



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/132956/>

Version: Accepted Version

Article:

Buryak, A, Shadrin, S and Zvonkine, D (2016) Top tautological group of Mg,n . Journal of the European Mathematical Society, 18 (12). pp. 2925-2951. ISSN: 1435-9855

<https://doi.org/10.4171/JEMS/657>

(c) 2016, EMS Publishing House. All rights reserved. This is an author produced version of a paper published in the Journal of the European Mathematical Society. Uploaded in accordance with the publisher's self-archiving policy.

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Top tautological group of $\mathcal{M}_{g,n}$

Alexandr Buryak

Sergey Shadrin

Dimitri Zvonkine

Abstract

We describe the structure of the top tautological group in the cohomology of the moduli space of smooth genus g curves with n marked points.

Keywords. Moduli space of curves, cohomology, tautological groups

1 Introduction

In this paper we study the cohomology groups of the moduli space of smooth genus g curves with n marked points. This moduli space is denoted by $\mathcal{M}_{g,n}$. The space $\mathcal{M}_{g,0}$ will be denoted by \mathcal{M}_g .

The cohomology of $\mathcal{M}_{g,n}$ has a distinguished subring of tautological classes

$$R^*(\mathcal{M}_{g,n}) \subset H^{\text{even}}(\mathcal{M}_{g,n}; \mathbb{Q})$$

studied extensively since Mumford's seminal article [Mum83].

A great step towards an understanding of the tautological ring of \mathcal{M}_g was done by C. Faber in [Fab99]. He formulated three conjectures that give a complete description of $R^*(\mathcal{M}_g)$. These conjectures are called the socle conjecture, the top intersection conjecture and the perfect pairing conjecture. The socle conjecture was proved in [Loo95], there are several proofs of the top intersection conjecture (see [GP98, LX09, BS11]). The perfect pairing conjecture is true up to genus 23, but the accumulating evidence suggests it may be wrong for $g \geq 24$.

A. Buryak: Department of Mathematics, ETH Zurich, Ramistrasse 101 8092, Zurich, Switzerland; e-mail: buryaksh@gmail.com, corresponding author

S. Shadrin: Korteweg-de Vries Institute for Mathematics, University of Amsterdam, P. O. Box 94248, 1090 GE Amsterdam, The Netherlands; e-mail: s.shadrin@uva.nl

D. Zvonkine: Institut Mathématique de Jussieu, CNRS and UPMC, 4 place Jussieu, 75013 Paris, France; e-mail: dimitri.zvonkine@gmail.com

Mathematics Subject Classification (2010): Primary 14H10; Secondary 55N10

The socle conjecture says that $R^{>g-2}(\mathcal{M}_g) = 0$ and $R^{g-2}(\mathcal{M}_g) = \mathbb{Q}$. We will recall the other two conjectures in Section 1.2.

Analogous statements can be formulated about the tautological ring of $\mathcal{M}_{g,1}$. The socle property in this case says that $R^{>g-1}(\mathcal{M}_{g,1}) = 0$ and $R^{g-1}(\mathcal{M}_{g,1}) = \mathbb{Q}$ ([Loo95]). The top intersection property for $\mathcal{M}_{g,1}$ can be easily derived from the original top intersection statement for \mathcal{M}_g . The perfect pairing conjecture in this case is also open.

In this paper we formulate and prove a socle and intersection numbers property for $\mathcal{M}_{g,n}$. In particular, the generalized socle property says that $R^{>g-1}(\mathcal{M}_{g,n}) = 0$ and $R^{g-1}(\mathcal{M}_{g,n}) = \mathbb{Q}^n$. The vanishing part $R^{>g-1}(\mathcal{M}_{g,n}) = 0$ was actually proved in [Ion02].

Let us say a few words about the idea of our proof. One can choose different spanning families in the tautological groups. On one hand the tautological groups of $\mathcal{M}_{g,n}$ are spanned by monomials in ψ -classes and κ -classes. On the other hand the tautological groups of $\mathcal{M}_{g,n}$ are spanned by double ramification cycles. A technique for working with these cycles was developed, e. g., in papers [Ion02, Sha03, SZ08, BSSZ12]. In [Ion02] it was used for proving the vanishing $R^{>g-1}(\mathcal{M}_{g,n}) = 0$ and in [Sha03] it was used for studying the intersection theory of the moduli space of curves. This technique was also applied in [BS11] in order to give a simple proof of Faber's top intersection conjecture. In this paper we develop the theory of double ramification cycles and use it for the proof of generalized socle and top intersection properties.

1.1 Tautological ring

In this section we briefly recall basic definitions related to the tautological ring of the moduli space of curves. We refer to [Vak08, Zvo12] for a more detailed introduction in this subject.

Let $\overline{\mathcal{M}}_{g,n}$ be the moduli space of stable genus g curves with n marked points. The class $\psi_i \in H^2(\overline{\mathcal{M}}_{g,n}; \mathbb{Q})$ is defined as the first Chern class of the line bundle over $\overline{\mathcal{M}}_{g,n}$ formed by the cotangent lines at the i -th marked point. Let $\pi: \overline{\mathcal{M}}_{g,n+1} \rightarrow \overline{\mathcal{M}}_{g,n}$ be the forgetful map that forgets the last marked point. The class $\kappa_k \in H^{2k}(\overline{\mathcal{M}}_{g,n}; \mathbb{Q})$ is defined as follows:

$$\kappa_k := \pi_*(\psi_{n+1}^{k+1}).$$

It is convenient to define multi-index kappa classes. Let $m \geq 1$ and consider the forgetful map $\pi: \overline{\mathcal{M}}_{g,n+m} \rightarrow \overline{\mathcal{M}}_{g,n}$ that forgets the last m marked points. Let k_1, k_2, \dots, k_m be non-negative integers. Define the class $\kappa_{k_1, k_2, \dots, k_m} \in H^{2\sum_{i=1}^m k_i}(\overline{\mathcal{M}}_{g,n}; \mathbb{Q})$ by

$$\kappa_{k_1, k_2, \dots, k_m} := \pi_*(\psi_{n+1}^{k_1+1} \psi_{n+2}^{k_2+1} \dots \psi_{n+m}^{k_m+1}).$$

Multi-index κ -classes can be expressed as polynomials in κ -classes with one index. Conversely, any polynomial in one index κ -classes can be written as a linear combination of multi-index κ -classes.

The tautological ring $R^*(\mathcal{M}_{g,n})$ is defined as the subring of $H^*(\mathcal{M}_{g,n}; \mathbb{Q})$ generated by the classes κ_j and ψ_i . The group $R^i(\mathcal{M}_{g,n})$ is defined by $R^i(\mathcal{M}_{g,n}) := R^*(\mathcal{M}_{g,n}) \cap H^{2i}(\mathcal{M}_{g,n}; \mathbb{Q})$.

1.2 Faber's conjectures

Here we recall Faber's conjectures from [Fab99] about the structure of the tautological ring $R^*(\mathcal{M}_g)$. Let $g \geq 2$.

- (Socle) $R^{>g-2}(\mathcal{M}_g) = 0$ and $R^{g-2}(\mathcal{M}_g) = \mathbb{Q}$.
- (Top intersection) Suppose that $k_1 + \dots + k_m = g - 2$ and $k_i \geq 0$. Then we have the following equation in $R^{g-2}(\mathcal{M}_g)$:

$$\kappa_{k_1, \dots, k_m} = \frac{(2g - 3 + m)!(2g - 3)!!}{(2g - 2)! \prod_{i=1}^m (2k_i + 1)!!} \kappa_{g-2}.$$

- (Perfect pairing) For any $0 \leq i \leq g - 2$, the cup product defines the pairing

$$R^i(\mathcal{M}_g) \times R^{g-2-i}(\mathcal{M}_g) \rightarrow R^{g-2}(\mathcal{M}_g) = \mathbb{Q}.$$

This pairing is non-degenerate.

It is easy to see that Faber's conjectures, if true, completely determine the structure of the tautological ring $R^*(\mathcal{M}_g)$.

1.3 Generalized Faber conjectures

In this section we formulate analogous properties of the tautological ring $R^*(\mathcal{M}_{g,n})$. Assume that $g \geq 2$ and $n \geq 1$.

