

BITANGENTS TO SYMMETRIC QUARTICS

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ABSTRACT. Recall that a non-singular planar quartic is a canonically embedded non-hyperelliptic curve of genus three. We say such a curve is *symmetric* if it admits non-trivial automorphisms. The classification of (necessarily finite) groups appearing as automorphism groups of non-singular curves of genus three dates back to the last decade of the 19th century. As these groups act on the quartic via projective linear transformations, they induce symmetries on the 28 bitangents. Given such an automorphism group $G = \text{Aut}(C)$, we leverage tools from equivariant homotopy theory to prove that the G -orbits of the bitangents are independent of the choice of C , and we compute them for all twelve types of smooth symmetric planar quartic curves. We further observe that techniques deriving from equivariant homotopy theory directly reveal patterns which are not obvious from a classical moduli perspective.

1. INTRODUCTION

The study of bitangents to plane quartics dates back to the 19th century, and has been one of the pillars of classical enumerative algebraic geometry. In 1850, Jacobi [Jac50] was the first to compute that the number of bitangents to a smooth planar quartic was 28, using work of Plücker from two decades earlier [Plü34]. This was extended to general quartics shortly thereafter by Hesse [Hes55]. The configurations of these lines, their combinatorics, and their sweeping connections throughout mathematics were objects of deep fascination throughout the 19th century, and their connections to other fields of geometry, e.g., Lie algebras, continue to be topics of interest to modern mathematicians [Man06]. The automorphism groups of genus three (non-hyperelliptic) curves have been completely classified, and we provide a historical overview of this work in Section 2.2. Since a planar quartic is a canonically embedded non-hyperelliptic genus three curve, any automorphism of a genus three curve will extend to an automorphism of the projective plane. Moreover, any such an automorphism group will be finite by the Hurwitz formula. In particular, the set of 28 bitangents of such a curve will inherit a natural action from the automorphism group of the curve. Leveraging tools from equivariant homotopy theory, we prove the action on the bitangents is independent of the choice of symmetric quartic. In each case, we compute the orbit decomposition of the action on the set of bitangents.

Theorem 1.1. Let G be any group which appears as the automorphism group of a genus three non-hyperelliptic curve. Then for any such curve C with $G \cong \text{Aut}(C)$, the action of G on the bitangents of C is independent of the choice of C , and is given by the following G -set:¹

¹See Section 4 for an explanation of the notation.

Type	$\text{Aut}(C)$	Order	28 bitangents
I	$\text{PSL}_2(7)$	168	$[\text{PSL}_2(7)/S_3]$
II	$C_4^{\times 2} \rtimes S_3$	96	$[C_4^{\times 2} \rtimes S_3/S_3] + [C_4^{\times 2} \rtimes S_3/C_8]$
III	$C_4 \odot A_4$	48	$[C_4 \odot A_4/C_2] + [C_4 \odot A_4/C_{12}]$
IV	S_4	24	$[S_4/C_2^o] + [S_4/C_2^e] + [S_4/S_3]$
V	P	16	$[P/C_2^{(1)}] + [P/C_2^{(2)}] + [P/C_2^{(3)}] + [P/C_4^Z]$
VI	C_9	9	$3[C_9/e] + [C_9/C_9]$
VII	D_8	8	$[D_8/e] + 2[D_8/C_2^{(1)}] + 2[D_8/C_2^{(2)}] + [D_8/C_2^Z]$
VIII	C_6	6	$4[C_6/e] + [C_6/C_2] + [C_6/C_6]$
IX	S_3	6	$3[S_3/e] + 3[S_3/C_2] + [S_3/S_3]$
X	K_4	4	$4[K_4/e] + 2[K_4/C_2^L] + 2[K_4/C_2^\Delta] + 2[K_4/C_2^R]$
XI	C_3	3	$9[C_3/e] + [C_3/C_3]$
XII	C_2	2	$12[C_2/e] + 4[C_2/C_2]$

The proof is given in Corollary 3.8.

Example 1.2. As an example, we visualize the 28 bitangents on the following *Edge quartic*.² This admits a clear D_8 symmetry on the xy -plane, which extends to an S_4 -symmetry by passing between the different affine patches.

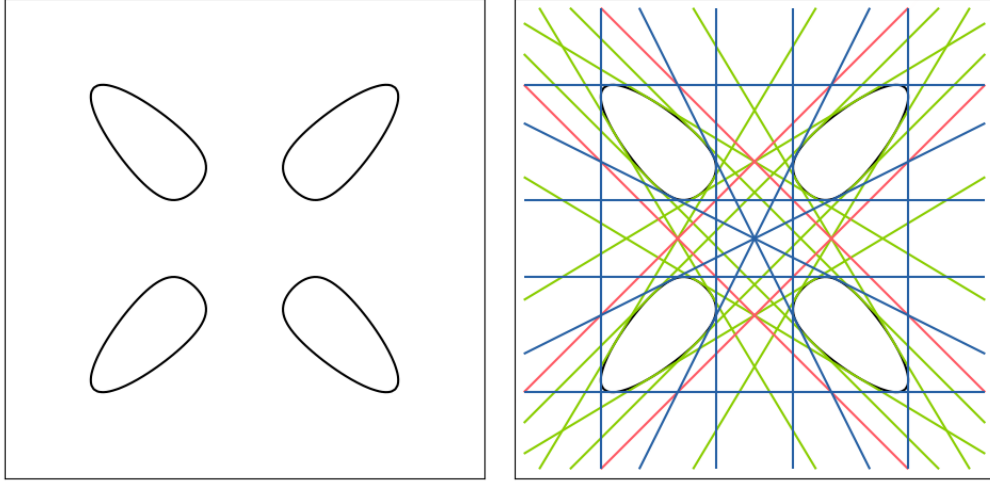


FIGURE 1. The *Edge quartic*, defined by the equation $25(x^4 + y^4 + z^4) - 34(x^2y^2 + x^2z^2 + y^2z^2)$, and its 28 real bitangents graphed with their S_4 orbits.

We prove Theorem 1.1 by leveraging the machinery of [Bra25]. First, we formulate the count of bitangents on a G -symmetric quartic as a G -equivariant vector bundle, then we compute its MU_G -valued Euler class. This proves that the action of $G \cong \text{Aut}(C)$ on the bitangents is independent of curve C with automorphism group G . We pick candidate curves in each automorphism class from [Dol12, Hen76] and compute equations for each of the bitangents using code modified from [PSV11]. Finally, we determine the orbits of lines and their isotropy under the action of the automorphism group. We provide figures in each case.

²See Remark 4.5 for a further discussion of Edge quartics.

Remark 1.3. There are multiple ways to argue that the action of the automorphism group on bitangents (and even θ -characteristics) is independent of the choice of curve, as in Theorem 1.1. A classical way is to observe that each component of the moduli space is connected, although we remark that our methods work even when this might fail. After finishing this work, the authors were made aware of a third way to prove this independence, which had appeared in a preprint of Braden and Disney–Hogg a few months prior [BDH24]. Braden–Disney–Hogg argue that curves in the same component of the moduli space have equivalent rational representations, and the orbit decomposition can be recovered by the rational representation. In particular, the table in our Theorem 1.1 can be found in Table 6 of [BDH24], although the authors there do not specify the isotropy type of each orbit.

Remark 1.4. (*Other related literature*)

- The orbits of the automorphism group of the Klein quartic on its 28 bitangents is well-studied, and visualizable over $\mathbb{P}_{\mathbb{F}_7}^1$ ([Cox83, JvOS94]). In general, the equivariant enumerative geometry of the Klein quartic has been a popular direction of research since the mid-to-late 1800’s. The action on the even theta characteristics is in [DK93], and the action on the Steiner complexes and Aronhold sets in [JvOS94]. See [Dol12, Remark 6.5.4] for more information.
- The bitangents of non-hyperelliptic curves of genus three with cyclic automorphisms of degree 3, 6, or 9 was recently studied in a paper of Liang [Lia20].

Remark 1.5. (*On rationality*) In 1873, Zeuthen proved that a smooth real quartic can have 4, 8, 16, or 28 bitangents, and this depends precisely on the topology of the real curve [Zeu74]. One might ask whether results in this paper can make general statements about the number of real bitangents to smooth real planar quartics with given automorphism group, in a way analogous to [Bra25, Theorem 1.3]. It is a straightforward numerical computation to obtain the possible numbers of real bitangents among real quartics of each type – we record the maximal such number in Figure 13.

1.1. Outline. The paper is organized as follows. Section 2 gives background information on canonical quartic plane curves and shows which groups can arise from their non-trivial automorphisms. Section 3 starts by defining the equivariant Euler number. Next, Section 3 defines the vector bundle which parameterizes the enumerative problem of counting bitangents to symmetric quartics, following the construction of [LV21]. Section 3 then shows the vector bundle is equivariant for any group G which arises as a non-trivial automorphism group of a canonical quartic. Finally, the equivariant Euler number is used to count orbits of bitangents on a G -symmetric quartic and conclude that the count is independent of the choice of quartic. Section 4 gives example quartics and illustrates orbits of real bitangents for every group. Section 5 concludes the paper with a subgroup lattice of automorphism groups of canonical quartics.

