

THE CLASSIFICATION OF MINIMAL PRODUCT-QUOTIENT SURFACES WITH $p_g = 0$.

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This article is dedicated to the memory of our dear friend and collaborator Fritz Grunewald

INTRODUCTION

The present article is the fourth in a series of papers (cf. [BC04], [BCG08], [BCGP08]), where the goal is to contribute to the classification problem of surfaces of general type by giving a systematic way to construct and distinguish algebraic surfaces.

We will use the basic notations from the classification theory of complex projective surfaces, in particular the basic numerical invariants K_S^2 , $p_g := h^0(S, \Omega_S^2)$, $q(S) := h^1(S, \mathcal{O}_S)$; the reader unfamiliar with these may consult e.g. [Be83].

The methods we introduced in the above cited articles, and substantially develop and refine in the present paper are in principle applicable to many more situations. Still we restrict ourselves to the case of surfaces of general type with geometric genus $p_g = 0$.

By Gieseker's theorem (cf. [Gie77]) and standard inequalities (cf. [BCP10, thm. 2.3 and the following discussion]) minimal surfaces of general type with $p_g = 0$ yield a finite number of irreducible components of the moduli space of surfaces of general type. Although it is theoretically possible to describe all irreducible components of the moduli space corresponding to surfaces of general type with $p_g = 0$, this ultimate goal is far out of reach, even if there has been a substantial progress in the study of these surfaces especially in the last five years. We refer to [BCGP08] and [BCP10] for a historical account and recent update on what is known about surfaces of general type with $p_g = 0$.

We study the following situation: let G be a finite group acting on two compact Riemann surfaces C_1, C_2 of respective genera at least 2. We shall consider the

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diagonal action of G on $C_1 \times C_2$ and in this situation we say for short: the action of G on $C_1 \times C_2$ is *unmixed*. By [Cat00] we may assume wlog that G acts faithfully on both factors.

Definition 0.1. *The minimal resolution S of the singularities of $X = (C_1 \times C_2)/G$, where G is a finite group with an unmixed action on the direct product of two compact Riemann surfaces C_1, C_2 of respective genera at least two, is called a product-quotient surface.*

X is called the quotient model of the product-quotient surface.

Remark 0.2. 1) It is possible that two product-quotient surfaces with different quotient models are birational or even isomorphic. By a slight abuse of notation, we still call $X = (C_1 \times C_2)/G$ "the" quotient model of the product-quotient surface, because we use this notation only if we have fixed two Riemann surfaces and the action of a finite group on each of them.

2) If X has "mild" (to be precise: at most canonical) singularities, then the quotient model X is equal to the canonical model of the product-quotient surface S , which is unique. For the definition of canonical surface singularities (which are also called rational double points) we refer to [Mat02], def. 4-2-1, thm. 4-6-7.

3) In the general setting, i.e., if X has non canonical singularities, S is not necessarily a minimal surface, i.e., it may contain smooth rational curves with selfintersection -1 . This is a substantial obstacle we have to overcome in the present paper. We profit from the fact that the construction of our surfaces is quite explicit (cf. section 5).

In general there is no way to determine rational curves on surfaces of general type. In fact, a famous still unsolved conjecture by S. Lang asserts that a surface of general type can contain only a finite number of rational curves.

The systematic classification of product-quotient surfaces with $p_g = 0$ was started and carried out in [BC04], [BCG08], [BCGP08] for all surfaces whose canonical model is equal to $(C_1 \times C_2)/G$.

[BC04] classifies the surfaces $X = (C_1 \times C_2)/G$ with G being an abelian group acting freely and $p_g(X) = 0$. This classification is extended in [BCG08] to the case of an arbitrary group G . We want to point out that in the first paper all calculations were done by hand, whereas in the second one the computations could not be done by hand, but they were still "computer aided hand calculations".

In [BCGP08] instead we dropped the assumption that G acts freely on $C_1 \times C_2$, we classified product-quotient surfaces with $p_g = 0$ whose quotient model is indeed the canonical model (i.e., X has at most canonical singularities, note that here automatically $K_X^2 > 0$). In this case for the first time a systematic use of a computer algebra program was strictly needed in order to obtain a complete classification.

In the present paper we drop any restriction on the singularities of X . We succeed to give a complete classification of product-quotient surfaces S with $K_S^2 > 0$.

In order to obtain this result we had to substantially refine our previous MAGMA code, and for the first time we encountered serious problems of complexity and memory usage. Especially, as K_S^2 gets smaller (≤ 0), the problem of finding the possible singular locus of X gets more and more time and memory consuming. In order to finish the classification of product quotient surfaces with $p_g = 0$ one has to deal not only with the above mentioned computational problems, but also with the problem of bounding the number of rational curves on S , which in view of the previously mentioned Lang's conjecture is foreseen to be hard.

We are interested in the minimal model of the constructed surfaces, in order to locate them in the geography of the fine classification of the surfaces of general type. We determined the minimal model of all these surfaces; the last two sections are dedicated to this scope. It turns out that all except one are in fact minimal. We call this last surface *the fake Godeaux surface*, because a minimal surface with the same invariants p_g and K^2 is called *numerical Godeaux surfaces*. The section 5 is dedicated to it.

Among others we prove the following

Theorem 0.3. *If S is a product-quotient surface with $p_g(S) = q(S) = 0$ and $K_S^2 > 0$, then one of the following is true*

- (1) *S is minimal and of general type.*
- (2) *S is the fake Godeaux surface, which has $K_S^2 = 1$, $\pi_1(S) = \mathbb{Z}/6\mathbb{Z}$ and its minimal model has $K^2 = 3$.*

In case (1), our classification yields 72 irreducible families of surfaces of general type.

Remark 0.4. 1) Each of our families maps onto an algebraic subset of the Gieseker moduli space, but the images of two different families may not be distinct. This is because we construct the surfaces through some algebraic data, and we classify these data modulo an equivalence relation which is weaker than the the equivalence relation "being isomorphic".

Indeed, 13 of the 72 families are families of surfaces isogenous to a product, classified in [BC04], [BCG08] (with a small correction due to [Fra11]). Among them, there are two surfaces (*i.e.* families of dimension 0) with group $(\mathbb{Z}/5\mathbb{Z})^2$, and [GJT11] shows that these two surfaces are isomorphic. Indeed these 13 families yield exactly 12 components of the moduli space of surfaces of general type

2) Of the 72 families of part (1), 40 are constructed in [BC04], [BCG08], [BCGP08]. The remaining 32 families, as well as the fake Godeaux surface are

new, and come out from our main classification result here. Therefore we contribute to the existing knowledge about the complex projective surfaces S of general type with $p_g(S) = 0$ and their moduli spaces, constructing 33 new families of such surfaces realizing 14 hitherto unknown topological types.

The product-quotient surfaces mentioned in part (1) of the above theorem are listed in tables 1 and 2. We list the following information in the columns of the tables:

- Sing X is given as a sequence of rational numbers with multiplicities, describing the types of the cyclic quotient singularities, e.g., $2/3^2$ means 2 singular points of type $\frac{1}{3}(1, 2)$;
- N is the number of irreducible families; indeed our tables have only 60 lines, but we collect in the same line N families, which share all the other data; the number of lines, counted with multiplicity N is 72 (the number of families of theorem 0.3, 2));
- K_S^2 is the selfintersection of the canonical divisor, G the group, H_1 is the homology, and π_1 is the fundamental group.
- t_1, t_2 are the signatures of the corresponding polygonal groups, cf. definition 0.8 and the subsequent discussion.

For the groups occurring in tables 1, 2, we use the following notation: we denote by \mathbb{Z}_d the cyclic group of order d , \mathfrak{S}_n is the symmetric group in n letters, \mathfrak{A}_n is the alternating group and Q_8 is the quaternion group of order 8.

$PSL(2, 7)$ is the group of 2×2 matrices over \mathbb{F}_7 with determinant 1 modulo the subgroup generated by $-Id$.

$D_{p,q,r} = \langle x, y | x^p, y^q, xyx^{-1}y^{-r} \rangle$, and $D_n = D_{2,n,-1}$ is the usual dihedral group of order $2n$.

$G(n, k)$ for instance is the k -th group of order n in the MAGMA database of small groups.

In the sequel we shall give some consequences of the above theorem:

Comparing tables 1 and 2 with the constructions existing in the literature, as listed in table 1 of [BCP10], we note

Corollary 0.5. *Minimal surfaces of general type with $p_g = q = 0$ and with $3 \leq K^2 \leq 6$ realize at least 45 topological types.*

Note that before proving the results summarized in theorem 0.3 only 12 topological types of surfaces of general type with $p_g = q = 0$ and with $3 \leq K^2 \leq 6$ were known. In 2010 Cartwright and Steger (cf. [CaSt10]) constructed 11 surfaces with $K_S^2 = 3$ and new mutually different fundamental groups, see [BCP10], especially table 1, for a more precise account on what was previously known in the literature.

In the present paper we construct 13 surfaces with new topological types (two of them were independently found by Cartwright and Steger).

TABLE 1. Minimal product-quotient surfaces of general type with $p_g = 0$, $K^2 \geq 4$

