E \rightarrow X$ is linearizable.

Stable linearizability and stable rationality of twisted forms are tightly linked [DR15, Theorem 1.1(d)]: A G -action on X is stably linearizable over F iff for every infinite field K/F and every form of X over K obtained via twisting by the G -action, the resulting variety is stably rational.

Kapranov blowup. We make use of the Kapranov blowup realization

$$\beta_n : \overline{\mathcal{M}}_{0,n} \rightarrow \mathbb{P}^{n-3}, \quad n \geq 4,$$

where β_n is an iterated blowup of $n - 1$ general points on $\mathbb{P}^{n-3}$, lines through pairs of points, etc., see, e.g., [HT02, Section 3.1]. Precisely,

we regard

$$\mathbb{P}^{n-3} = \mathbb{P}(k[\mathfrak{S}_{n-1}]/(1, \dots, 1)),$$

so that the $\mathfrak{S}_{n-1}$ -action is linear. Boundary divisors D_I are labeled by partitions

$$[1, \dots, n] = I \sqcup I^c, \quad |I|, |I^c| \geq 2.$$

Recall that the Picard group $\text{Pic}(\overline{\mathcal{M}}_{0,n})$ has rank $2^{n-1} - \binom{n}{2} - 1$, and an explicit basis is given by

$$\{H, E_{i_1}, E_{i_1, i_2}, \dots, E_{i_1, \dots, i_{n-4}}\},$$

where H is the (pullback of the) hyperplane class on $\mathbb{P}^{n-3}$, and the other elements are (classes of) exceptional divisors from blowups of points, lines, etc. The boundary divisors D_I expressed in this basis are

$$D_{i_1, \dots, i_k, n} = E_{i_1, \dots, i_k}, \quad \{i_1, \dots, i_k\} \subset \{1, \dots, n-1\}, \quad k \leq n-4,$$

and

$$[D_{i_1, \dots, i_{n-3}, n}] = L - E_{i_1} - E_{i_2} - \dots - E_{i_1, \dots, i_{n-4}} - E_{i_2, \dots, i_{n-3}}.$$

The $\mathfrak{S}_n$ -action on $\text{Pic}(\overline{\mathcal{M}}_{0,n})$ is best understood in terms of the natural $\mathfrak{S}_n$ -action on the boundary divisors via permutations of indices of D_I . In particular, there is a distinguished $\mathfrak{S}_{n-1} \subset \mathfrak{S}_n$ acting via permutation of indices on E_i , for $i \in \{1, \dots, n-1\}$.

The Kapranov construction has applications to linearizability:

Proposition 3. *Suppose that $G \subseteq \mathfrak{S}_{n-1}$ acts on $\overline{\mathcal{M}}_{0,n}$ leaving the n th point invariant. Then the action of G is linearizable.*

For $n = 2m + 1$ and $G \subseteq \mathfrak{S}_{2m+1}$, the G -action on $\overline{\mathcal{M}}_{0,n}$ is stably linearizable.

More generally, for $G \subseteq \mathfrak{S}_n$ leaving an odd cycle invariant, the G -action on $\overline{\mathcal{M}}_{0,n}$ is stably linearizable.

Proof. The first assertion reflects the fact that the Kapranov morphism β_n is $\mathfrak{S}_{n-1}$ invariant and the $\mathfrak{S}_{n-1}$ -action on $\mathbb{P}^{n-3}$ is linear. The second assertion is a special case of the third. For the third statement, consider the universal curve

$$\overline{\mathcal{C}}_{0,n} \rightarrow \overline{\mathcal{M}}_{0,n}.$$

Lemma 4. *Let $G \subset \mathfrak{S}_n$ act on $\overline{\mathcal{M}}_{0,n}$ by permutation of the marked points. Then there is a canonical lift of the action to the universal curve*

$$\phi : \overline{\mathcal{C}}_{0,n} \rightarrow \overline{\mathcal{M}}_{0,n}.$$

We prove the lemma. Interpreting $\overline{\mathcal{C}}_{0,n} = \overline{\mathcal{M}}_{0,n+1}$, we have

$$\mathrm{Aut}(\overline{\mathcal{C}}_{0,n}) = \mathfrak{S}_{n+1} \supset \mathfrak{S}_n \hookrightarrow \mathrm{Aut}(\overline{\mathcal{M}}_{0,n}),$$

with the last inclusion an equality when $n \geq 5$. The induced action on $\mathrm{Aut}(\overline{\mathcal{C}}_{0,n})$ is equivariant under forgetting the $(n+1)$ st point.

Returning to the Proposition, we assume that G leaves an odd cycle invariant. Then the forgetting morphism ϕ – an étale $\mathbb{P}^1$ -bundle over $\mathcal{M}_{0,n}$ – admits a multisection of odd degree. It must therefore be the projectivization of a rank-two G -equivariant vector bundle over $\mathcal{M}_{0,n}$. However, we have already seen that the G -action on $\overline{\mathcal{C}}_{0,n} = \overline{\mathcal{M}}_{0,n+1}$ is linearizable. We conclude then that $\overline{\mathcal{M}}_{0,n}$ is stably linearizable. $\square$

A similar argument yields dividends for the Galois-theoretic question:

Proposition 5. *Let L/F be a Galois extension with Galois group Γ . Fix a representation*

$$\rho : \Gamma \rightarrow \mathfrak{S}_n$$

and let ${}^\rho\overline{\mathcal{M}}_{0,n}$ denote the corresponding twist of $\overline{\mathcal{M}}_{0,n}$ defined over F .

- *If ρ factors through an $\mathfrak{S}_{n-1} \subset \mathfrak{S}_n$ then ${}^\rho\overline{\mathcal{M}}_{0,n}$ is rational over F .*
- *If n is odd then $\mathbb{P}^1 \times {}^\rho\overline{\mathcal{M}}_{0,n}$ is rational. The same holds if ρ leaves an odd cycle invariant.*

This gives a weaker version of [FR18, Theorem 1.2]; however, our statement is valid over a finite field as well. See Remark 22 below for a related result.

Proof. The Kapranov morphism $\beta : \overline{\mathcal{M}}_{0,n} \rightarrow \mathbb{P}^{n-3}$ is equivariant for $\mathfrak{S}_{n-1}$, which acts linearly on the target. Thus it descends to

$${}^\rho\overline{\mathcal{M}}_{0,n} \xrightarrow{\sim} \mathbb{P}^{n-3}$$

over F , proving rationality. For the second assertion, the Kapranov construction yields

$${}^\rho\overline{\mathcal{C}}_{0,2m+1} \xrightarrow{\sim} \mathbb{P}^{2m-1};$$

moreover

$${}^\rho\overline{\mathcal{C}}_{0,2m+1} \rightarrow {}^\rho\overline{\mathcal{M}}_{0,2m+1}$$

is a $\mathbb{P}^1$ -bundle over a Zariski open subspace of the base. (The generic fiber is a smooth genus zero curve with a cycle of odd degree.) In particular, $\mathbb{P}^1 \times {}^\rho\overline{\mathcal{M}}_{0,2m+1}$ is rational over F . $\square$

Example 6. Let $\mathfrak{S}_n$ act on $\overline{\mathcal{M}}_{0,n}$, for $n \geq 5$. This action is not linearizable since $\mathfrak{S}_n$ does not act linearly and generically freely on $\mathbb{P}^{n-3}$. Indeed, the smallest faithful representation of $\mathfrak{S}_n$ has dimension $n - 1$. When $n = p$ is a prime, then even the action of the Frobenius subgroup $\mathfrak{F}_p = \text{Aff}_1(\mathbb{F}_p) \subset \mathfrak{S}_p$ is not linearizable, for the same reason.

The Losev-Manin construction. This construction [LM00], [Has03, Section 6.4] is a distinguished factorization

$$\beta_n : \overline{\mathcal{M}}_{0,n} \rightarrow \overline{L}_n \rightarrow \mathbb{P}^{n-3},$$

where we blow up linear subspaces spanned by just $(n - 2)$ points in linear general position. (Note that our indexing of $\overline{L}_n$ differs from [LM00].) The first arrow contracts the boundary divisors

$$D_{i_1, \dots, i_k, (n-1), n}, \{i_1, \dots, i_k\} \subset \{1, \dots, n - 2\}, \quad k \leq n - 5,$$

by allowing points indexed by

$$\{1, \dots, n - 2\} \setminus \{i_1, \dots, i_k\}$$

to coincide.

We record some properties:

- $\overline{L}_n$ is toric [LM00, Section 2.6];
- the Losev-Manin construction is equivariant under $\mathfrak{S}_{n-2} \times \mathfrak{S}_2 \subset \mathfrak{S}_n$, realized as permutations of $\{1, \dots, n - 2\}$ and $\{n - 1, n\}$ [LM00, Theorem 2.5(b)].

The constructions of Losev-Manin give an explicit realization of the torus $\mathbb{T}$ and its character module $\mathfrak{X}^*(\mathbb{T})$. Let P denote the permutation module for $\mathfrak{S}_{n-2}$ associated with the first $n - 2$ letters and L the non-trivial rank-one module for $\mathfrak{S}_2$ corresponding to $n - 1$ and n . We regard these as modules for $\mathfrak{S}_{n-2} \times \mathfrak{S}_2$. Consider the short exact sequence

$$0 \rightarrow P_0 \rightarrow P \rightarrow \mathbb{Z} \rightarrow 0$$

associated with summing over the $n - 2$ letters. Then we have

$$(2.1) \quad \mathfrak{X}^*(\mathbb{T}) = L \otimes P_0.$$

Indeed, we may describe the open torus orbit in $\overline{L}_n$ in geometric terms: We identify the points $n - 1$ and n as 0 and ∞ and the first $n - 2$ points as elements of

$$\text{Hom}(P, \mathbb{P}^1 \setminus \{0, \infty\}) = \text{Hom}(P, \mathbb{T}_L),$$

where $\mathbb{T}_L$ is the rank-one torus associated with L . To get moduli, we quotient out by the diagonal action of $\mathbb{T}_L$.

We record one last observation: Consider the Kapranov blowups associated with points $n-1$ and n :

$$\beta_n[n-1], \beta_n[n] : \overline{\mathcal{M}}_{0,n} \rightarrow \mathbb{P}^{n-3}.$$

These two maps are related by an elementary Cremona transformation

$$\text{Cr} : \mathbb{P}^{n-3} \dashrightarrow \mathbb{P}^{n-3}$$

associated with the points indexed by $\{1, \dots, n-2\}$. This is equivariant for the $\mathbb{T}$ -actions and we obtain a birational contraction

$$\overline{L}_n \rightarrow \text{Graph}(\text{Cr}).$$

We summarize this as follows:

Proposition 7. *Consider a twist of $\overline{\mathcal{M}}_{0,n}$ associated with a subgroup of $\mathfrak{S}_n$ leaving a pair of points invariant. This variety is necessarily toric, realized as a twist of the Losev-Manin space.*

This applies in both equivariant and Galois-theoretic situations.