1.2. Data availability. Throughout the paper are various **Computation** environments. These refer to numerical solutions for bitangents to example quartic curves for each type, whose orbits under the automorphism group of the curve were then checked on a computer (but can also be verified by hand). Code used to compute bitangents and their orbits is available in the following repository:

https://github.com/tbrazel/bitangents_code

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2. BACKGROUND

2.1. The basics of plane quartic curves. Nonsingular curves of genus $g \geq 2$ come in two flavors, being *canonical* and *hyperelliptic* quartic curves, depending on whether the canonical class is very ample. When the canonical class of a smooth genus $g \geq 2$ curve C is very ample, we have that $\Gamma(C, \omega_C)$ is a vector space of dimension g . A choice of basis of holomorphic forms defines an embedding $C \rightarrow \mathbb{P}^{g-1}$ called a *canonical embedding*. Any automorphism induces an automorphism of the canonical sheaf ω_C by pullback, and therefore extends to an automorphism of \mathbb{P}^{g-1} . Thus the automorphism groups of canonical curves are all *geometric* in the sense that they act on the embedded curve via projective linear transformations.

Recall that a *non-singular planar quartic curve* is a canonically embedded, non-hyperelliptic curve of degree 4 (hence genus 3). It is a classical fact that a general non-hyperelliptic curve of genus $g \geq 3$ admits no nontrivial automorphisms. This motivates the following definition.

Definition 2.1. We say a non-hyperelliptic non-singular curve of genus g is *symmetric* if it admits any automorphism other than the identity.

2.2. Automorphisms of smooth quartics. Here we provide a brief history of the classification of the automorphism groups of genus 3 non-singular, non-hyperelliptic curves. This is a history which is scattered throughout the literature, and some references contain minor errors, so we feel it is worth recounting.

In 1878, Schwarz proved that the automorphism group of a compact Riemann surface of genus $g \geq 2$ is finite. He argued this by observing that the automorphism group of a non-hyperelliptic curve acts faithfully on the Weierstrass points of the curve, of which there are only finitely many. In 1892, Hurwitz determined an upper bound of $84(g-1)$ on the size of such automorphism groups [Hur92], however for many g this bound is not attained. A famous example where it is attained is the so-called *Klein quartic* (Type I in our classification), which was studied extensively by Felix Klein [Kle78], and has an automorphism group of size 168.

During this time, Kantor worked on understanding periodic transformations on the projective plane, informed by algebraic questions arising from the Hermite and Frobenius programs on quadratic forms [Kan95a]. In modern language, we might understand this as the study of cyclic subgroups of $\mathrm{PGL}_3(\mathbb{C})$. In the course of this work, Kantor observed the following result.

Theorem 2.2. [Kan95b, p. 40] Given any finite subgroup $G \leq \mathrm{PGL}_3(\mathbb{C})$, there exists a planar curve of genus $g \geq 3$ which is G -invariant.

Given this result, one might fix a genus g and study which finite groups can act on smooth non-hyperelliptic planar curves of this genus. Further, one may ask what the full automorphism groups of such curves are. Kantor claimed in this same work to classify the automorphism groups of plane quartic curves. However, this classification contained many errors, which were corrected shortly thereafter by Wiman in 1896 [Wim96]. In particular, following Hurwitz's work [Hur92], the prime factors of $\#\text{Aut}(C)$ must be 2, 3, or 7, which was known to Wiman [Wim96, p. 223]. Although it does not satisfy modern standards of rigor, Wiman correctly identified all the possible orders of automorphism groups of genus three non-hyperelliptic non-singular curves and provided an indication as to the generators of these groups.

In 1910, Ciani extended this classification to all irreducible quartics (not necessarily nonsingular) [Cia10]. The subtleties in such a classification can be seen in the following example, which drifts beyond the reach of the Hurwitz theorem.

Example 2.3. Observe that the quartic $x^3y + z^4$ (which is singular at the point $[0 : 1 : 0]$) admits a symmetry of arbitrary order $r \geq 7$ given by $(x, y, z) \mapsto (\zeta_r x, \zeta_r^{-3} y, z)$, where ζ_r denotes a primitive r^{th} root of unity [Cia10, N. 19]. In particular, its automorphism group is necessarily infinite.

It is unclear which results were known or lost in the literature throughout the 20th century. In 1976, Henn recomputed the automorphism groups of genus three non-hyperelliptic curves via the action on Weierstrass points, and he obtained a classification of finite groups occurring as automorphism groups of smooth planar quartics [Hen76]. This essentially recovered the computation done by Wiman nearly a century earlier.

Around the mid-1960's, many mathematicians published work studying compact Riemann surfaces equipped with non-trivial involutions. This body of work is far too encompassing to mention all of the relevant players, but we highlight a particular program of mathematics emanating from work of A. Kuribayashi. This program studied the moduli of compact Riemann surfaces equipped with non-trivial automorphisms [Kur66, Kur76], leveraging tools from Teichmüller theory. In [KK77], the authors studied smooth projective genus three curves which are cyclic covers of the projective line or of an elliptic curve, and determine their automorphism groups, again recovering the classification initially due to Wiman.

By the dawn of the 21st century, computer-aided research had become increasingly ubiquitous in mathematics. Tremendous progress was made by Breuer, who determined which finite groups can act on a curve of genus ≤ 48 [Bre00]. This leveraged group-theoretic constraints on such subgroups arising from covering space theory and an exhaustive search through a library of finite groups in GAP [GAP24]. Magaard, Shaska, Shpectorov and Völkei provided a lovely discussion of how to re-derive the classification for genus $g = 3$ from the data obtained by Breuer (that paper also contains rich historical background for the interested reader) [MSSV02].

A beautiful resource for automorphisms of quartics is Dolgachev's book [Dol12, §6.5], which recasted the research of Kantor and Wiman in modern language and rigor. Before this book was published, Bars [Bar05] sketched the classification of automorphism groups of quartics, which followed both Henn's thesis and the aforementioned paper of Komiya and Kuribayashi. Bars' note also corrected errors in the classification appearing in the lecture notes that eventually became Dolgachev's book.

With all this in mind, we state the following classification. We feel it is fair to attribute the classification to Wiman, although we refer the reader to [Dol12, p. 270] for a rigorous proof.

Theorem 2.4. [Wim96] The following groups G are the only groups occurring as the automorphism group of a smooth plane quartic. In each case we provide an equation for quartics $F(x, y, z)$ of that type, with generators for its automorphism group (c.f. [Bar05, Dol12]). Here ζ_n denotes a primitive n th root of unity, and in $\mathrm{PSL}_2(7)$ we have $\alpha := \frac{\zeta_7^5 - \zeta_7^2}{\sqrt{-7}}$, $\beta = \frac{\zeta_7^6 - \zeta_7}{\sqrt{-7}}$ and $\gamma = \frac{\zeta_7^3 - \zeta_7^4}{\sqrt{-7}}$

Type	$\mathrm{Aut}(C)$	GAP ID	$F(x, y, z)$	Generators in $\mathrm{PGL}_3(\mathbb{C})$
I	$\mathrm{PSL}_2(7)$	[168, 42]	$x^3y + y^3z + z^3x$	$\begin{pmatrix} \zeta_7^4 & 0 & 0 \\ 0 & \zeta_7^2 & 0 \\ 0 & 0 & \zeta_7 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} \beta & \alpha & \gamma \\ \alpha & \gamma & \beta \\ \gamma & \beta & \alpha \end{pmatrix}$
II	$C_4^{\times 2} \rtimes S_3$	[96, 64]	$x^4 + y^4 + z^4$	$\begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, \begin{pmatrix} -i & 0 & 0 \\ 0 & 0 & 1 \\ 0 & i & 0 \end{pmatrix}$
III	$C_4 \odot A_4$	[48, 33]	$x^4 + y^4 + z^4 + (4\zeta_3 + 2)x^2y^2$	$\begin{pmatrix} \frac{1+i}{2} & \frac{-1+i}{2} & 0 \\ \frac{1-i}{2} & \frac{1-i}{2} & 0 \\ 0 & 0 & \zeta_3 \end{pmatrix}, \begin{pmatrix} \frac{1+i}{2} & \frac{-1-i}{2} & 0 \\ \frac{-1+i}{2} & \frac{-1-i}{2} & 0 \\ 0 & 0 & \zeta_3^2 \end{pmatrix}$
IV	S_4	[24, 12]	$x^4 + y^4 + z^4 + a(x^2y^2 + y^2z^2 + z^2x^2)$	$\begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
V	P	[16, 13]	$x^4 + y^4 + z^4 + ax^2y^2$	$\begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} i & 0 & 0 \\ 0 & -i & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
VI	C_9	[9, 1]	$x^4 + xy^3 + yz^3$	$\begin{pmatrix} \zeta_3 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \zeta_9 \end{pmatrix}$
VII	D_8	[8, 3]	$x^4 + y^4 + z^4 + ax^2y^2 + bxyz^2$	$\begin{pmatrix} i & 0 & 0 \\ 0 & -i & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
VIII	C_6	[6, 2]	$z^3y + x^4 + ax^2y^2 + y^4$	$\begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \zeta_3 \end{pmatrix}$
IX	S_3	[6, 1]	$x^3z + y^3z + x^2y^2 + axyz^2 + bz^4$	$\begin{pmatrix} \zeta_3 & 0 & 0 \\ 0 & \zeta_3^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
X	K_4	[4, 2]	$x^4 + y^4 + z^4 + ax^2y^2 + by^2z^2 + cx^2z^2$	$\begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
XI	C_3	[3, 1]	$z^3y + x(x-y)(x-ay)(x-by)$	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \zeta_3 \end{pmatrix}$
XII	C_2	[2, 1]	$x^4 + y^4 + z^4 + x^2(ay^2 + byz + cz^2) + dy^2z^2$	$\begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$

The equations are subject to the following constraints:

- Type IV: we have $a \neq 0$ since this yields a Type II curve, and $a \neq \frac{3}{2}(-1 \pm \sqrt{-7})$ since otherwise one obtains a Type I curve.
- Type V: $a \notin \{0, \pm 2\sqrt{-3}, \pm 6\}$. If $a = 0$ or $a = \pm 6$, then we obtain a Type II quartic. If $a = \pm 2\sqrt{-3}$, then we obtain a Type III quartic.
- Type VII: $b \neq 0$. For $b = 0$, we obtain a Type V quartic.
- Type VIII: $a \neq 0$. For $a = 0$, we obtain a Type III quartic.