K_S^2	Sing X	t_1	t_2	G	N	$H_1(S, \mathbb{Z})$	$\pi_1(S)$
8	\emptyset	$2, 5^2$	3^4	\mathfrak{A}_5	1	$\mathbb{Z}_3^2 \times \mathbb{Z}_{15}$	$1 \rightarrow \Pi_{21} \times \Pi_4 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	5^3	$2^3, 3$	\mathfrak{A}_5	1	\mathbb{Z}_{10}^2	$1 \rightarrow \Pi_6 \times \Pi_{13} \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	$3^2, 5$	2^5	\mathfrak{A}_5	1	$\mathbb{Z}_2^3 \times \mathbb{Z}_6$	$1 \rightarrow \Pi_{16} \times \Pi_5 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	$2, 4, 6$	2^6	$\mathfrak{S}_4 \times \mathbb{Z}_2$	1	$\mathbb{Z}_2^4 \times \mathbb{Z}_4$	$1 \rightarrow \Pi_{25} \times \Pi_3 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	$2^2, 4^2$	$2^3, 4$	$G(32, 27)$	1	$\mathbb{Z}_2^2 \times \mathbb{Z}_4 \times \mathbb{Z}_8$	$1 \rightarrow \Pi_5 \times \Pi_9 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	5^3	5^3	\mathbb{Z}_5^2	2	\mathbb{Z}_5^2	$1 \rightarrow \Pi_6 \times \Pi_6 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	$3, 4^2$	2^6	\mathfrak{S}_4	1	$\mathbb{Z}_2^4 \times \mathbb{Z}_8$	$1 \rightarrow \Pi_{13} \times \Pi_3 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	$2^2, 4^2$	$2^2, 4^2$	$G(16, 3)$	1	$\mathbb{Z}_2^2 \times \mathbb{Z}_4 \times \mathbb{Z}_8$	$1 \rightarrow \Pi_5 \times \Pi_5 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	$2^3, 4$	2^6	$D_4 \times \mathbb{Z}_2$	1	$\mathbb{Z}_2^3 \times \mathbb{Z}_4^2$	$1 \rightarrow \Pi_9 \times \Pi_3 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	2^5	2^5	\mathbb{Z}_2^4	1	\mathbb{Z}_2^4	$1 \rightarrow \Pi_5 \times \Pi_5 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	3^4	3^4	\mathbb{Z}_3^3	1	\mathbb{Z}_3^3	$1 \rightarrow \Pi_4 \times \Pi_4 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
8	\emptyset	2^5	2^6	\mathbb{Z}_2^3	1	\mathbb{Z}_2^6	$1 \rightarrow \Pi_3 \times \Pi_5 \rightarrow \pi_1 \rightarrow G \rightarrow 1$
6	$1/2^2$	$2^3, 4$	$2^4, 4$	$\mathbb{Z}_2 \times D_4$	1	$\mathbb{Z}_2^2 \times \mathbb{Z}_4^2$	$1 \rightarrow \mathbb{Z}^2 \times \Pi_2 \rightarrow \pi_1 \rightarrow \mathbb{Z}_2^2 \rightarrow 1$
6	$1/2^2$	$2^4, 4$	$2, 4, 6$	$\mathbb{Z}_2 \times \mathfrak{S}_4$	1	$\mathbb{Z}_2^3 \times \mathbb{Z}_4$	$1 \rightarrow \Pi_2 \rightarrow \pi_1 \rightarrow \mathbb{Z}_2 \times \mathbb{Z}_4 \rightarrow 1$
6	$1/2^2$	$2, 5^2$	$2, 3^3$	\mathfrak{A}_5	1	$\mathbb{Z}_3 \times \mathbb{Z}_{15}$	$\mathbb{Z}^2 \rtimes \mathbb{Z}_{15}$
6	$1/2^2$	$2, 4, 10$	$2, 4, 6$	$\mathbb{Z}_2 \times \mathfrak{S}_5$	1	$\mathbb{Z}_2 \times \mathbb{Z}_4$	$\mathfrak{S}_3 \times D_{4,5,-1}$
6	$1/2^2$	$2, 7^2$	$3^2, 4$	$\text{PSL}(2, 7)$	2	\mathbb{Z}_{21}	$\mathbb{Z}_7 \times \mathfrak{A}_4$
6	$1/2^2$	$2, 5^2$	$3^2, 4$	\mathfrak{A}_6	2	\mathbb{Z}_{15}	$\mathbb{Z}_5 \times \mathfrak{A}_4$
5	$1/3, 2/3$	$2, 4, 6$	$2^4, 3$	$\mathbb{Z}_2 \times \mathfrak{S}_4$	1	$\mathbb{Z}_2^2 \times \mathbb{Z}_4$	$1 \rightarrow \mathbb{Z}^2 \rightarrow \pi_1 \rightarrow D_{2,8,3} \rightarrow 1$
5	$1/3, 2/3$	$2^4, 3$	$3, 4^2$	\mathfrak{S}_4	1	$\mathbb{Z}_2^2 \times \mathbb{Z}_8$	$1 \rightarrow \mathbb{Z}^2 \rightarrow \pi_1 \rightarrow \mathbb{Z}_8 \rightarrow 1$
5	$1/3, 2/3$	$4^2, 6$	$2^3, 3$	$\mathbb{Z}_2 \times \mathfrak{S}_4$	1	$\mathbb{Z}_2^2 \times \mathbb{Z}_8$	$1 \rightarrow \mathbb{Z}^2 \rightarrow \pi_1 \rightarrow \mathbb{Z}_8 \rightarrow 1$
5	$1/3, 2/3$	$2, 5, 6$	$3, 4^2$	\mathfrak{S}_5	1	\mathbb{Z}_8	$D_{8,5,-1}$
5	$1/3, 2/3$	$3, 5^2$	$2^3, 3$	\mathfrak{A}_5	1	$\mathbb{Z}_2 \times \mathbb{Z}_{10}$	$\mathbb{Z}_5 \times Q_8$
5	$1/3, 2/3$	$2^3, 3$	$3, 4^2$	$\mathbb{Z}_2^4 \rtimes \mathfrak{S}_3$	1	$\mathbb{Z}_2 \times \mathbb{Z}_8$	$D_{8,4,3}?$
5	$1/3, 2/3$	$3, 5^2$	$2^3, 3$	\mathfrak{A}_5	1	$\mathbb{Z}_2 \times \mathbb{Z}_{10}$	$\mathbb{Z}_2 \times \mathbb{Z}_{10}$
4	$1/2^4$	2^5	2^5	\mathbb{Z}_2^3	1	$\mathbb{Z}_2^3 \times \mathbb{Z}_4$	$1 \rightarrow \mathbb{Z}^4 \rightarrow \pi_1 \rightarrow \mathbb{Z}_2^2 \rightarrow 1$
4	$1/2^4$	$2^2, 4^2$	$2^2, 4^2$	$\mathbb{Z}_2 \times \mathbb{Z}_4$	1	$\mathbb{Z}_2^3 \times \mathbb{Z}_4$	$1 \rightarrow \mathbb{Z}^4 \rightarrow \pi_1 \rightarrow \mathbb{Z}_2^2 \rightarrow 1$
4	$1/2^4$	2^5	$2^3, 4$	$\mathbb{Z}_2 \times D_4$	1	$\mathbb{Z}_2^2 \times \mathbb{Z}_4$	$1 \rightarrow \mathbb{Z}^2 \rightarrow \pi_1 \rightarrow \mathbb{Z}_2 \times \mathbb{Z}_4 \rightarrow 1$
4	$1/2^4$	$3, 6^2$	$2^2, 3^2$	$\mathbb{Z}_3 \times \mathfrak{S}_3$	1	\mathbb{Z}_3^2	$\mathbb{Z}^2 \rtimes \mathbb{Z}_3$
4	$1/2^4$	$3, 6^2$	$2, 4, 5$	\mathfrak{S}_5	1	\mathbb{Z}_3^2	$\mathbb{Z}^2 \rtimes \mathbb{Z}_3$
4	$1/2^4$	2^5	$2, 4, 6$	$\mathbb{Z}_2 \times \mathfrak{S}_4$	1	\mathbb{Z}_2^3	$\mathbb{Z}^2 \rtimes \mathbb{Z}_2$
4	$1/2^4$	$2^2, 4^2$	$2, 4, 6$	$\mathbb{Z}_2 \times \mathfrak{S}_4$	1	$\mathbb{Z}_2^2 \times \mathbb{Z}_4$	$\mathbb{Z}^2 \rtimes \mathbb{Z}_4$
4	$1/2^4$	2^5	$3, 4^2$	\mathfrak{S}_4	1	$\mathbb{Z}_2^2 \times \mathbb{Z}_4$	$\mathbb{Z}^2 \rtimes \mathbb{Z}_4$
4	$1/2^4$	$2^3, 4$	$2^3, 4$	$\mathbb{Z}_2^4 \rtimes \mathbb{Z}_2$	1	\mathbb{Z}_4^2	$G(32, 2)$
4	$1/2^4$	$2, 5^2$	$2^2, 3^2$	\mathfrak{A}_5	1	\mathbb{Z}_{15}	\mathbb{Z}_{15}
4	$1/2^4$	$2^2, 3^2$	$2^2, 3^2$	$\mathbb{Z}_3^2 \rtimes \mathbb{Z}_2$	1	\mathbb{Z}_3^3	\mathbb{Z}_3^3
4	$2/5^2$	$2^3, 5$	$3^2, 5$	\mathfrak{A}_5	1	$\mathbb{Z}_2 \times \mathbb{Z}_6$	$\mathbb{Z}_2 \times \mathbb{Z}_6$
4	$2/5^2$	$2, 4, 5$	$4^2, 5$	$\mathbb{Z}_2^4 \rtimes D_5$	3	\mathbb{Z}_8	$\mathbb{Z}_8?$
4	$2/5^2$	$2, 4, 5$	$3^2, 5$	\mathfrak{A}_6	1	\mathbb{Z}_6	\mathbb{Z}_6

TABLE 2. Minimal product-quotient surfaces of general type with $p_g = 0$, $K^2 \leq 3$

K_S^2	Sing X	t_1	t_2	G	N	$H_1(S, \mathbb{Z})$	$\pi_1(S)$
3	1/5, 4/5	$2^3, 5$	$3^2, 5$	\mathfrak{A}_5	1	$\mathbb{Z}_2 \times \mathbb{Z}_6$	$\mathbb{Z}_2 \times \mathbb{Z}_6$
3	1/5, 4/5	2, 4, 5	$4^2, 5$	$\mathbb{Z}_2^4 \rtimes D_5$	3	\mathbb{Z}_8	$\mathbb{Z}_8?$
3	1/3, 1/2 ² , 2/3	$2^2, 3, 4$	2, 4, 6	$\mathbb{Z}_2 \times \mathfrak{S}_4$	1	$\mathbb{Z}_2 \times \mathbb{Z}_4$	$\mathbb{Z}_2 \times \mathbb{Z}_4$
3	1/5, 4/5	2, 4, 5	$3^2, 5$	\mathfrak{A}_6	1	\mathbb{Z}_6	\mathbb{Z}_6
2	1/3 ² , 2/3 ²	$2, 6^2$	$2^2, 3^2$	$\mathbb{Z}_2 \times \mathfrak{A}_4$	1	\mathbb{Z}_2^2	Q_8
2	1/2 ⁶	4^3	4^3	\mathbb{Z}_4^2	1	\mathbb{Z}_2^3	\mathbb{Z}_2^3
2	1/2 ⁶	$2^3, 4$	$2^3, 4$	$\mathbb{Z}_2 \times D_4$	1	$\mathbb{Z}_2 \times \mathbb{Z}_4$	$\mathbb{Z}_2 \times \mathbb{Z}_4$
2	1/3 ² , 2/3 ²	$2^2, 3^2$	$3, 4^2$	\mathfrak{S}_4	1	\mathbb{Z}_8	\mathbb{Z}_8
2	1/3 ² , 2/3 ²	$3^2, 5$	$3^2, 5$	$\mathbb{Z}_5^2 \times \mathbb{Z}_3$	2	\mathbb{Z}_5	$\mathbb{Z}_5?$
2	1/2 ⁶	$2, 5^2$	$2^3, 3$	\mathfrak{A}_5	1	\mathbb{Z}_5	\mathbb{Z}_5
2	1/2 ⁶	$2^3, 4$	2, 4, 6	$\mathbb{Z}_2 \times \mathfrak{S}_4$	1	\mathbb{Z}_2^2	\mathbb{Z}_2^2
2	1/3 ² , 2/3 ²	$3^2, 5$	$2^3, 3$	\mathfrak{A}_5	1	\mathbb{Z}_2^2	\mathbb{Z}_2^2
2	1/2 ⁶	2, 3, 7	4^3	$\text{PSL}(2, 7)$	2	\mathbb{Z}_2^2	\mathbb{Z}_2^2
2	1/2 ⁶	$2, 6^2$	$2^3, 3$	$\mathfrak{S}_3 \times \mathfrak{S}_3$	1	\mathbb{Z}_3	\mathbb{Z}_3
2	1/2 ⁶	$2, 6^2$	2, 4, 5	\mathfrak{S}_5	1	\mathbb{Z}_3	\mathbb{Z}_3
2	1/4, 1/2 ² , 3/4	2, 4, 7	$3^2, 4$	$\text{PSL}(2, 7)$	2	\mathbb{Z}_3	\mathbb{Z}_3
2	1/4, 1/2 ² , 3/4	2, 4, 5	$3^2, 4$	\mathfrak{A}_6	2	\mathbb{Z}_3	\mathbb{Z}_3
2	1/4, 1/2 ² , 3/4	2, 4, 5	3, 4, 6	\mathfrak{S}_5	2	\mathbb{Z}_3	\mathbb{Z}_3
1	1/3, 1/2 ⁴ , 2/3	$2^3, 3$	$3, 4^2$	\mathfrak{S}_4	1	\mathbb{Z}_4	\mathbb{Z}_4
1	1/3, 1/2 ⁴ , 2/3	2, 3, 7	$3, 4^2$	$\text{PSL}(2, 7)$	1	\mathbb{Z}_2	\mathbb{Z}_2
1	1/3, 1/2 ⁴ , 2/3	2, 4, 6	$2^3, 3$	$\mathbb{Z}_2 \times \mathfrak{S}_4$	1	\mathbb{Z}_2	\mathbb{Z}_2

The biggest impact on the "zoo" of surfaces of general type with $p_g = 0$ of our work is the case $K_S^2 = 5$: here we raise the number of known different topological types from one to seven.

Surfaces with $p_g = 0$ are also very interesting in view of Bloch's conjecture ([Blo75]), predicting that for surfaces with $p_g = 0$ the group of zero cycles modulo rational equivalence is isomorphic to \mathbb{Z} .

Using Kimura's results ([Kim05], see also [GP03]), the present results, and those of the previous papers [BC04], [BCG08], [BCGP08], we get the following:

Corollary 0.6. *All the families in theorem 0.3 fulfill Bloch's conjecture, i.e., there are 77 families of surfaces of general type with $p_g = 0$ for which Bloch's conjecture holds.*

Let us briefly illustrate the strategy of proof for the above theorem and point out the difficulties arising in our more general situation.

Our goal is to find all product-quotient surfaces S of general type with $p_g = 0$.

Remark 0.7. 1) Let S be a surface of general type. Then $p_g(S) \geq q(S) := h^1(S, \mathcal{O}_S)$. In particular, $p_g = 0$ implies $q = 0$. If S is minimal, then $K_S^2 > 0$.

2) Let S be a product-quotient surface with quotient model $X = (C_1 \times C_2)/G$. If $q(S) = 0$, then $C_i/G \cong \mathbb{P}^1$. If S is of general type, then $g(C_i) \geq 2$.

By the above, we only need to recall the definition of a special case of an orbifold surface group: a polygonal group, (cf. [BCGP08] for the general situation).

Definition 0.8. A polygonal group of signature (m_1, \dots, m_r) is the group presented as follows:

$$\mathbb{T}(m_1, \dots, m_r) := \langle c_1, \dots, c_r \mid c_1^{m_1}, \dots, c_r^{m_r}, c_1 \cdot \dots \cdot c_r \rangle.$$

Let $p, p_1, \dots, p_r \in \mathbb{P}^1$ be $r + 1$ different points and for each $1 \leq i \leq r$ choose a simple geometric loop γ_i in $\pi_1(\mathbb{P}^1 \setminus \{p_1, \dots, p_r\}, p)$ around p_i , such that $\gamma_1 \cdot \dots \cdot \gamma_r = 1$.

Then $\mathbb{T}(m_1, \dots, m_r)$ is the factor group of $\pi_1(\mathbb{P}^1 \setminus \{p_1, \dots, p_r\}, p)$ by the subgroup normally generated by $\gamma_1^{m_1}, \dots, \gamma_r^{m_r}$.

Hence, by Riemann's existence theorem, any curve C together with an action of a finite group G on it such that $C/G \cong \mathbb{P}^1$ is determined (modulo automorphisms) by the following data:

- 1) the branch point set $\{p_1, \dots, p_r\} \subset \mathbb{P}^1$;
- 2) the kernel of the monodromy homomorphism $\pi_1(\mathbb{P}^1 \setminus \{p_1, \dots, p_r\}, p) \rightarrow G$ which, once chosen loops γ_i as above, factors through $\mathbb{T}(m_1, \dots, m_r)$, where m_i is the branching index of p_i ; therefore giving the monodromy homomorphism is equivalent to give
- 2') an *appropriate orbifold* homomorphism

$$\varphi: \mathbb{T}(m_1, \dots, m_r) \rightarrow G,$$

i.e., a surjective homomorphism such that $\varphi(c_i)$ is an element of order exactly m_i , with the property that the *Hurwitz' formula* for the genus g of C holds:

$$2g - 2 = |G| \left(-2 + \sum_{i=1}^r \left(1 - \frac{1}{m_i} \right) \right).$$

An r -tuple (g_1, \dots, g_r) of elements of a group G is called a *spherical system of generators of G* , if $\langle g_1, \dots, g_r \rangle = G$ and $g_1 \cdot \dots \cdot g_r = 1$.