- (Generalized socle) $R^{>g-1}(\mathcal{M}_{g,n}) = 0$ and $R^{g-1}(\mathcal{M}_{g,n}) = \mathbb{Q}^n$. The classes ψ_i^{g-1} , $i = 1, 2, \dots, n$, form a basis in $R^{g-1}(\mathcal{M}_{g,n})$.
- (Generalized top intersection) Suppose that $d_1 + \dots + d_n + k_1 + \dots + k_m = g - 1$ and $d_i, k_j \geq 0$. Then we have the following equation in $R^{g-1}(\mathcal{M}_{g,n})$:

$$\begin{aligned} \prod_{i=1}^n \psi_i^{d_i} \cdot \kappa_{k_1, k_2, \dots, k_m} &= \frac{(2g - 1)!!}{\prod_{i=1}^n (2d_i + 1)!! \prod_{j=1}^m (2k_j + 1)!!} \frac{(2g - 3 + n + m)!}{(2g - 2 + n)!} \times \\ &\times \sum_{i=1}^n \frac{(2g - 2 + n)d_i + \sum k_j}{g - 1} \psi_i^{g-1}. \end{aligned}$$

- (Generalized perfect pairing) The ring $R^*(\mathcal{M}_{g,n})$ is level of type n . In other words, a polynomial in $\psi_1, \dots, \psi_n, \kappa_1, \dots, \kappa_{g-1}$ vanishes, if and only if its products with all classes of complementary dimension vanish in $R^{g-1}(\mathcal{M}_{g,n})$.

Similarly to Faber's conjectures, these properties, if true, completely determine the structure of the ring $R^*(\mathcal{M}_{g,n})$.

In this paper we prove the generalized socle and top intersection properties. As for the perfect pairing property, it is true in many cases that can be checked on computer, but recent evidence leads to serious doubts that it is valid in general. The main result of this paper is the following theorem.

Theorem 1.1. *The generalized socle and top intersection properties are true.*

1.4 Organization of the paper

In Section 2 we prove the generalized top intersection property, assuming that the generalized socle conjecture is true. We also show that $\dim R^{g-1}(\mathcal{M}_{g,n}) \geq n$ (the easy part of the socle property). The rest of the paper is devoted to the hard part of the socle property, that is, the inequality $\dim R^{g-1}(\mathcal{M}_{g,n}) \leq n$.

In Section 3 we formulate three main ingredients of the proof of the generalized socle property: Lemma 3.1, Proposition 3.2 and Proposition 3.3. We show how the socle property follows from them. These statements will be proved in the subsequent sections and the proof of the last proposition is the hardest one.

In Section 4 we introduce the main tool for proving these statements – double ramification cycles.

Section 5 contains several linear algebra lemmas that simplify the proofs of Propositions 3.2 and 3.3.

In Section 6 we prove Lemma 3.1, Proposition 3.2 and Proposition 3.3.

2 Generalized top intersection

In this section we show that the classes ψ_i^{g-1} are linearly independent in $R^{g-1}(\mathcal{M}_{g,n})$ and, thus, $\dim R^{g-1}(\mathcal{M}_{g,n}) \geq n$. Then we prove the generalized top intersection property assuming the equality $\dim R^{g-1}(\mathcal{M}_{g,n}) = n$. This equality will be proved in the subsequent sections.

Proposition 2.1. *The classes $\alpha_s := \lambda_g \lambda_{g-1} \psi_1 \cdots \widehat{\psi_s} \cdots \psi_n$ (where the hat means a missing factor) vanish on the boundary of $\overline{\mathcal{M}}_{g,n}$.*

Proof. It is well-known (see [Fab97], Lemma 1) that $\lambda_g \lambda_{g-1}$ vanishes on $\overline{\mathcal{M}}_{g,n} \setminus \mathcal{M}_{g,n}^{\text{rt}}$, where $\mathcal{M}_{g,n}^{\text{rt}}$ is the space of stable curves with one genus g component and possibly several “rational tails” composed of genus 0 components. Thus, it remains to show that the classes α_s also vanish on $\mathcal{M}_{g,n}^{\text{rt}} \setminus \mathcal{M}_{g,n}$. Every boundary divisor in $\mathcal{M}_{g,n}^{\text{rt}}$ is isomorphic to a product $\mathcal{M}_{g,n_1+1}^{\text{rt}} \times \overline{\mathcal{M}}_{0,n_2+1}$, where $n_1 + n_2 = n$. Among the ψ -classes that make part of α_s , at least $n_2 - 1$ are sitting on the second factor. Since the dimension of $\overline{\mathcal{M}}_{0,n_2+1}$ equals $n_2 - 2$, we see that the class α_s vanishes on our boundary divisor for dimension reasons. \square

Let $\pi: \mathcal{M}_{g,N}^{\text{rt}} \rightarrow \mathcal{M}_g$ be the forgetful map. Let l_1, l_2, \dots, l_N be non-negative integers such that $l_1 + l_2 + \dots + l_N = g - 2$. Recall that Faber’s top intersection conjecture says that

$$\pi_*(\psi_1^{l_1+1} \dots \psi_N^{l_N+1}) = \frac{(2g-3+N)!(2g-3)!!}{(2g-2)! \prod_{i=1}^N (2l_i+1)!!} \kappa_{g-2}. \quad (2.1)$$

The following small generalization of this formula will be useful for us. Define $(-1)!! := 1$.

Lemma 2.2. *Let l_1, \dots, l_N be integers such that $l_1 + \dots + l_N = g - 2$. Suppose that at most one of l_1, \dots, l_N is equal to -1 and the others are non-negative. Then formula (2.1) holds.*

Proof. If all l_i ’s are non-negative, then equation (2.1) is exactly Faber’s top intersection conjecture.

Suppose one of l_i ’s is equal to -1 . We proceed by induction on N . If $N = 1$, then $l_1 = g - 2 \geq 0$, so the formula is true. Suppose $N \geq 2$. Without loss of generality we can assume that $l_1 = -1$. Using the string equation and the induction assumption, we get

$$\begin{aligned} \pi_*(\psi_2^{l_2+1} \dots \psi_N^{l_N+1}) &= \sum_{i=2}^N \frac{(2g-4+N)!(2g-3)!!}{(2g-2)!(2l_i-1)!! \prod_{\substack{2 \leq j \leq N \\ j \neq i}} (2l_j+1)!!} \kappa_{g-2} = \\ &= \frac{(2g-3+N)!(2g-3)!!}{(2g-2)! \prod_{i=1}^N (2l_i+1)!!} \kappa_{g-2}. \end{aligned}$$

The lemma is proved. \square

Let d_1, \dots, d_n and k_1, \dots, k_m be nonnegative integers. Assume that $\sum d_i + \sum k_i = g - 1$. These integers will be fixed for the rest of the section. Denote

$$C := \frac{(2g-3+n+m)!(2g-3)!!}{(2g-2)! \prod_{i=1}^n (2d_i+1)!! \prod_{j=1}^m (2k_j+1)!!}.$$

Lemma 2.3. *Let $\pi: \mathcal{M}_{g,n}^{\text{rt}} \rightarrow \mathcal{M}_g$ be the forgetful map. Then in $R^{g-2}(\mathcal{M}_g)$ we have*

$$\pi_* \left(\psi_1^{d_1+1} \cdots \psi_s^{d_s} \cdots \psi_n^{d_n+1} \kappa_{k_1, \dots, k_m} \right) = C \cdot (2d_s + 1) \cdot \kappa_{g-2}.$$

Proof. Let $\pi': \mathcal{M}_{g,n+m}^{\text{rt}} \rightarrow \mathcal{M}_g$ be the forgetful map. We have

$$\begin{aligned} \pi_* \left(\psi_1^{d_1+1} \cdots \psi_s^{d_s} \cdots \psi_n^{d_n+1} \kappa_{k_1, \dots, k_m} \right) &= \pi'_* \left(\psi_1^{d_1+1} \cdots \psi_s^{d_s} \cdots \psi_n^{d_n+1} \psi_{n+1}^{k_1+1} \cdots \psi_{n+m}^{k_m+1} \right) = \\ &\stackrel{\text{by Lemma 2.2}}{=} C \cdot (2d_s + 1) \cdot \kappa_{g-2}. \end{aligned}$$

□

Denote by A_g the nonzero intersection number

$$A_g := \int_{\overline{\mathcal{M}}_g} \kappa_{g-2} \lambda_g \lambda_{g-1} = \frac{(-1)^{g-1} B_{2g} (g-1)!}{2^g (2g)!},$$

where B_{2g} is the Bernoulli number (see [Fab97], Lemma 2).