The Gelfand-MacPherson correspondence. Our main source is Kapranov [Kap93].

Let $\text{Mat}(2, n)$ denote the $2 \times n$ matrices. The group GL_2 acts via multiplication from the left

$$A \cdot M \mapsto AM$$

and the torus $\mathbb{T} = \mathbb{G}_m^n$ acts via multiplication from the right

$$M \cdot T \mapsto MT, \quad T = \text{diag}(t_1, \dots, t_n).$$

Considering the action by the product $\text{GL}_2 \times \mathbb{G}_m^n$, with the elements

$$(t^{-1} I_2, \text{diag}(t, t, \dots, t))$$

in the kernel, we obtain a faithful action of the quotient group

$$(\text{GL}_2 \times \mathbb{G}_m^n) / \mathbb{G}_m.$$

We have an exact sequence

$$1 \rightarrow \mu_2 \rightarrow \text{SL}_2 \times \mathbb{G}_m^n \rightarrow (\text{GL}_2 \times \mathbb{G}_m^n) / \mathbb{G}_m \rightarrow 1,$$

where

$$\mu_2 = (-I_2, \text{diag}(-1, -1, \dots, -1)).$$

The invariant theory quotient is

$$\text{SL}_2 \backslash \text{Mat}(2, n) = \text{CGr}(2, n),$$

the cone over the Grassmannian $\text{Gr}(2, n)$ in its Plücker imbedding. The residual action of $\mathbb{G}_m^n$ on this cone has generic stabilizer μ_2 ; the action

on the Grassmannian has generic stabilizer $\mathbb{G}_m = \text{diag}(t, t, \dots, t)$. On the other hand, the geometric invariant theory quotient

$$\text{Mat}(2, n) // \mathbb{G}_m, \quad \mathbb{G}_m = \text{diag}(t, t, \dots, t)$$

yields $(\mathbb{P}^1)^n$ with factors induced by the columns of the matrix. The residual SL_2 acts on this product with the distinguished linearization introduced above, which is $\mathfrak{S}_n$ -symmetric. Again, this action fails to be faithful, as $\mu_2 \subset \text{SL}_2$ acts trivially.

The Gelfand-MacPherson construction yields isomorphisms

$$(2.2) \quad (\text{CGr}(2, n) \setminus \{0\}) / \mathbb{G}_m^n \xrightarrow{\sim} \text{SL}_2 \backslash \backslash (\mathbb{P}^1)^n,$$

where both sides are interpreted as GIT quotients [Kap93, 2.4.7]. Note that we have numerous choices for how to linearize the actions on the left- and right-hand sides, reflecting linearizations of the torus action and ample line bundles on the product; Kapranov's result makes clear how to identify these choices. Let X_n denote the quotient arising from the $\mathfrak{S}_n$ -symmetric linearization.

Recall that the stable and strictly semistable loci on $(\mathbb{P}^1)^n$ are easily identified

$$(2.3) \quad (p_1, \dots, p_n) \text{ stable if there is no point with multiplicity } \geq \frac{n}{2}.$$

It is semistable if all points have multiplicity $\leq \frac{n}{2}$. For odd n , stable and semistable coincide; for even $n = 2m$, collections of points where m indices coincide are strictly stable, with closed orbits consisting of collections where

$$p_{i_1} = \dots = p_{i_m}, \quad p_{i_{m+1}} = \dots = p_{i_{2m}}, \quad \{i_1, \dots, i_{2m}\} = \{1, \dots, 2m\}.$$

In particular, $X_{2m}, m \geq 3$ has $\frac{1}{2} \binom{2m}{m}$ distinguished singular points over which the orbits are identified.

The stable loci on the Grassmannian $\text{Gr}(2, n)$ for the action of $\mathbb{G}_m^n \cap \text{SL}_n$ may be described as well: Choose a basis diagonalizing the torus action and let $(A_{ij}), 1 \leq i < j \leq n$ denote the associated Plücker coordinates. The point (A_{ij}) is stable if there are

- (1) no index i with $A_{ij} = 0$ for every j ; and
- (2) no subset $I \subset \{1, \dots, n\}$ with $|I| \geq \frac{n}{2}$ and $A_{ij} = 0$ for all $i, j \in I$.

These descriptions yield an $\mathfrak{S}_n$ -equivariant stratified blowup [Kap93, 0.4.3, 4.1.8]

$$\beta : \overline{\mathcal{M}}_{0,n} \rightarrow X_n.$$

This blows down all the boundary divisors D_I except those where $|I|$ or $|I^c| = 2$. The divisors D_I with $2|I| = n$ are collapsed to the distinguished singular points $\Sigma \subset X_{2m}$ where $m = |I|$ and $n = 2m$.

The Gelfand-MacPherson construction is a powerful tool for computing class groups. The induced homomorphism

$$(2.4) \quad \beta_* : \text{Pic}(\overline{\mathcal{M}}_{0,n}) = \text{Cl}(\overline{\mathcal{M}}_{0,n}) \rightarrow \text{Cl}(X_n)$$

is surjective because β is a fibration away from the distinguished singular points. Thus we get an exact sequence

$$(2.5) \quad 0 \rightarrow N \rightarrow M \rightarrow Q \rightarrow 0,$$

where

$$N = \ker(\beta_*), \quad M = \text{Pic}(\overline{\mathcal{M}}_{0,n}).$$

In particular, N is generated by the D_I where $|I|, |I^c| \neq 2$. We can easily compute Q is well. Write

$$\mathfrak{X}^*(\mathbb{G}_m^n) = \mathbb{Z}g_1 + \cdots + \mathbb{Z}g_n,$$

so the quotient acting faithfully on the $\text{CGr}(2, n)$ has characters

$$\left\{ \sum a_i g_i : a_i \in \mathbb{Z}, \sum a_i \equiv 0 \pmod{2} \right\}.$$

These give rise to line bundles on $X_n \setminus \Sigma$ and divisor classes on the full space. Thus we deduce that

$$Q \subset \mathbb{Z}[\mathfrak{S}_n / \mathfrak{S}_{n-1}]$$

as an index-two subgroup. Note that the element $g_{i_1} + g_{i_2}, i_1 \neq i_2$ corresponds to the boundary divisor $D_{i_1 i_2}$; indeed, this locus is cut out by the 2×2 determinant on $\mathbb{P}_{i_1}^1 \times \mathbb{P}_{i_2}^1$. Since Q is an index-two subgroup of a permutation module, we have

$$(2.6) \quad H^1(G, Q) = 0 \text{ or } \mathbb{Z}/2\mathbb{Z} \quad \text{and} \quad H^1(G, M) = 0 \text{ or } \mathbb{Z}/2\mathbb{Z}.$$

When n is odd, i.e., $n = 2m + 1$, then X_{2m+1} is nonsingular,

$$\text{Pic}(X_{2m+1}) = \text{Cl}(X_{2m+1}),$$

and β is the iteration of a sequence of blowups along smooth disjoint centers. Precisely, we blow up the strata where m points coincide, then where $m - 1$ points coincide, etc. (see [Has03, §8]); this is naturally equivariant under the $\mathfrak{S}_{2m+1}$ -action. By the blowup formula [Ful98, Prop. 6.7], we have

$$\text{Pic}(\overline{\mathcal{M}}_{0,2m+1}) = \text{Pic}(X_{2m+1}) \oplus \{\text{free group on the exceptional divisors}\}.$$

We summarize this in algebraic terms:

Proposition 8. *For odd $n = 2m + 1$, the exact sequence (2.5) splits $\mathfrak{S}_{2m+1}$ -equivariantly:*

$$M \simeq N \oplus Q.$$

On the other hand, for n even, e.g., $n = 6$, there are examples of $G \subset \mathfrak{S}_n$ such that the sequence does not split equivariantly, since in those cases $H^1(G, Q) \neq 0$ while $H^1(G, M) = 0$ (see Example 27).

We return to the isomorphism (2.2) over nonclosed fields. Up to this point, we have been working with schemes but this is compatible with the μ_2 -gerbe structure over the dense open subset where this is the full stabilizer. When $n = 2m$ the stabilizers may be larger, e.g., where the sequence in $(\mathbb{P}^1)^{2m}$ consists of m copies of a pair of points conjugate over a quadratic extension. In the cone over the Grassmannian, $2\binom{m}{2} = m^2 - m$ coordinates vanish and the m^2 remaining coordinates are equal to the determinant of the conjugate pair.

We can apply the same analysis to nonsplit actions. This includes working over nonclosed fields, where the n points are a Galois orbit, or in the equivariant context, where the n points are invariant under the action of a finite group. In the former situation, over a ground field F of characteristic zero, let E/F be an étale algebra of degree n classified by a representation of the Galois group $\Gamma_F \rightarrow \mathfrak{S}_n$. We replace the group $(\mathrm{GL}_2 \times \mathbb{G}_m^n)/\mathbb{G}_m$ with $(\mathrm{GL}_2 \times R_{E/F}\mathbb{G}_m)/\mathbb{G}_m$ and $(\mathbb{P}^1)^n$ with $R_{E/F}\mathbb{P}^1$ (see [FR18, §4]). Note however that twisting $\mathrm{Mat}(2, n) = \mathbb{A}^{2n}$ yields a variety isomorphic to $\mathbb{A}^{2n}$, albeit with an action of a nonsplit torus.

The μ_2 -gerbe has an explicit geometric interpretation along $\mathcal{M}_{0,n}$: It is encoded by the universal family

$$\phi : \mathcal{C}_{0,n} \rightarrow \mathcal{M}_{0,n},$$

a conic fibration, in general.

3. RATIONALITY CONSTRUCTIONS

In this section, we work over an arbitrary field F , and we let Γ be the absolute Galois group of F .

Schubert calculus background. Our reference is [Kly85].

Consider the Grassmannian $\mathrm{Gr} = \mathrm{Gr}(p, p + q)$ of p -dimensional subspaces of a vector space of dimension $p + q$. The maximal torus $\mathrm{T} = \mathbb{G}_m^{p+q}$ acts diagonally on the vector space. Let X be a generic orbit in Gr .

We set combinatorial notation: Consider shuffles of $\{1, \dots, p+q\}$

$$I = \{i_1 < \dots < i_p\}, \quad J = \{j_1 < \dots < j_q\}.$$

For each such shuffle, record the pairs (k, ℓ) , $k = 1, \dots, p$, $\ell = 1, \dots, q$, such that $i_k > j_\ell$. Write

$$\lambda_{p+1-k} = \#\{\ell : j_\ell < i_k\}$$

and note that

$$q \geq \lambda_1 \geq \dots \geq \lambda_p.$$

Write $\lambda = (\lambda_1, \dots, \lambda_p)$ and use the same notation for the associated Young diagram, which fits into a $p \times q$ rectangle. The *height* $\text{ht}(\lambda)$ is the number of indices i with $\lambda_i > 0$. Set $|\lambda| = \lambda_1 + \dots + \lambda_p$ and let σ_λ denote the associated Schubert cycle on Gr , a class in $H^{2|\lambda|}(\text{Gr}, \mathbb{Z})$.