- Type IX:³ $a \neq 0$, otherwise we obtain a Type IV quartic.
- Type X: all the values $\{\pm a, \pm b, \pm c\}$ are distinct, otherwise we obtain a Type VII curve.
- Type XI: if either $a = \zeta_3$ or $b = \zeta_3$, then we obtain a Type VI curve. If either $a = -1$ or $b = -1$, then we obtain a Type VIII curve.
- Type XII:⁴ if $b = 0$, then we obtain a Type X quartic. If $a = -2$, $b = 0$, and $c = -d$, then we obtain a Type IX curve.

These are the only groups we need consider counting orbits of bitangents for, as they are the only groups for which symmetric, smooth, non-hyperelliptic quartic curves can exist. We explicitly prove the equivariant Euler number counts orbits of bitangents of quartics symmetric for the groups above in Corollary 3.7. Moreover, we show that all quartic curves with the same automorphism group G appearing above have the same bitangent orbit decomposition in Corollary 3.8.

The reader may notice subgroup containment between some of these groups, we discuss how this manifests in our computations in Section 5.

Remark 2.5. The quartic equations appearing in Theorem 2.4 are in fact the only quartic equations (up to projective transformation) with the given automorphism group. One proves this by first providing normal forms for cyclic actions, then doing a case-by-case analysis as in [Dol12, §6.4]. When free parameters appear, they correspond to the dimension of the moduli of smooth planar quartics having the given automorphism group. In that sense, the free coefficients in the equations of Theorem 2.4 give an indication of how the moduli of symmetric quartics is stratified.

3. THE EULER NUMBER FOR BITANGENTS

Before proving Theorem 1.1, we provide a brief overview of the definition of the equivariant Euler number from [Bra25].

3.1. The equivariant Euler number. Let G be a finite group. Given a G -equivariant complex vector bundle $E \rightarrow M$ of rank n over a smooth compact complex n -manifold, one can assign an *equivariant Euler number* $n_G(E)$. This number is valued in the *Burnside ring* $A(G)$, which is the Grothendieck group completion of the monoid of G -isomorphism classes of finite G -sets under disjoint union. This has a ring structure under cartesian product. A general element $[S]$ of $A(G)$ can be written

$$(1) \quad [S] = \sum_{(H_i)} m_i [G/H_i],$$

³Our equation differs slightly from [Dol12] by rescaling variables.

⁴Our equation for a Type XII quartic matches that found in [Dol12, Theorem 6.5.2], which is a priori different from [Dol12, Lemma 6.5.1] and [Hen76, Bar05]. A Type XII quartic is of the form $x^4 + x^2 L_2(y, z) + L_4(y, z)$, where L_k denotes a homogeneous binary form of degree k . By the classical theory of quartics, we recall that every binary quartic form admits a *canonical form* $y^4 + dy^2 z^2 + z^4$ after a projective linear transformation, a fact that dates back to Cayley but can be found in [Ell13, Chapter XII]. This is the source of the quartic equation we use here.

where (H_i) are conjugacy classes of subgroups of G and m_i are integers. Indeed, classes of transitive G -sets $[G/H]$ are the additive generators of $A(G)$. See [tD79] for an extensive study of the Burnside ring of a finite group.

Given a G -equivariant section of E which is transverse to the zero section, the Euler number $n_G(E)$ counts the zeros of the section and simultaneously encodes the G -action on the zeros. Specifically, let $\sigma: X \rightarrow E$ be such a G -equivariant section. The set of zeros of σ ,

$$Z(\sigma) = \{p \in X : \sigma(p) = 0\},$$

is a G -invariant set of finitely many points of X . Since $Z(\sigma)$ is a G -set, $Z(\sigma)$ can be decomposed as a disjoint union of its G -orbits. As disjoint union defines the addition law in $A(G)$, the G -isomorphism class $[Z(\sigma)]$ can be represented as a sum of its G -orbits in $A(G)$. For the computational purposes of this paper, one can take the definition of the *equivariant Euler number* $n_G(E)$ to be this sum in $A(G)$ representing the class of $Z(\sigma)$,

$$n_G(E) = [Z(\sigma)] = \sum_{\{G \cdot p \subseteq Z(\sigma)\}} m_p [G/G_p],$$

where G_p is the stabilizer of $p \in Z(\sigma)$ and m_p is the number of orbits with stabilizer G_p .

The zero set of *any* equivariant section transverse to the zero section has the same cardinality and the same orbit decomposition in $A(G)$. Thus the equivariant Euler number is an invariant of the bundle E rather than an invariant of a general section σ ; this is an equivariant enhancement of a phenomenon known as *conservation of number*. See [Bra25] for the rigorous construction of $n_G(E)$ using equivariant homotopy theory.

3.2. Equivariant conservation for bitangents. The proof of Theorem 1.1 relies on the fact that we can obtain a G -equivariant count of the 28 bitangents to a smooth quartic C for $G \cong \text{Aut}(C)$ using the equivariant Euler number of [Bra25], and this count will be independent of choice of quartic with automorphism group G . We use the bundle parameterizing bitangents to smooth quartics following the construction of [LV21], which we recount exactly below.

Let

$$\mathcal{S} \rightarrow (\mathbb{P}^2)^\vee$$

denote the tautological bundle over the moduli of lines in \mathbb{P}^2 . Let $X := \mathbb{P}(\text{Sym}^2 \mathcal{S}^\vee)$ so that a point on X is a pair (L, Z) where $L \subseteq \mathbb{P}^2$ is a line and $Z \subseteq L$ is a degree two subscheme. Writing $\pi: X \rightarrow (\mathbb{P}^2)^\vee$ for the natural projection map, we have the commutative diagram:

$$(2) \quad \begin{array}{ccc} \pi^* \text{Sym}^2 \mathcal{S}^\vee & \longrightarrow & \text{Sym}^2 \mathcal{S}^\vee \\ \downarrow & & \downarrow \\ X & \xrightarrow{\pi} & (\mathbb{P}^2)^\vee. \end{array}$$

Note that any fiber of $\mathcal{O}_X(-1) \subseteq \pi^* \text{Sym}^2 \mathcal{S}^\vee$ determines a choice of equations defining $Z \subseteq L$, whence the quotient of

$$(3) \quad \mathcal{O}_X(-1) \rightarrow \pi^* \text{Sym}^2 \mathcal{S}^\vee$$

parameterizes quadratic equations on L vanishing along Z . Squaring, we obtain the composite

$$(4) \quad \mathcal{O}_X(-2) \rightarrow \mathrm{Sym}^2 \mathcal{S}^\vee \otimes \mathrm{Sym}^2 \mathcal{S}^\vee \rightarrow \mathrm{Sym}^4 \mathcal{S}^\vee.$$

The vector bundle for our enumerative problem will be the quotient bundle

$$E := \mathrm{Sym}^4 \mathcal{S}^\vee / \mathcal{O}_X(-2),$$

which will parameterize quartic polynomials on L vanishing at the square of an equation of Z . In other words, the quotient $\mathrm{Sym}^4 \mathcal{S}^\vee \rightarrow E$ over the fiber (L, Z) in

$$(5) \quad 0 \rightarrow \mathcal{O}_X(-2) \rightarrow \mathrm{Sym}^4 \mathcal{S}^\vee \rightarrow E \rightarrow 0$$

realizes E as the evaluation of a quartic polynomial on L along $2Z$.

Theorem 3.6. Let $G \leq \mathrm{PGL}_3$ be contained in a group that appears as the automorphism group of a smooth non-hyperelliptic plane quartic. Then

$$E \rightarrow X$$

as constructed above is a G -equivariant vector bundle, and any planar quartic C with $G \leq \mathrm{Aut}(C)$ induces a G -equivariant section of this bundle whose zeros count the bitangents to C .