Corollary 2.4. *We have $\int_{\overline{\mathcal{M}}_{g,n}} \prod_{i=1}^n \psi_i^{d_i} \kappa_{k_1, \dots, k_m} \cdot \alpha_s = C \cdot (2d_s + 1) \cdot A_g$.*

Proof. Compute the integral by first projecting on $\overline{\mathcal{M}}_g$ and use Lemma 2.3. □

Proposition 2.5. *The $n \times n$ matrix $M_{is} := \int_{\overline{\mathcal{M}}_{g,n}} \psi_i^{g-1} \alpha_s$ is non-degenerate.*

Proof. Denote by U the $n \times n$ matrix given by $U_{is} = 1$ for all i, s . It has exactly two eigenvalues: 0 and n . Therefore $U + a\text{Id}$ is non-degenerate whenever $a \neq 0, -n$.

According to the corollary, we have $M_{ii} = C \cdot A_g \cdot (2g-1)$ and $M_{is} = C \cdot A_g$, for $i \neq s$. Thus,

$$M = C \cdot A_g \cdot (U + (2g-2)\text{Id}),$$

so it is non-degenerate. □

Proposition 2.6. *The classes*

$$\prod_{i=1}^n \psi_i^{d_i} \kappa_{k_1, \dots, k_m}$$

and

$$C \frac{(2g-1)!}{(2g-2+n)!} \sum_{i=1}^n \frac{(2g-2+n)d_i + \sum k_j}{g-1} \psi_i^{g-1}$$

have the same intersection number with every α_s .

Proof. Apply Corollary 2.4 and divide both intersection numbers by the common factor CA_g . We obtain the following equality that needs to be checked:

$$\begin{aligned}
2d_s + 1 &\stackrel{?}{=} \frac{2g-1}{(2g-2+n)!} \sum_{i=1}^n \left[\frac{(2g-2+n)d_i + \sum k_j}{g-1} \cdot \frac{(2g-3+n)!}{2g-1} (1 + (2g-2)\delta_{is}) \right] = \\
&= \frac{1}{(2g-2+n)(g-1)} \sum_{i=1}^n \left((2g-2+n)d_i + \sum k_j \right) (1 + (2g-2)\delta_{is}) = \\
&= \frac{1}{(2g-2+n)(g-1)} \left[(2g-2+n) \left(\sum d_i + \sum k_j \right) + (2g-2+n)(2g-2)d_s \right] = \\
&= \frac{1}{g-1} [(g-1) + (2g-2)d_s] = 2d_s + 1.
\end{aligned}$$

Thus, the equality is, indeed, right. \square

Let us sum up the results of our computations. We have found n classes α_s , $1 \leq s \leq n$, of degree $2g+n-2$ that vanish on the boundary of $\overline{\mathcal{M}}_{g,n}$ and, thus, can be used as linear forms on the group $R^{g-1}(\mathcal{M}_{g,n})$. We have proved that the intersection matrix of the classes ψ_i^{g-1} and α_s is non-degenerate and, therefore, $\dim R^{g-1}(\mathcal{M}_{g,n}) \geq n$. Finally, we have computed the intersection numbers of all tautological classes in $R^{g-1}(\mathcal{M}_{g,n})$ with the classes α_s . Assuming that (ψ_i^{g-1}) is a basis of $R^{g-1}(\mathcal{M}_{g,n})$, this allowed us to decompose any class in this basis, thus, proving the generalized top intersection property.

3 Generalized socle property: three statements

In this section we formulate three statements and show how to use them for the proof of the generalized socle property. We will prove these statements in the next sections.

3.1 Three statements

Denote by $\pi_k: \mathcal{M}_{g,n} \rightarrow \mathcal{M}_{g,n-1}$ the forgetful map that forgets the k -th marked point. Let $i_{k,l}: \mathcal{M}_{g,n} \rightarrow \mathcal{M}_{g,n}$ be the map that interchanges the k -th and the l -th marked points.

Let $S_{k,l}^j(\mathcal{M}_{g,n})$ be the subspace of $R^j(\mathcal{M}_{g,n})$ defined by

$$S_{k,l}^j(\mathcal{M}_{g,n}) := \{\alpha \in R^j(\mathcal{M}_{g,n}) \mid i_{k,l}^* \alpha = \alpha\}.$$

Lemma 3.1. *Let $n \geq 2$ and $1 \leq k < l \leq n$, then we have*

$$S_{k,l}^{g-1}(\mathcal{M}_{g,n}) \subset \pi_k^*(R^{g-1}(\mathcal{M}_{g,n-1})) + \pi_l^*(R^{g-1}(\mathcal{M}_{g,n-1})).$$

Proposition 3.2. *For any $n \geq 1$, we have*

$$R^{g-1}(\mathcal{M}_{g,n}) = \pi_1^*(R^{g-1}(\mathcal{M}_{g,n-1})) + \psi_1 \pi_1^*(R^{g-2}(\mathcal{M}_{g,n-1})).$$

Proposition 3.3. *For any $n \geq 1$, we have*

$$R^{g-2}(\mathcal{M}_{g,n}) = \pi_1^*(R^{g-2}(\mathcal{M}_{g,n-1})) + \psi_1 \pi_1^*(R^{g-3}(\mathcal{M}_{g,n-1})) + \sum_{1 \leq k < l \leq n} S_{k,l}^{g-2}(\mathcal{M}_{g,n}).$$

3.2 Proof of the generalized socle conjecture

In Section 2 we have proved the inequality $\dim R^{g-1}(\mathcal{M}_{g,n}) \geq n$. It remains to prove that $\dim R^{g-1}(\mathcal{M}_{g,n}) \leq n$

Let $p_i: \mathcal{M}_{g,n} \rightarrow \mathcal{M}_{g,1}$ be the forgetful map that forgets all marked points except the i -th. Since $\dim R^{g-1}(\mathcal{M}_{g,1}) = 1$ ([Loo95]), it is sufficient to prove that, for any $n \geq 1$, the group $R^{g-1}(\mathcal{M}_{g,n})$ is spanned by the pullbacks $p_i^*(R^{g-1}(\mathcal{M}_{g,1}))$, where $1 \leq i \leq n$. Equivalently, we have to prove that

$$R^{g-1}(\mathcal{M}_{g,n}) = \sum_{i=1}^n \pi_i^*(R^{g-1}(\mathcal{M}_{g,n-1})), \quad (3.1)$$

for any $n \geq 2$.

From Propositions 3.2 and 3.3 it follows that

$$\begin{aligned} R^{g-1}(\mathcal{M}_{g,n}) = & \pi_1^*(R^{g-1}(\mathcal{M}_{g,n-1})) + \psi_1(\pi_2 \circ \pi_1)^*(R^{g-2}(\mathcal{M}_{g,n-2})) + \\ & + \psi_1 \psi_2(\pi_2 \circ \pi_1)^*(R^{g-3}(\mathcal{M}_{g,n-2})) + \psi_1 \pi_1^* \left(\sum_{2 \leq k < l \leq n} S_{k,l}^{g-2}(\mathcal{M}_{g,n-1}) \right). \end{aligned}$$

Obviously, we have

$$\begin{aligned} \psi_1(\pi_2 \circ \pi_1)^*(R^{g-2}(\mathcal{M}_{g,n-2})) & \subset \pi_2^*(R^{g-1}(\mathcal{M}_{g,n-1})), \\ \psi_1 \psi_2(\pi_2 \circ \pi_1)^*(R^{g-3}(\mathcal{M}_{g,n-2})) & \subset S_{1,2}^{g-1}(\mathcal{M}_{g,n}), \\ \psi_1 \pi_1^*(S_{k,l}^{g-2}(\mathcal{M}_{g,n-1})) & \subset S_{k,l}^{g-1}(\mathcal{M}_{g,n}), \text{ where } 2 \leq k < l \leq n. \end{aligned}$$

Applying Lemma 3.1 to the last two formulas, we get (3.1). The generalized socle conjecture is proved.

4 Double ramification cycles

Here we give the definition of a particular type of double ramification cycles that we need in this paper and formulate main formulas that we will use.

In Section 4.1 we define double ramification cycles. In Section 4.2 we prove main formulas with double ramification cycles. In Section 4.3 we formulate Hain's result. In Section 4.4 we explain that double ramification cycles span the tautological groups of $\mathcal{M}_{g,n}$.

4.1 Definition of double ramification cycles

Let a_1, \dots, a_n , $n \geq 1$, be a list of integers satisfying $\sum a_i = 0$. Suppose that not all of them are equal to zero. Denote by n_+ the number of positive integers among the a_i 's. They form a partition $\mu = (\mu_1, \dots, \mu_{n_+})$. Similarly, denote by n_- the number of negative integers among the a_i 's. After a change of sign they form another partition $\nu = (\nu_1, \dots, \nu_{n_-})$. Both μ and ν are partitions of the same integer

$$d := \frac{1}{2} \sum_{i=1}^n |a_i|.$$

Finally, let n_0 be the number of vanishing a_i 's.