We recall dimension formulae for representations. Let V be an n -dimensional vector space and $\lambda = (\lambda_1, \dots, \lambda_n)$ a partition of $|\lambda|$ as above; in particular, $n \geq \text{ht}(\lambda)$. The Schur functor $\mathbb{S}_\lambda(V)$ is a representation of $\text{SL}(V)$ with dimension [FH91, Theorem 6.3, Exercise 6.4]:

$$\begin{aligned} d_n(\lambda) := \dim \mathbb{S}_\lambda(V) &= \prod_{1 \leq i < j \leq n} \frac{\lambda_i - \lambda_j + j - i}{j - i} \\ &= \prod_{(a,b)} \frac{n - a + b}{h_{ab}}, \end{aligned}$$

where $a = 1, \dots, n$ labels the rows of λ (from top to bottom), b labels the columns (from left to right), and h_{ab} labels the “hook length”. This is defined as the number of boxes immediately below and to the right of a given box, including the box. For $n < \text{ht}(\lambda)$ we set $d_n(\lambda) = 0$.

For example, when $\lambda = (\lambda_1, \lambda_2, 0, \dots)$ and $n \geq 2$,

$$\begin{aligned} d_n(\lambda_1, \lambda_2) &= \frac{(n-1+1) \cdots (n-1+\lambda_1)}{1 \cdots (\lambda_1 - \lambda_2)(\lambda_1 - \lambda_2 + 2) \cdots (\lambda_1 + 1)} \frac{(n-2+1) \cdots (n-2+\lambda_2)}{1 \cdots \lambda_2} \\ &= \binom{n-1+\lambda_1}{\lambda_1} \binom{n-2+\lambda_2}{\lambda_2} \frac{\lambda_1 - \lambda_2 + 1}{\lambda_1 + 1}. \end{aligned}$$

For instance,

$$d_n(2, 1) = \frac{(n+1)n(n-1)}{3}, \quad n \geq 1.$$

Another combinatorial quantity is

$$m_k(\lambda) := \sum_{i=0}^k (-1)^i \binom{|\lambda|+1}{i} d_{k-i}(\lambda).$$

If λ has height k then $m_k(\lambda) = d_k(\lambda)$, as the terms in the sum with $i > 0$ are zero.

We record a fact that we will use repeatedly in examples:

Proposition 9. *Fix an integer $d \geq 0$. If $f(x)$ is a polynomial of degree $\leq d$ then the $(d+1)$ th iterated difference*

$$\sum_{i=0}^{d+1} (-1)^i \binom{d+1}{i} f(x-i) = 0.$$

When $\lambda = (\lambda_1, \lambda_2, 0, \dots)$ we have:

$$m_k(\lambda_1, \lambda_2) = \sum_{i=0}^k (-1)^i \binom{\lambda_1 + \lambda_2 + 1}{i} \binom{k-i-1+\lambda_1}{\lambda_1} \binom{k-i-2+\lambda_2}{\lambda_2} \frac{\lambda_1 - \lambda_2 + 1}{\lambda_1 + 1}.$$

For instance, when $\lambda_1 = 2$ and $\lambda_2 = 1$ we have

$$\begin{aligned} m_k(2, 1) &= \sum_{i=0}^k (-1)^i \binom{4}{i} \frac{(k-i+1)(k-i)(k-i-1)}{3} \\ &= 2 \left(\binom{k+1}{3} - 4 \binom{k}{3} + 6 \binom{k-1}{3} - 4 \binom{k-2}{3} + \binom{k-3}{3} \right) \\ &= \begin{cases} 2 & \text{if } k = 2, \\ 0 & \text{if } k \geq 3. \end{cases} \end{aligned}$$

For general λ_1 and λ_2 ,

$$m_2(\lambda_1, \lambda_2) = \lambda_1 - \lambda_2 + 1$$

and

$$m_3(\lambda_1, \lambda_2) = \frac{\lambda_1(\lambda_2 - 1)(\lambda_1 - \lambda_2 + 1)}{2}.$$

Theorem 10. [Kly85, Theorem 5] *If X is the generic torus orbit in $\text{Gr} = \text{Gr}(p, p+q)$ and λ is a partition with $|\lambda| = p+q-1$ then*

$$[X] \cdot \sigma_\lambda = m_p(\lambda).$$

For example, take $p = 2$. For $q = 2$

$$[X] \cdot \sigma_{21} = 2$$

and when $q = 3$ we have

$$[X] \cdot \sigma_{22} = 1, \quad [X] \cdot \sigma_{31} = 3.$$

For general q , we have $\lambda_1 \geq \lambda_2 = q + 1 - \lambda_1 \geq 0$, i.e.,

$$\frac{q+1}{2} \leq \lambda_1 \leq q+1.$$

Here we have

$$[X] \cdot \sigma_{\lambda_1, q+1-\lambda_1} = 2\lambda_1 - q;$$

in particular, when $q = 2m - 1$ and $\lambda_1 = m$ we find

$$[X] \cdot \sigma_{mm} = 1.$$

Remark 11. The signs in the formula for $m_k(\lambda)$ obscure the positivity of the result. An alternate formula [BF17, Theorem 5.1] makes this clearer:

$$[X] = \sum_{\lambda \subset (q-1)^{p-1}} \sigma_\lambda \sigma_{\tilde{\lambda}},$$

where $\tilde{\lambda}$ is the complement to λ in the rectangle $(q-1)^{p-1}$:

$$\lambda = (\lambda_1, \dots, \lambda_{p-1}), \quad \tilde{\lambda} = (q-1-\lambda_{p-1}, \dots, q-1-\lambda_1).$$

We refer the reader to [Lia23] for the combinatorics directly relating these formulas.

This extends to general $p \in \mathbb{N}$:

Proposition 12. *Let V be a vector space with $\dim(V) = mp + 1$ so that*

$$q = (m-1)p + 1 \quad \text{and} \quad (p-1)(q-1) = (m-1)(p-1)p.$$

Consider the coefficient of

$$\underbrace{\sigma_{(m-1)(p-1) \dots (m-1)(p-1)}}_{p \text{ times}}$$

in the expansion of $[X]$ in $H^{2(p-1)(q-1)}(\text{Gr}(p, p+q))$. This equals 1, i.e.,

$$[X] \cdot \underbrace{\sigma_m \dots m}_{p \text{ times}} = 1.$$

Indeed, this follows from Klyachko's formula (Theorem 10) and

$$m_p(\underbrace{m, \dots, m}_{p \text{ times}}) = d_p(\underbrace{m, \dots, m}_{p \text{ times}}) = 1.$$

Example 13. When $\dim(V) = 3m + 1$ the generic orbit X for the action of T on $\mathrm{Gr}(3, V)$ has codimension $3(3m - 2) - 3m = 6(m - 1)$ and

$$[X] \cdot \sigma_{mmm} = m_3(m, m, m) = d_3(m, m, m) = 1.$$

This is not the case when $\dim(V) = 3m + 2, m > 1$, e.g.,

$$[X] = 10\sigma_{5,3} + 8\sigma_{5,2,1} + 15\sigma_{4,4} + 15\sigma_{4,3,1} + 6\sigma_{4,2,2} + 3\sigma_{3,3,2}.$$

Grassmann geometry and rationality.

Theorem 14. *Let $\mathbb{T}$ be a maximal torus – possibly nonsplit – for SL_{pm+1} over a field F . Take $\mathrm{Gr}(p, V)$ for $\dim_F(V) = pm + 1$ with the resulting $\mathbb{T}$ -action. Choose a subspace $W \subset V$ with*

$$\dim_F(W) = (p - 1)m + 1$$

and transverse to $\mathbb{T}$ in the sense that $\mathrm{Gr}(p, W) \subset \mathrm{Gr}(p, V)$ meets some stable $\mathbb{T}$ -orbit properly. Then $\mathrm{Gr}(p, W)$ is a rational section of the quotient

$$\mathrm{Gr}(p, V) \dashrightarrow \mathrm{Gr}(p, V)/\mathbb{T}.$$

Thus if $\mathrm{Gr}(p, W)$ is rational, linearizable, or stably linearizable then the same holds true of the quotient.

Florence [Flo13, §3] has obtained similar results when V carries a suitable F -algebra structure.

Proof. The stability assumption guarantees that the quotient map is defined over a non-empty open subset of $\mathrm{Gr}(p, W)$. Properness of the intersection – which has degree one by Proposition 12 – implies $\mathrm{Gr}(p, W)$ is mapped birationally to the quotient. $\square$

Proposition 15. *Retain the notation of Theorem 14.*

If F is infinite then $\mathrm{Gr}(p, V)$ admits a codimension- m subspace $W \subset V$ satisfying the transversality condition.

If F is finite and $p = 2$ then $\mathrm{Gr}(2, V)$ admits a stable F -rational point.

If F is arbitrary and $p = 2$ then for each stable point there exists a subspace W satisfying the transversality assumption.

Combining with Theorem 14 gives a generalization of the results of [FR18]:

Corollary 16. *Let F be a finite field and ρ a representation of its Galois group in $\mathfrak{S}_{2m+1}$. Then ${}^{\rho}\overline{\mathcal{M}}_{0,2m+1}$ is rational over F .*

We also obtain analogs in higher dimensions:

Corollary 17. *Let $m \geq 1$ and $p \geq 2$ be integers. Consider the moduli space of $pm + 1$ points in $\mathbb{P}^{p-1}$ up to projective equivalence. Let X be a variety obtained by twisting via permutations of the points, over an infinite field F . Then X is rational.*

Proof of Proposition 15. Assume F is infinite; here we use [Kap93, §1.2]. While Kapranov assumes the ground field has characteristic zero, the toric constructions and interpretation of $\overline{\mathcal{M}}_{0,n}$ as a Chow quotient for the PGL_2 -action are valid in positive characteristic [GG14].

The Grassmannian is rational over F so its F -rational points are Zariski dense. We note that the torus action determines a collection of $\overline{F}$ -subspaces

$$V_I \subset V, \quad \emptyset \neq I = \{i_1, \dots, i_r\} \subset \{0, \dots, mp\},$$

spanned by eigenvectors of the torus. Consider the

$$W \in \mathrm{Gr}(mp + 1 - m, mp + 1)$$

meeting some of these improperly, i.e.,

$$\dim(W \cap V_I) > \dim(W) + \dim(V) - \dim(V_I).$$

This is a Zariski closed proper subset of the Grassmannian, defined over F ; its complement has F -rational points. Given such a subspace $W \subset V$, choose

$$w \in \Lambda \subset W, \quad \dim(\Lambda) = p,$$

defined over F , with w not contained in any of the $V_I \subsetneq V$ and Λ meeting all the V_I properly. Thus Λ is stable for the torus action and the torus orbit of Λ meets $\mathrm{Gr}(p, W)$ transversally there.