Note that $(\varphi(c_1), \dots, \varphi(c_r))$ is a spherical system of generators of G . Vice versa, a spherical system of generators of G determines a polygonal group \mathbb{T} together with an appropriate orbifold homomorphism $\varphi: \mathbb{T} \rightarrow G$.

Therefore a product-quotient surface S of general type with $p_g = 0$ determines the following data

- a finite group G ;
- two sets of (branch) points in \mathbb{P}^1 ;
- two polygonal groups \mathbb{T}_1 and \mathbb{T}_2 ;
- (once chosen appropriate loops as above) two appropriate orbifold homomorphisms $\varphi_i: \mathbb{T}_i \rightarrow G$,

or equivalently,

- a finite group G ;
- two sets of points $\{p_1, \dots, p_r\}$ and $\{q_1, \dots, q_s\}$ in \mathbb{P}^1 ;
- two spherical systems of generators of G of respective length r and s .

Vice versa, the data above determine the product-quotient surface.

But different data may determine the same surface.

Consider the braid group

$$(1) \quad \mathbf{B}_r := \left\langle \sigma_1, \dots, \sigma_{r-1} \mid \begin{array}{l} \sigma_i \sigma_j = \sigma_j \sigma_i \text{ if } |i - j| > 1, \\ \sigma_i \sigma_{i+1} \sigma_i = \sigma_{i+1} \sigma_i \sigma_{i+1} \end{array} \right\rangle.$$

Fixing a group G , \mathbf{B}_r acts on the set of all spherical systems of generators of length r of G as follows: for $T = (g_1, \dots, g_r)$ define

$$(2) \quad \sigma_i(T) := (g_1, \dots, g_{i-1}, g_i \cdot g_{i+1} \cdot g_i^{-1}, g_i, g_{i+2}, \dots, g_r).$$

We let the automorphism group $\text{Aut}(G)$ of G act on a pair of spherical systems of generators by simultaneous application of an automorphism to the coordinates of a tuple.

Let $\mathbf{B}(G, r, s)$ be the set of pairs of spherical generators of a given group G of respective length r and s . For $(\gamma_1, \gamma_2, \varphi) \in \mathbf{B}_r \times \mathbf{B}_s \times \text{Aut}(G)$ and $(T_1, T_2) \in \mathbf{B}(G, r, s)$, we set

$$(3) \quad (\gamma_1, \gamma_2, \varphi) \cdot (T_1, T_2) := (\varphi(\gamma_1(T_1)), \varphi(\gamma_2(T_2))).$$

This defines an action of $\mathbf{B}_r \times \mathbf{B}_s \times \text{Aut}(G)$ on $\mathbf{B}(G, r, s)$.

This group action has been introduced in [BCG08], where it is also shown that two pairs of spherical systems of generators of a group G in the same $\mathbf{B}_r \times \mathbf{B}_s \times \text{Aut}(G)$ - orbit (fixed the branch points) give rise to isomorphic product-quotient surfaces.

The aim is to produce a Magma code which finds all possible $(G, \mathbb{T}_i, \varphi_i)$ yielding surfaces of general type with $p_g = 0$ modulo the above described action of the appropriate $\mathbf{B}_r \times \mathbf{B}_s \times \text{Aut}(G)$.

First of all we use the combinatorial restriction imposed by the assumption $p_g = 0$, and the condition that the quotient model of a product-quotient surface can only have cyclic quotient singularities.

This allows, for each value of $K^2 := K_S^2$, to restrict to a finite number of *baskets* of singularities (i.e., the combinatorial data given by the singular locus of X) and for each possible basket of singularities to a finite list of possible signatures t_1, t_2 of the respective polygonal groups.

Using prop. 1.14, a MAGMA ([BCP97]) script provides a finite list of possible signatures t_1, t_2 . The order of G is now determined by t_1, t_2 and by K^2 : it follows that there are only finitely many groups to consider.

A second MAGMA script computes, for each K^2 and each possible basket \mathcal{B} , all possible triples (t_1, t_2, G) , where G is a quotient of both polygonal groups (of respective signatures t_1, t_2) and has the right order. Note that our code skips a

few pairs of signatures giving rise to groups of large order, either not covered by the MAGMA SmallGroup database, or causing extreme computational complexity. These cases left out by our program are then excluded via a case by case argument.

For each of the triples (t_1, t_2, G) in the output, there are several pairs of surjections (φ_1, φ_2) , each giving a product-quotient surface.

Recall that the triple (t_1, t_2, G) depends on a previously fixed basket \mathcal{B} . The product-quotient surface is a surface of general type with $p_g = 0$ and $K_S^2 = K^2$ if and only if the singularities are as prescribed.

A third MAGMA script produces the final list of surfaces, discarding the ones whose singular locus is not correct.

The script returns exactly one representative for each orbit of the $\mathbf{B}_r \times \mathbf{B}_s \times \text{Aut}(G)$ - action.

A last script calculates, using a result by Armstrong ([Arm65], [Arm68]), the fundamental groups.

In the case of infinite fundamental groups the structure theorem proven in [BCGP08] turns out to be extremely helpful to give an explicit description of these groups (since in general a presentation of a group does not say much about it).

Our code produces 73 families of product-quotient surfaces with $K_S^2 > 0$. We want to determine the minimal model of S . The construction of our surfaces is purely algebraic, the way from algebra to geometry is given by the Riemann existence theorem, which is not constructive. Therefore it is not straightforward how to get hold on delicate geometrical features of S .

We develop a criterion (cf. section 4) for the minimality of a product-quotient surface arguing on the combinatorics of the basket of singularities. In all cases except one this criterion works and the minimality follows.

The remaining case turns out to be non minimal. We construct two very special singular G -invariant correspondences between C_1 and C_2 such that the respective strict transforms on S of their images in X are rational (-1) -curves. We prove that the surface obtained contracting these two (-1) -curves is minimal applying the previous criterion.

The paper is organized as follows:

In section 1 we discuss finite group actions on a product of compact Riemann surfaces of respective genera at least two, developing all the theory necessary to implement the algorithm.

In the second and third section we discuss the main classification algorithm.

Section 4 deals with rational curves of selfintersection (-1) on product-quotient surfaces. Here we give the criterion for the minimality of S , and show that it works for all the constructed surfaces except the fake Godeaux.

In section 5 we determine the minimal model of the fake Godeaux surface. The last section is devoted to comments about the computational complexity of the algorithms we used.

An expanded version of tables 1, 2 describing all the needed data if one wants to do explicit computations with one of the surfaces and a commented version of the MAGMA code we used can be downloaded from:

<http://www.science.unitn.it/~pignatel/papers.html>.

1. THEORETICAL BACKGROUND

Let C_1, C_2 be two compact Riemann surfaces of respective genera $g_1, g_2 \geq 2$. Let G be a finite group acting faithfully on both curves and consider the diagonal action of G on $C_1 \times C_2$. This determines a product-quotient surface S , the minimal resolution of the singularities of $X := (C_1 \times C_2)/G$.

Remark 1.1. 1) Note that there are finitely many points on $C_1 \times C_2$ with non trivial stabilizer, which is automatically cyclic. Hence the quotient surface $X := (C_1 \times C_2)/G$ has a finite number of cyclic quotient singularities.

Recall that every cyclic quotient singularity is locally analytically isomorphic to the quotient of \mathbb{C}^2 by the action of a diagonal linear automorphism with eigenvalues $\exp(\frac{2\pi i}{n}), \exp(\frac{2\pi ia}{n})$ with $\text{g.c.d.}(a, n) = 1$; this is called a *singularity of type $\frac{1}{n}(1, a)$* . Two singularities of respective types $\frac{1}{n}(1, a)$ and $\frac{1}{n'}(1, a')$ are locally analytically isomorphic if and only if $n = n'$ and either $a = a'$ or $aa' \equiv 1 \pmod{n}$.

2) We denote by K_X the canonical (Weil) divisor on the normal surface X corresponding to $i_*(\Omega_{X^0}^2)$, $i: X^0 \rightarrow X$ being the inclusion of the smooth locus of X . According to Mumford we have an intersection product with values in \mathbb{Q} for Weil divisors on a normal surface, and in particular we may consider the selfintersection of the canonical divisor,

$$(4) \quad K_X^2 = \frac{8(g(C_1) - 1)(g(C_2) - 1)}{|G|} \in \mathbb{Q},$$

which is not necessarily an integer.

3) It is well known that the exceptional divisor E of the minimal resolution of a cyclic quotient singularity of type $\frac{1}{n}(1, a)$ is a *Hirzebruch-Jung string*, i.e., $E = \bigcup_{i=1}^l E_i$ where all E_i are smooth rational curves, $E_i^2 = -b_i$, $E_i \cdot E_{i+1} = 1$ for $i \in \{1, \dots, l-1\}$ and $E_i \cdot E_j = 0$ otherwise. The b_i are given by the formula

$$\frac{n}{a} = b_1 - \frac{1}{b_2 - \frac{1}{b_3 - \dots}}$$

4) Since the minimal resolution $\pi: S \rightarrow X$ of the singularities of X replaces each singular point by a tree of smooth rational curves, we have, by van Kampen's theorem, that $\pi_1(X) = \pi_1(S)$.

5) Moreover, we have (in a neighbourhood of x)

$$K_S = \pi^* K_X + \sum_{i=1}^l a_i E_i,$$

where the rational numbers a_i are determined by the conditions

$$(K_S + E_j)E_j = -2, \quad (K_S - \sum_{i=1}^l a_i E_i)E_j = 0, \quad \forall j = 1, \dots, l.$$

The above formulae allow us to calculate the self intersection number of the canonical divisor K_S . In fact, we need the following

Definition 1.2. *Let X be a normal complex surface and suppose that the singularities of X are cyclic quotient singularities. Then we define a representation of the basket of singularities of X to be a multiset*

$$\mathcal{B}(X) := \left\{ \lambda \times \left(\frac{1}{n}(1, a) \right) : X \text{ has exactly } \lambda \text{ singularities of type } \frac{1}{n}(1, a) \right\}.$$

I.e., $\mathcal{B}(X) = \{2 \times \frac{1}{3}(1, 1), \frac{1}{4}(1, 3)\}$ means that the singular locus of X consists of two $\frac{1}{3}(1, 1)$ -points and one $\frac{1}{4}(1, 3)$ -point.

Remark 1.3. We observe that in general a normal surface X with cyclic quotient singularities has several representations of its basket, *e.g.*,

$$\left\{ 2 \times \frac{1}{5}(1, 2) \right\}, \left\{ 1 \times \frac{1}{5}(1, 2), 1 \times \frac{1}{5}(1, 3) \right\}, \left\{ 2 \times \frac{1}{5}(1, 3) \right\}.$$

This motivates the following

Definition 1.4. *Consider the set of multisets of the form*

$$\mathcal{B} := \left\{ \lambda \times \left(\frac{1}{n}(1, a) \right) : a, n, \lambda \in \mathbb{N}, a < n, \gcd(a, n) = 1 \right\},$$

and consider the equivalence relation generated by " $\frac{1}{n}(1, a)$ is equivalent to $\frac{1}{n}(1, a')$ ", where $a' = a^{-1}$ in $(\mathbb{Z}/n\mathbb{Z})^*$. A basket of singularities is then an equivalence class.

Definition 1.5. *Let x be a singularity of type $\frac{1}{n}(1, a)$ with $\gcd(n, a) = 1$ and let $1 \leq a' \leq n - 1$ such that $a' = a^{-1}$ in $(\mathbb{Z}/n\mathbb{Z})^*$. Moreover, write $\frac{n}{a}$ as a continued fraction:*

$$\frac{n}{a} = b_1 - \frac{1}{b_2 - \frac{1}{b_3 - \dots}} =: [b_1, \dots, b_l].$$

Then we define the following correction terms:

- i) $k_x := k(\frac{1}{n}(1, a)) := -2 + \frac{2+a+a'}{n} + \sum (b_i - 2) \geq 0$;
- ii) $e_x := e(\frac{1}{n}(1, a)) := l + 1 - \frac{1}{n} \geq 0$;
- iii) $B_x := 2e_x + k_x$.

Let \mathcal{B} be the basket of singularities of X (recall that X is normal and has only cyclic quotient singularities). Then we use the following notation

$$k(\mathcal{B}) := \sum_{x \in \mathcal{B}} k_x, \quad e(\mathcal{B}) := \sum_{x \in \mathcal{B}} e_x, \quad B(\mathcal{B}) := \sum_{x \in \mathcal{B}} B_x.$$

Proposition 1.6 ([BCGP08], prop. 2.6, and [MP10], cor. 3.6). *Let $S \rightarrow X := (C_1 \times C_2)/G$ be the minimal resolution of singularities of X . Then we have the following two formulae for the self intersection of the canonical divisor of S and the topological Euler characteristic of S :*

$$K_S^2 = \frac{8(g_1 - 1)(g_2 - 1)}{|G|} - k(\mathcal{B});$$

$$e(S) = \frac{4(g_1 - 1)(g_2 - 1)}{|G|} + e(\mathcal{B}).$$

A direct consequence of the above is the following:

Corollary 1.7. *Let $S \rightarrow X := (C_1 \times C_2)/G$ be the minimal resolution of singularities of X . Then*

$$K_S^2 = 8\chi(S) - \frac{1}{3}B(\mathcal{B}).$$

Proof. By prop. 1.6 we have

$$e(S) = \frac{K_S^2 + B(\mathcal{B})}{2}.$$

By Noether's formula we obtain

$$12\chi(S) = K_S^2 + e(S) = \frac{3K_S^2 + B(\mathcal{B})}{2}$$

□

We shall now list some properties of the basket of singularities of the quotient model $X = (C_1 \times C_2)/G$ of a product-quotient surface.