Let $\overline{\mathcal{M}}_{g,n_0}(\mu, \nu)$ be the moduli space of “rubber” stable maps to $\mathbb{C}\mathbb{P}^1$ relative to 0 and ∞ (see e.g. [GJV11, OP06]). Partitions μ and ν correspond to ramification profiles over 0 and ∞ . Denote by ρ the forgetful map $\overline{\mathcal{M}}_{g,n_0}(\mu, \nu) \rightarrow \overline{\mathcal{M}}_{g,n}$.

The double ramification cycle without forgotten points is defined by

$$DR_g \left(\prod_{i=1}^n m_{a_i} \right) := \rho_* \left([\overline{\mathcal{M}}_{g,n_0}(\mu, \nu)]^{virt} \right),$$

where $[\overline{\mathcal{M}}_{g,n_0}(\mu, \nu)]^{virt}$ is the virtual fundamental class in the homology of $\overline{\mathcal{M}}_{g,n_0}(\mu, \nu)$ (see e.g. [GJV11]).

General double ramification cycles are defined as follows. Let $k \geq 0$ and $a_1, a_2, \dots, a_n, b_1, \dots, b_k$ are integers such that not all of them are equal to zero and $\sum_{i=1}^n a_i + \sum_{j=1}^k b_j = 0$. Let $\pi: \overline{\mathcal{M}}_{g,n+k} \rightarrow \overline{\mathcal{M}}_{g,n}$ be the forgetful map that forgets the last k marked points. Then

$$DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k \tilde{m}_{b_j} \right) := \pi_* \left(DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k m_{b_j} \right) \right).$$

In this notation the i -th marked point corresponds to the ramification of order a_i , so the order of symbols m_{a_i} is important. On the other hand, the order of symbols \tilde{m}_{b_j} is irrelevant. Sometimes we will place them in different positions in the bracket. For example, $DR_g(m_a \tilde{m}_b)$ and $DR_g(\tilde{m}_b m_a)$ are, by definition, the same classes.

The Poincaré dual of $DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k \tilde{m}_{b_j} \right)$ in the cohomology of $\overline{\mathcal{M}}_{g,n}$ will be denoted by the same symbol. We have (see e.g. [GJV11])

$$\begin{aligned} DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k \tilde{m}_{b_j} \right) &= 0, & \text{if } k \geq g+1; \\ DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k \tilde{m}_{b_j} \right) &\in H^{2(g-k)}(\overline{\mathcal{M}}_{g,n}; \mathbb{Q}), & \text{if } k \leq g. \end{aligned}$$

In [FP05] it is proved that double ramification cycles belong to the tautological ring of $\overline{\mathcal{M}}_{g,n}$. Below we use a lot the restriction of the classes $DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k \tilde{m}_{b_j} \right)$ to the open moduli space $\mathcal{M}_{g,n}$. Abusing notation we denote the restriction by the same symbol.

4.2 Main formulas with double ramification cycles

Here we list main properties of double ramification cycles.

Lemma 4.1. *We have*

$$DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{i=1}^k \tilde{m}_{b_i} \right) = DR_g \left(\prod_{i=1}^n m_{-a_i} \prod_{i=1}^k \tilde{m}_{-b_i} \right). \quad (4.1)$$

Proof. The proof is obvious from the definition of double ramification cycles. \square

Lemma 4.2. *Let a_1, a_2, \dots, a_n , $n \geq 1$, and b_1, b_2, \dots, b_k , $1 \leq k \leq g + 1$, be non-zero integers such that $\sum_{i=1}^n a_i + \sum_{j=1}^k b_j = 0$. Then we have the following equation in $R^{g-k+1}(\mathcal{M}_{g,n})$:*

$$\begin{aligned} \psi_1 DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k \tilde{m}_{b_j} \right) = & - \sum_{1 \leq i < j \leq k} \frac{b_i + b_j}{ra_1} DR_g \left(\prod_{l=1}^n m_{a_l} \tilde{m}_{b_i + b_j} \prod_{l \neq i, j} \tilde{m}_{b_l} \right) \\ & - \sum_{i=2}^n \sum_{j=1}^k \frac{a_i + b_j}{ra_1} DR_g \left(\prod_{l=1}^n m_{a_l + \delta_{l,i} b_j} \prod_{l \neq j} \tilde{m}_{b_l} \right) \\ & + \sum_{j=1}^k \frac{-a_1 + (r-1)b_j}{ra_1} DR_g \left(m_{a_1 + b_j} \prod_{i=2}^n m_{a_i} \prod_{l \neq j} \tilde{m}_{b_l} \right), \end{aligned} \quad (4.2)$$

where $r := 2g - 2 + n + k$.

Proof. First, observe that for $k = 1$ we have a trivial identity, because $R^g(\mathcal{M}_{g,n}) = 0$. For $k = g + 1$ the left-hand side of this equation is equal to zero, while the vanishing of the right-hand side follows from the substitution

$$DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^g \tilde{m}_{b_j} \right) = g! \prod_{j=1}^g b_j^2.$$

The proof of this formula in the general case is based on [BSSZ12, Theorem 4]. Indeed, by definition, the class $DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k \tilde{m}_{b_j} \right)$ is the restriction to $\mathcal{M}_{g,n} \subset \overline{\mathcal{M}}_{g,n}$ of the push-forward of the class $DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k m_{b_j} \right)$ defined in the tautological ring of $\overline{\mathcal{M}}_{g,n+k}$. To prove the identity we will use the projection formula. Namely, we lift the class ψ_1 to $\overline{\mathcal{M}}_{g,n+k}$, intersect it there with the class $DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k m_{b_j} \right)$

using [BSSZ12, Theorem 4] and then push forward this intersection to $\overline{\mathcal{M}}_{g,n}$ and restrict the result to $\mathcal{M}_{g,n}$.

Consider the class $\pi^*\psi_1$ for $\pi: \overline{\mathcal{M}}_{g,n+k} \rightarrow \overline{\mathcal{M}}_{g,n}$. This class is equal to $\psi_1 - D$, where D is the class of the divisor on which the points labeled by a_1 and b_i , $i \in I \subset \{1, \dots, k\}$ lie on a rational tail. The choice of a subset $I \neq \emptyset$ here corresponds to a choice of an irreducible component of D . For dimensional reasons, the only non-trivial contribution under the push-forward is given by the irreducible components of $-D$ that correspond to $|I| = 1$, that is, the point a_1 lie on a separate bubble with exactly one point b_i , $i = 1, \dots, k$. The push-forward π_* of this intersection is equal to the class

$$-\sum_{j=1}^k DR_g \left(m_{a_1+b_j} \prod_{i=2}^n m_{a_i} \prod_{l \neq j} \tilde{m}_{b_l} \right) \quad (4.3)$$

(See, e. g. the local computation of multiplicity in [SZ08, Lemma 3.3]. Here we have a different global geometry of the space, but the local multiplicity is computed in exactly the same way).

Now we use the formula for the intersection $\psi_1 \cdot DR_g \left(\prod_{i=1}^n m_{a_i} \prod_{j=1}^k m_{b_j} \right)$ in [BSSZ12, Theorem 4]. We have there a sum over all possible degenerations of the DR-cycle into two DR-cycles

$$DR_{g_1} \left(\prod_{i \in I} m_{a_i} \prod_{j \in J} m_{b_j} \prod_{l=1}^p m_{-c_k} \right) \boxtimes DR_{g_2} \left(\prod_{i \in I'} m_{a_i} \prod_{j \in J'} m_{b_j} \prod_{l=1}^p m_{c_k} \right),$$

where $g_1 + g_2 + p - 1 = g$, $I \sqcup I' = \{1, \dots, n\}$, and $J \sqcup J' = \{1, \dots, k\}$, with some combinatorially defined coefficients. Here the symbol \boxtimes refers to the gluing of the points $-c_k$ and c_k to a node, $k = 1, \dots, p$, and for the full definition we refer to [BSSZ12, Section 2.1]. Now we claim, that the only degenerations of the DR-cycle, that do not vanish under the restriction of the push-forward π_* to the open moduli space $\mathcal{M}_{g,n}$, can be described in the following way:

1. We have $p = 1$;
2. Either $g_1 = 0$ or $g_2 = 0$;
3. The genus zero component has only three special points, where one point is $m_{\pm c_1}$, and the other two are either a pair m_{a_i}, m_{b_j} , or a pair m_{b_i}, m_{b_j} .