Now assume that F is finite and $p = 2$. We use the stability criterion (2.3) for points on $\mathbb{P}^1$ and Kapranov's analysis of the Gelfand-MacPherson correspondence. Here the Galois action ρ on the $2m + 1$ points is encoded by a single element $\sigma \in \mathfrak{S}_{2m+1}$. Express σ as a product of r disjoint cycles of lengths ℓ_i with

$$\ell_1 + \dots + \ell_r = 2m + 1, \quad \ell_1 \geq \ell_2 \geq \dots \geq \ell_r.$$

Only ℓ_1 can possibly be greater than m ; if $\ell_1 \leq m$ then we have $r \geq 3$. When $\ell_1 > m$, choose a configuration of ℓ_1 points defined over a degree- ℓ_1 extension of F . Allow the remaining points to all coincide. We turn to the situation where $\ell_1 \leq m$. If $r = 3$ then we allow ℓ_1 points to

coincide with $[0, 1]$, ℓ_2 points to coincide with $[1, 0]$, and ℓ_3 points to coincide with $[1, 1]$. We may therefore assume that $r \geq 4$ and work inductively on r . There exists two indices, say ℓ_3 and ℓ_4 , whose sum is less than m . Use this to “degenerate” to a new partition of $2m + 1$, refined by $(\ell_1, \dots, \ell_r)$ but of length $r - 1$, all of whose entries are less than m . For example, we could take

$$(\ell_1, \ell_2, \ell_3 + \ell_4, \ell_5, \dots, \ell_r).$$

Continuing in this way, we generate a partition

$$\{1, 2, \dots, r\} = A \sqcup B \sqcup C$$

such that

$$\sum_{a \in A} \ell_a, \sum_{b \in B} \ell_b, \sum_{c \in C} \ell_c \leq m.$$

Let points coincide in three groups according to this coarsening of our original partition, the first group to $[0, 1]$, the second to $[1, 0]$, and the third to $[1, 1]$.

Assume $p = 2$ and F is arbitrary. We continue to assume that $\Lambda \subset V$ is a two-dimensional subspace that is stable in the sense of Geometric Invariant Theory. Let $\mathbf{T}_{2m}$ denote the tangent space to the torus orbit at Λ

$$\mathbf{T}_{2m} \subset \text{Hom}(\Lambda, V/\Lambda),$$

an $2m$ -dimensional subspace of the tangent space to $\text{Gr}(2, V)$ at Λ . We claim there exists a subspace

$$\Lambda \subset W \subset V,$$

where W has codimension m in V , such that the composition

$$\mathbf{T}_{2m} \subset \text{Hom}(\Lambda, V/\Lambda) \rightarrow \text{Hom}(\Lambda, V/W)$$

has full rank $2m$. Since the latter space is the normal directions to $\text{Gr}(2, W)$ at Λ , this will yield transversality.

We record some basic geometry:

Lemma 18. *There is a distinguished orbit*

$$\mathbb{P}^1 \times \mathbb{P}^{m-2} \simeq \mathbb{P}(\Lambda^*) \times \mathbb{P}(V/\Lambda) \subset \mathbb{P}(\text{Hom}(\Lambda, V/\Lambda))$$

invariant under automorphisms of $\text{Gr}(2, V)$ fixing $[\Lambda]$.

The subspace $\mathbb{P}^{2m-1} \simeq \mathbb{P}(\mathbf{T}_{2m})$ cuts out the graph of a rational normal curve

$$\begin{aligned} \varrho : \mathbb{P}_{s_0, s_1}^1 &\hookrightarrow \mathbb{P}_{x_0, \dots, x_{2m-2}}^{2m-2} \\ [s_0, s_1] &\mapsto [s_0^{2m-2}, \dots, s_1^{2m-2}]. \end{aligned}$$

In these coordinates, the rational normal curve has equations

$$s_0 x_{i+1} = s_1 x_i, \quad i = 0, \dots, 2m-1.$$

Let $\Gamma \subset \mathbb{P}^1$ denote the length- $(2m+1)$ subscheme that is the image of the eigenvectors for $\mathbf{T}_{2m}$ under $V^* \rightarrow \Lambda^*$. Then ϱ realizes the Gale transform for $\Gamma \subset \mathbb{P}^1$ as a subscheme of $\mathbb{P}^{2m-2}$ contained in a rational normal curve.

The first assertion reflects the fact that the parabolic subgroup of PGL_{2m+1} fixing $[\Lambda]$ has semisimple part $(\mathrm{GL}_2 \times \mathrm{GL}_{2m-1})/\mathbb{G}_m$. Note that the unipotent part acts trivially on the tangent space. The second assertion is true for the generic codimension- $(2m-2)$ linear slice of $\mathbb{P}^1 \times \mathbb{P}^{2m-1}$. Of course, one has to show that this applies in our situation! This follows from the third assertion, a special case of [EP00, Corollary 3.2] – the first application following the statement. This completes the proof of the lemma.

Returning to the proof of the Proposition, we may take W as the subspace given by

$$\{x_{2j} = 0, j = 0, \dots, m-1\},$$

where we interpret $x_j \in (V/\Lambda)^* a$. It is clear that the products

$$\{s_i x_{2j}, i = 0, 1, j = 0, \dots, m-1\}$$

have the desired spanning property; the elements

$$s_0^{2m-1}, \dots, s_1^{2m-1}$$

are a basis for bilinear forms of degree $2m-1$. □

Partitioning the points. We start with a general construction: Let $n \geq 3$ be an integer and $n = \ell m$ a factorization in integers $\ell, m > 1$. Suppose that $H \subset \mathfrak{S}_\ell, A \subset \mathfrak{S}_m$ are subgroups. The *wreath product*

$$A \wr H = A \wr_{1, \dots, \ell} H$$

is the semidirect product $A^\ell \rtimes H$ where

$$(a_1, \dots, a_\ell) \cdot h = (a_{h^{-1}(1)}, \dots, a_{h^{-1}(\ell)}).$$

This comes with a natural embedding

$$\rho : A \wr H \hookrightarrow \mathfrak{S}_{\ell m}$$

as permutations of pairs

$$(i, j), \quad i \in \{1, \dots, m\}, j \in \{1, \dots, \ell\}.$$

Now assume that $m \geq 3$. Forgetting maps yield an equivariant morphism

$$\phi : {}^\rho\overline{\mathcal{M}}_{0,\ell m} \rightarrow \prod_H {}^\alpha\overline{\mathcal{M}}_{0,m},$$

where $\alpha : A \hookrightarrow \mathfrak{S}_m$ and the twisted product denotes ℓ copies of the moduli space with the associated H -action. The generic fiber of this morphism is irreducible of dimension

$$(\ell m - 3) - \ell(m - 3) = 3\ell - 3.$$

It is birational to the Hilbert scheme of multidegree- $(1, \dots, 1)$ curves in the H -twisted product $\prod_H C_j$ of ℓ genus-zero curves. Geometrically, this is a compactification of the homogeneous space

$$\underbrace{\mathrm{PGL}_2 \times \cdots \times \mathrm{PGL}_2}_{\ell \text{ times}} / \mathrm{PGL}_2$$

with the last PGL_2 embedded diagonally.

We record some observations on the generic fiber of ϕ :

- Suppose $\ell = 2$. Geometrically, $(1, 1)$ curves in $\mathbb{P}^1 \times \mathbb{P}^1$ are parametrized by $\mathbb{P}^3$ – the dual to the projective space containing the Segre embedding of $\mathbb{P}^1 \times \mathbb{P}^1$. Over an arbitrary field the fiber is a Brauer-Severi threefold.
- Suppose that m is odd. Then the genus-zero curves C_j appearing in the twisted product are split and – over the extension/subgroup associated with $A^\ell \subset A \wr H$ – isomorphic to $\mathbb{P}^1$'s. Here the twisted product $\prod_H C_j$ is rational, as it is isomorphic to the restriction of scalars of $\mathbb{P}^1$.
- Now assume $\ell = 2$ and m odd. Here the generic fiber of ϕ is isomorphic to $\mathbb{P}^3$ over the function field/linearizable for the full wreath product.

Example 19. Suppose $n = 6$ and consider $G = \mathfrak{S}_3 \wr \mathfrak{S}_2 \subset \mathfrak{S}_6$, a subgroup of index 10 preserving an unordered partition

$$\{1, 2, 3, 4, 5, 6\} = \{i, j, k\} \sqcup \{a, b, c\}.$$

Then the associated ${}^\rho\overline{\mathcal{M}}_{0,6}$ is rational/linearizable. These actions correspond to situations where the associated Segre threefold admits an invariant node (cf. Theorem 34 below).

Theorem 20. *Let $n = 2m$, with $m \geq 3$ odd. Fix a subgroup $A \subset \mathfrak{S}_m$ and the diagonal subgroup*

$$G := A \times \mathfrak{S}_2 \subset A \wr \mathfrak{S}_2 \subset \mathfrak{S}_{2m}.$$

- For each Galois representation $\rho : \Gamma \rightarrow G$ the twist ${}^\rho\overline{\mathcal{M}}_{0,n}$ is rational over F .
- The G action on $\overline{\mathcal{M}}_{0,n}$ is stably linearizable.

Proof. We assume $\mathfrak{S}_m$ permutes the points with odd and even indices respectively.

We focus first on the arithmetic case. Let L/F be the quadratic extension associated with A . Over L , the generic point of the twisted moduli space corresponds to $\mathbb{P}^1$ equipped with reduced and disjoint zero-cycles $Z_{\text{odd}}, Z_{\text{even}} \subset \mathbb{P}^1$ of length m . The parity of m ensures that the underlying curve is $\mathbb{P}^1$.

Note that the variety ${}^\rho\overline{\mathcal{M}}_{0,n}$ is already stably rational over L by Proposition 5.

Consider forgetting the even and odd points

$$(\pi_{\text{odd}}, \pi_{\text{even}}) : ({}^\rho\overline{\mathcal{M}}_{0,n})_L \rightarrow {}^{\varpi_{\text{odd}}}\overline{\mathcal{M}}_{0,m} \times {}^{\varpi_{\text{even}}}\overline{\mathcal{M}}_{0,m}$$

where the Galois actions come via restriction to the even and odd points. These actions are conjugate for the quadratic extension L/F . Descent therefore gives a morphism over F

$$\phi : {}^\rho\overline{\mathcal{M}}_{0,n} \rightarrow R_{L/F}({}^{\varpi_{\text{odd}}}\overline{\mathcal{M}}_{0,m}),$$

where the target is the restriction of scalars. The twists of $\overline{\mathcal{M}}_{0,m}$ are rational over L by [FR18] and Corollary 16. The restriction of scalars of a rational variety is rational.