Lemma 1.8. *Let $X = (C_1 \times C_2)/G$ be as above. There exists a representation of the basket*

$$\mathcal{B}(X) = \left\{ \lambda_1 \times \frac{1}{n_1}(1, a_1), \dots, \lambda_R \times \frac{1}{n_R}(1, a_R) \right\}$$

such that

$$\sum \lambda_i \frac{a_i}{n_i} \in \mathbb{Z}.$$

Proof. Consider the fibration $X \rightarrow C_1/G$, and let F_1, \dots, F_r be the singular fibres taken with the reduced structure. Let \tilde{F}_i be the strict transform of F_i on S .

Then, by [P10, Proposition 2.8], for a suitable representation of the basket

$$\sum \lambda_i \frac{a_i}{n_i} = - \sum \tilde{F}_i^2 \in \mathbb{Z}.$$

□

Definition 1.9. A multiset

$$\mathcal{B} := \left\{ \lambda_1 \times \frac{1}{n_1}(1, a_1), \dots, \lambda_R \times \frac{1}{n_R}(1, a_R) \right\}$$

is called a possible basket of singularities for (K^2, χ) if and only if it satisfies the following conditions:

- there is a representation of \mathcal{B} , say

$$\mathcal{B} := \left\{ \lambda'_1 \times \frac{1}{n'_1}(1, a'_1), \dots, \lambda'_{R'} \times \frac{1}{n'_{R'}}(1, a'_{R'}) \right\}$$

such that $\sum \lambda'_i \frac{a'_i}{n'_i} \in \mathbb{Z}$,

- $B(\mathcal{B}) = 3(8\chi(S) - K^2)$.

It is now obvious that the basket of the quotient model X of a product-quotient surface S is a possible basket of singularities for $(K_S^2, \chi(\mathcal{O}_S))$.

1.1. Finiteness of the classification problem. The next lemma shows that, for every pair $(K^2, \chi) \in \mathbb{Z} \times \mathbb{Z}$, there are only finitely many possible baskets of singularities for (K^2, χ) .

Lemma 1.10. Let $C \in \mathbb{Q}$ be fixed. Then there are finitely many baskets \mathcal{B} such that

$$B(\mathcal{B}) = C.$$

More precisely, we have:

- $|\mathcal{B}| \leq \frac{C}{3}$,
- if $\lambda \times \frac{1}{n}(1, a) \in \mathcal{B}$ and $\frac{n}{a} = [b_1, \dots, b_l]$, then $\lambda \sum b_i \leq C$.

Proof. Observe first that $B(\frac{1}{n}(1, a)) = \frac{a+a'}{n} + \sum b_i \geq 3$. In particular,

$$C = B(\mathcal{B}) \geq 3|\mathcal{B}|,$$

which shows (i). (ii) is obvious. □

Remark 1.11. Note that, by [Ser96], if $S \rightarrow X = C_1 \times C_2/G$ is a product-quotient surface, then $q(S) = g(C_1/G) + g(C_2/G)$. Therefore $q(S) = 0 \Leftrightarrow g(C_1/G) = g(C_2/G) = 0$. This implies that a product-quotient surface S of general type with quotient model $X = (C_1 \times C_2)/G$ has $p_g(S) = 0$ if and only if

- $\chi(\mathcal{O}_S) = 1$ and
- $C_1/G \cong C_2/G \cong \mathbb{P}^1$.

From now on we shall restrict ourselves to product-quotient surfaces S of general type with $p_g(S) = 0$. Let $\lambda_i: C_i \rightarrow \mathbb{P}^1$, $i = 1, 2$ be the two Galois covers associated to it.

Recall that, by Riemann's existence theorem (cf. the introduction for more details), an action of a finite group G on a compact Riemann surface C of genus g such that $C/G \cong \mathbb{P}^1$ is given by an appropriate orbifold homomorphism

$$\varphi: \mathbb{T}(m_1, \dots, m_r) \rightarrow G$$

such that the Riemann-Hurwitz relation holds:

$$2g - 2 = |G| \left(-2 + \sum_{i=1}^r \left(1 - \frac{1}{m_i} \right) \right).$$

Then $\lambda_i: C_i \rightarrow \mathbb{P}^1$, $i = 1, 2$ induce two appropriate orbifold homomorphisms

$$\varphi_1: \mathbb{T}(m_1, \dots, m_r) \rightarrow G,$$

$$\varphi_2: \mathbb{T}(n_1, \dots, n_s) \rightarrow G.$$

Here λ_1 is branched in r points $p_1, \dots, p_r \in \mathbb{P}^1$ with branching indices m_1, \dots, m_r , and λ_2 is branched in s points $p'_1, \dots, p'_s \in \mathbb{P}^1$ with branching indices n_1, \dots, n_s .

We need the following

Definition 1.12. Fix an r -tuple of natural numbers $t := (m_1, \dots, m_r)$ and a basket of singularities \mathcal{B} . Then we associate to these the following numbers:

$$\Theta(t) := -2 + \sum_{i=1}^r \left(1 - \frac{1}{m_i} \right);$$

$$\alpha(t, \mathcal{B}) := \frac{12 + k(\mathcal{B}) - e(\mathcal{B})}{6\Theta(t)}.$$

Moreover, we recall the following

Definition 1.13. The minimal positive integer I_x such that $I_x K_X$ is Cartier in x is called the index of the singularity x .

The index of X is the minimal positive integer I such that IK_X is Cartier. In particular, $I = \text{lcm}_{x \in \text{Sing } X} I_x$.

It is well known (cf. e.g. [Mat02], theorem 4-6-20) that the index of a cyclic quotient singularity $\frac{1}{n}(1, a)$ is

$$I_x = \frac{n}{\text{gcd}(n, a + 1)}.$$

By lemma 1.10, fixed $k \in \mathbb{Z}$, there are finitely many possible baskets of singularities for $(K_S^2, \chi(\mathcal{O}_S)) = (k, 1)$.

We shall bound now, for fixed K^2 and \mathcal{B} , the possibilities for:

- $|G|$,
- $t_1 := (m_1, \dots, m_r)$,
- $t_2 := (n_1, \dots, n_s)$,

of a product-quotient surface S with $K_S^2 = K^2$ and basket of singularities of the quotient model X equal to \mathcal{B} .

Proposition 1.14. *Fix $K^2 \in \mathbb{Z}$, and fix a possible basket of singularities \mathcal{B} for $(K^2, 1)$. Let S be a product-quotient surface S of general type such that*

- i) $p_g(S) = 0$,
- ii) $K_S^2 = K^2$,
- iii) *the basket of singularities of the quotient model $X = (C_1 \times C_2)/G$ of S equals \mathcal{B} .*

Then:

- a) $g(C_1) = \alpha(t_2, \mathcal{B}) + 1$, $g(C_2) = \alpha(t_1, \mathcal{B}) + 1$;
- b) $|G| = \frac{8\alpha(t_1, \mathcal{B})\alpha(t_2, \mathcal{B})}{K^2 + k(\mathcal{B})}$;
- c) $r, s \leq \frac{K^2 + k(\mathcal{B})}{2} + 4$;
- d) m_i divides $2\alpha(t_1, \mathcal{B})I$, n_j divides $2\alpha(t_2, \mathcal{B})I$;
- e) *there are at most $|\mathcal{B}|/2$ indices i such that m_i does not divide $\alpha(t_1, \mathcal{B})$, and similarly for the n_j ;*
- f) $m_i \leq \frac{1+I\frac{K^2+k(\mathcal{B})}{2}}{f(t_1)}$, $n_i \leq \frac{1+I\frac{K^2+k(\mathcal{B})}{2}}{f(t_2)}$, where I is the index of X , and $f(t_1) := \max(\frac{1}{6}, \frac{r-3}{2})$, $f(t_2) := \max(\frac{1}{6}, \frac{s-3}{2})$;
- g) *except for at most $|\mathcal{B}|/2$ indices i , the sharper inequality $m_i \leq \frac{1+\frac{K^2+k(\mathcal{B})}{4}}{f(t_1)}$ holds, and similarly for the n_j .*

Remark 1.15. Note that prop. 1.14, b) shows that t_1, t_2 determine the order of G . c), f) imply that there are only finitely many possibilities for the types t_1, t_2 . Parts d), e) and g) are strictly necessary to obtain an efficient algorithm.

Proof. a) Observe that by corollary 1.7, since $\chi(\mathcal{O}_S) = 1$, we have

$$\Theta(t_1)\alpha(t_1, \mathcal{B}) = \frac{12 + k(\mathcal{B}) - e(\mathcal{B})}{6} = \frac{24 - B(\mathcal{B}) + 3k(\mathcal{B})}{12} = \frac{K^2 + k(\mathcal{B})}{4}$$

and then by prop. 1.6 and Hurwitz' formula

$$\alpha(t_1, \mathcal{B}) = \frac{K^2 + k(\mathcal{B})}{4\Theta(t_1)} = \frac{8(g(C_1) - 1)(g(C_2) - 1)}{4|G|(-2 + \sum_{i=1}^r(1 - \frac{1}{m_i}))} = \frac{8(g(C_1) - 1)(g(C_2) - 1)}{4(2g(C_1) - 2)}.$$

b)

$$|G| = \frac{8(g(C_1) - 1)(g(C_2) - 1)}{K^2 + k(\mathcal{B})} = \frac{8\alpha(t_2, \mathcal{B})\alpha(t_1, \mathcal{B})}{K^2 + k(\mathcal{B})}.$$

c) Note that $r \leq 2 \sum_{i=1}^r(1 - \frac{1}{m_i}) = 2\Theta(t_1) + 4$. On the other hand, since $g(C_j) \geq 2$, we have $1 \leq \alpha(t_i, \mathcal{B}) = \frac{K^2 + k(\mathcal{B})}{4\Theta(t_i)}$. This implies that $(0 <) \Theta(t_i) \leq \frac{K^2 + k(\mathcal{B})}{4}$.

d) Each m_i is the branching index of a branch point p_i of $\lambda_1: C_1 \rightarrow C_1/G \cong \mathbb{P}^1$. Let F_i be the fibre over p_i of the map $X \rightarrow C_1/G$. Then $F_i = m_i W_i$ for some

irreducible Weil divisor W_i .

$$2\alpha(t_1, \mathcal{B}) = 2g(C_2) - 2 = K_X F_i = m_i K_X W_i.$$

Therefore

$$\frac{2\alpha(t_1, \mathcal{B})I}{m_i} = (IK_X)W_i \in \mathbb{Z}.$$

e) By [Ser96], if F_i contains a singular point of X , then it contains at least 2 singular points. Therefore there are at most $|\mathcal{B}|/2$ indices i ($1 \leq i \leq r$) such that $F_i \cap \text{Sing } X \neq \emptyset$.

For all other indices j we have $F_j \cap \text{Sing } X = \emptyset$. Then W_j is Cartier and K_X is Cartier in a neighbourhood of W_j . In particular, $\frac{\alpha(t_1, \mathcal{B})I}{m_j} = \frac{K_X W_j}{2} \in \mathbb{Z}$.

f) Note that $\Theta(t_1) + \frac{1}{m_i} \geq \frac{r-3}{2}$. Moreover, $\Theta(t_1) > 0$ implies that $r \geq 3$. Obviously, if $r = 3$, since $\Theta(2, 2, m) = -\frac{1}{m} < 0$, then $\Theta(t_1) + \frac{1}{m_i} \geq \frac{1}{6}$. Therefore $\Theta(t_1) + \frac{1}{m_i} \geq f(t_1)$, whence $m_i \leq \frac{1+\Theta(t_1)m_i}{f(t_1)}$.

By d) $m_i \leq 2\alpha(t_1, \mathcal{B})I = \frac{K^2+k(\mathcal{B})}{2\Theta(t_1)}I$. This implies

$$m_i \leq \frac{1 + \Theta(t_1)m_i}{f(t_1)} \leq \frac{1 + \Theta(t_1)\frac{K^2+k(\mathcal{B})}{2\Theta(t_1)}I}{f(t_1)} = \frac{1 + \frac{K^2+k(\mathcal{B})}{2}I}{f(t_1)}.$$

g) This is proved by the same argument as in f), using e) instead of d). \square

1.2. How to read the basket \mathcal{B} from the group theoretical data. Our next goal is to describe explicitly how the two appropriate orbifold homomorphisms

$$\varphi_1: \mathbb{T}(m_1, \dots, m_r) \rightarrow G,$$

$$\varphi_2: \mathbb{T}(n_1, \dots, n_s) \rightarrow G.$$

determine the singularities of the quotient model X .

We denote the images of the standard generators (the c_i in definition 0.8) of $\mathbb{T}(m_1, \dots, m_r)$ (resp. of $\mathbb{T}(n_1, \dots, n_s)$) by (g_1, \dots, g_r) (resp. by (h_1, \dots, h_s)).

Moreover we set $H_i := \langle g_i \rangle$ and $H_j := \langle h_j \rangle$.