Indeed, if $p > 1$, or both $g_1, g_2 \geq 1$, or the genus 0 component contains at least two points a_i, a_j , then the push-forward of this class lies on the boundary of the moduli space $\overline{\mathcal{M}}_{g,n}$. So, we have genus zero component with at most 1 point a_i . Then this component should contain precisely two points from the list $a_1, \dots, a_n, b_1, \dots, b_k$ for dimensional reasons. This way we come to the description above.

Thus, we have three essentially different cases: the two marked points on the genus 0 component can be either m_{b_i}, m_{b_j} , or m_{a_i}, m_{b_j} , $i \neq 1$, or m_{a_1}, m_{b_j} . In the first case, the class (including the coefficient) that we get is equal to

$$-\frac{b_i + b_j}{ra_1} DR_g \left(\prod_{l=1}^n m_{a_l} \tilde{m}_{b_i+b_j} \prod_{l \neq i,j} \tilde{m}_{b_l} \right).$$

The sum of these classes is exactly the first summand on the right hand side of equation (4.2). In the second case, after the push-forward and restriction to the open part, we obtain the class

$$-\frac{a_i + b_j}{ra_1} DR_g \left(\prod_{l=1}^n m_{a_l + \delta_{l,i} b_j} \prod_{l \neq j} \tilde{m}_{b_l} \right),$$

and these classes sum up to the second summand of our final formula (4.2). In the last case, we have the class

$$\frac{(r-1)(a_1 + b_j)}{ra_1} DR_g \left(m_{a_1+b_j} \prod_{i=2}^n m_{a_i} \prod_{l \neq j} \tilde{m}_{b_l} \right). \quad (4.4)$$

Recall that we already got a contribution of the same class with a different coefficient in (4.3). The sum of the classes (4.4) and the corresponding summand in (4.3) is equal to

$$\frac{-a_1 + (r-1)b_j}{ra_1} DR_g \left(m_{a_1+b_j} \prod_{i=2}^n m_{a_i} \prod_{l \neq j} \tilde{m}_{b_l} \right).$$

The sum of these terms is precisely the third summand in equation (4.2). \square

Lemma 4.3. *Let a_1, a_2, \dots, a_n , $n \geq 0$, and b_1, b_2, \dots, b_k , $1 \leq k \leq g$, be non-zero integers such that $\sum_{i=1}^n a_i + \sum_{j=1}^k b_j = 0$. Then we have the following relation in $R^{g-k+1}(\mathcal{M}_{g,n+1})$:*

$$\sum_{i=1}^k b_i DR_g \left(m_{b_i} \prod_{j \neq i} \tilde{m}_{b_j} \prod_{l=1}^n m_{a_l} \right) \in \pi_1^*(R^{g-k+1}(\mathcal{M}_{g,n})). \quad (4.5)$$

Proof. There are several possible proofs of this lemma. In the case $k = 1$, the lemma is obvious, since the class (4.5) is equal to zero. If we assume that $n \geq 1$, then we can prove this lemma in the following way. We consider the class ψ_2 (this is the ψ -class at the point labelled by a_1) multiplied by $\pi_1^* DR_g \left(\prod_{j=1}^k \tilde{m}_{b_j} \prod_{i=1}^n m_{a_i} \right)$. On the open part it is equal to $\pi_1^* \psi_2 \cdot \pi_1^* DR_g \left(\prod_{j=1}^k \tilde{m}_{b_j} \prod_{i=1}^n m_{a_i} \right)$, so it is a pull-back. On the other hand, we can compute this class using [BSSZ12, Theorem 5] (we should assign to the point x_1 the multiplicity zero), and, via the same argument as in the proof of Lemma 4.2, we see, that the only terms, that contribute to the restriction of the class, that we obtain, to the open moduli space, are the class (4.5) and further classes in $\pi_1^*(R^{g-k+1}(\mathcal{M}_{g,n}))$. In the general case we use the argument very close to the one in [Ion02, Proposition 2.8].

Consider the space $\overline{\mathcal{M}}_{g,1}(\mu, \nu)$ of rubber maps to \mathbb{CP}^1 with one marked point x_1 . We assume that the collection of multiplicities $\{\mu_1, \dots, \mu_{m_+}, -\nu_1, \dots, -\nu_{m_-}\}$ is equal to $\{a_1, \dots, a_n, b_1, \dots, b_k\}$, up to a reordering. The branching morphism σ takes the space $\overline{\mathcal{M}}_{g,1}(\mu, \nu)$ to the space LM_{r+1}/S_r , that is, to the quotient of the Losev-Manin moduli space ([LM00]) by the action of the symmetric group that permutes the branch points of the rubber maps. We refer to [BSSZ12, Section 2.2] for a full discussion of this branching morphism in this setting.

We consider the following divisors in LM_{r+1} . Let p_1, \dots, p_r be the branch points and let q be the image of x_1 . We consider the S_r -symmetrization of the divisor $D_{0,p_1|q,\infty} - D_{0,q|p_1,\infty}$, where by $D_{a,b|c,d}$ we denote the divisor of two-component curves, where the pairs of points a, b and c, d lie on different components. Denote this symmetrized divisor by D . The class of $D_{0,p_1|q,\infty} - D_{0,q|p_1,\infty}$ is equal to zero, therefore, the class σ^*D of the pull-back of the symmetrization of this divisor to $\overline{\mathcal{M}}_{g,1}(\mu, \nu)$ is also equal to zero.

We consider the maps $\rho: \overline{\mathcal{M}}_{g,1}(\mu, \nu) \rightarrow \overline{\mathcal{M}}_{g,n+k+1}$ and $\pi: \overline{\mathcal{M}}_{g,n+k+1} \rightarrow \overline{\mathcal{M}}_{g,n+1}$. Our goal now is to compute the restriction to the open moduli space $\mathcal{M}_{g,n+1}$ of the class $\pi_*\rho_*\sigma^*D$. We claim that his class is equal to the sum of the class (4.5) and a class in $\pi_1^*(R^{g-k+1}(\mathcal{M}_{g,n}))$. Since, on the other hand, we know that $\pi_*\rho_*\sigma^*D = 0$, this proves the lemma.

So let us compute $\pi_*\rho_*\sigma^*D$. We can do it for each component separately along the lines of the computation of the analogous class in [BSSZ12, Lemma 2.4]. Using the same argument, as in the proof of Lemma 4.2, we obtain a non-trivial contribution only from the divisors

$$DR_{g_1} \left(\prod_{i \in I} m_{a_i} \prod_{j \in J} m_{b_j} \prod_{l=1}^p m_{-c_l} \right) \boxtimes DR_{g_2} \left(\prod_{i \in I'} m_{a_i} \prod_{j \in J'} m_{b_j} \prod_{l=1}^p m_{c_l} \right),$$

of two possible types. One type is exactly the divisors described in Lemma 4.2, that is, $p = 1$, one component is of genus 0, it contains exactly two marked points that are labeled either by a_i, b_j or b_i, b_j , and the marked point x_1 lies on the other component. The last condition follows from dimensional reason. Since there are no restrictions on the position of x_1 , all classes of this type project to $\pi_1^*(R^{g-k+1}(\mathcal{M}_{g,n}))$.

Let us describe the other possible type. We still have $p = 1$ and one of the components is of genus 0 (otherwise, the restriction to the open moduli space would be trivial), and on the component of genus 0 we have only two marked points (that is for dimensional reason), but now these two marked points will be x_1 and b_i . This class projects to the i -th term in the sum (4.5), and its coefficient, according to [BSSZ12, Lemma 2.4], is precisely b_i . This completes the proof of the lemma. \square

4.3 Hain's formula

Consider the moduli space $\mathcal{M}_{g,n}^{\text{rt}}$ of stable curves with rational tails. In this section we work in the cohomology of $\mathcal{M}_{g,n}^{\text{rt}}$. Let $\psi_i^\dagger = p_i^* \psi_i$, where $p_i: \mathcal{M}_{g,n}^{\text{rt}} \rightarrow \mathcal{M}_{g,1}^{\text{rt}}$ is the forgetful map that forgets all marked points except the i -th. Let J be any subset of $\{1, 2, \dots, n\}$ such that $|J| \geq 2$. Denote by D_J the divisor in $\mathcal{M}_{g,n}^{\text{rt}}$ that is formed by stable curves with a rational component that contains exactly marked points numbered by the subset J .

There is the following formula discovered by Hain ([Hain11]):

$$DR_g \left(\prod_{i=1}^n m_{a_i} \right) = \frac{1}{g!} \left(\sum_{i=1}^n \frac{a_i^2 \psi_i^\dagger}{2} - \sum_{\substack{J \subset \{1,2,\dots,n\} \\ |J| \geq 2}} \left(\sum_{i,j \in J, i < j} a_i a_j \right) D_J \right)^g. \quad (4.6)$$

To be precise, in [Hain11] this formula was proved for a version of double ramification cycles that is constructed using the universal Jacobian over the moduli space of curves. Luckily, in [CMW11] it is proved that this version coincides with our version, if we restrict them to $\mathcal{M}_{g,n}^{\text{rt}}$.