We claim that the generic fiber of ϕ is rational over the function field of the base, which implies rationality for ${}^\rho\overline{\mathcal{M}}_{0,n}$ over F . This follows from the analysis above for $\ell = 2$ and odd m .

For the equivariant case, our geometric argument shows that the G -variety $\overline{\mathcal{M}}_{0,n}$ is birationally the projectivization of an equivariant vector bundle over a stably linearizable variety (by Proposition 5). Note that restriction of scalars in the arithmetic situation corresponds to passing to an induced representation in the equivariant context; thus stable linearizability is clearly preserved. We conclude then that $\overline{\mathcal{M}}_{0,n}$ is stably linearizable. $\square$

Corollary 21. *Let C_{2m} , with m odd, be a cyclic group. Then twists of $\overline{\mathcal{M}}_{0,n}$ by this group are rational (in the Galois case) and stably linearizable (in the equivariant situation).*

Proof. If the action has an odd orbit then this follows from Propositions 3 and 5. Otherwise, all the orbits are even and we may apply Theorem 20. $\square$

Remark 22. Similar reasoning applies for a Galois action

$$\rho : \Gamma \rightarrow \mathfrak{S}_{m_1} \times \mathfrak{S}_{m_2} \subset \mathfrak{S}_{m_1+m_2}, \quad m_1, m_2 \geq 3 \text{ odd},$$

with restricted actions ϖ_1 and ϖ_2 on the first m_1 points and last m_2 points respectively. Proposition 5 already gives stable rationality in this case. The forgetting morphism

$$\phi : {}^\rho \overline{\mathcal{M}}_{0, m_1+m_2} \rightarrow {}^{\varpi_1} \overline{\mathcal{M}}_{0, m_1} \times {}^{\varpi_2} \overline{\mathcal{M}}_{0, m_2}$$

has generic fiber birational to $\mathbb{P}^3$ by the reasoning above. Since the factors ${}^{\varpi_i} \overline{\mathcal{M}}_{0, m_i}$ are rational, ${}^\rho \overline{\mathcal{M}}_{0, m_1+m_2}$ is rational as well.

4. STABLE LINEARIZABILITY VIA TORSORS

Let G be a finite group and $\mathbb{T}$ a G -torus, i.e., a torus equipped with a representation of G on its character module $\mathfrak{X}^*(\mathbb{T})$. Recall that $\mathbb{T}$ is stably linearizable if $\mathfrak{X}^*(\mathbb{T})$ is stably permutation, see, e.g., [HT23, Proposition 2].

Proposition 23. *Let U be a smooth quasi-projective variety with G -action. Assume that we have a $\mathbb{T}$ -torsor*

$$\mathcal{P} \rightarrow U,$$

i.e., a $\mathbb{T}$ -principal homogeneous space over U , in the category of G -varieties. Assume that

- *the G -action on U is generically free,*
- *the characters $\mathfrak{X}^*(\mathbb{T})$ are a stably permutation G -module,*
- *the G -action on $\mathcal{P}$ is stably linearizable.*

Then the G -action on U is stably linearizable.

Proof. We claim there is a G -equivariant birational map,

$$\begin{array}{ccc} \mathcal{P} & \xrightarrow{\sim} & \mathbb{T} \times U \\ & \searrow & \swarrow \\ & U & \end{array}$$

which would follow if $\mathcal{P} \rightarrow U$ admits a G -equivariant rational section. We clearly have such a section after discarding the G -action, by Hilbert's Theorem 90.

Since $\mathbb{T}$ is stably permutation, a product $\mathbb{T} \times \mathbb{T}_1$, where $\mathbb{T}_1$ is a permutation torus, is isomorphic to a permutation torus and may be

realized as a dense open subset of affine space. It follows that we have an open embedding

$$\begin{array}{ccc} \mathcal{P} \times_U \mathbb{T}_1 & \hookrightarrow & \mathcal{V} \\ & \searrow \quad \swarrow & \\ & U & \end{array}$$

where $\mathcal{V} \rightarrow U$ is a vector bundle with G -action. The vector bundle admits a rational section (by the No-Name Lemma) thus $\mathcal{P}$ does as well.

We assumed that $\mathcal{P}$ is stably linearizable, i.e. $\mathcal{P} \times \mathbb{G}_m^r$ is linearizable for some r . Thus $U \times \mathbb{T} \times \mathbb{G}_m^r$ is as well. We observed that $\mathbb{T}$ is stably linearizable because its character module is stably permutation, i.e. $\mathbb{T} \times \mathbb{T}_1$ is a permutation torus. Another application of the No-Name Lemma, using the assumption that the action on U is generically free, gives that U is stably linearizable. $\square$

We recall the exact sequence (2.5)

$$0 \rightarrow N \rightarrow M \rightarrow Q \rightarrow 0,$$

with $M = \text{Pic}(\overline{\mathcal{M}}_{0,n})$, N an $\mathfrak{S}_n$ -permutation module, and Q is an index-2 submodule of the permutation module $\mathbb{Z}[\mathfrak{S}_n/\mathfrak{S}_{n-1}]$. We record:

- if $H^1(G, Q) = 0$ for some $G \subset \mathfrak{S}_n$, then also $H^1(G, M) = 0$, by the long exact sequence in cohomology,
- if Q is a stably permutation G -module, then the sequence splits and $\text{Pic}(\overline{\mathcal{M}}_{n,0})$ is a stably permutation module, by [CTS77, Lemma 1].

Theorem 24. *Let $G \subseteq \mathfrak{S}_n$ be a subgroup such that Q is a stably permutation module. Then the G -action on $\overline{\mathcal{M}}_{0,n}$ is stably linearizable.*

Let X be a form of $\overline{\mathcal{M}}_{0,n}$ over F such that the action of the absolute Galois group on Q gives rise to a stable permutation module. Then X is stably rational over F .

Proof. For the equivariant statement, we apply Proposition 23. Here $\mathbb{T}$, with character module Q acts on $\text{CGr}(2, n)$ (see Section 2). Let $V \subset \text{CGr}(2, n)$ the open subset over which $\mathbb{T}$ acts freely and $U \subset X_n$ the corresponding locus in the quotient, i.e., remove all the strictly semistable points. We have a torsor

$$V \xrightarrow{\mathbb{T}} U.$$

By [HT23, Proposition 19], the $\mathfrak{S}_n$ -action on $\text{Gr}(2, n)$ (and its cone) is stably linearizable. Assuming that $Q = \mathfrak{X}^*(\mathbb{T})$ is a stable permutation

module for $G \subset \mathfrak{S}_n$, and applying Proposition 23, we conclude that the G -action on U , and thus $\overline{\mathcal{M}}_{0,n}$, is stably linearizable as well.

The Galois-theoretic result is proven analogously, with [BCTSSD85, Prop. 3] playing the role of Proposition 23. This is an application of the torsor formalism of [CTS87]. $\square$

Remark 25. There exist linearizable G -actions on $\overline{\mathcal{M}}_{0,n}$ such that the induced action on Q is not stably permutation. Consider n even and $G = C_2$ generated by $\sigma := (1, 2) \cdots (n-1, n)$; we have $H^1(C_2, Q) \neq 0$ (see Remark 32) so Q is not stably permutation. This action is equivariantly birational – by Proposition 7 – to an action on a torus $T = \mathbb{G}_m^{n-3}$. Its character module consists of the elements of $\mathbb{Z}^{n-2}$ – the twisted permutation module on $\{1, \dots, n-2\}$ – whose coordinates sum to zero (see Equation 2.1). The action of C_2 on the twisted permutation module consists of $(n-2)/2$ copies of $\begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix}$. Hence $\mathfrak{X}^*(T)$ decomposes as a sum of $\frac{n}{2} - 2$ permutation modules and one invariant, a permutation module. We conclude T is linearizable.

Remark 26. By [FR18, Remark 5.5], for *odd* n , every form of $\overline{\mathcal{M}}_{0,n}$ over a nonclosed field F is an F -rational variety. *A priori*, this does *not* imply that $\overline{\mathcal{M}}_{0,n}$ is (stably) linearizable for $\mathfrak{S}_n$. However, this does imply that M is a stable permutation module, for the $\mathfrak{S}_n$ -action.

For n *odd*, we have

$$(4.1) \quad M \simeq N \oplus Q,$$

as $\mathfrak{S}_n$ -modules, by Proposition 8. Since N is a permutation module, for all n , and M a stably permutation module, for odd n , we see that Q is also stably permutation, for odd n . Thus, the $\mathfrak{S}_n$ -action on $\overline{\mathcal{M}}_{0,n}$ is stably linearizable, by Theorem 24.

The splitting (4.1) can also be seen explicitly: Recall that under the Kapranov basis, $Q = M/N$ is generated by the image of the classes

$$H, \quad E_i, \quad i = 1, \dots, n-1$$

in M under the projection modulo N . The $\mathbb{Z}$ -linear map

$$s : Q \rightarrow M,$$

given on these generators by

$$H \mapsto H + \sum_{\substack{I \subset \{1, \dots, n-1\}, \\ |I| = \frac{n-1}{2}, \dots, n-4.}} (|I| - 1) \cdot E_I, \quad E_i \mapsto E_i + \sum_{\substack{I \subset \{1, \dots, n-1\}, i \in I, \\ |I| = \frac{n-1}{2}, \dots, n-4.}} E_I.$$

is a section of the exact sequence (2.5). We check that it is $\mathfrak{S}_n$ -equivariant. Let $\tau = (1, 2)$ and $\sigma = (1, \dots, n)$. In Q , one has

$$H = D_{12} + \sum_{i=3}^n E_i$$

and $\tau(H) = H$, $\tau(E_1) = E_2$, $\tau(E_2) = E_1$ and $\tau(E_i) = E_i$. Note that s is τ -equivariant by construction. Next, observe

$$\begin{aligned} s\sigma(H) &= s\left(\sigma\left(D_{12} + \sum_{i=3}^n E_i\right)\right) = s\left((n-3)H - (n-4)\sum_{i=2}^{n-1} E_i\right) \\ &= (n-3)H - (n-4)\sum_{i=2}^{n-1} E_i - \sum_{\substack{I \subset \{1, \dots, n-1\}, 1 \notin I, \\ |I| = \frac{n-1}{2}, \dots, n-4.}} (n-|I|-3) \cdot E_I \\ &\quad + \sum_{\substack{I \subset \{1, \dots, n-1\}, 1 \in I, \\ |I| = \frac{n-1}{2}, \dots, n-4.}} (|I|-1) \cdot E_I. \\ \sigma s(H) &= \sigma\left(H + \sum_{|I| = \frac{n-1}{2}, \dots, n-4} (|I|-1) \cdot E_I\right) \\ &= \sigma\left(D_{n-2, n-1} + \sum_{\substack{I \subset \{1, \dots, n-3\}, \\ |I| = 1, \dots, n-4.}} E_I + \sum_{|I| = \frac{n-1}{2}, \dots, n-4.} (|I|-1) \cdot E_I\right) \\ &= E_{n-1} + \sum_{\substack{I \subset \{2, \dots, n-2\} \\ |I| = 1, \dots, n-5}} D_{I \cup \{n-1, n\}} + \sum_{i=2}^{n-2} D_{1, i} \\ &\quad + \underbrace{\sum_{\substack{I \subset \{2, \dots, n-1\}, \\ |I| = \frac{n-1}{2}-1, \dots, n-5.}} E_{\{1\} \cup I} + \sum_{\substack{I \subset \{2, \dots, n-1\}, \\ |I| = 2, \dots, \frac{n-1}{2}-1.}} (n-3-|I|)E_I}_{:=A} \\ &= (n-3)H - (n-4)\sum_{i=2}^{n-1} E_i - \sum_{\substack{I \subset \{2, \dots, n-1\}, i \notin I, \\ |I| = 1, \dots, n-4.}} E_I \end{aligned}$$

$$+ \sum_{\substack{I \subset \{2, \dots, n-2\}, \\ |I|=1, \dots, n-5.}} D_{I \cup \{n-1, n\}} + A.$$