We have now the following commutative diagram:

$$(5) \quad \begin{array}{ccccc} & & C_1 \times C_2 & & \\ & \swarrow p_1 & \downarrow \lambda_{12} & \searrow p_2 & \\ C_1 & & & & C_2 \\ \downarrow \lambda_1 & & & & \downarrow \lambda_2 \\ C_1/G \cong \mathbb{P}^1 & \xleftarrow{f_1} & X = (C_1 \times C_2)/G & \xrightarrow{f_2} & C_2/G \cong \mathbb{P}^1 \\ & \swarrow & \downarrow \lambda & \searrow & \\ & & C_1/G \times C_2/G \cong \mathbb{P}^1 \times \mathbb{P}^1 & & \end{array}$$

Note that the singular points of X are the points $Q = \lambda_{12}(q, q')$ such that the stabilizer

$$\text{Stab}(q, q') := \text{Stab}(q) \cap \text{Stab}(q') \neq \{1\}.$$

In particular, if $Q \in \text{Sing}(X)$ then $\lambda(Q) = (p_i, p'_j)$, where p_i (resp. p'_j) is a critical value of λ_1 (resp. λ_2).

We first prove the following

Proposition 1.16. *Let $i \in \{1, \dots, r\}$, $j \in \{1, \dots, s\}$. Then*

- (1) *there is a G -equivariant bijective map $(\lambda \circ \lambda_{12})^{-1}(p_i, p'_j) \rightarrow G/H_i \times G/H'_j$, where the G -action on the target is given by left multiplication (simultaneously on both factors);*
- (2) *intersecting with $\{\bar{1}\} \times G/H'_j$ gives a bijection between the orbits of the above G -action on $G/H_i \times G/H'_j$ with the orbits of the H_i -action on G/H'_j , i.e. with $(G/H'_j)/H_i$*

Proof. 1) Wlog we can assume $(i, j) = (1, 1)$. We fix the following notation

$$\pi_1^{-1}(p_1) = \{q_1, \dots, q_k\}, \quad \pi_2^{-1}(p'_1) = \{q'_1, \dots, q'_l\}.$$

There is a G -equivariant bijection between $\{q_1, \dots, q_k\}$ and the set of left cosets

$$\{a_1 H_1, \dots, a_k H_1\},$$

mapping each q_j in $\{g \in G \mid gq_1 = q_j\}$; similarly there is a bijection between $\{q'_1, \dots, q'_l\}$ and

$$\{a'_1 H'_1, \dots, a'_l H'_1\}.$$

This gives a G -equivariant bijection between $(\lambda \circ \lambda_{12})^{-1}(p_1, p'_1)$ and $G/H_1 \times G/H'_1$.

2) We consider the (diagonal) G -action on $G/H_1 \times G/H'_1$ by left multiplication. Note that the G -orbits are in one-to-one correspondence with the points of $\lambda((\lambda \circ \lambda_{12})^{-1}(p_1, p'_1))$.

Observe that

- i) $(hH_1, h'H'_1)$ is in the same G -orbit as $(H_1, h^{-1}h'H'_1)$;
- ii) (H_1, gH'_1) is in the same G -orbit as $(H_1, g'H'_1)$ if and only if gH'_1 and $g'H'_1$ are in the same orbit for the action of H_1 .

□

Remark 1.17. Recall that $\text{Sing}(X) \subset \lambda^{-1}(\{(p_i, p'_j)\})$. Observe moreover that proposition 1.16 gives for each (i, j) a bijection between $\lambda^{-1}(p_i, p'_j)$ and $(G/H'_j)/H_i$.

We still have to determine the types of the singularities. This is done in the following

Proposition 1.18. *An element $[g] \in (G/H'_j)/H_i$ corresponds to a point $\frac{1}{n}(1, a)$, where $n = |H_i \cap gH'_jg^{-1}|$, and a is given as follows: let δ_i be the minimal positive number such that there exists $1 \leq \gamma_j \leq o(h_j)$ with $g_i^{\delta_i} = gh_j^{\gamma_j}g^{-1}$. Then $a = \frac{n\gamma_j}{o(h_j)}$.*

Proof. Again we can assume wlog. that $(i, j) = (1, 1)$. Then $[g]$ corresponds to a (singular) point of type $\frac{1}{n}(1, a)$ with $n = |\text{Stab}(q_1, gq'_1)| = |H_1 \cap gH'_1g^{-1}|$. Recall that $H_1 = \langle g_1 \rangle$, and $H'_1 = \langle h_1 \rangle$.

Let δ be the minimal positive number such that there is $\gamma \in \mathbb{N}$ (which can be chosen such that $1 \leq \gamma \leq o(h_1)$) such that $g_1^\delta = gh_1^\gamma g^{-1}$. Then $\langle g_1^\delta \rangle = \text{Stab}(q_1, gq'_1)$.

Therefore $o(g_1) = n\delta$. In local analytic coordinates (x, y) of $C_1 \times C_2$, g_1^δ acts as

$$e^{\frac{2\pi i}{n}} = e^{\frac{2\pi i\delta}{o(g_1)}}$$

on the variable x and as

$$e^{\frac{2\pi ia}{n}} = e^{\frac{2\pi i\gamma}{o(h_1)}}.$$

on the variable y . This shows that $a = \frac{n\gamma}{o(h_1)}$. □

To better understand Proposition 1.18, let's do an example. Assume $G = PSL(2, 7)$, and take two systems of spherical generators $(g_1, \dots, g_r), (h_1, \dots, h_s)$. We compute the singularities coming from (g_1, h_1) under the assumption that $g_1 = h_1 =: g$ is an element of order 7.

We note that g is conjugate to g^2 and g^4 but not to g^3, g^5 and g^6 .

$G/H'_1 = G/\langle g \rangle$ has 24 elements. The action of $H_1 = \langle g \rangle$ on it has three orbits of cardinality 7 and three of cardinality 1. More precisely, if $g = h^{-1}g^2h = k^{-1}g^4k$, then the fixed points of the action of H_1 are H'_1, hH'_1 and kH'_1 .

By Proposition 1.18 the three orbits of cardinality 7 give 3 smooth points of X ; $\{H'_1\}$ gives $n = 7, a = 1$, $\{hH'_1\}$ gives $n = 7, a = 4$, $\{kH'_1\}$ gives $n = 7, a = 2$: therefore we get three singular points of type $\frac{1}{7}(1, 1), \frac{1}{7}(1, 4)$ and $\frac{1}{7}(1, 2)$.

2. DESCRIPTION AND IMPLEMENTATION OF THE CLASSIFICATION ALGORITHM

Now we use the results of the previous section to write a MAGMA script to find all minimal surfaces S of general type with $p_g = 0$, which are product-quotient surfaces.

The full code is rather long and a commented version of it can be downloaded from:

<http://www.science.unitn.it/~pignatel/papers.html>.

We describe here the strategy, and explain the most important scripts.

First of all, by rem. 0.7, cor. 1.7, $1 \leq K_S^2 \leq 8$. The case $K_S^2 = 8$ has been classified in [BCG08].

Therefore we fix a value of $K^2 \in \{1, \dots, 7\}$.

Step 1: The script **Baskets** lists all the *possible baskets of singularities* for $(K^2, 1)$ as in definition 1.9. Indeed, there are only finitely many of them by lemma 1.10. The input is $3(8 - K^2)$, as in lemma 1.10, so to get *e.g.*, all baskets for $K_S^2 = 5$, we need to ask *Baskets(9)*.

Step 2: By proposition 1.14, once we know the basket of singularities of X , then there are finitely many possible signatures. **ListOfTypes** computes them using the inequalities we have proved in proposition 1.14. Here the input is K^2 , so **ListOfTypes** first computes *Baskets(3(8 - K²))* and then computes for each basket all numerically compatible signatures. The output is a list of pairs, the first element of each pair being a basket and the second element being the list of all signatures compatible with that basket.

Step 3: Every surface produces two signatures, one for each curve C_i , both compatible with the basket of singularities of X ; if we know the signatures and the basket, Proposition 1.14, b) tells us the order of G . **ListGroups**, whose input is K^2 , first computes *ListOfTypes(K²)*. Then for each pair of signatures in the output, it calculates the order of the group. Next it searches for the groups of the given order which admit appropriate orbifold homomorphism from the polygonal groups corresponding to both signatures. For each affirmative answer it stores the triple (basket, pair of signatures, group) in a list which is the main output.

The script has some shortcuts.

- If one of the signatures is $(2,3,7)$, then G , being a quotient of $\mathbb{T}(2, 3, 7)$, is perfect. MAGMA knows all perfect groups of order ≤ 50000 , and then **ListGroups** checks first if there are perfect group of the right order: if not, this case can't occur.
- If:
 - either the expected order of the group is 1024 or bigger than 2000, since MAGMA does not have a list of the finite groups of this order;
 - or the order is a number as *e.g.*, 1728, where there are too many isomorphism classes of groups;

then `ListGroups` just stores these cases in a list, secondary output of the script. We will consider these "exceptional" cases in the next subsection, showing that they do not occur.

Step 4: ExistingSurfaces runs on the output of `ListGroups(K2)` and throws away all triples giving rise only to surfaces whose singularities do not correspond to the basket.

Step 5: Each triple in the output of `ExistingSurfaces(K2)` gives many different pairs of appropriate orbifold homomorphisms. On them there is the action of $\mathbf{B}_r \times \mathbf{B}_s \times \text{Aut}(G)$ described in the introduction.

The script **FindSurfaces** produces, given a triple (basket, pair of types, group), only one representative for each orbit.

Step 6: Pi1 uses Armstrong's result ([Arm65], [Arm68]) to compute the fundamental group of each of the constructed surfaces.

Remark 2.1. We performed step 5 to avoid useless repetitions (note that the cardinality of some equivalence class is a few millions). Nevertheless, it is still possible that two different outputs of `FindSurfaces` give isomorphic surfaces. One of the reasons for running step 6 is indeed to show that this is in many cases not true, since the fundamental group distinguishes them even topologically.

We would also like to point out that, even if our families have a natural number of parameters, we do not make any claim on the dimension of the induced subsets of the Gieseker moduli space of the surfaces of general type.

Remark 2.2. The output of `Pi1` is a (sometimes rather complicated) presentation of the fundamental groups of the respective surfaces. We use the structure theorem on the fundamental group of product-quotient surfaces [BCGP08, Theorem 4.1] to give the (nicer) description of the fundamental groups in tables 1 and 2.

We have run `FindSurfaces` on each triple of the output of `ListGroups(K2)`, $K^2 \in \{1 \dots 7\}$. This has given all the families in tables 1 and 2, and one more, the "fake Godeaux surface".

To prove theorem 0.3 it remains to show that

- all cases skipped by `ListGroups` do not occur,
- all the families in tables 1 and 2 are minimal surfaces of general type,
- the "fake Godeaux surface" has the properties in thm. 0.3, 3).

This will be accomplished in sections 3, 4 and 5.

product-quotient surfaces with $p_g = q = 0$ and $K_S^2 \geq 1$, as soon as we prove that the cases skipped by `ListGroups` cannot occur. This is done in the next section.

3. THE EXCEPTIONAL CASES

The cases skipped by `ListGroups` and stored in its secondary output are listed in table 3.

In this section we shall show that all these cases do not occur.

We will denote by $\text{SmallGroup}(n,m)$ the m -th group of order n in the MAGMA database of finite groups.

Proposition 3.1. *There is no finite quotient of $\mathbb{T}(2,3,7)$ of order 2520, 2688 or 6048.*

Proof. A finite quotient of $\mathbb{T}(2,3,7)$ is perfect. The only perfect groups of order 2520 resp. 6048 are \mathfrak{A}_7 resp. $SU(3,3)$; running the MAGMA script *ExSphGens* on these two groups, it turns out that both cannot be a quotient of $\mathbb{T}(2,3,7)$.

There are 3 perfect groups of order 2688. Let G be one of these three groups. Investigating their normal subgroups we find that G is either an extension of the form

$$1 \rightarrow (\mathbb{Z}/2\mathbb{Z})^3 \rightarrow G \rightarrow SU(2,7) \rightarrow 1$$

or of the form

$$1 \rightarrow \mathbb{Z}/2\mathbb{Z} \rightarrow G \rightarrow \text{SmallGroup}(1344, 11686) \rightarrow 1.$$

Running *ExSphGens* on $SU(2,7)$ and on $\text{SmallGroup}(1344, 11686)$, we see that none of them is quotient of $\mathbb{T}(2,3,7)$. Since $\mathbb{T}(3,7) = \{1\}$, this implies that G is not a quotient of $\mathbb{T}(2,3,7)$. \square

Proposition 3.2. *There is no finite quotient of $\mathbb{T}(2,3,8)$ of order 1152 or 2016.*

Proof. Assume that G is a group of order 1152 or 2016 admitting a surjective homomorphism $\mathbb{T}(2,3,8) \rightarrow G$.

Since $\mathbb{T}(2,3,8)^{ab} \cong \mathbb{Z}/2\mathbb{Z}$, the abelianization of G is a quotient of $\mathbb{Z}/2\mathbb{Z}$ and since there are no perfect groups of order 1152 or 2016, $G^{ab} \cong \mathbb{Z}/2\mathbb{Z}$.