Proof. The G -action on \mathbb{P}^2 defines an action on \mathbb{P}^{2^\vee} and thus on $\mathcal{S} \rightarrow (\mathbb{P}^2)^\vee$. The symmetric power $\mathrm{Sym}^2 \mathcal{S}^\vee \rightarrow (\mathbb{P}^2)^\vee$ is thus a G -vector bundle, and the projectivization $X := \mathbb{P}(\mathrm{Sym}^2 \mathcal{S}^\vee) \xrightarrow{\pi} (\mathbb{P}^2)^\vee$ is as well. As the actions on X , $\mathrm{Sym}^2 \mathcal{S}^\vee$, and $\pi^* \mathrm{Sym}^2 \mathcal{S}^\vee$ are all inherited from that on $(\mathbb{P}^2)^\vee$, diagram (2) commutes equivariantly.

Since the G -action on $\mathcal{O}_X(-1)$ is inherited from that of $\pi^* \mathrm{Sym}^2 \mathcal{S}^\vee$, the inclusion $\mathcal{O}_X(-1) \rightarrow \pi^* \mathrm{Sym}^2 \mathcal{S}^\vee$ is G -equivariant. Squaring, we deduce that

$$\mathcal{O}_X(-2) \hookrightarrow (\pi^* \mathrm{Sym}^2 \mathcal{S}^\vee)^{\otimes 2}$$

is G -equivariant as well. Since over any particular (L, Z) in X , the composition

$$\mathcal{O}_X(-2)_{(L,Z)} \hookrightarrow ((\mathrm{Sym}^2 \mathcal{S}^\vee)^{\otimes 2})_{(L,Z)} \rightarrow (\mathrm{Sym}^4 \mathcal{S}^\vee)_{(L,Z)}$$

is just the composition of inclusions of the space spanned by the square of a quadratic on Z , $\langle q_Z^2 \rangle \mapsto \langle q_Z^2 \rangle \mapsto \langle q_Z^2 \rangle$, into the space $(\mathrm{Sym}^4 \mathcal{S}^\vee)_{(L,Z)}$ of all degree 4 polynomials on L ,

$$\mathcal{O}_X(-2) \rightarrow \mathrm{Sym}^4 \mathcal{S}^\vee$$

is G -equivariant. In order to argue that the quotient bundle E can be chosen equivariantly, we pick a G -invariant Hermitian metric in $\mathrm{Sym}^4 \mathcal{S}^\vee$ in order to induce an equivariant splitting of the short exact sequence of bundles

$$\mathcal{O}_X(-2) \rightarrow \mathrm{Sym}^4 \mathcal{S}^\vee \rightarrow E.$$

Therefore $E \rightarrow X$ is a G -equivariant vector bundle, and G -equivariant planar quartics induce equivariant sections of the bundle. \square

We have shown $E \rightarrow X$ is a G -equivariant vector bundle, whence we may take its equivariant Euler number $n_G(E)$. Recall from sub-section 3.1 that $n_G(E)$ is the element of $A(G)$ corresponding to the $(G$ -invariant) set of zeros of a G -equivariant section $X \rightarrow E$. If f is a quartic polynomial defining a G -symmetric, smooth, non-hyperelliptic plane quartic $C = V(f)$ and σ_f is the G -equivariant section $X \rightarrow E$ determined by C , then σ_f vanishing at $(L, Z) \in X$

exactly means that L is a bitangent of C with points of bitangency at $Z \subset L$. Thus σ_f being a G -equivariant section and C having exactly 28 bitangents implies that

$$Z(\sigma_f) = \{(L, Z) : \sigma_f(L, Z) = 0\}$$

is a size 28 G -set whose orbits are equal to those of the 28 bitangents to C . G acts transitively on the orbits of $Z(\sigma_f)$, hence G acts transitively on the orbits of bitangents of C . In particular, the equivariant Euler number $n_G(E) = [Z(\sigma_f)]$ is equal in $A(G)$ to the isomorphism class of the G -set of 28 bitangents of C .

Recall from Theorem 2.4 in the introduction the classification due to Wiman [Wim96] of subgroups of PGL_3 that can appear as the automorphism group of a smooth non-hyperelliptic plane quartic. Since these are the only groups which can occur as the automorphism group of a smooth non-hyperelliptic quartic curve, i.e., these are the only groups G for which a G -equivariant section of E corresponds to a quartic C with $\mathrm{Aut}(C) \cong G$, these are the only groups we need consider counting orbits of bitangents for.

We state the conclusion that $n_G(E)$ counts in $A(G)$ orbits of bitangents to smooth non-hyperelliptic quartics with automorphism group G appearing in Theorem 2.4 explicitly:

Corollary 3.7. Let G be as in Theorem 2.4. Then the bitangents of any smooth planar quartic which is G -symmetric have G -orbits given by the Euler class $n_G(E)$.

Any such smooth, non-hyperelliptic quartic which is G -symmetric defines a section $X \rightarrow E$ which can be used to compute $n_G(E)$. Since $n_G(E)$ is independent of choice of section, the count of orbits of bitangents is independent of symmetric quartic C with $\mathrm{Aut}(C) \cong G$:

Corollary 3.8. Let G be any group which appears as the automorphism group of a genus three non-hyperelliptic curve. Then for any such curve C with $G \cong \mathrm{Aut}(C)$, the action of G on the bitangents of C is independent of the choice of C .

Proof. This is a direct consequence of equivariant conservation of number, pulling back an Euler class for equivariant homotopical bordism to the Burnside ring of the group [Bra25, Theorem 5.24]. \square

This proves Theorem 1.1. Formulas in $A(G)$ for the 28 bitangents of G -symmetric quartics are given in the table included with the statement of the main result in the introduction, which we do not repeat in this section for brevity.

Remark 3.9. It is worth noting that for any subgroup H of G we have a restriction map $\mathrm{Res}_H^G : A(G) \rightarrow A(H)$ that sends the class of any G -set to the H -set with H -action induced from the action of G . In particular, any G -symmetric quartic C is H -symmetric, and a G -action on the bitangents of C descends to an H -action on the bitangents of C via restriction. We explore consequences of this for equivariant counts of bitangents in Section 5.

4. SYMMETRIC QUARTICS AND THEIR BITANGENTS

In this section we compute the action of the automorphism group of a symmetric quartic on its 28 bitangents for all 12 types. Given $H \leq G$ a subgroup, $[G/H]$ denotes the transitive G -set given by the isomorphism class of the G -set of left cosets of H in G . Every finite G -set decomposes as a disjoint union of its orbits, each isomorphic to G/H for H the stabilizer of

the orbit. Recall from Section 3.1 that addition in $A(G)$ is given by disjoint union, whence every finite G -set can be written as a sum of transitive orbits $[G/H]$ in $A(G)$. For each type of symmetric quartic, we compute the action of its automorphism group action on its bitangents as a sum of transitive G -sets.

Before computing orbits of bitangents to symmetric quartics explicitly, we recall Remark 2.5 — specifically, the quartic equation that appears for each group in this section is the unique quartic equation with the given automorphism group up to projective transformation.

Remark 4.1. As remarked earlier in the paper, the number of real bitangents can vary in each family. In each type, we graph a real curve with the *maximum possible* number of real bitangents.

4.1. Type I: The Klein quartic. The most well-studied symmetric quartic, which boasts its own book [Lev01], and its own sculpture at SLMath (formerly MSRI)⁵, is the so-called *Klein quartic*:

$$x^3y + y^3z + z^3x.$$

Its automorphism group G_{168} is the maximum possible by the Hurwitz bound, making it a prototypical example of what is called a *Hurwitz curve*. Its automorphism group is isomorphic to the projective special linear group over the finite field with seven elements, which acts on \mathbb{P}^2 in the following way:

$$\mathrm{PSL}_2(7) \cong \left\langle \begin{pmatrix} \zeta_7^4 & 0 & 0 \\ 0 & \zeta_7^2 & 0 \\ 0 & 0 & \zeta_7 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} \beta & \alpha & \gamma \\ \alpha & \gamma & \beta \\ \gamma & \beta & \alpha \end{pmatrix} \right\rangle \leq \mathrm{PGL}_3(\mathbb{C}),$$

where ζ_7 is a primitive seventh root of unity, and α, β, γ are defined in Theorem 2.4.

We give a partial indication as to how to visualize this group. The Klein quartic, considered as a Riemann surface, can be tiled with 24 heptagons. In fact, it is a quotient of the hyperbolic plane via the congruence subgroup $\Gamma(7) \leq \mathrm{PSL}(2, \mathbb{Z})$. The quotient $\mathrm{PSL}_2(7)$ acts via deck transformations and is the automorphism group of the Klein quartic. This group can be understood as the automorphisms attached to the tiling: a heptagon can be sent to any other of the 24 heptagons, and a heptagon has a sevenfold rotation. In total, there are $24 \times 7 = 168 = \#\mathrm{PSL}_2(7)$ symmetries of the Klein quartic.⁶

Alternatively via the automorphism $\mathrm{PSL}_2(7) \cong \mathrm{PSL}_3(2)$, the automorphism group of the Klein quartic can be visualized as the symmetries of the *Fano plane* as in Figure 2.

The automorphism group acts on bitangents, so we recover our first computation, which was undoubtedly known to Klein.