One can then verify $\sigma s(H) = s\sigma(H)$ by comparing the coefficients of each generator E_I . To check actions on E_i , for $i = 1, \dots, n-2$, one has

$$\begin{aligned} s\sigma(E_i) &= s(H - \sum_{k=2, k \neq i+1}^{n-1} E_k) \\ &= H - \sum_{k=2, k \neq i+1}^{n-1} E_k - \sum_{\substack{I \subset \{1, \dots, n-1\}, \\ 1, i+1 \notin I, \\ |I| = \frac{n-1}{2}, \dots, n-4.}} E_I + \sum_{\substack{I \subset \{1, \dots, n-1\}, \\ 1, i+1 \in I, \\ |I| = \frac{n-1}{2}, \dots, n-4.}} E_I. \end{aligned}$$

On the other hand,

$$\begin{aligned} \sigma s(E_i) &= \sigma(E_i + \sum_{\substack{I \subset \{1, \dots, n-1\}, i \in I, \\ |I| = \frac{n-1}{2}, \dots, n-4.}} E_I) \\ &= H - \sum_{\substack{I \subset \{2, \dots, n-1\}, i+1 \notin I, \\ |I| = 1, \dots, n-4.}} D_{I \cup \{n\}} + \sum_{\substack{I \subset \{2, \dots, n-1\}, \\ |I| = \frac{n-1}{2} - 1, \dots, n-5.}} D_{I \cup \{1, n\}} \\ &\quad + \sum_{\substack{I \subset \{2, \dots, n-1\}, i+1 \notin I, \\ |I| = 2, \dots, \frac{n-1}{2} - 1.}} E_I. \end{aligned}$$

Similarly, one can check $\sigma s(E_i) = s\sigma(E_i)$ for $i \neq n-1$ by comparing the coefficients. Finally, one can verify

$$s(\sigma(E_{n-1})) = s(E_1) = \sigma(s(E_{n-1})).$$

5. COMPUTING COHOMOLOGY

In this section, we study the G -module

$$M = \text{Pic}(\overline{\mathcal{M}}_{0,n}),$$

and the quotient $Q = M/N$, from (2.5), for various $G \subset \mathfrak{S}_n$.

Cohomological criteria. We focus on two properties, which are necessary for linearizability of a regular G -action on a smooth projective rational variety X , see, e.g., [BP13, Proposition 2.5]:

(H1) For all subgroups $G' \subset G$ one has

$$H^1(G', \text{Pic}(X)) = H^1(G', \text{Pic}(X)^*) = 0.$$

(SP) The G -module $\text{Pic}(X)$ is stably permutation.

Since H^1 vanishes on permutation modules, **(SP)** implies **(H1)**, but the converse does not hold, in general. Computationally, it is easier to check **(H1)**.

Example 27. For $n = 6$ and $G \subseteq \mathfrak{S}_6$, property **(H1)** for the action on $M = \text{Pic}(\overline{\mathcal{M}}_{0,6})$ does not imply **(SP)**, e.g., for the action of

$$G \simeq C_2 \times C_4 := \langle (3, 4), (1, 2, 5, 6) \rangle,$$

and

$$G \simeq (C_2)^3 := \langle (1, 5)(2, 6), (3, 4), (1, 2)(5, 6) \rangle,$$

see the analysis in [CTZ23, Section 6], as well as [Kun87, Section 4]. Furthermore, there are $G \subset \mathfrak{S}_6$ such that

- Q fails **(H1)** but M satisfies it, e.g., for $G = \langle (1, 2)(3, 4)(5, 6) \rangle$, one has

$$H^1(G, M) = 0, \quad H^1(G, Q) = \mathbb{Z}/2.$$

Actually, M is a permutation module while Q is not. Indeed, under appropriate choices of basis, M is of the form

$$\mathbb{Z}^4 \oplus \mathbb{Z}[C_2]^6,$$

and Q is of the form

$$\mathbb{Z} \oplus \mathbb{Z}[C_2]^2 \oplus \mathbb{Z}[e],$$

where G acts on e via -1 .

- Both Q and M fail **(H1)**: all groups containing $G = C_2^2$ from Proposition 28, in these cases we have

$$H^1(G, M) = H^1(G, Q) = \mathbb{Z}/2.$$

Statement of results.

Proposition 28. For $n_1, n_2, n_3 \in \mathbb{N}$ with $2(n_1 + n_2 + n_3) = n$ let

$$\iota_1 = (1, 2) \dots (2n_1 - 1, 2n_1)(2(n_1 + n_2) + 1, 2(n_1 + n_2) + 2) \dots (n - 1, n),$$

$$\iota_2 = (2n_1 + 1, 2n_1 + 2), \dots, (2(n_1 + n_2) - 1, 2(n_1 + n_2)) \dots (n - 1, n),$$

and put $G := \langle \iota_1, \iota_2 \rangle$. Then

$$H^1(G, M) = \mathbb{Z}/2.$$

The first part of Theorem 1 follows:

Corollary 29. *For every even $n > 5$ and every subgroup of $\mathfrak{S}_n$ containing G , the induced action on $\overline{\mathcal{M}}_{0,n}$ is not stably linearizable.*

For example, when $n_1 = n_2 = n_3 = 1$

$$\iota_1 = (12)(56), \quad \iota_2 = (34)(56),$$

and the corresponding action on $\overline{\mathcal{M}}_{0,6}$, which is $\mathfrak{S}_6$ -equivariantly birational to the Segre cubic, is not stably linearizable.

We apply the results above to rationality questions over nonclosed fields, completing the proof of Theorem 1:

Theorem 30. *Let F be a field admitting a biquadratic extension. Then, for all even $n \geq 6$ there exist forms of $\overline{\mathcal{M}}_{0,n}$ over F that are not retract rational, and thus not stably rational, over F .*

In particular, this yields nonrational forms over $F = \mathbb{C}(t)$, a field with trivial Brauer group.

Proof. Indeed, let $G \simeq C_2^2$ be the group identified in Proposition 28, with $H^1(G, \text{Pic}(\overline{\mathcal{M}}_{0,n})) = \mathbb{Z}/2$. Let $\Gamma = \text{Gal}(F'/F)$ be the Galois group of the biquadratic extension F'/F . We construct a form X of $\overline{\mathcal{M}}_{0,n}$ over F such that Γ acts on $\text{Pic}(\overline{X}) = \text{Pic}(\overline{\mathcal{M}}_{0,n})$ via G . This gives an (H1)-obstruction to retract rationality. $\square$

Proof of Proposition 28. Put

$$\sigma := \iota_1 \iota_2 = (1, 2) \cdots (2(n_1 + n_2) - 1, 2(n_1 + n_2)),$$

$$\tau := \iota_2 = (2n_1 + 1, 2n_1 + 2) \cdots (n - 1, n),$$

so that $G = \langle \sigma, \tau \rangle$. We will repeatedly use the inflation-restriction exact sequence

$$(5.1) \quad 0 \rightarrow H^1(\langle \tau \rangle, A^\sigma) \rightarrow H^1(G, A) \rightarrow H^1(\langle \sigma \rangle, A)^\tau,$$

with the usual notation for invariants under the actions of σ, τ .

Step 1. Observe that M admits a decomposition, as a G -module,

$$M = L \oplus P,$$

where L consists of $\mathbb{Z}$ -linear combinations of H and E_I , with $n - 1 \notin I$, and P is generated, over $\mathbb{Z}$, by E_I with $n - 1 \in I$. We have

$$H^1(G, M) = H^1(G, L) \oplus H^1(G, P).$$

Step 2. The involution σ is contained in $\mathfrak{S}_{n-1}$, permuting $(n-1)$ points and therefore linearizable. Thus

$$H^1(\langle\sigma\rangle, M) = H^1(\langle\sigma\rangle, L) = H^1(\langle\sigma\rangle, P) = 0.$$

Moreover, P is a G -permutation module. Indeed, for I with $n-1 \in I$, $\sigma E_I = E_{\sigma(I)} \in P$, and $\tau E_I = E_{(\tau \cdot (n-1, n))(I)} \in P$. It follows that

$$H^1(G, P) = 0,$$

and

$$H^1(G, M) = H^1(G, L) = H^1(\langle\tau\rangle, L^\sigma).$$

Remark 31. Geometrically, cohomology is already contributed on the *toric model* $\overline{L}_n$, obtained by blowing up $(n-2)$ general points on $\mathbb{P}^{n-3}$.

Step 3. Let $N \subset L$ be the submodule of $\mathbb{Z}$ -linear combinations of E_I with $|I| \geq 2$ and $n-1 \notin I$. We have a short exact sequence

$$0 \rightarrow N \rightarrow L \rightarrow Q \rightarrow 0,$$

of G -modules, with Q generated by $H, E_1, \dots, E_{n-2}$, modulo N , and the corresponding long exact sequence of $\langle\tau\rangle$ -modules:

$$0 \rightarrow N^\sigma \rightarrow L^\sigma \rightarrow Q^\sigma \rightarrow H^1(\langle\sigma\rangle, N) \rightarrow \dots$$

Since $\sigma(E_I) = E_{\sigma(I)}$, the σ -action on N yields naturally a permutation module, realized via permutation of indices of E_I . So

$$H^1(\langle\sigma\rangle, N) = 0.$$

The short exact sequence

$$0 \rightarrow N^\sigma \rightarrow L^\sigma \rightarrow Q^\sigma \rightarrow 0$$

gives rise to the long exact sequence

$$(5.2) \quad H^1(\langle\tau\rangle, N^\sigma) \rightarrow H^1(\langle\tau\rangle, L^\sigma) \rightarrow H^1(\langle\tau\rangle, Q^\sigma) \rightarrow H^2(\langle\tau\rangle, N^\sigma).$$

Step 4. The $\langle\tau\rangle$ -module N^σ has the form:

$$N^\sigma = \mathbb{Z}[\langle\tau\rangle] \oplus \dots \oplus \mathbb{Z}[\langle\tau\rangle].$$

In particular,

$$H^1(\langle\tau\rangle, N^\sigma) = H^2(\langle\tau\rangle, N^\sigma) = 0.$$

Indeed, a $\mathbb{Z}$ -basis of N^σ is given by

$$e_I := \begin{cases} E_I + E_{\sigma(I)} & \text{if } \sigma(I) \neq I, \\ E_I & \text{if } \sigma(I) = I, \end{cases}$$

for

$$I \subset \{1, 2, \dots, n-2\}, \quad 2 \leq |I| \leq n-4.$$

To show that N^σ is a direct sum of copies of $\mathbb{Z}[\langle \tau \rangle]$, it suffices to show that $\tau(e_I) = e_{I'}$, for some $I' \neq I$ and $e_I \neq e_{I'}$. Observe that

$$\sigma(I)^c = \sigma(I^c), \quad I^c := \{1, \dots, n-2\} \setminus I.$$

There are three cases:

- If $\sigma(I) = \tau(I) = I$, then

$$\tau(e_I) = \tau(E_I) = D_{I \cup \{n-1\}} = E_{I^c} = e_{I^c}$$

and thus $e_I \neq e_{I^c}$.