TABLE 3. Secondary output of *ListGroups*

K^2	Basket	t_1	t_2	$ G $
6	$1/2^2$	2, 3, 7	2, 4, 5	2520
5	$2/3, 1/3$	2, 3, 8	2, 4, 6	768
5	$2/3, 1/3$	2, 3, 8	2, 3, 7	2688
5	$2/3, 1/3$	2, 3, 8	2, 3, 8	1536
5	$2/3, 1/3$	2, 3, 8	2, 3, 9	1152
4	$1/2, 1/4^2$	2, 3, 7	2, 4, 5	2520
4	$1/2^4$	2, 3, 8	2, 3, 8	1152
2	$1/4^4$	2, 4, 5	2, 3, 7	2520
2	$1/2^3, 1/4^2$	2, 3, 8	2, 3, 8	1152
2	$2/3^2, 1/3^2$	2, 3, 8	2, 3, 8	768
1	$1/4, 1/5, 11/20$	2, 3, 8	2, 3, 8	2016
1	$2/7^2, 1/7$	2, 3, 7	2, 3, 7	6048
1	$1/4, 2/5, 3/20$	2, 3, 8	2, 3, 8	2016
1	$1/4, 5/8, 1/8$	2, 3, 8	2, 3, 8	2016

$|G| = 1152$. We check among all groups of order 1152 having abelianization of order 2, that none has a spherical system of generators of signature $(2, 3, 8)$.

$|G| = 2016$. Since $G^{ab} \cong \mathbb{T}(2, 3, 8)^{ab}$, $[\mathbb{T}(2, 3, 8), \mathbb{T}(2, 3, 8)] \cong \mathbb{T}(3, 3, 4)$ surjects onto $[G, G]$ and therefore $[G, G]$ is a group of order 1008 admitting an appropriate orbifold homomorphism from $\mathbb{T}(3, 3, 4)$.

Since $\mathbb{T}(3, 3, 4)^{ab} \cong \mathbb{Z}/3\mathbb{Z}$ and since there are no perfect groups of order 1008, we checked that no group of order 1008 and abelianization of order 3 has a spherical system of generators of signature $(3, 3, 4)$. \square

Proposition 3.3. *There is exactly one group G of order 1536 admitting an appropriate orbifold homomorphism $\mathbb{T}(2, 3, 8) \rightarrow G$.*

There is no product-quotient surface of general type with $p_g = 0$ with group G , whose quotient model has $\{\frac{1}{3}(1, 1), \frac{1}{3}(1, 2)\}$ as basket of singularities.

Proof. There are 408641062 groups of order 1536. There is exactly one group (`SmallGroup(1536,408544637)`) having abelianization of order 2 and a spherical system of generators of signature $(2, 3, 8)$. We use `FindSurfaces` to check that there is no surfaces with basket $\{\frac{1}{3}(1, 1), \frac{1}{3}(1, 2)\}$. \square

Proposition 3.4. *1) There is exactly one group G (`SmallGroup(768,1085341)`) of order 768 admitting an appropriate orbifold homomorphism $\mathbb{T}(2, 3, 8) \rightarrow G$.*

2) G does not admit an appropriate orbifold homomorphism $\mathbb{T}(2, 4, 6) \rightarrow G$.

3) There is no product-quotient surface of general type with $p_g = 0$ with group G , whose quotient model has $\{2 \times \frac{1}{3}(1, 1), 2 \times \frac{1}{3}(1, 2)\}$ as basket of singularities.

Proof. The proof is almost identical to the previous one. \square

Propositions 3.1, 3.2, 3.3 and 3.4 exclude all cases in table 3.

4. RATIONAL CURVES ON PRODUCT-QUOTIENT SURFACES

We need to recall diagram 5:

$$\begin{array}{ccccc}
 & & C_1 \times C_2 & & \\
 & \swarrow p_1 & \downarrow \lambda_{12} & \searrow p_2 & \\
 C_1 & & X = (C_1 \times C_2)/G & & C_2 \\
 \downarrow \lambda_1 & \swarrow f_1 & \downarrow \lambda & \searrow f_2 & \downarrow \lambda_2 \\
 C_1/G \cong \mathbb{P}^1 & & C_1/G \times C_2/G \cong \mathbb{P}^1 \times \mathbb{P}^1 & & C_2/G \cong \mathbb{P}^1
 \end{array}$$

Assume that $\Gamma \subset X$ is a (possibly singular) rational curve. Let $\tilde{\Gamma} := \lambda_{12}^*(\Gamma) = \sum_1^k n_i \Gamma_i$ be the decomposition in irreducible components of its pull back to $C_1 \times C_2$.

Observe that $n_i = 1, \forall i$ (since λ_{12} has discrete ramification), and that G acts transitively on the set $\{\Gamma_i | i \in \{1, \dots, k\}\}$. Hence there is a subgroup $H \leq G$ of index k acting on Γ_1 such that $\lambda_{12}(\Gamma_1) = \Gamma_1/H = \Gamma$.

Normalizing Γ_1 and Γ , we get the following commutative diagram:

$$(6) \quad \begin{array}{ccc}
 \tilde{\Gamma}_1 & \longrightarrow & \Gamma_1 \\
 \gamma \downarrow & & \downarrow \\
 \mathbb{P}^1 & \xrightarrow{\nu} & \Gamma
 \end{array}$$

and, since each automorphism lifts to the normalization, H acts on $\tilde{\Gamma}_1$ and γ is the quotient map $\tilde{\Gamma}_1 \rightarrow \tilde{\Gamma}_1/H \cong \mathbb{P}^1$.

Lemma 4.1. *Let p be a branch point of γ of multiplicity m . Then $\nu(p)$ is a singular point of X of type $\frac{1}{n}(1, a)$, where $m|n$.*

Proof. Let $p' \in \tilde{\Gamma}_1$ be a ramification point of γ and $g \in H$ a generator of its stabilizer. The stabilizer A of the image of p' in $C_1 \times C_2$ (with respect of the action of G) contains g , whence $m = o(g)$ divides $n = |A|$. \square

Remark 4.2. It follows from the Enriques-Kodaira classification of complex algebraic surfaces that, if $q(S) = 0$, either

- i) S is rational, or
- ii) S is of general type, or
- iii) $K_S^2 \leq 0$.

Remark 4.3. On a smooth surface S of general type every irreducible curve C with $K_S C \leq 0$ is smooth and rational.

Proof. Consider the morphism $f: S \rightarrow M$ to its minimal model. Assume that there is an irreducible curve $C \subset S$ with $K_S C \leq 0$ which is either singular or irrational. Then C is not contracted by f and $C' := f(C)$ is a still singular resp. irrational curve with $K_M C' \leq K_S C \leq 0$ which, by a classical argument (e.g. cf. [Bom73], prop. 1), implies that C' is a smooth rational curve of selfintersection (-2) , a contradiction. \square

Proposition 4.4. *Let S be a product-quotient surface of general type. Let $\pi: S \rightarrow X$ be the minimal resolution of singularities of the quotient model. Assume that $\pi_*^{-1}(\Gamma)$ is a (-1) -curve in S and let $x \in \text{Sing}(X)$ be a point of type $\frac{1}{n}(1, a)$, with $\frac{n}{a} = [b_1, \dots, b_r]$. Consider the map ν in diagram (6). Then*

- i) $\#\nu^{-1}(x) \leq 1$, if $a = n - 1$;
- ii) $\#\nu^{-1}(x) \leq \sum_{\{b_i \geq 4\}} (b_i - 3) + \#\{i : b_i = 3\}$, if $a \neq n - 1$.

Proof. Note that, since we are assuming $\pi_*^{-1}(\Gamma)$ smooth, $\nu = \pi|_{\pi_*^{-1}(\Gamma)}$.

Let D_i be i -th curve in the resolution graph of x : D_i is smooth, rational with $D_i^2 = -b_i$, whence $K_S D_i = b_i - 2$. We set $d_i := D_i \cdot \pi_*^{-1}(\Gamma)$.

After contracting $\pi_*^{-1}(\Gamma)$, D_i maps to D'_i with $K D'_i = K D_i - d_i$. By remark 4.3, either D'_i is smooth or $K D'_i > 0$. In particular: $d_i \leq \max(1, b_i - 3)$.

If $b_i = 2$ then D_i intersects $\pi_*^{-1}(\Gamma)$ transversally in at most in one point. Moreover, $\pi_*^{-1}(\Gamma)$ can't intersect two D_j with selfintersection -2 , since this would produce, after contracting $\pi_*^{-1}(\Gamma)$, two intersecting (-1) -curves which is impossible on a surface of general type.

Therefore, if $a = n - 1$, $\pi_*^{-1}(\Gamma)$ intersects the whole Hirzebruch-Jung string in at most one point. This shows part i).

In general,

$$\begin{aligned}
 (7) \quad \#\nu^{-1}(x) &\leq \pi_*^{-1}(\Gamma) \left(\sum D_i \right) = \\
 &= \pi_*^{-1}(\Gamma) \left(\sum_{\{b_i \geq 4\}} D_i \right) + \pi_*^{-1}(\Gamma) \left(\sum_{\{b_i = 3\}} D_i \right) + \pi_*^{-1}(\Gamma) \left(\sum_{\{b_i = 2\}} D_i \right) \leq \\
 &\leq \sum_{\{b_i \geq 4\}} (b_i - 3) + \#\{i : b_i = 3\} + 1.
 \end{aligned}$$

It remains to show that, for $a \neq n - 1$, the above inequality cannot be an equality.

In fact, if equality holds, there is an i such that D'_i is a (-1) -curve and $\forall j \neq i$ we have

- $K D'_j = 0$, D'_j is smooth, or
- $K D'_j = 1$, D'_j is singular.

D'_i cannot intersect any singular D'_j , otherwise the surface obtained after contracting D'_i would violate remark 4.3. With the same argument we see that D'_i intersects at most one of the smooth D'_j .

In fact, if $r > 1$, D'_i intersects exactly one smooth D'_j , because a Hirzebruch-Jung string is connected. After the contraction of D'_i , D'_j becomes negative with respect to K , whence it can be contracted. Recursively, we contract all curves. It follows that the dual graph of the union of $\pi_*^{-1}(\Gamma)$ with the Hirzebruch-Jung string of the singularity is a tree. By the connectedness of the Hirzebruch-Jung string, $\pi_*^{-1}(\Gamma)(\sum D_i) = 1$. Therefore $\forall i, b_i = 2$ which is equivalent to $a = n - 1$. \square

The following is an immediate consequence of the above.

Corollary 4.5. *With the same hypotheses as in prop. 4.4 we have:*

- i) $\#\nu^{-1}(\frac{1}{n}(1, 1)) \leq \max(1, n - 3)$;
- ii) $\#\nu^{-1}(\frac{1}{n}(1, a)) \leq 1$, for $n \leq 7, a \neq 1$.

One possible definition of a rational double point (RDP for short) is the following. For more details we refer to [BPV84].

Definition 4.6. A *rational double point* is a singular point of a surface, such that all the exceptional curves of the minimal resolution of it have selfintersection -2 .

Proposition 4.7. *Assume that S is a product-quotient surface of general type and assume that the basket of singularities of the quotient model X is one of the following:*

- 1) $\{\frac{1}{n}(1, a), \frac{1}{n}(1, n - a)\}$ with either $n \leq 4$ or $n \leq 7, 1 \neq a < \frac{n}{2}$;
- 2) at most one point $\frac{1}{n}(1, a)$ with either $n \leq 4$ or $n \leq 7, a \neq 1$, and RDPs;
- 3) $\{2 \times \frac{1}{3}(1, 1) + RDPs\}, \{\frac{1}{5}(1, 1), \frac{1}{5}(1, 4)\}$.

Then S is minimal.

Proof. Assume by contradiction that S contains a (-1) -curve E . Then we can apply prop. 4.4 to $\Gamma := \pi_*(E) \subset X$.

1) In this case, by cor. 4.5 and lemma 4.1, γ (cf. diagram 6) has at most two critical values, corresponding to the singular points of X . Therefore Γ_1 is rational, a contradiction.

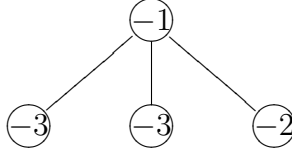
2) Note that E cannot intersect two distinct (-2) - curves. In particular, Γ can pass through at most one rational double point, and has to be smooth in this point.

Therefore, this case is excluded by the same argument as above.

3) We have to treat each basket separately.

$\{2 \times \frac{1}{3}(1, 1) + RDPs\}$: by corollary 4.5 γ has at most 3 branch points, whence by the above argument it has exactly 3. Therefore Γ passes through both triple points and through one rational double point of X : we have found a configuration of rational curves on S whose dual graph is

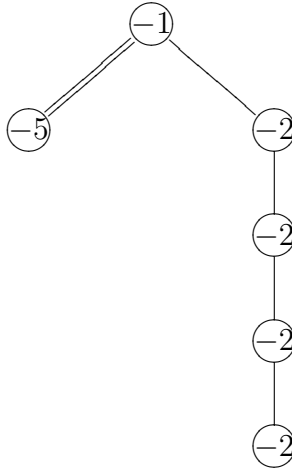
(8)



which cannot occur on a surface of general type because, after contracting the (-1) - and the (-2) -curve, one gets two intersecting (even tangentially) (-1) -curves.

$\{\frac{1}{5}(1, 1), \frac{1}{5}(1, 4)\}$: We get

(9)



Contracting E and the whole H-J string coming from the singularity $\frac{1}{5}(1, 4)$, the image of the (-5) -curve violates rem. 4.3. \square

Theorem 4.8. *The minimal product-quotient surfaces of general type with $p_g = 0$ form 72 families which are listed in tables 1 and 2.*

Proof. The case $K^2 = 8$ has been already classified in [BC04], [BCG08].

Running our program for $K^2 \in \{7, 6, 5, 4, 3, 2, 1\}$ we have found the surfaces listed in tables 1 and 2 and one more surface, which we called "the fake Godeaux surface", having $K_S^2 = 1$ and $\pi_1(S) = \mathbb{Z}/6\mathbb{Z}$ (hence cannot be minimal, cf. [Rei78]).