From (4.6) it follows that, as a cohomology class in $H^{2g}(\mathcal{M}_{g,n}^{\text{rt}}; \mathbb{Q})$, the class

$$DR_g \left(m_{-\sum_{i=2}^n a_i} \prod_{i=2}^n m_{a_i} \right)$$

is a homogeneous polynomial of degree $2g$ in the variables a_2, \dots, a_n . Let us prove the following simple lemma.

Lemma 4.4. *As a cohomology class in $H^{2g-2}(\mathcal{M}_{g,n}^{\text{rt}}; \mathbb{Q})$, the class*

$$DR_g \left(m_{-\sum_{i=2}^n a_i} \prod_{i=2}^{n-1} m_{a_i} \tilde{m}_{a_n} \right)$$

is a homogeneous polynomial of degree $2g$ in the variables a_2, \dots, a_n . Moreover, this polynomial is divisible by a_n .

Proof. Let $a_1 := -\sum_{i=2}^n a_i$. We have $DR_g \left(\prod_{i=1}^{n-1} m_{a_i} \tilde{m}_{a_n} \right) = \pi_* \left(DR_g \left(\prod_{i=1}^n m_{a_i} \right) \right)$, where $\pi: \mathcal{M}_{g,n}^{\text{rt}} \rightarrow \mathcal{M}_{g,n-1}^{\text{rt}}$ is the forgetful morphism that forgets the last marked point. Thus, the first statement is clear.

It is easy to see that

$$\begin{aligned} & \left(\sum_{i=1}^n \frac{a_i^2 \psi_i^\dagger}{2} - \sum_{\substack{J \subset \{1,2,\dots,n\} \\ |J| \geq 2}} \left(\sum_{i,j \in J, i < j} a_i a_j \right) D_J \right) \Big|_{a_n=0} = \\ & = \pi_n^* \left(\sum_{i=1}^{n-1} \frac{a_i^2 \psi_i^\dagger}{2} - \sum_{\substack{J \subset \{1,2,\dots,n-1\} \\ |J| \geq 2}} \left(\sum_{i,j \in J, i < j} a_i a_j \right) D_J \right). \end{aligned}$$

Therefore, if we set $a_n = 0$ on the right-hand side of (4.6) and push it forward to $\mathcal{M}_{g,n-1}^{\text{rt}}$, we get zero. Hence, the second statement of the lemma is also proved. \square

4.4 DR-cycles and the tautological ring of $\mathcal{M}_{g,n}$

Lemma 4.5. *Let $n \geq 1$ and $1 \leq k \leq g$. The group $R^{g-k}(\mathcal{M}_{g,n})$ is spanned by the double ramification cycles of the form*

$$DR_g \left(\prod_{i=1}^{n-1} m_{a_i} m_{-d} \prod_{j=1}^k \tilde{m}_{b_j} \right), \quad (4.7)$$

where $a_1, \dots, a_{n-1}, b_1, \dots, b_k$ and d are positive integers such that $a_1 + \dots + a_{n-1} + b_1 + \dots + b_k = d$.

Proof. This lemma is a version of [Ion02, Corollary 2.5] adapted to our situation (we are using the DR-cycles defined by “rubber” stable relative maps rather than the admissible coverings, we want to have the DR-cycles with exactly one negative multiplicity, and we consider the restriction of the DR-cycles to the open part of the moduli space).

We want to show that the push-forward of any monomial of ψ -classes on $\overline{\mathcal{M}}_{g,n+l}$ to the space $\overline{\mathcal{M}}_{g,n}$, and further restricted to its open part, is expressed in terms of the DR-cycles of the form (4.7).

We represent the degree zero class $g! \prod_{i=1}^g b_i^2$ on $\overline{\mathcal{M}}_{g,n+l}$ as a DR-cycle

$$DR_g \left(\prod_{i=1}^{n+l} m_{a_i} \prod_{j=1}^g \tilde{m}_{b_j} \right),$$

where a_n is the only one negative index. Obviously, we can choose the multiplicities in this way. Then we lift the monomial of psi-classes to the moduli space $\overline{\mathcal{M}}_{g,n+l+g}$ (as we did in the proof of Lemma 4.2 above) and intersect it there with the DR-cycle $DR_g \left(\prod_{i=1}^{n+l} m_{a_i} \prod_{j=1}^g m_{b_j} \right)$ using [BSSZ12, Theorem 4]. Then we apply the push-forward to the space $\overline{\mathcal{M}}_{g,n}$ and restrict it to the open moduli space $\mathcal{M}_{g,n}$.

Let us discuss the structure of the class that we obtain. First of all, since we are interested only in the non-degenerate restrictions to the open moduli space, one of the components in the degeneration formula

$$DR_{g_1} \left(\prod_{i \in I} m_{a_i} \prod_{j \in J} m_{b_j} \prod_{l=1}^p m_{-c_k} \right) \boxtimes DR_{g_2} \left(\prod_{i \in I'} m_{a_i} \prod_{j \in J'} m_{b_j} \prod_{l=1}^p m_{c_k} \right),$$

must be of genus g . This implies, exactly as in the proofs of Lemmas 4.2 and 4.3, that $p = 0$ and the other component has genus 0. This means that on the component of genus g we again have the structure of a DR-cycle with exactly one negative index. So, if we are interested only in the terms that can be non-trivially restricted to the open part of the moduli space, then this property of a DR-cycle is preserved throughout the computation of the monomial of ψ -classes. It is also preserved under the push-forward that forgets some of the marked points. This implies that the expression that we obtain for a push-forward of a monomial of ψ -classes is a linear combination of DR-cycles with one negative index. It is also easy to see that the only negative index in these cycles corresponds to the n -th marked point. This is precisely the statement of the lemma. \square

5 Technical lemmas

Here we collect several linear algebra lemmas that we will use in Section 6.

Lemma 5.1. *Let V be a vector space and $x_1, x_2, \dots, x_{p-2} \in V$, where $p \geq 3$. Suppose that for any positive integers $\lambda_1, \lambda_2, \lambda_3$ such that $\lambda_1 + \lambda_2 + \lambda_3 = p$ we have*

$$x_{\lambda_1} + x_{\lambda_2} + x_{\lambda_3} = 0.$$

Then there exists a vector $\alpha \in V$ such that $x_i = \left(\frac{i}{p} - \frac{1}{3}\right) \alpha$.

Proof. If $p = 3$ the lemma is obvious. Suppose $p \geq 4$. We have

$$x_i + x_{p-1-i} = -x_1, \text{ for } i = 1, 2, \dots, p-2.$$

On the other hand

$$x_i + x_{p-2-i} = -x_2, \text{ for } i = 1, 2, \dots, p-3.$$

Let us subtract the second equation from the first one. We obtain

$$x_{p-1-i} - x_{p-2-i} = x_2 - x_1, \text{ for } i = 1, 2, \dots, p-3.$$

Hence, $x_i = x_1 + (i-1)(x_2 - x_1)$. Let us substitute this formula in the equation $2x_1 + x_{p-2} = 0$, we get $x_1 = -\frac{(p-3)(x_2 - x_1)}{3}$. Therefore, $x_i = \left(i - \frac{p}{3}\right)(x_2 - x_1)$. The lemma is proved. \square

Lemma 5.2. *Let V be a vector space. Suppose that we have vectors $v_{i,j} \in V, i, j \geq 1$. Define the vectors $z_{i,j}$ by*

$$z_{i,j} := -v_{i,j} - v_{j,i}.$$

Suppose that the vectors $v_{i,j}$ and $z_{i,j}$ satisfy the following system:

$$\begin{cases} \sum_{\substack{\{i,j,k\}=\{1,2,3\} \\ i < j}} (v_{a_k, a_i + a_j} + z_{a_i, a_j}) = 0, & \text{if } a_1, a_2, a_3 \geq 1; \\ z_{a_1, a_2} - z_{c_1, c_2} - \sum_{a_i > c_j} v_{c_j, a_i - c_j} + \sum_{c_i > a_j} v_{a_j, c_i - a_j} = 0, & \text{if } a_1 + a_2 = c_1 + c_2. \end{cases} \quad (5.1)$$

Then there exist vectors $\alpha_2, \alpha_3, \dots \in V$ such that

$$v_{i,j} = \left(\frac{i}{i+j} - \frac{1}{3} \right) \alpha_{i+j} + \left(\frac{1}{3} - \frac{i+j}{i} \right) \alpha_i + \frac{1}{3} \alpha_j. \quad (5.2)$$

Here we, by definition, put $\alpha_1 := 0$.