- If $\sigma(I) \neq I$ and $\tau(I) = I$, then

$$\begin{aligned} \tau(e_I) &= \tau(E_I) + \tau(E_{\sigma(I)}) = D_{I \cup \{n-1\}} + D_{\sigma(I) \cup \{n-1\}} \\ &= E_{I^c} + E_{\sigma(I)^c} = E_{I^c} + E_{\sigma(I^c)} = e_{I^c}. \end{aligned}$$

Since $I^c \neq I$ and $I^c \neq \sigma(I^c)$, we know that $e_I \neq e_{I^c}$.

- If $\tau(I) \neq I$, then $\sigma(I) \neq I$, and

$$\begin{aligned} \tau(e_I) &= E_{\tau(I)^c} + E_{(\tau\sigma(I))^c} = E_{\tau(I)^c} + E_{(\sigma\tau(I))^c} \\ &= E_{\tau(I)^c} + E_{\sigma(\tau(I)^c)} = e_{\tau(I)^c}. \end{aligned}$$

To be concrete, assume that $1 \in I$ and $2 \notin I$. Then $1 \in \tau(I)^c$ and $1 \notin \sigma(I)$, so that $\tau(I)^c \neq \sigma(I)$. Since $|I| \geq 2$, one can see that $\tau(I)^c \neq I$ and thus $e_{\tau(I)^c} \neq e_I$.

In conclusion, $\tau(e_I) \neq e_I$, in all cases, and N^σ is as claimed, and thus has vanishing first and second cohomology. It follows that

$$H^1(\langle \tau \rangle, M^\sigma) = H^1(\langle \tau \rangle, L^\sigma) = H^1(\langle \tau \rangle, Q^\sigma).$$

Step 5. To show that $H^1(\langle \tau \rangle, Q^\sigma) = \mathbb{Z}/2$, let

$$\Sigma_i := \sum_{|I|=i} E_I,$$

where the sum is over $I \subseteq \{1, 2, \dots, n-2\}$ with $|I| = i$. Put $\Sigma := \Sigma_1$ and set

$$\begin{aligned} e_0 &:= H - \Sigma, \\ e_i &:= H - \Sigma + (E_{2i-1} + E_{2i}), & 1 \leq i \leq n_1 + n_2, \\ w_j &:= E_{2j-1}, & n_1 + n_2 + 1 \leq j \leq \frac{n-2}{2}, \\ v_j &:= H - \Sigma + E_{2j}, & n_1 + n_2 + 1 \leq j \leq \frac{n-2}{2}. \end{aligned}$$

Then

$$\{e_i, w_j, v_j\}$$

for $0 \leq i \leq n_1 + n_2$ and $n_1 + n_2 + 1 \leq j \leq \frac{n-2}{2}$ gives a $\mathbb{Z}$ -basis of Q^σ . Moreover, for $1 \leq i \leq n_1 + n_2$ and $n_1 + n_2 + 1 \leq j \leq \frac{n-2}{2}$, one has

$$\tau(e_0) = -e_0, \quad \tau(e_i) = e_i, \quad \text{and} \quad \tau(w_j) = v_j.$$

Indeed, Q^σ is generated, over $\mathbb{Z}$, by

$$H, (E_1 + E_2), \dots, (E_{2(n_1+n_2)-1} + E_{2(n_1+n_2)}), E_{2(n_1+n_2)+1}, \dots, E_{n-2}.$$

We now show that $\{e_i, w_j, v_j\}$ gives another basis. First, observe that

$$H - \Sigma = D_{34\dots n} - (E_1 + E_2) + \underbrace{\sum_{\substack{1,2 \notin I, E_I \in N \\ \in N^\sigma}} E_I}.$$

Indeed, if $1, 2 \notin I$ and $E_I \in N$, $1, 2 \notin \sigma(I)$ and $E_{\sigma(I)}$ will also appear in the summand. Then $\sigma(H - \Sigma) = H - \Sigma \pmod{N^\sigma}$ and

$$e_j, w_j, v_j \in Q^\sigma.$$

Moreover, $\{e_j, w_j, v_j\}$ generates Q^σ since

$$E_{2i-1} + E_{2i} = e_i - e_0, \quad E_{2j} = v_j - e_0$$

and

$$H = \left(\frac{4-n}{2}\right)e_0 + \sum_{i=1}^{n_1+n_2} e_i + \sum_{j=n_1+n_2+1}^{\frac{n-2}{2}} (w_j + v_j).$$

To compute the τ -action on this basis, one can first compute

$$\begin{aligned} H - \Sigma &= D_{34\dots n} - (E_1 + E_2) \pmod{N^\sigma} \\ &\xrightarrow{\tau} D_{34\dots n} - D_{1,n-1} - D_{2,n-1} \\ &= D_{34\dots n} - 2H + 2\Sigma - (E_1 + E_2) \pmod{N^\sigma} \\ &= H - \Sigma + (E_1 + E_2) - 2H + 2\Sigma + (E_1 + E_2) \pmod{N^\sigma} \\ &= -H + \Sigma, \end{aligned}$$

i.e.,

$$\tau(e_0) = -e_0.$$

Then we have

$$\begin{aligned} H - \Sigma + E_{2i-1} + E_{2i} &\xrightarrow{\tau} -H + \Sigma + D_{2i-1,n-1} + D_{2i,n-1} \\ &= -H + \Sigma + 2H - 2\Sigma + (E_{2i-1} + E_{2i}) \pmod{N^\sigma} \\ &= H - \Sigma + (E_{2i-1} + E_{2i}) \pmod{N^\sigma}. \end{aligned}$$

Note that the equalities hold for all $1 \leq i \leq \frac{n}{2}$. In particular,

$$\tau(e_i) = e_i, \quad \text{for } 1 \leq i \leq n_1 + n_2.$$

Finally,

$$\begin{aligned} \tau(w_j) &= D_{2j, n-1} = H - \Sigma + E_{2j} - \sum_{\substack{2j \notin I \\ E_I \in N}} E_I \\ &= H - \Sigma + E_{2j} \pmod{N^\sigma}, \end{aligned}$$

i.e.,

$$\tau(w_j) = v_j, \quad \text{for } n_1 + n_2 + 1 \leq j \leq \frac{n-2}{2}.$$

In conclusion,

$$Q^\sigma = \mathbb{Z}[e_0] + \sum_{i=1}^{n_1+n_2} \mathbb{Z}[e_i] + \sum_{j=n_1+n_2+1}^{\frac{n-2}{2}} \mathbb{Z}[w_j, v_j],$$

where τ acts trivially on e_i , permutes w_j and v_j , and the unique (-1) -eigenvector e_0 contributes to

$$H^1(\langle \tau \rangle, Q^\sigma) = \mathbb{Z}/2.$$

This completes the proof of Proposition 28.

Remark 32. Notice that when $n_1 = n_2 = 0$, the argument above shows

$$H^1(C_2, Q) = \mathbb{Z}/2,$$

where the C_2 is generated by $(1, 2)(3, 4) \dots (n-1, n)$. Computational experiments suggest that

$$H^1(H, M) = 0,$$

for all cyclic subgroups $H \subset \mathfrak{S}_n$.

Small dimensional examples.

n = 6: By Theorem 1 and the analysis in Section 6 of [CTZ23], we know that the G -action on $\text{Pic}(\overline{\mathcal{M}}_{0,6})$ satisfies **(SP)** iff the G -action is linearizable, thus, nonlinearizable actions are not stably linearizable, as they fail **(SP)**.

Remark 33. This indicates an error in the application in [HT23, p. 295]: Proposition 21 there asserts that the standard and non-standard actions of $\mathfrak{A}_5$ are stably birational, contradicting our cohomology computation. The gap occurs in the sentence: “However, for any finite group G and automorphism $a : G \rightarrow G$, precomposing by a yields an

action on G -modules; this respects permutation and stably permutation modules.”

n = 8: There is a unique (conjugacy class of) $G' = C_2^2 \subset \mathfrak{S}_8$ such that

$$H^1(G', \text{Pic}(\overline{\mathcal{M}}_{0,8})) = \mathbb{Z}/2,$$

and all $G \subseteq \mathfrak{S}_8$ failing **(H1)** on M contain G' . With `magma`, we find:

- There are 66 (conjugacy classes of) groups containing this G' .
- Of the remaining 230 classes, 96 are contained in the (unique) $\mathfrak{S}_7 \subset \mathfrak{S}_8$, the corresponding actions are linearizable.
- After that, there are 56 contained in the (unique) $\mathfrak{S}_6 \times C_2$ – these actions are birational to an action on a 5-dimensional torus; such actions have been analyzed, over nonclosed fields, in [HY17].
- We are left with 78 classes. Applying [HY17, Algorithm F4] to these classes, we found at least 37 classes of groups $G \subset \mathfrak{S}_8$ having vanishing cohomology but with $\text{Pic}(\overline{\mathcal{M}}_{0,8})$ failing the **(SP)** condition.
- Among the 41 remaining classes, 13 leave invariant an odd cycle. These actions are stably linearizable by Proposition 3.
- There are 28 remaining classes, including a minimal

$$C_2^2 = \langle (1, 2)(3, 4)(5, 6)(7, 8), (1, 3)(2, 4)(5, 7)(6, 8) \rangle,$$

which (up to conjugation) is contained in every remaining class. The action of this C_2^2 on M yields a permutation module:

$$\mathbb{Z}[C_2^2]^{19} \oplus \mathbb{Z}[C_2^2/C_2]^3 \oplus \mathbb{Z}[C_2^2/C_2']^3 \oplus \mathbb{Z}[C_2^2/C_2'']^3 \oplus \mathbb{Z}^5.$$

However, on Q , this action fails **(H1)**, and Theorem 24 is not applicable to any of these cases.

n = 10: We find more minimal groups contributing cohomology:

$$H^1(G, \text{Pic}(\overline{\mathcal{M}}_{0,10})) = \mathbb{Z}/2$$

when

- $G = C_2^2 = \langle (1, 2)(3, 4)(5, 6)(7, 8), (1, 2)(9, 10) \rangle,$
- $G = C_2^2 = \langle (1, 2)(3, 4)(5, 6), (5, 6)(7, 8)(9, 10) \rangle,$
- $G = C_2 \times C_4 = \langle (3, 6)(8, 10), (1, 2)(5, 9), (1, 2)(3, 10, 6, 8)(4, 7) \rangle,$
- $G = \mathfrak{D}_4 = \langle (3, 6)(8, 10), (1, 2)(5, 9)(8, 10), (1, 2)(3, 10, 6, 8)(4, 7) \rangle.$

6. THREE-DIMENSIONAL CASE

Next, we give a criterion for rationality of the Segre cubic, exhibit forms failing stable rationality over arbitrary fields admitting a bi-quadratic extension, and establish stable rationality, provided Q is stably permutation, for the action of the absolute Galois group.