All the other surfaces are minimal by comparing the baskets appearing in tables 1 and 2 with proposition 4.7 (remembering that $\frac{1}{5}(1, 2) = \frac{1}{5}(1, 3)$). \square

5. THE FAKE GODEAUX SURFACE

Our program produces 73 families of product-quotient surfaces of general type with $p_g = 0$ and $K^2 > 0$, and theorem 4.8 shows that 72 of them are families of minimal surfaces.

The 73rd output in the form of tables 1 and 2 is the following

More precisely, the computer gives exactly one pair of appropriate orbifold homomorphisms, which is the following.

We see $G = PSL(2, 7)$ as subgroup of \mathfrak{S}_8 generated by $(367)(458), (182)(456)$. Then (note that $\mathbb{T}(a, b, c) \cong \mathbb{T}(c, b, a)$)

$$\begin{array}{ll} \varphi_1: \mathbb{T}(7, 3, 3) \rightarrow G, & \varphi_2: \mathbb{T}(7, 4, 2) \rightarrow G \\ c_1 \mapsto (1824375) & c_1 \mapsto (1658327) \\ c_2 \mapsto (136)(284) & c_2 \mapsto (1478)(2653) \\ c_3 \mapsto (164)(357) & c_3 \mapsto (15)(23)(36)(47). \end{array}$$

As explained in the introduction, choosing three points $p_1, p_2, p_3 \in \mathbb{P}^1$ (as branch points of λ_1), three simple loops γ_i around them with $\gamma_1\gamma_2\gamma_3 = 1$, φ_1 determines the monodromy homomorphism and then C_1 and $\lambda_1: C_1 \rightarrow C_1/G \cong \mathbb{P}^1$. Since the covering is determined by the kernel of the monodromy homomorphism, C_1 and λ_1 do not depend on the choice of the loops.

Since $\text{Aut}(\mathbb{P}^1)$ is 3-transitive, a different choice of the three branch points will give rise to an isomorphic covering.

Therefore in our situation (up to isomorphism) C_1 and λ_1 are unique. The same holds C_2 and λ_2 . Hence the pair (φ_1, φ_2) above determines exactly one product-quotient surface S , which we have called "the fake Godeaux surface".

Note that by remark 4.2 S is a surface of general type.

This section is devoted to the proof of the following

Theorem 5.1. *The fake Godeaux surface S has two (-1) -curves. Its minimal model has $K^2 = 3$.*

We first construct two (-1) -curves on S .

5.1. The rational curve E' . We can choose the branch points p_i of λ_1 and p'_j of λ_2 at our convenience. We set $(p_1, p_2, p_3) = (1, 0, \infty)$, $(p'_1, p'_2, p'_3) = (0, \infty, -\frac{9}{16})$.

Consider the normalization \hat{C}'_1 of the fibre product between λ_1 and the $\mathbb{Z}/3\mathbb{Z}$ -cover $\xi': \mathbb{P}^1 \rightarrow \mathbb{P}^1$ defined by $\xi'(t) = t^3$. We have a diagram

$$\begin{array}{ccc} \hat{C}'_1 & \xrightarrow{\xi'} & C_1 \\ \downarrow \lambda'_1 & & \downarrow \lambda_1 \\ \mathbb{P}^1 & \xrightarrow{\xi'} & \mathbb{P}^1 \end{array}$$

where the horizontal maps are $\mathbb{Z}/3\mathbb{Z}$ -covers and the vertical maps are $PSL(2, 7)$ -covers. Note that ξ' branches on p_2, p_3 which have branching index 3 for λ_1 : it follows that $\hat{\xi}'$ is étale.

TABLE 4

K_S^2	Sing X	t_1	t_2	G	N	$H_1(S, \mathbb{Z})$	$\pi_1(S)$
1	$1/7, 2/7^2$	$3^2, 7$	$2, 4, 7$	$PSL(2, 7)$	1	\mathbb{Z}_6	\mathbb{Z}_6

The branch points of $\hat{\lambda}'_1$ are the three points in $\xi'^{-1}(p_1)$, all with branching index 7.

For C_2 , we take the normalized fibre product between λ_2 and the map $\eta': \mathbb{P}^1 \rightarrow \mathbb{P}^1$ defined by $\eta'(t) = \frac{(t^3-1)(t-1)}{(t+1)^4}$.

Note that η' has degree 4 and factors through the involution $t \mapsto \frac{1}{t}$. Therefore it is the composition of two double covers, say $\eta' = \eta'_1 \circ \eta'_2$. We get the following diagram

$$\begin{array}{ccccc}
 & & \hat{\eta}' & & \\
 & \hat{C}'_2 & \xrightarrow{\hat{\eta}'_2} & \bar{C}'_2 & \xrightarrow{\hat{\eta}'_1} & C_2 \\
 & \downarrow \hat{\lambda}'_2 & & \downarrow \bar{\lambda}'_2 & & \downarrow \lambda_2 \\
 \mathbb{P}^1 & \xrightarrow{\eta'_2} & \mathbb{P}^1 & \xrightarrow{\eta'_1} & \mathbb{P}^1 \\
 & & \eta' & &
 \end{array}$$

where the horizontal maps are $\mathbb{Z}/2\mathbb{Z}$ -covers and the vertical maps are $PSL(2, 7)$ -covers.

A straightforward computation shows that η'_1 branches only on p'_2, p'_3 and therefore $\hat{\eta}'_1$ is étale.

The branch points of $\bar{\lambda}'_2$ are the two points in $(\eta'_1)^{-1}(p'_1)$ with branching index 7, and the point $(\eta'_1)^{-1}(p'_2)$ with branching index 2.

A similar computation shows that the branch points of η'_2 are $(\eta'_1)^{-1}(p'_2)$ and a point $q' \in (\eta'_1)^{-1}(p'_1)$: $\hat{\eta}'_2$ branches on the 24 points of $(\bar{\lambda}'_2)^{-1}(q')$.

The branch points of $\hat{\lambda}'_2$ are the three points of $(\eta')^{-1}(p'_1)$, each with branching index 7.

Lemma 5.2. *$(\hat{C}'_1, \hat{\lambda}'_1)$ and $(\hat{C}'_2, \hat{\lambda}'_2)$ are isomorphic as Galois covers of \mathbb{P}^1 .*

Proof. By construction they have the same group $G = PSL(2, 7)$ and the same branch points, the third roots of 1, each with branching index 7.

We ask the computer for all appropriate orbifold homomorphisms $\varphi: \mathbb{T}(7, 7, 7) \rightarrow PSL(2, 7)$ modulo automorphisms (i.e., inner automorphisms of $PSL(2, 7)$ and the action of \mathbf{B}_3 , described in the introduction). The computer finds two possibilities, returned as the sequence $[\varphi(c_1), \varphi(c_2), \varphi(c_3)]$.

```

> FindCurves({* 7^3 *}, PSL(2,7));
{
  [
    (1, 7, 8, 4, 6, 2, 3),
    (1, 5, 4, 6, 8, 7, 3),
    (1, 2, 6, 8, 4, 5, 3)
  ],
  [

```

(1, 5, 8, 2, 3, 4, 6),
 (1, 6, 3, 4, 7, 5, 8),
 (1, 5, 7, 3, 4, 2, 8)

] }
 }

There are two conjugacy classes of elements of order 7 in $PSL(2, 7)$. In both sequences the three entries belong to the same conjugacy class, whereas (1784623) is not conjugate to (1582346).

We note the following elementary, but crucial fact: let $\varphi: \mathbb{T} \rightarrow G$ be an appropriate orbifold homomorphism such that all $\varphi(c_i)$ belong to the same conjugacy class \mathcal{C} . Let φ' be an appropriate orbifold homomorphism which is equivalent to φ under the equivalence relation generated by inner automorphisms of G and by the action of \mathbf{B}_3 . Then $\varphi'(c_i) \in \mathcal{C}$ for every i .

We denote by $\hat{\varphi}_i$ an appropriate orbifold homomorphism associated to $\hat{\lambda}'_i$.

To prove the lemma it suffices now to show that there exist i, j such that $\hat{\varphi}_1(c_i)$ is conjugate to $\hat{\varphi}_2(c_j)$.

By construction, the branch points of $\hat{\lambda}'_1$ are the three points in $\xi'^{-1}(p_1)$, and they are all regular points of ξ' . This implies that $\hat{\varphi}_1(c_i)$ is conjugate to $\varphi_1(c_1) = (1824375)$.

Similarly, the branch points of $\hat{\lambda}'_2$ are the three points of $(\eta')^{-1}(p'_1)$, two of them are regular points of η' . This implies that two of the $\hat{\varphi}_2(c_i)$ are conjugate to $\varphi_2(c_1) = (1658327)$, which is conjugate to (1824375). □

Consider the curve $\hat{C}' := \hat{C}'_1 = \hat{C}'_2$. By Hurwitz' formula it is a smooth curve of genus $1 + \frac{168}{2}(-2 + 3\frac{6}{7}) = 49$ on which we have an action of $G = PSL(2, 7)$, an action of $\mathbb{Z}/3\mathbb{Z}$, and an action of $\mathbb{Z}/2\mathbb{Z}$ (given by $\hat{\eta}'_2$). Note that the last two commute with the first (in fact, these two generate an action of \mathfrak{S}_3 on \hat{C}' , just look at the induced action on $\hat{C}'/G = \mathbb{P}^1$, and how they permute the third roots of 1, so we have an explicit faithful action of $PSL(2, 7) \times \mathfrak{S}_3$ on \hat{C}').

We have then a divisor $C' := (\hat{\xi}', \hat{\eta}')(\hat{C}') \subset C_1 \times C_2$ which is G -invariant, and the quotient is a rational curve $\hat{C}'/G \cong \mathbb{P}^1 \xrightarrow{e'} D'$ contained in the quotient model X of the fake Godeaux surface S .

Proposition 5.3. *D' has an ordinary double point at the singular point $\frac{1}{7}(1, 1)$, and contains one more singular point of X .*

Let E' be the strict transform of D' on S , let E_7 be the exceptional divisor over the singular point of type $\frac{1}{7}(1, 1)$, E_2, E_4 be the exceptional divisors over the other singular point contained in D' , with $E_d^2 = -d$.

*Then $E'E_7 = 2$, $E'E_4 = 1$, $E'E_2 = 0$ and E' is numerically equivalent to $\pi^*D' - \frac{1}{7}(2E_7 + E_2 + 2E_4)$.*

Moreover, E' is a smooth rational curve with selfintersection -1 .

Proof. The composition of e' with λ is the map (ξ', η') , which is birational onto its image. Therefore e' is also birational, and D' is singular at most over the singular points of $(\xi', \eta')(\mathbb{P}^1) =: R'$.

Consider the point $(1, 0) \in \mathbb{P}^1 \times \mathbb{P}^1$; it is the image of the third roots of 1 under the map (ξ', η') , so R' has a triple point z there.

The points of \hat{C}' lying over z are exactly the 72 points with nontrivial stabilizer for the action of G , divided in 3 orbits, one for each branch of the triple point z of R' .

Choose a branch, let $P \in \hat{C}'$ be one of the 24 points in the corresponding orbit. Since $\hat{\xi}'$ is étale, the map $(\hat{\xi}', \hat{\eta}')$ is a local diffeomorphism near P . $\hat{\lambda}'_2(P)$ is one of the three branch points of $\hat{\lambda}'_2$ (depending only on the chosen branch of the singular point z) one of which is of ramification for η'_2 , two are not.

In the latter case, both $\hat{\xi}'$, $\hat{\eta}'$ are local diffeomorphisms, equivariant for the action of the stabilizer of P . It follows that there are local coordinates in $C_1 \times C_2$ such that the corresponding branch of C' is $\{x = y\}$ and the group acts as $(x, y) \mapsto (e^{\frac{2\pi i}{7}}x, e^{\frac{2\pi i}{7}}y)$: we have then two branches of D' through the singular point $\frac{1}{7}(1, 1)$.

If instead $\hat{\lambda}'_2(P)$ is a ramification point of η'_2 , the local equation of the branch is $\{x^2 = y\}$ and the action is $(x, y) \mapsto (e^{\frac{2\pi i}{7}}x, e^{\frac{4\pi i}{7}}y)$: the corresponding branch of D' passes through a point $\frac{1}{7}(1, 2)$ and a local computation shows that its strict transform intersects transversally the (-4) -curve and does not intersect the (-2) -curve.

We have computed how E' intersects the E_d , the claim on the numerical equivalence follows by standard intersection arguments.

Then

$$\begin{aligned} K_{C_1 \times C_2} C' &= 18 \cdot 4 + 3 \cdot 32 = 168 \\ \Rightarrow K_X \cdot D' = 1 &\Rightarrow K_S \cdot E' = K_X \cdot D' - \frac{1}{7}(2K_S E_7 + K_S E_2 + 2K_S E_4) = -1 \end{aligned}$$

Since S is of general type and E' is irreducible with $K_S E' < 0$, by remark 4.3 E' is smooth. This concludes the proof. \square

5.2. The rational curve E'' . The construction is similar to the previous one. We change the choice of the branch points, here $(p_1, p_2, p_3) = (0, \frac{i}{3\sqrt{3}}, -\frac{i}{3\sqrt{3}})$, $(p'_1, p'_2, p'_3) = (1, \infty, 0)$.

We define three maps $\mathbb{P}^1 \rightarrow \mathbb{P}^1$ as follows: $\xi''_2(t) = \frac{2t}{t^2+1}$, $\xi''_1(t) = \frac{t^2-1}{t^3-9t}$, $\eta''(t) = t^4$.