Computation 4.2. The automorphism group of the Klein quartic acts transitively on the 28 bitangents, with isotropy given by the symmetric group $S_3 \leq \mathrm{PSL}_2(7)$.

The Klein quartic has exactly four real bitangents, which we visualize in Figure 3.

⁵The sculpture is called *The Eightfold Way*, created by Helaman Ferguson and installed in 1993. Thurston wrote a paper about the Klein quartic in honor of the statue's inauguration [Thu99].

⁶Reflections of the heptagons are not considered since they don't preserve the complex structure.

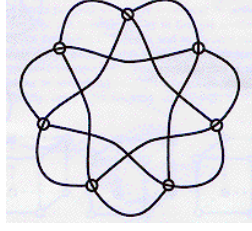


FIGURE 2. An artistic rendering of the sevenfold symmetries on the Fano plane, drawn by Burkard Polster, found on John Baez' blog [Bae13].

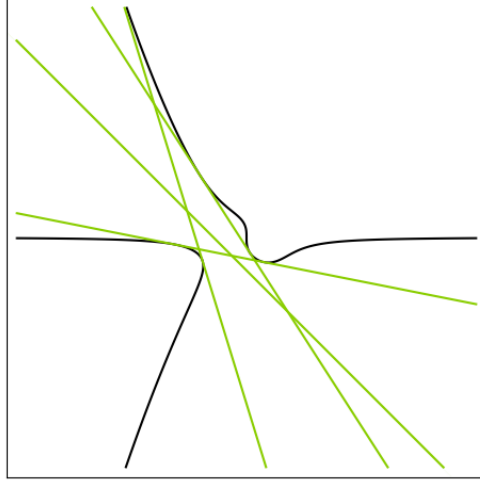


FIGURE 3. The four real bitangents graphed on the Klein quartic. All lines lie in the same orbit.

4.2. Type II: The Dyck quartic. Up to a projective change of coordinates, the quartic of type two has equation

$$x^4 + y^4 + z^4,$$

and was first studied in an 1880 paper by W. Dyck [Dyc80], who ascertained that it admits 96 symmetries. The automorphism group has isomorphism type $G_{96} \cong C_4^{\times 2} \rtimes S_3$, acting on the projective plane in the following way:

$$(3) \quad C_4^{\times 2} \rtimes S_3 \cong \left\langle \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, \begin{pmatrix} -i & 0 & 0 \\ 0 & 0 & 1 \\ 0 & i & 0 \end{pmatrix} \right\rangle \leq \mathrm{PGL}_3(\mathbb{C}).$$

Computation 4.4. Any Type II quartic has bitangents with orbits

$$[C_4^{\times 2} \rtimes S_3 / S_3] + [C_4^{\times 2} \rtimes S_3 / C_8].$$

While the Dyck quartic has no real points, it does admit real bitangents, where the points of tangency are complex. These are given by

$$\begin{aligned} x - y - z \\ x + y - z \\ x - y + z \\ x + y + z, \end{aligned}$$

and they all lie in the $[C_4^{\times 2} \rtimes S_3/S_3]$ orbit.

Remark 4.5. Edge wrote an entire paper about this quartic in 1938 [Edg38], in which he investigates its determinantal forms. Explicit equations for each of the 28 bitangents is included in [Edg38, p. 14], though he attributes this computation to Cayley. In [Edg38, Section 14], Edge extends his computations of bitangents and Cayley octads for the Dyck quartic to a more general family of quartics, mainly those of the form

$$(6) \quad (1 + \gamma^2)^2(x^4 + y^4 + z^4) - 2(1 + \gamma^4)(y^2z^2 + x^2y^2 + x^2z^2) = 0.$$

When $\gamma = \zeta_8$ is a primitive 8th root of unity, we obtain an equation that defines a Type II quartic. In general, quartics of the form above given by Equation (6) are called *Edge quartics*, and obtaining a Type II quartic by choosing $\gamma = \zeta_8$ is just one example of an Edge quartic.

In general, Equation (6) defines a Type IV quartic for many values of γ . The Edge quartic obtained by setting $\gamma = \pm\sqrt{5}$ was studied in [PSV11, p. 713]. This is a Type IV quartic with $a = -\frac{52}{36}$, which has automorphism group S_4 . This is certainly not the only value of γ for which the Edge quartic is Type IV, indeed any γ which is not a primitive 8th root of unity and such that $\frac{-2(1+\gamma^4)}{(1+\gamma^2)^2}$ is not equal to $\frac{3}{2}(-1 \pm \sqrt{7})$ or 0 defines a Type IV quartic. As another final example, $\gamma = \pm 2$ yields a Type IV quartic with $a = -\frac{34}{25}$, see Example 1.2.

4.3. Type III: Order 48. Order 48, structure $C_4 \odot A_4$.

There is a unique Type III quartic given by the equation:

$$x^4 + y^4 + z^4 + (4\zeta_3 + 2)x^2y^2,$$

with automorphism group given by

$$C_4 \odot A_4 = \left\langle \begin{pmatrix} \frac{1+i}{2} & \frac{-1+i}{2} & 0 \\ \frac{1+i}{2} & \frac{1-i}{2} & 0 \\ 0 & 0 & \zeta_3 \end{pmatrix}, \begin{pmatrix} \frac{1+i}{2} & \frac{-1-i}{2} & 0 \\ \frac{-1+i}{2} & \frac{-1-i}{2} & 0 \\ 0 & 0 & \zeta_3^2 \end{pmatrix} \right\rangle \leq \text{PGL}_3(\mathbb{C}).$$

The 28 bitangents on the Type III quartic break into two orbits of sizes 24 and four. The first orbit has isotropy $C_2 \leq C_4 \odot A_4$, which is the non-normal cyclic subgroup of order two in A_4 . The second orbit has isotropy given by the unique subgroup of order 12, which is cyclic. In total:

Computation 4.7. The bitangents to a Type III quartic have orbits

$$[C_4 \odot A_4/C_2] + [C_4 \odot A_4/C_{12}].$$

This curve has no real points and no real bitangents, so we unfortunately cannot visualize this example.

4.4. Type IV: The pencil of octahedral quartics. Order 24, structure S_4 .

Up to change of coordinates, Type IV quartics are given by the following pencil, which we call the pencil of *octahedral quartics*

$$x^4 + y^4 + z^4 + a(x^2y^2 + y^2z^2 + z^2x^2),$$

for $a \neq \frac{3}{2}(-1 \pm \sqrt{-7})$ (this would give the Klein quartic) and $a \neq 0$ (this would give the Dyck quartic). As a varies, we sweep out a pencil of quartics, first studied by Wiman and Ciani independently. A modern discussion of this pencil of quartics can be found in [DK93, §8]. The paper [RGA97] is dedicated solely to the study of this pencil, where the authors study (among other things) the Fuschian uniformizations and the Jacobians of these quartics.

A Type IV quartic has automorphism group isomorphic to the symmetric group S_4 . For any such a as above, we see the automorphism group is

$$S_4 \cong \left\langle \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right\rangle \leq \mathrm{PGL}_3(\mathbb{C}).$$

Computation 4.8. The bitangents of a Type IV quartic have orbits

$$[S_4/C_2^o] + [S_4/C_2^e] + [S_4/S_3].$$

Here C_2^o is an *odd* copy of $C_2 \leq S_4$, i.e., it is a single transposition, and C_2^e is a product of two disjoint transpositions, hence it is *even*.

Example 4.9. When $a = -3/2$, we compute there are 28 real bitangents. We visualize this in Figure 4.

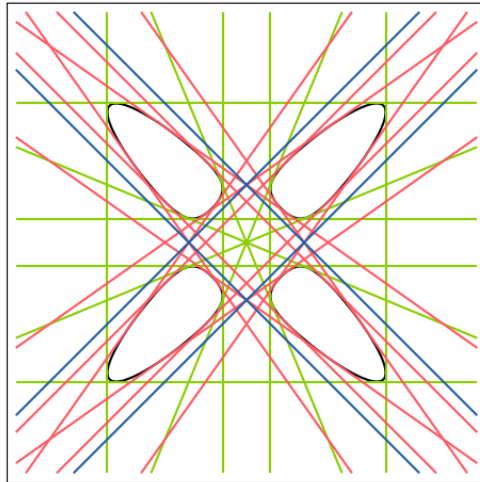


FIGURE 4. The orbits of the real bitangents on the Type IV quartic with $a = -3/2$. Lines in green are in the $[S_4/C_2^o]$ orbit, and lines in pink are in the $[S_4/C_2^e]$ orbit, and lines in blue form the $[S_4/S_3]$ orbit.

4.5. Type V: Order 16. Order 16, structure $P = C_4 \odot K_4$ the *Pauli group*.

Notation 4.10. The automorphism group of a type V curve is the *Pauli group*, which we denote by P . In particular there are three non-central conjugacy classes of cyclic subgroups of order two, which we denote by $C_2^{(1)}$, $C_2^{(2)}$, and $C_2^{(3)}$, and the center is a cyclic group of order four which we denote by C_4^Z .