Recall that X_6 denotes the symmetrically linearized GIT quotient with equivalent presentations:

- $(\mathbb{P}^1)^6$ under the diagonal action of SL_2 ; or
- $\mathrm{Gr}(2, 6)$ under the diagonal action of the torus $\mathbb{T} \simeq \mathbb{G}_m^5$.

These have ten isolated nodes, the images of the $D_I, |I| = 3$ under the blow down $\beta : \overline{\mathcal{M}}_{0,6} \rightarrow X_6$. These are classically embedded $X_6 \subset \mathbb{P}^4$ as cubic threefolds, known as Segre cubic threefolds [CTZ23]. The remaining boundary divisors $D_I, |I| = 2$ correspond to planes passing through four nodes.

Theorem 34. *Let X be a form of the Segre cubic threefold over a nonclosed field F of characteristic zero, and $\tilde{X}$ its standard resolution of singularities, a form of $\overline{\mathcal{M}}_{0,6}$. Then X is rational over F if and only if the Galois-module $\mathrm{Pic}(\overline{\mathcal{M}}_{0,6})$ satisfies (SP).*

Proof. This is closely related to the linearizability result [CTZ23, Theorem 1]. The group-theoretic analysis there shows that the only cases where the Galois action on the Picard group is stably permutation are:

- when one of the ten nodes is Galois invariant;
- the Galois action is contained in an $\mathfrak{S}_5$ -action associated with permutations of *five* of the marked points;
- the Galois group acts via C_2^2 , leaving three planes invariant, and the set of nodes splits into a union of five Galois orbits of length two.

Note that the first two cases are easily shown to be rational: Projecting from a node gives a birational map to $\mathbb{P}^3$, cf. Example 19. And when the action factors through $\mathfrak{S}_5$, the moduli space arises via the Kapranov construction, i.e., is a blow-up of $\mathbb{P}^3$.

Recall that in the third case, the Galois action factors through $\mathfrak{S}_2 \times \mathfrak{S}_4 \subset \mathfrak{S}_6$ corresponding to a partition of the six points conjugate to

$$\{1, 2, 3, 4, 5, 6\} = \{3, 4\} \cup \{1, 2, 5, 6\}.$$

Our $C_2 \times C_2$ action is conjugate to

$$\langle (34), (15)(26) \rangle \subset \mathfrak{S}_6$$

This leaves the boundary divisors D_{34} , D_{15} , and D_{26} invariant. Identifying singular points with the boundary divisors in $\overline{\mathcal{M}}_{0,6}$, the orbits are

$$\begin{aligned} \{D_{123} = D_{456}, D_{124} = D_{356}\}, & \quad \{D_{125} = D_{346}, D_{156} = D_{234}\}, \\ \{D_{126} = D_{345}, D_{256} = D_{134}\}, & \quad \{D_{135} = D_{246}, D_{145} = D_{236}\}, \\ \{D_{136} = D_{245}, D_{146} = D_{235}\}. \end{aligned}$$

We emphasize that the invariant divisor classes reflect boundary divisors defined over F . Indeed, our moduli space has F -rational smooth points so there is no obstruction to descending Galois-invariant divisors.

We claim this moduli space is birational over F to a toric threefold, i.e., an equivariant compactification of a nonsplit torus over F .

Consider the Losev-Manin moduli space associated to the partition above. Specifically, points 3 and 4 are not permitted to collide with other points but points from $\{1, 2, 5, 6\}$ may collide with one another. This is toric by Proposition 7, i.e., the orbits of the homogeneous quartic forms vanishing along $\{1, 2, 5, 6\}$ modulo the torus fixing $\{3, 4\}$. This geometric description is compatible with the Galois action.

Rationality of three-dimensional toric varieties has been settled in [Kun87, Theorem 2]: The variety is rational over F iff the Picard module is stably permutation for the Galois action.

Here is an alternative rationality construction: Pick one of the boundary divisors D_I , $|I| = 2$ invariant under the Galois action. With our choice of indexing this could be D_{34} , D_{15} , or D_{26} ; we take D_{34} . This corresponds to a plane $P \subset X$ containing four ordinary singularities, i.e., the images of D_{34j} , $j = 1, 2, 5, 6$. We blow this plane up – inducing a small resolution of the four singularities – and then blow down the proper transform of the plane. This yields a complete intersection of two quadrics $X_{2,2} \subset \mathbb{P}^5$ with six singularities, the images of the singularities of X *not* contained in P . Under the $C_2 \times C_2$ action, we have three orbits each with two singular points. For each orbit, the line joining the singularities is contained in $X_{2,2}$. Projecting from that line gives

$$X_{2,2} \xrightarrow{\sim} \mathbb{P}^3;$$

the birationality is classical cf. [CTSSD87, Proposition 2.2]. □

REFERENCES

- [Avi20] A. A. Avilov. Forms of the Segre cubic. *Math. Notes*, 107(1):3–9, 2020.
- [BCTSSD85] A. Beauville, J.-L. Colliot-Thélène, J.-J. Sansuc, and P. Swinnerton-Dyer. Variétés stablement rationnelles non rationnelles. *Ann. of Math. (2)*, 121(2):283–318, 1985.
- [BF17] A. Berget and A. Fink. Equivariant Chow classes of matrix orbit closures. *Transform. Groups*, 22(3):631–643, 2017.
- [BM13] A. Bruno and M. Mella. The automorphism group of $\overline{M}_{0,n}$. *J. Eur. Math. Soc. (JEMS)*, 15(3):949–968, 2013.
- [BP13] F. Bogomolov and Yu. Prokhorov. On stable conjugacy of finite subgroups of the plane Cremona group, I. *Cent. Eur. J. Math.*, 11(12):2099–2105, 2013.
- [CTS77] J.-L. Colliot-Thélène and J.-J. Sansuc. La R-équivalence sur les tores. *Ann. Sci. Éc. Norm. Supér. (4)*, 10:175–229, 1977.
- [CTS87] J.-L. Colliot-Thélène and J.-J. Sansuc. La descente sur les variétés rationnelles. II. *Duke Math. J.*, 54(2):375–492, 1987.
- [CTSSD87] J.-L. Colliot-Thélène, J.-J. Sansuc, and P. Swinnerton-Dyer. Intersections of two quadrics and Châtelet surfaces. I. *J. Reine Angew. Math.*, 373:37–107, 1987.
- [CTZ23] I. Cheltsov, Yu. Tschinkel, and Zhijia Zhang. Equivariant geometry of the Segre cubic and the Burkhardt quartic, 2023. [arXiv:2308.15271](https://arxiv.org/abs/2308.15271).
- [DR15] A. Duncan and Z. Reichstein. Versality of algebraic group actions and rational points on twisted varieties. *J. Algebr. Geom.*, 24(3):499–530, 2015.
- [EP00] D. Eisenbud and S. Popescu. The projective geometry of the Gale transform. *J. Algebra*, 230(1):127–173, 2000.
- [FH91] W. Fulton and J. Harris. *Representation theory*, volume 129 of *Graduate Texts in Mathematics*. Springer-Verlag, New York, 1991. A first course, Readings in Mathematics.
- [Flo13] Mathieu Florence. Géométrie birationnelle équivariante des grassmanniennes. *J. Reine Angew. Math.*, 674:81–98, 2013.
- [FR18] M. Florence and Z. Reichstein. The rationality problem for forms of $\overline{M}_{0,n}$. *Bull. Lond. Math. Soc.*, 50(1):148–158, 2018.
- [Ful98] W. Fulton. *Intersection theory*, volume 2 of *Ergeb. Math. Grenzgeb., 3. Folge*. Springer, 2nd ed. edition, 1998.
- [GG14] N. Giansiracusa and W. D. Gillam. On Kapranov’s description of $\overline{M}_{0,n}$ as a Chow quotient. *Turkish J. Math.*, 38(4):625–648, 2014.
- [Has03] B. Hassett. Moduli spaces of weighted pointed stable curves. *Adv. Math.*, 173(2):316–352, 2003.
- [HT02] B. Hassett and Yu. Tschinkel. On the effective cone of the moduli space of pointed rational curves. In *Topology and geometry: commemorating SISTAG. Proceedings of the Singapore international symposium in topology and geometry (SISTAG), Singapore, July 2–6, 2001*, pages 83–96. Providence, RI: American Mathematical Society (AMS), 2002.

- [HT23] B. Hassett and Yu. Tschinkel. Torsors and stable equivariant birational geometry. *Nagoya Math. J.*, 250:275–297, 2023.
- [HY17] A. Hoshi and A. Yamasaki. Rationality problem for algebraic tori. *Mem. Amer. Math. Soc.*, 248(1176):v+215, 2017.
- [Kap93] M. M. Kapranov. Chow quotients of Grassmannians. I. In *I. M. Gelfand seminar. Part 2: Papers of the Gelfand seminar in functional analysis held at Moscow University, Russia, September 1993*, pages 29–110. Providence, RI: American Mathematical Society, 1993.
- [Kly85] A. A. Klyachko. Orbits of a maximal torus on a flag space. *Funktsional. Anal. i Prilozhen.*, 19(1):77–78, 1985.
- [Kun87] B. È. Kunyavskii. Three-dimensional algebraic tori. In *Investigations in number theory (Russian)*, pages 90–111. Saratov. Gos. Univ., Saratov, 1987. Translated in *Selecta Math. Soviet.* **9** (1990), no. 1, 1–21.
- [Lia23] C. Lian. Torus orbit closures and 1-strip-less tableaux, 2023. [arXiv:2305.11289](https://arxiv.org/abs/2305.11289).
- [LM00] A. Losev and Yu. Manin. New moduli spaces of pointed curves and pencils of flat connections. *Mich. Math. J.*, 48:443–472, 2000.

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