Note that ξ''_2 is the quotient by the involution $t \mapsto \frac{1}{t}$, ξ''_1 is the $\mathbb{Z}/3\mathbb{Z}$ -cover given by $t \mapsto \frac{t-3}{t+1}$, and η'' is the $\mathbb{Z}/4\mathbb{Z}$ -cover given by $t \mapsto it$.

By taking normalized fibre products as in the previous case, we get two commutative diagrams:

$$\begin{array}{ccccc}
& & \hat{\xi}'' & & \\
& \nearrow & & \searrow & \\
\hat{C}_1'' & \xrightarrow{\hat{\xi}_2''} & \bar{C}_1'' & \xrightarrow{\hat{\xi}_1''} & C_1 \\
\downarrow \hat{\lambda}_1'' & & \downarrow \bar{\lambda}_1'' & & \downarrow \lambda_1 \\
\mathbb{P}^1 & \xrightarrow{\xi_2''} & \mathbb{P}^1 & \xrightarrow{\xi_1''} & \mathbb{P}^1 \\
& \searrow & & \nearrow & \\
& & \xi'' & &
\end{array}$$

$$\begin{array}{ccc}
\hat{C}_2'' & \xrightarrow{\hat{\eta}''} & C_2 \\
\downarrow \hat{\lambda}_2'' & & \downarrow \lambda_2 \\
\mathbb{P}^1 & \xrightarrow{\eta''} & \mathbb{P}^1
\end{array}$$

where the vertical maps are $PSL(2, 7)$ -covers and the horizontal maps are cyclic covers.

Note that η'' branches on p'_2, p'_3, ξ_1'' on p_2, p_3, ξ_2'' on $\{\pm 1\} \subset (\xi_1'')^{-1}(p_1)$.

Lemma 5.4. $(\hat{C}_1'', \hat{\lambda}_1'')$ and $(\hat{C}_2'', \hat{\lambda}_2'')$ are isomorphic as Galois cover of \mathbb{P}^1 .

Proof. Arguing as in the previous case, we see that $\hat{\lambda}_1''$ is a $PSL(2, 7)$ -cover with the four branch points $\xi''^{-1}(p_1)$, each of branching index 7, and $\hat{\lambda}_2''$ is a $PSL(2, 7)$ -cover with the four branch points $\eta''^{-1}(p'_1)$, each of branching index 7. Indeed, $\xi''^{-1}(p_1) = \eta''^{-1}(p'_1)$ is the set of the fourth roots of unity.

We denote by $\hat{\varphi}_i$ an appropriate orbifold homomorphism associated to $\hat{\lambda}_i''$. Arguing as in the proof of lemma 5.2 we see that for all i , $\hat{\varphi}_1(c_i)$ is conjugate to $\varphi_1(c_1)$ or to $\varphi_1(c_1)^2$. Similarly, $\hat{\varphi}_2(c_i)$ is conjugate to $\varphi_2(c_1)$. Since the three elements $\varphi_1(c_1)$, $\varphi_1(c_1)^2$ and $\varphi_2(c_1)$ are conjugate in G , all $\hat{\varphi}_j(c_i)$ are conjugate to $\varphi_1(c_1) = (1824375)$.

The following computation shows that there are two equivalence classes of appropriate orbifold homomorphisms $\varphi: \mathbb{T}(7, 7, 7, 7) \rightarrow PSL(2, 7)$, distinguished by the following feature: in one class the $\varphi(c_i)$ are always pairwise distinct.

```

> #FindCurves({* 7^4 *}, PSL(2,7));
8
> L:={@ @};
> for seq in FindCurves({* 7^4 *}, PSL(2,7)) do test:= true;
for> for g in seq do
for|for> if not IsConjugate(PSL(2,7),g,PSL(2,7)!(1,8,2,4,3,7,5))
then test:=false; break g;
for|for|if> end if;
for|for> end for;
for> if test then Include(~L,seq);

```

```

for|if> end if;
for> end for;
> #L;
2
> for k in [1..#L] do
for> M:={@ @};
for> for seq in HurwitzOrbit(L[k]) do
for|for> for i in [1..3] do for j in [i+1..4] do
for|for|for|for> if seq[i] eq seq[j] then Include(~M, seq);break i;
for|for|for|for|if> end if; end for; end for;end for;
for> #M;
for> end for;
0
840
>

```

We need to show that $\hat{\varphi}_1$ and $\hat{\varphi}_2$ belong to same class, in fact to the second.

$\hat{\varphi}_2$: Consider the map η'' , and choose as base point for $\pi_1(\mathbb{P}^1 \setminus \{\pm 1, \pm i\}, p)$ a point $p = \epsilon$, $\epsilon \in \mathbb{R}$, $0 < \epsilon \ll 1$.

We define the following geometric loops with starting point ϵ :

- γ_1 moves on the real axis from ϵ to $1 - \epsilon$, then makes a circle counterclockwise around 1, and moves back on the real axis to ϵ .
- $\gamma_2 = \alpha(i\gamma_1)\alpha^{-1}$ where α is a quarter of a circle around 0 from ϵ to $i\epsilon$.
- $\gamma_3 = \beta(-\gamma_1)\beta^{-1}$ where β is a half circle around 0 from ϵ to $-\epsilon$.
- γ_4 is a similarly defined loop around $-i$.

Then $\gamma_1 \cdots \gamma_4 = 1$. Now it is easy to see (since 0 is a branch point of branching index 2 for λ_2) that the image of γ_1 in G is the same as the image of γ_3 (and the image of γ_2 is the same as the image γ_4).

$\hat{\varphi}_1$: Let $\gamma_1, \gamma_\infty, \gamma_{-1}$ be geometric loops with base point $p = 0$, γ_j around j , $\gamma_1\gamma_\infty\gamma_{-1} = 1$ in $\pi_1(\mathbb{P}^1 \setminus \{\pm 1, \infty\})$. Then we can find geometric loops $\mu_1, \mu_i, \mu_{-1}, \mu_{-i}$ with base point 0, μ_j around j , $\mu_1\mu_i\mu_{-1}\mu_{-i} = 1$ in $\pi_1(\mathbb{P}^1 \setminus \{\pm 1, \pm i\})$, such that $\xi_2'' \circ \mu_i = \gamma_\infty$, $\xi_2'' \circ \mu_{-i} = \gamma_1^7 \gamma_\infty$, which have the same image in G . \square

The curve $\hat{C}''' := \hat{C}_1''' = \hat{C}_2'''$ is a smooth curve of genus $1 + \frac{168}{2}(-2 + 4\frac{6}{7}) = 121$ with an action of $\mathrm{PSL}(2,7)$ (in fact, of $\mathrm{PSL}(2,7) \times D_4$, where D_4 is the dihedral group of order 8). The divisor $C''' := (\hat{\xi}'', \hat{\eta}'')(\hat{C}''') \subset C_1 \times C_2$ is G -invariant, and the quotient is a rational curve $\hat{C}'''/G \cong \mathbb{P}^1 \xrightarrow{e''} D'' \subset X$. Note that $\lambda \circ e'' = (\xi'', \eta'')$, which is birational. Therefore e'' is also birational.

Proposition 5.5. *D'' has an ordinary double point at the singular point $\frac{1}{7}(1, 1)$ and contains both the other singular points of X .*

Let E'' be the strict transform of D'' on S , let E_7 be the exceptional divisor over the singular point of type $\frac{1}{7}(1, 1)$, E_2, E_4, E'_2, E'_4 be the other exceptional divisors, with $E_d^2 = (E'_d)^2 = -d$, $E_2E_4 = E'_2E'_4 = 1$.

Then $E''E_7 = 2$, $E''E_4 = E''E'_4 = 1$, $E''E_2 = E''E'_2 = 0$ and E'' is numerically equivalent to $D'' - \frac{1}{7}(2E_7 + E_2 + 2E_4 + E'_2 + 2E'_4)$.

Moreover, E'' is a smooth rational curve with selfintersection -1 .

Proof. Consider the point $(0, 1)$, quartuple point of R' . The points of \hat{C}'' dominating it are exactly the 96 points with nontrivial stabilizer for the action of G , divided in 4 orbits, one for each branch of R' .

Choose a branch of the quartuple point, let $P \in \hat{C}''$ be one of the 24 points in the corresponding orbit above it. Since $\hat{\eta}''$ is étale, the map $(\hat{\xi}'', \hat{\eta}'')$ is a local diffeomorphism near P . $\hat{\lambda}'_1(P)$ is one of the branch points of $\hat{\lambda}'_1$ (depending only on the chosen branch), two of which are ramification points of ξ''_2 , two are not.

In the latter case, arguing as in the proof of proposition 5.3, the corresponding branch of D'' passes through the singular point of type $\frac{1}{7}(1, 1)$ and is smooth there. Instead, in the first case, it passes through a point of type $\frac{1}{7}(1, 2)$, and its strict transform intersects transversally the (-4) -curve and does not intersect the (-2) -curve.

It follows that $E''E_7 = 2$, $E''E_2 = E''E'_2$, $E''(E_4 + E'_4) = 2$. We still do not know whether D'' passes through both singular points $\frac{1}{7}(1, 2)$ (equivalently $E''E_4 = E''E'_4 = 1$), or misses one of them and passes twice through the other.

Then

$$\begin{aligned} K_{C_1 \times C_2} C'' &= 18 \cdot 4 + 6 \cdot 32 = 264 \\ \Rightarrow K_X \cdot D'' &= \frac{11}{7} \Rightarrow K_S \cdot E'' = \frac{11}{7} - 2\frac{5}{7} - 2\frac{4}{7} = -1. \end{aligned}$$

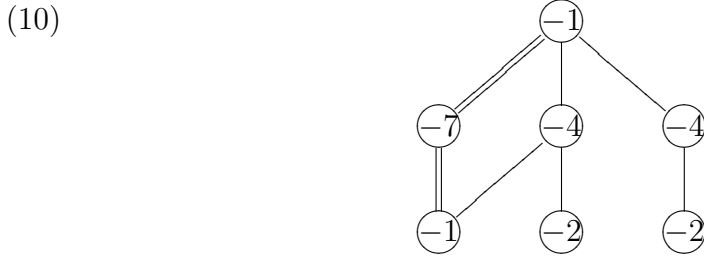
Since S is of general type and E'' is irreducible with $K_S E'' < 0$, by remark 4.3, E'' is smooth. This proves that E'' is a rational (-1) -curve.

If $E''E_4 = 2$ or $E''E'_4 = 2$, after contracting E'' , we get a contradiction to remark 4.3.

Therefore, $E''E_4 = E''E'_4 = 1$. □

Corollary 5.6. *Let $\pi': S \rightarrow S'$ be the blow down of E' and E'' . Then S' is minimal.*

Proof. Since S is of general type, E' and E'' are disjoint. We have a configuration of rational curves on S , whose dual graph is the following:



After contracting E' and E'' the induced configuration consists of a singular (-3) -curve, three smooth (-2) -curves and a smooth (-3) -curve.

Assume that there is a smooth rational curve E''' with selfintersection (-1) on S' . By the same arguments as in prop. 4.4 E''' can intersect only one of the (-2) -curves (with multiplicity one), and the smooth (-3) -curve (again with multiplicity one). The singular (-3) curve instead cannot intersect E''' , because this would (after contracting E''') give a contradiction to remark 4.3.

Let $\Gamma \subset X$ be the rational curve $\pi_*\pi'^{-1}E'''$ on X . Then, by lemma 4.1 the induced map γ (cf. diagram 6) has at most two critical values, and therefore Γ_1 is rational, a contradiction (cf. proof of prop. 4.7). \square

6. SOME REMARKS ABOUT THE COMPUTATIONAL COMPLEXITY

In this short section we will comment on the necessity to use a computer algebra program in this paper, and also on the time and memory that is needed for the various calculation we did.

We use the computer algebra program MAGMA, but our algorithms can be implemented in any other computer algebra program which has a database of finite groups (e.g. GAP4).

The heaviest computational problem we encountered are caused by the first step of the algorithm in section 2: there we compute for each $1 \leq K^2 \leq 7$ the possible baskets of singularities for $(K^2, 1)$. Our algorithm is quite slow, but has a very low memory usage. Indeed, making the algorithm quicker had disastrous effects on the memory usage.

In the following table we report the computation time and memory usage of the script *Baskets* for each K^2 . Almost all computations have been done on a simple workstation with 4GB of RAM.

K^2	7	6	5	4	3	2	1	0
time (s)	0.00	0.00	0.01	0.11	2.16	45.99	1185.85	43316.7
memory (MB)	7.64	7.64	7.64	7.64	7.64	8.31	9.83	18.42

An improvement of this algorithm (i.e., to make it faster without substantially increasing the memory usage) would constitute the major step towards extending

the results of the present paper to negative values of K^2 . Indeed we give the analogous table for *ExistingSurfaces*.

K^2	7	6	5	4	3	2	1	0
time (s)	0.00	1811	3659	5132	385	8065	2632	84989
memory (MB)	7.64	119.03	119.03	119.55	118.64	120.06	120.23	397.39

ExistingSurfaces first runs *Baskets*. We notice that for the first cases the time requested by this first computation is negligible. For $K^2 = 0$ it is more or less the half.

The other scripts in the main algorithm are quite harmless in time and memory usage.

The computations in sections 3, 5 are neither time nor memory consuming, except for propositions 3.3 and 3.4, where we had to use a SmallGroup Process (and they actually are quite heavy). In fact, we had to run those two computations on a better workstation (32GB of RAM).

The first lasted 192261.54 sec. (53-54 hours) and needed 19102.22 MB, the second lasted 4581.27 sec. and needed 4509.09 MB.

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