Type V quartics are given by the equation

$$x^4 + y^4 + z^4 + ax^2y^2$$

for $a \notin \{0, \pm 2\sqrt{-3}, \pm 6\}$. Their automorphism groups are of the form

$$P \cong \left\langle \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} i & 0 & 0 \\ 0 & -i & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right\rangle \leq \text{PGL}_3(\mathbb{C}).$$

Computation 4.11. Any quartic of Type V has bitangents with orbits

$$[P/C_2^{(1)}] + [P/C_2^{(2)}] + [P/C_2^{(3)}] + [P/C_4^Z].$$

Example 4.12. When $a = -4$ we see eight real bitangents, as in Figure 5.

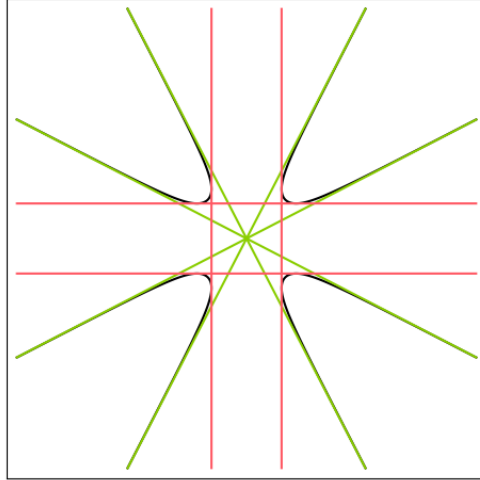


FIGURE 5. The orbits of the real bitangents on a Type V quartic. The four in green form the the orbit whose isotropy is the central C_4^Z . The four lines in pink are part of an orbit with $C_2^{(1)}$ isotropy.

4.6. Type VI: Order 9. Order 9, structure C_9 .

There is a unique Type VI quartic, given by the equation

$$x^4 + xy^3 + yz^3,$$

whose automorphism group is cyclic of order nine:

$$C_9 \cong \left\langle \begin{pmatrix} \zeta_3 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \zeta_9 \end{pmatrix} \right\rangle \leq \text{PGL}_3(\mathbb{C}).$$

Computation 4.13. The Type VI quartic has bitangents with orbits

$$3[C_9/e] + [C_9/C_9].$$

The notation e above denotes the identity element of C_9 , so $[C_9/e]$ is the element of $A(G)$ representing the isomorphism class of C_9 itself. This quartic has four real lines, one in each orbit, as depicted in Figure 6.

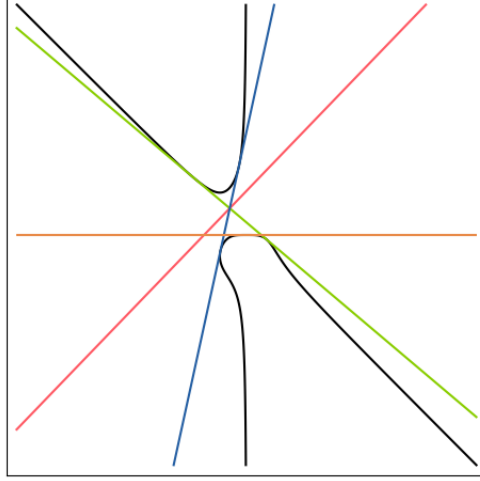


FIGURE 6. The orbits of real bitangents on the quartic of Type VI. In green is the line in the first trivial isotropy orbit. In pink is the line in the 2nd trivial isotropy orbit. In blue is the line in the 3rd trivial isotropy orbit. Finally, the orange line is in the $[C_9/C_9]$ orbit.

4.7. Type VII: Order 8. Order 8, structure D_8 .

Type VII quartics are given by the equation

$$x^4 + y^4 + z^4 + ax^2y^2 + bxyz^2$$

for $b \neq 0$. The automorphism group is given by

$$D_8 \cong \left\langle \begin{pmatrix} i & 0 & 0 \\ 0 & -i & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right\rangle \leq \text{PGL}_3(\mathbb{C}).$$

Writing the first generator as r and the second as s , we have three conjugacy classes of subgroups of order two, namely

$$\begin{aligned} C_2^{(1)} &:= \langle s \rangle \cong \langle r^2s \rangle \\ C_2^{(2)} &:= \langle rs \rangle \cong \langle r^3s \rangle \\ C_2^Z &:= \langle r^2 \rangle, \end{aligned}$$

where the superscript Z denotes that it is central.

Computation 4.14. The bitangents of any Type VII quartic have orbits

$$[D_8/e] + 2[D_8/C_2^{(1)}] + 2[D_8/C_2^{(2)}] + [D_8/C_2^Z].$$

Example 4.15. For $a = -3$ and $b = 1$, we see eight real bitangents, pictured in Figure 7.

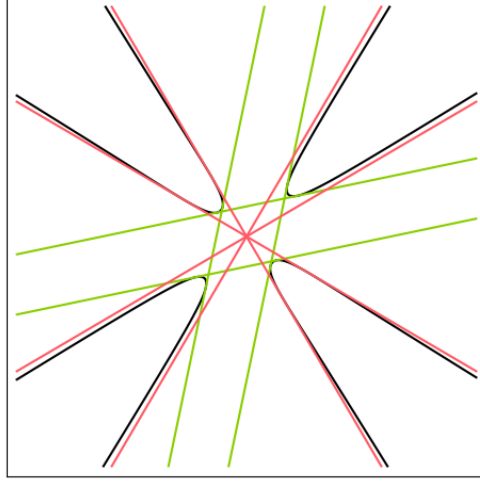


FIGURE 7. The orbits of real bitangents on an example quartic of Type VII. The green lines have trivial isotropy, i.e. they live in the $[D_8/e]$ orbit, while the pink lines form the $[D_8/C_2^Z]$ orbit.

4.8. Type VIII: Order 6. Order 6, structure C_6 .

Type VIII quartics are given by

$$x^4 + y^4 + ax^2y^2 + yz^3$$

for $a \neq 0$. Its automorphism group is given by

$$C_6 \cong \left\langle \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \zeta_3 \end{pmatrix} \right\rangle \leq \mathrm{PGL}_3(\mathbb{C}).$$

Computation 4.16. The bitangents of any Type VIII quartic have orbits

$$4[C_6/e] + [C_6/C_2] + [C_6/C_6].$$

Example 4.17. When $a = -3$, we see four real bitangents, two occurring in distinct orbits with trivial isotropy, one in the orbit with C_3 isotropy, and one fixed under the action of the automorphism group, pictured in Figure 8.

4.9. Type IX: Order 6. Order 6, structure S_3

Type IX quartics are given by the equation

$$x^3z + y^3z + x^2y^2 + axyz^2 + bz^4$$

for $a \neq 0$. Its automorphism group is given by

$$S_3 \cong \left\langle \begin{pmatrix} \zeta_3 & 0 & 0 \\ 0 & \zeta_3^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right\rangle \leq \mathrm{PGL}_3(\mathbb{C}).$$

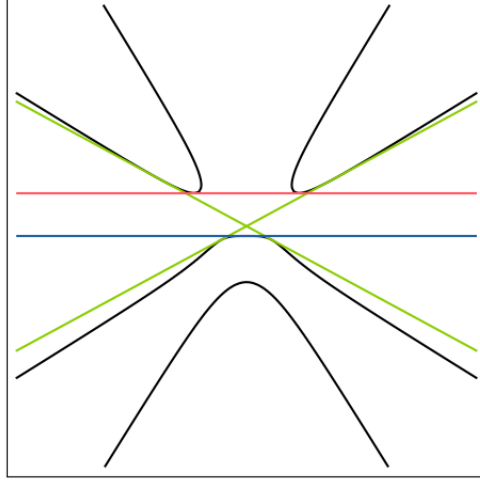


FIGURE 8. The orbits of real bitangents on an example quartic of Type VIII. In green are lines in the $[C_6/e]$ orbit. The pink line is in the $[C_6/C_2]$ orbit. The blue line is in the $[C_6/C_6]$ orbit.

Computation 4.18. The orbits of the bitangents on any Type IX quartic are given by

$$3[S_3/e] + 3[S_3/C_2] + [S_3/S_3].$$

Example 4.19. When $a = -25$ and $b = 10$, we compute eight real bitangents, pictured in Figure 9.

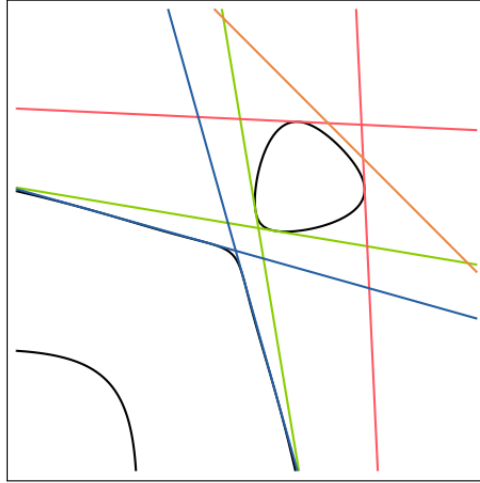


FIGURE 9. The orbits of real bitangents on an example quartic of Type IX. In green, pink, and blue are lines in different $[S_3/e]$ orbits. The line in orange lies in an $[S_3/C_2]$ orbit. Not pictured is a bitangent $z = 0$ at infinity which forms the $[S_3/S_3]$ orbit.