Proof. Obviously, $\alpha_2 = 6v_{1,1}$. Suppose $d \geq 3$ and we have found vectors $\alpha_2, \dots, \alpha_{d-1}$ such that formula (5.2) holds for $i+j \leq d-1$. Let us construct a vector α_d such that equation (5.2) holds for $i+j = d$. For $i+j = d$, define the vectors $\tilde{v}_{i,j}$ and $\tilde{z}_{i,j}$ by

$$\begin{aligned} \tilde{v}_{i,j} &:= v_{i,j} - \left(\frac{1}{3} - \frac{d}{i} \right) \alpha_i - \frac{1}{3} \alpha_j, \\ \tilde{z}_{i,j} &:= -\tilde{v}_{i,j} - \tilde{v}_{j,i}. \end{aligned}$$

It is easy to check that from (5.1) it follows that

$$\begin{cases} \sum_{\substack{\{i,j,k\}=\{1,2,3\} \\ i < j}} \tilde{v}_{a_k, a_i + a_j} = 0, & \text{if } a_1 + a_2 + a_3 = d; \\ \tilde{z}_{a_1, a_2} - \tilde{z}_{c_1, c_2} = 0, & \text{if } a_1 + a_2 = c_1 + c_2 = d. \end{cases}$$

If $d = 3$, then we can take $\alpha_3 = 3\tilde{v}_{2,1}$. Suppose $d \geq 4$. By Lemma 5.1, there exists a vector α_d such that $\tilde{v}_{i, d-i} = \left(\frac{i}{d} - \frac{1}{3} \right) \alpha_d$, for $i \leq d-2$. Since $\tilde{z}_{1, d-1} = \tilde{z}_{2, d-2}$, we also have $\tilde{v}_{d-1, 1} = \left(\frac{d-1}{d} - \frac{1}{3} \right) \alpha_d$. The lemma is proved. \square

Lemma 5.3. *Let V be a vector space and $d \geq 3$. Suppose we have vectors $v_{i,j,k} \in V$, where $i+j+k = d$ and $i, j, k \geq 1$, that satisfy the following system of equations:*

$$\sum_{\substack{\{i,j,k\}=\{1,2,3\} \\ i < j}} v_{b_k, b_i + b_j, a} = 0, \text{ if } b_1 + b_2 + b_3 + a = d \text{ and } a, b_i \geq 1; \quad (5.3)$$

$$kv_{i,j,k} + jv_{i,k,j} = 0. \quad (5.4)$$

If $d = 3, 4$, then $v_{i,j,k} = 0$. If $d \geq 5$, then there exists a vector $\alpha \in V$ such that

$$v_{i,j,k} = \left(\frac{i}{d-1} - \frac{1}{3} \right) \left(\delta_{k,1} - \frac{1}{k} \delta_{j,1} \right) \alpha.$$

Proof. The cases $d = 3, 4, 5$ can be easily done by a direct computation.

Suppose that $d \geq 6$. By Lemma 5.1, there exist vectors $\alpha_3, \alpha_4, \dots, \alpha_{d-1} \in V$ such that

$$v_{i,j,k} = \left(\frac{i}{i+j} - \frac{1}{3} \right) \alpha_{i+j}, \text{ if } j \geq 2.$$

Let us prove that

$$\alpha_{d-k} = 0, \text{ if } 2 \leq k \leq \frac{d-1}{2}. \quad (5.5)$$

From (5.4) it follows that $v_{i,j,k} = 0$, if $j = k$. Therefore, if $2 \leq k \leq \frac{d-1}{2}$, then $\left(\frac{d-2k}{d-k} - \frac{1}{3} \right) \alpha_{d-k} = 0$. If $d \neq \frac{5}{2}k$, then $\alpha_{d-k} = 0$. Suppose that $d = \frac{5}{2}k$. We have $v_{\frac{k}{2}+1, k-1, k} = -\frac{k-1}{k} v_{\frac{k}{2}+1, k, k-1} = 0$. On the other hand, $v_{\frac{k}{2}+1, k-1, k} = \left(\frac{\frac{k}{2}+1}{d-k} - \frac{1}{3} \right) \alpha_{d-k}$. The coefficient of α_{d-k} here is not equal to zero, therefore, $\alpha_{d-k} = 0$. Thus, (5.5) is proved.

We see that $v_{i,j,k} = 0$, if $j \geq 2$ and $2 \leq k \leq \frac{d-1}{2}$. If we apply (5.4), we get that $v_{i,j,k} = 0$, if $k \geq 2$ and $2 \leq j \leq \frac{d-1}{2}$, thus, $v_{i,j,k} = 0$, if $j \geq 2$ or $k \geq 2$.

If $2 \leq j \leq d-2$, then $v_{d-j-1, j, 1} = \left(\frac{d-j-1}{d-1} - \frac{1}{3} \right) \alpha_{d-1}$ and $v_{d-j-1, 1, j} = -\frac{1}{j} v_{d-j-1, 1, j} = -\frac{1}{j} \left(\frac{d-j-1}{d-1} - \frac{1}{3} \right) \alpha_{d-1}$. Also we have $v_{d-2, 1, 1} = 0$. This completes the proof of the lemma. \square

6 Proofs of Lemma 3.1 and Propositions 3.2 and 3.3

In this last section we prove Lemma 3.1, Proposition 3.2 and Proposition 3.3.

6.1 Proof of Lemma 3.1

Without loss of generality, we can assume that $k = 1$ and $l = 2$. It is sufficient to prove that

$$\alpha + i_{1,2}^* \alpha \in \pi_1^*(R^{g-1}(\mathcal{M}_{g,n-1})) + \pi_2^*(R^{g-1}(\mathcal{M}_{g,n-1})), \quad (6.1)$$

for any $\alpha \in R^{g-1}(\mathcal{M}_{g,n})$. By Lemma 4.5, we can assume that $\alpha = DR_g \left(\prod_{i=1}^n m_{a_i} \tilde{m}_b \right)$.

From Lemma 4.3 it follows that

$$\begin{aligned} & DR_g \left(m_{a_1} \tilde{m}_b m_{a_2} \prod_{i=3}^n m_{a_i} \right) + \frac{b}{a_1} DR_g \left(m_b \tilde{m}_{a_1} m_{a_2} \prod_{i=3}^n m_{a_i} \right) \in \pi_1^*(R^{g-1}(\mathcal{M}_{g,n-1})), \\ & \frac{b}{a_1} DR_g \left(m_b m_{a_2} \tilde{m}_{a_1} \prod_{i=3}^n m_{a_i} \right) + \frac{b}{a_2} DR_g \left(m_b m_{a_1} \tilde{m}_{a_2} \prod_{i=3}^n m_{a_i} \right) \in \pi_2^*(R^{g-1}(\mathcal{M}_{g,n-1})), \\ & \frac{b}{a_2} DR_g \left(m_b \tilde{m}_{a_2} m_{a_1} \prod_{i=3}^n m_{a_i} \right) + DR_g \left(m_{a_2} \tilde{m}_b m_{a_1} \prod_{i=3}^n m_{a_i} \right) \in \pi_1^*(R^{g-1}(\mathcal{M}_{g,n-1})). \end{aligned}$$

If we sum the first and the third rows and subtract the second row, we get

$$DR_g \left(m_{a_1} m_{a_2} \tilde{m}_b \prod_{i=3}^n m_{a_i} \right) + DR_g \left(m_{a_2} m_{a_1} \tilde{m}_b \prod_{i=3}^n m_{a_i} \right) \in \pi_1^*(R^{g-1}(\mathcal{M}_{g,n-1})) + \pi_2^*(R^{g-1}(\mathcal{M}_{g,n-1})).$$

The lemma is proved.

6.2 Proof of Proposition 3.2

Suppose $n = 1$. We know that $R^{g-1}(\mathcal{M}_{g,1}) = \mathbb{Q}$, $R^{g-2}(\mathcal{M}_g) = \mathbb{Q}$ and that $R^{g-2}(\mathcal{M}_g)$ is spanned by κ_{g-2} (see [Loo95]). Therefore, it is sufficient to prove that $\psi_1 \pi_1^*(\kappa_{g-2}) \neq 0$. It is true, because $(\pi_1)_*(\psi_1 \pi_1^*(\kappa_{g-2})) = (2g-2)\kappa_{g-2}$.