4.10. **Type X: Order 4.** Order 4, structure K_4

Type X quartics are given by the equation

$$x^4 + y^4 + z^4 + ax^2y^2 + by^2z^2 + cx^2z^2$$

for a, b, c all distinct. Its automorphism group is given by

$$K_4 \cong \left\langle \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right\rangle \leq \mathrm{PGL}_3(\mathbb{C}).$$

Computation 4.20. The bitangents on any Type X quartic have orbits

$$4[K_4/e] + 2[K_4/C_2^L] + [2K_4/C_2^\Delta] + 2[K_4/C_2^R].$$

We have denoted the three copies of C_2 in $K_4 \cong C_2 \times C_2$ by $C_2^L = C_2 \times e$, $C_2^R = e \times C_2$, and $C_2^\Delta = \{(e, e), (g, g)\}$ where e is the identity element of C_2 and g is the non-identity element.

Example 4.21. When $(a, b, c) = (-9, -3, -8)$, we compute 16 real bitangents, forming four orbits with trivial isotropy, pictured in Figure 10.

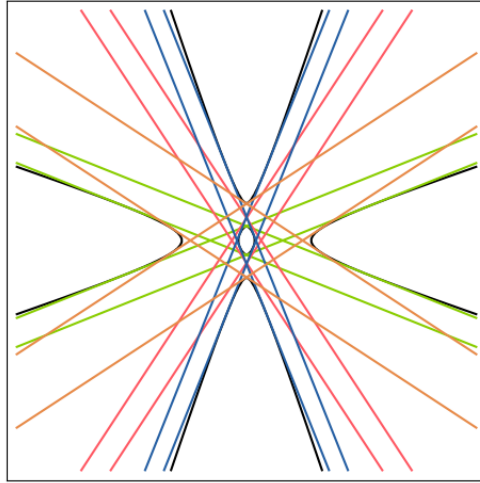


FIGURE 10. The orbits of real bitangents on an example quartic of Type X. There are 16 bitangents, forming four orbits of the form $[K_4/e]$.

4.11. Type XI: Order 3. Order 3, structure C_3

Type XI quartics are given by the equation

$$x(x - y)(x - ay)(x - by) + yz^3,$$

for a, b such that $a \neq 1$, $b \neq 1 - a$, and $(x - a)(x - b) \neq x^2 + x + 1$. It has automorphism group

$$C_3 \cong \left\langle \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \zeta_3 \end{pmatrix} \right\rangle \leq \mathrm{PGL}_3(\mathbb{C}).$$

Computation 4.22. The bitangents on any Type XI quartic have orbits

$$9[C_3/e] + [C_3/C_3].$$

Example 4.23. When $a = 2$ and $b = 3$, we compute four real bitangents, pictured in Figure 11.

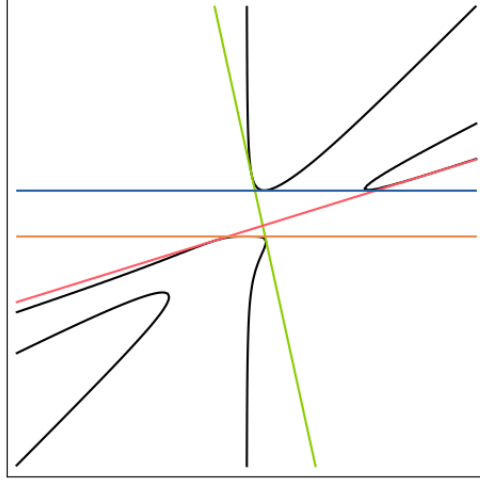


FIGURE 11. The orbits of real bitangents on an example quartic of Type XI. Orbits with colors green, pink, and blue have trivial isotropy. The orange line is in a $[C_3/C_3]$ orbit, i.e. it is fixed by the automorphism group.

4.12. **Type XII: Order 2.** Order 2, structure C_2 .

All Type XII quartics are given by

$$x^4 + y^4 + z^4 + x^2(ay^2 + byz + cz^2) + dy^2z^2.$$

If $a = -2$, $b = 0$, and $c = -d$, we obtain a Type IX quartic. If $b = 0$, we obtain a Type X quartic. The type does not change except in the two cases above; for example, we still obtain a Type XII curve if $b \neq 0$ but $a = -2$ and $c = -d$.

The Type XII quartic has automorphism group

$$C_2 \cong \left\langle \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right\rangle \leq \mathrm{PGL}_3(\mathbb{C}).$$

Computation 4.24. The bitangents on any Type XII quartic have orbits

$$12[C_2/e] + 4[C_2/C_2].$$

Example 4.25. For the Type XII quartic defined by the equation

$$x^4 + y^4 + z^4 + x^2(-8y^2 + 4yz + 50z^2) - 5y^2z^2,$$

we have 28 real bitangents, forming three orbits, pictured in Figure 12.

4.13. **Real bitangents in each type.** For ease of reference we include the maximal number of bitangents in each type in Figure 13.

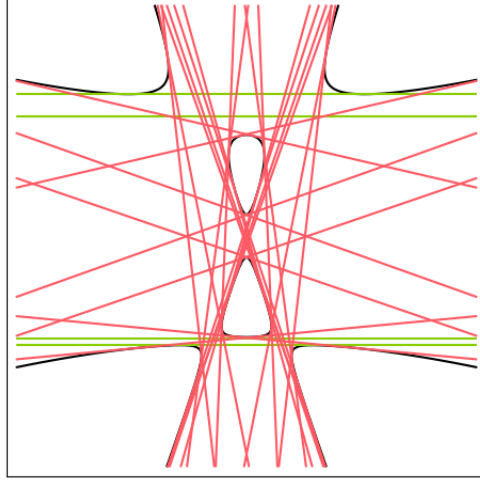


FIGURE 12. The orbits of real bitangents on an example quartic of Type XII with $(a, b, c, d) = (-8, 4, 50, -5)$. The green lines have no x coefficient and are hence fixed by the action of C_2 , while the lines in pink come in pairs, forming $[C_2/e]$ orbits.

Type	Automorphism group	Maximum number of real bitangents
I	$\mathrm{PSL}_2(7)$	4
II	$C_4^{\times 2} \rtimes S_3$	4
III	$C_4 \odot A_4$	0
IV	S_4	28
V	P	8
VI	C_9	4
VII	D_8	8
VIII	C_6	4
IX	S_3	8
X	K_4	16
XI	C_3	4
XII	C_2	28

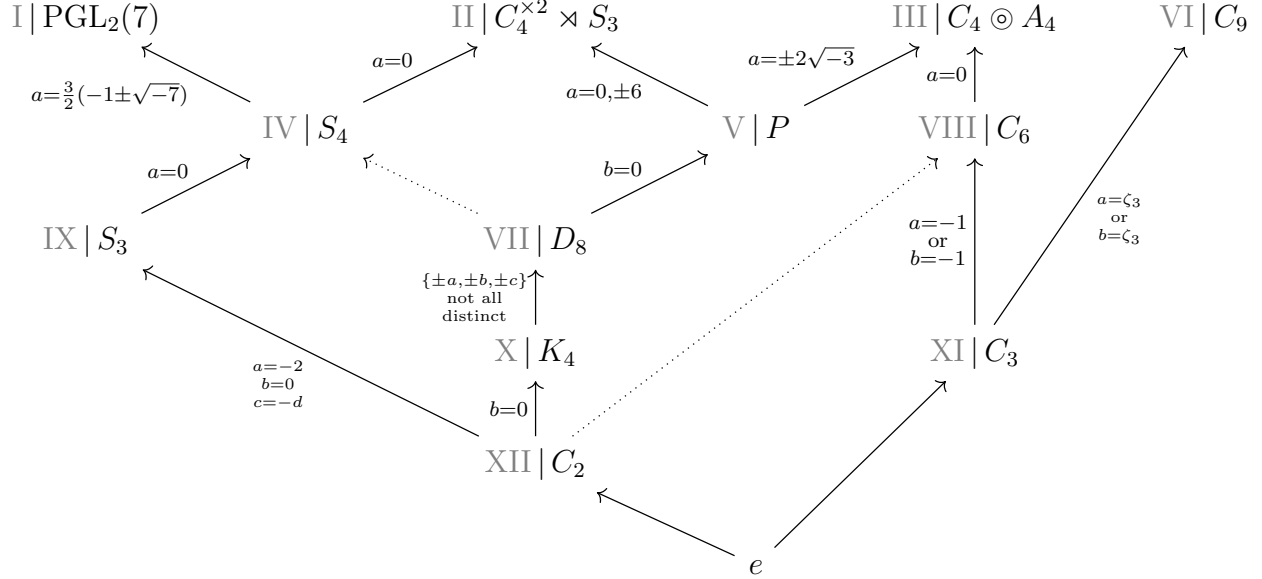
FIGURE 13. The maximum number of real bitangents for each type of smooth symmetric real planar quartic.

5. THE SUBGROUP LATTICE AND RESTRICTION

As mentioned in Remark 3.9, we may restrict our attention to a subgroup $H \leq G \cong \mathrm{Aut}(C)$ of automorphisms for a given curve, and the action of that group on the bitangents is the restriction of the G -set of bitangents to the subgroup H . As we have seen in Theorem 2.4, we have families of curves attached to certain values of a, b , etc. When these take particular values, the type of the quartic can change. This often occurs because the entire family is invariant under the automorphism group, but a new polynomial relation holds for a special value of the coefficients. This new relation introduces an extra automorphism to the equation and enlarges the automorphism group of the curve. To that end, it is important to understand

which automorphism groups are subgroups of one another, or really subconjugate to one another inside of $\mathrm{PGL}_3(\mathbb{C})$.

We therefore copy a table from [Hen76] demonstrating subconjugacy. For each entry we include both the type and automorphism group, and, where relevant, we label the inclusions with the special values from the example forms of quartics provided in Theorem 2.4.



The groups as we've presented them may not be literally subgroups of one another, a projective change of basis may be needed. We explain the meaning behind the dashed arrows in Remark 5.4.

Example 5.1. Some lovely examples of the phenomenon we're discussing can be found in [Dol12, pp. 269–270]; we include one such example here, where we show how to derive the special values $a = -6, 0, 6$ where the pencil of Type V quartics becomes a Dyck quartic. Recall the equation for a Type V quartic:

$$x^4 + y^4 + z^4 + ax^2y^2.$$

It is clear that by setting $a = 0$ we obtain the Dyck quartic, but where do the other values $a = \pm 6$ come from? The Pauli group P is not literally a subgroup of $C_4^{\times 2} \rtimes S_3$ as presented, nevertheless $C_4^{\times 2} \rtimes S_3$ contains a unique conjugacy class of subgroups isomorphic to P . This is reflected via a change of basis matrix, unique up to conjugacy in $C_4^{\times 2} \rtimes S_3$.

$$g = \begin{pmatrix} 1 & 1 & 0 \\ 1 & -1 & 0 \\ 0 & 0 & 8^{1/4} \end{pmatrix}.$$

Note there are three conjugate copies of P in $C_4^{\times 2} \rtimes S_3$. Conjugating P by this change of basis, we see that $gPg^{-1} \leq C_4^{\times 2} \rtimes S_3$, and the equation for a Type V quartic changes to be

$$(x + y)^4 + (x - y)^4 + 8^{1/4}z^4 + a(x + y)^2(x - y)^2 = (a + 2)x^4 + (a + 2)y^4 + 8z^4 + (12 - 2a)x^2y^2.$$

We can now ask for which values of a does such a quartic satisfy the $C_4^{\times 2} \rtimes S_3$ symmetries in Equation (3). The first generator cyclically permutes the variables, from which we deduce that $12 - 2a = 0$ must necessarily be true for the x^2y^2 term to vanish. In other words, we need $a = 6$. For this choice of a we satisfy the full symmetry group $C_4^{\times 2} \rtimes S_3$ and hence obtain the Type II quartic. The case $a = -6$ is similar, but using a conjugate change of basis.

Remark 5.2. We remark this line of reasoning is basically equivalent to being aware of clever relations for working with homogeneous polynomials and their vanishing loci. Dolgachev remarks that the constraint above comes from knowing the identity

$$x^4 + y^4 = \frac{1}{8} \left((x+y)^4 + (x-y)^4 + 6(x+y)^2(x-y)^2 \right).$$

Leveraging identities such as these in projective geometry is characteristic of much of algebra in the latter half of the 19th century.

What happens when this line of reasoning fails? Consider the following example:

Proposition 5.3. There are no special values of a, b, c, d for which a Type XII quartic becomes a Type VIII quartic.

Proof. Since C_6 is abelian and C_2 is a subgroup as written, we just have to check whether any special values of a, b, c, d exist for which a Type XII quartic can satisfy a sixfold symmetry. Recall the general form of a Type XII quartic is $x^4 + y^4 + z^4 + x^2(ay^2 + byz + cz^2) + dy^2z^2$. Applying the generator for C_6 to a Type XII quartic, we obtain

$$x^4 + y^4 + \zeta_3 z^4 + x^2(ay^2 + b\zeta_3 yz + c\zeta_3^2 z^2) + d\zeta_3^2 y^2 z^2,$$

and there are no values of a, b, c, d for which this is equal to the original equation. \square

Remark 5.4. This is precisely the meaning of the dashed arrows in our subgroup diagram. In the language of the moduli of symmetric quartics, this means the Type VIII quartics don't lie on the boundary of the Type XII quartics, but rather they share a common boundary at the Type III quartics. The argument for the dashed arrow from Type VII to Type IV is omitted.

5.1. Leveraging Euler classes to explore restricted actions. We've seen that the locus of D_8 -symmetric quartics is not glued to the locus of S_4 -symmetric quartics, so from the naive perspective of the moduli space, we shouldn't expect that there is much coherence between how these groups act on bitangents. Nevertheless we can see the following example:

Example 5.5. Consider the Edge quartic (of Type IV) with its restricted $D_8 \leq S_4$ -symmetry on the xy -plane. The D_8 -orbits of the lines are graphed in Figure 14

This is the same count as the D_8 -action on the bitangents of a Type VII quartic (Computation 4.14), despite the fact that the Edge quartic cannot be obtained by deforming a family of quartics with automorphism group D_8 . So the fact that we obtained the same answer above is perhaps not obvious from the moduli perspective. It is, however, obvious from the perspective of equivariant Euler classes!

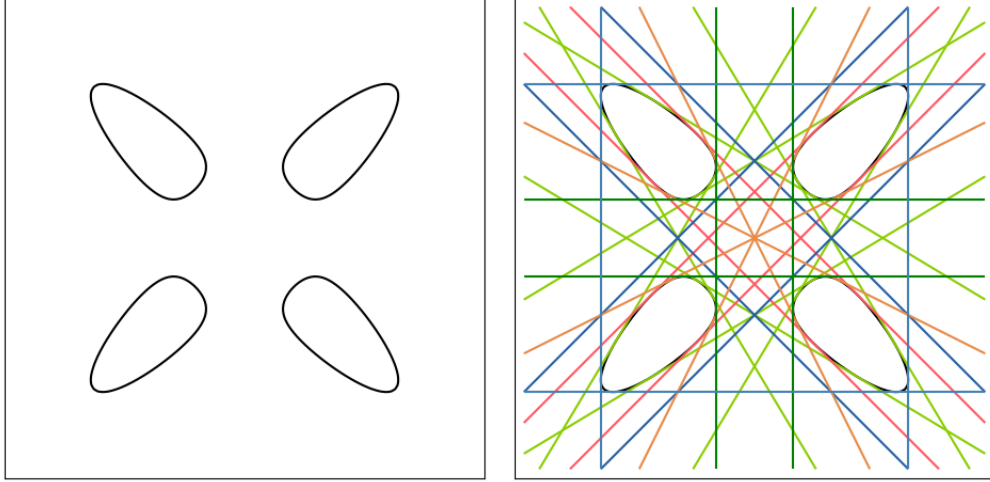


FIGURE 14. The *Edge quartic*, with D_8 -orbits on its bitangents given by $[D_8/e] + 2[D_8/C_2^{(1)}] + 2[D_8/C_2^{(2)}] + [D_8/C_2^Z]$.

Proposition 5.6. Let $H \leq G$ be a subgroup, and let $g \in G$ be arbitrary. Then we can consider restricting a G -set along the inclusion of H in G , or along the group homomorphism $c_g: H \rightarrow G$ given by $h \mapsto ghg^{-1}$. These induce naturally isomorphic functors $\text{Fin}_G \rightarrow \text{Fin}_H$.

Proof. It suffices to observe that conjugacy by g is a natural isomorphism on the category of finite G -sets. \square

We deduce the following Corollary, with a warning that the proof relies on results from equivariant homotopy theory that are outside the scope of this paper. Specifically, the proof of Corollary 5.7 relies on equivariant nilpotence [BGH20, 3.20], which is not explained here.

Corollary 5.7. Let $E \rightarrow M$ be any G -equivariant enumerative problem satisfying the hypotheses in [Bra25, 1.1] (e.g. counting lines on symmetric cubic surfaces or counting bitangents to planar quartics). Then the restricted Euler class $n_H(E)$, obtained as the image of

$$\begin{aligned} \pi_0^G \text{MU}_G &\rightarrow \pi_0^H \text{MU}_H \\ n_G(E) &\mapsto n_H(E) \end{aligned}$$

depends only on the conjugacy class of H in G .

Proof. Equivariant Euler classes valued in homotopical bordism are in the injective image of the Burnside ring by [Bra25, 5.24], hence it suffices to prove the statement there. This follows directly from group completing isomorphism classes of finite G -sets and applying Proposition 5.6. \square

This explains what we observed in Example 5.5. Although there we cannot deform Type VII quartics into Type IV quartics, there are unique conjugacy classes of D_8 and S_4 in PGL_3 occurring as the automorphism groups of quartics, and the copy of D_8 is subconjugate to S_4 .

Remark 5.8.

- (1) This means that we can still restrict computations along the dashed arrows in our subgroup lattice, despite the fact that the associated components in the moduli are not attached directly to one another.
- (2) This line of reasoning fails for isomorphic subgroups which are not conjugate. Given an S_4 -symmetric cubic surface, the restricted action on its lines via the two non-conjugate cyclic subgroups of order two are different, as computed in [Bra25, 6.5].

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