Suppose that $n \geq 2$. We denote by K the subspace of $R^{g-1}(\mathcal{M}_{g,n})$ defined by

$$K := \pi_1^*(R^{g-1}(\mathcal{M}_{g,n-1})) + \psi_1 \pi_1^*(R^{g-2}(\mathcal{M}_{g,n-1})).$$

By Lemma 4.5, it is sufficient to prove that

$$DR_g \left(\tilde{m}_b \prod_{i=1}^{n-1} m_{a_i} m_{-d} \right) \in K, \quad (6.2)$$

where $a_1, \dots, a_{n-1}, b, d$ are positive integers such that $a_1 + \dots + a_{n-1} + b = d$. We do it by double induction on d and on $\tilde{d} := b + a_1$. If $\tilde{d} = 2$, then $b = a_1 = 1$, and from Lemma 4.3 it immediately follows that

$$DR_g \left(\tilde{m}_1 m_1 \prod_{i=2}^n m_{a_i} m_{-d} \right) \in \pi_1^*(R^{g-1}(\mathcal{M}_{g,n-1})). \quad (6.3)$$

Suppose that $\tilde{d} \geq 3$. Consider positive integers b_1, b_2, b_3 such that $b_1 + b_2 + b_3 = \tilde{d}$. By Lemma 4.3, we have

$$\sum_{i=1}^3 b_i DR_g \left(m_{b_i} \prod_{j \neq i} \tilde{m}_{b_j} \prod_{l=2}^{n-1} m_{a_l} m_{-d} \right) \in \pi_1^*(R^{g-2}(\mathcal{M}_{g,n-1})).$$

Let us multiply the both sides of this formula by ψ_1 . Using Lemmas 4.2, 4.3 and the induction assumption we get

$$\sum_{i=1}^3 \frac{\tilde{d} + (r-3)b_i}{r} DR_g \left(\tilde{m}_{\tilde{d}-b_i} m_{b_i} \prod_{j=2}^{n-1} m_{a_j} m_{-d} \right) \in K, \quad (6.4)$$

where $r = 2g + n$.

Let us fix a_2, a_3, \dots, a_n and analyze relation (6.4). Let

$$u_i := DR_g \left(\tilde{m}_{\tilde{d}-i} m_i \prod_{j=2}^{n-1} m_{a_j} m_{-d} \right), \text{ for } i = 1, 2, \dots, \tilde{d} - 1.$$

For any two classes $\alpha, \beta \in R^{g-1}(\mathcal{M}_{g,n})$, we will write $\alpha \stackrel{\text{mod } K}{=} \beta$, if $\alpha - \beta \in K$.

From (6.4) and Lemma 5.1 it follows that there exists a class $\alpha \in R^{g-1}(\mathcal{M}_{g,n})$ such that

$$\frac{\tilde{d} + (r-3)i}{r} u_i \stackrel{\text{mod } K}{=} \left(\frac{i}{\tilde{d}} - \frac{1}{3} \right) \alpha, \text{ for } i = 1, \dots, \tilde{d} - 2. \quad (6.5)$$

By Lemma 4.3, we have

$$i u_i + (\tilde{d} - i) u_{\tilde{d}-i} \in \pi_1^*(R^{g-1}(\mathcal{M}_{g,n-1})), \text{ for } i = 1, 2, \dots, \tilde{d} - 1. \quad (6.6)$$

Let us prove that relations (6.5) and (6.6) imply that $u_i \in K$, for $i = 1, \dots, \tilde{d} - 1$. This will complete the proof of the proposition.

Suppose $\tilde{d} = 3$, then from (6.5) it follows that $u_1 \in K$, and from (6.6) it follows that $u_2 \in K$.

Suppose $\tilde{d} \geq 4$. From (6.5) and (6.6) we see that it is sufficient to prove that $\alpha \in K$. Let $2 \leq i \leq \tilde{d} - 2$. From (6.5) it follows that

$$i u_i + (\tilde{d} - i) u_{\tilde{d}-i} \stackrel{\text{mod } K}{=} \frac{\left(i - \frac{\tilde{d}}{2}\right)^2 \left(3 - \frac{r}{3}\right) + \frac{\tilde{d}^2(r-1)}{12}}{\left(\tilde{d} + (r-3)i\right) \left(\tilde{d} + (r-3)(\tilde{d}-i)\right)} r \alpha. \quad (6.7)$$

If $\tilde{d} = 4$ or $\tilde{d} = 5$, then, for $i = 2$, the numerator in (6.7) is nonzero. Therefore, $\alpha \in K$. Suppose $\tilde{d} \geq 6$. It is clear that the numerator in (6.7) cannot be zero for two different values of i that are greater or equal to $\frac{\tilde{d}}{2}$. Hence, $\alpha \in K$. The proposition is proved.

6.3 Proof of Proposition 3.3: main relation

In this section we construct a relation between double ramification cycles that is a main ingredient in the proof of Proposition 3.3.

In Section 6.3.1 we construct a basic relation using the same idea as in the proof of Proposition 3.2. The problem is that this relation is too complicated to work with. In Section 6.3.2 we introduce new variables that are linear combinations of double ramification cycles. This change of variables allows us to simplify the basic relation a lot. This is done in Section 6.3.3.

6.3.1 Basic relation

We denote by K the subspace of $R^{g-2}(\mathcal{M}_{g,n})$ defined by

$$K = \pi_1^*(R^{g-2}(\mathcal{M}_{g,n-1})) + \psi_1 \pi_1^*(R^{g-3}(\mathcal{M}_{g,n-1})) + \sum_{1 \leq i < j \leq n} S_{i,j}^{g-2}(\mathcal{M}_{g,n}).$$

Let us fix a triple $((b_1, b_2, b_3), b_4, (a_1, a_2, \dots, a_{n-1}))$, where (b_1, b_2, b_3) is an unordered triple of non-zero integers, b_4 is a non-zero integer, $(a_1, a_2, \dots, a_{n-1})$ is an ordered sequence of non-zero integers and $\sum b_i + \sum a_j = 0$. By Lemma 4.3, we have

$$\sum_{i=1}^4 b_i DR_g \left(m_{b_i} \prod_{j \neq i} \tilde{m}_{b_j} \prod_{p=1}^{n-1} m_{a_p} \right) \in \pi_1^*(R^{g-3}(\mathcal{M}_{g,n-1})). \quad (6.8)$$

Let us multiply both sides of (6.8) by ψ_1 . Using Lemmas 4.2 and 4.3 we get

$$\begin{aligned} & \sum_{\substack{\{i,j,k\}=\{1,2,3\} \\ i < j}} \frac{b_i + b_j}{r} \left(r - 2 + \frac{b_i + b_j}{b_4} \right) DR_g \left(\tilde{m}_{b_4} \tilde{m}_{b_k} m_{b_i + b_j} \prod_{l=1}^{n-1} m_{a_l} \right) \\ & - \sum_{\substack{\{i,j,k\}=\{1,2,3\} \\ i < j}} \frac{b_i + b_j}{r} \left(1 - \frac{b_k}{b_4} \right) DR_g \left(\tilde{m}_{b_4} \tilde{m}_{b_i + b_j} m_{b_k} \prod_{l=1}^{n-1} m_{a_l} \right) \\ & - \sum_{l=1}^{n-1} \sum_{\{i,j,k\}=\{1,2,3\}} \frac{b_i + a_l}{r} \left(1 - \frac{b_j}{b_4} \right) DR_g \left(\tilde{m}_{b_4} \tilde{m}_{b_k} m_{b_j} \prod_{p=1}^{n-1} m_{a_p + \delta_{p,l} b_i} \right) \\ & + \sum_{l=1}^{n-1} \sum_{\substack{\{i,j,k\}=\{1,2,3\} \\ i < j}} \frac{b_j - b_i}{r} DR_g \left(\tilde{m}_{b_4 + a_l} \tilde{m}_{b_k} m_{b_i} \prod_{p=1}^{n-1} m_{a_p + \delta_{p,l} (b_j - a_l)} \right) \\ & - \sum_{\{i,j,k\}=\{1,2,3\}} \frac{b_4 + b_k + (r-2)b_i}{r} DR_g \left(\tilde{m}_{b_4 + b_k} \tilde{m}_{b_j} m_{b_i} \prod_{l=1}^{n-1} m_{a_l} \right) \in K, \end{aligned} \quad (6.9)$$

where $r = 2g + n + 1$. This relation will be called the basic relation.

6.3.2 New variables

Let f_1, f_2, \dots, f_{n+1} be arbitrary integers such that not all of them are equal to zero. We introduce the cycle $Z_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) \in R^{g-2}(\mathcal{M}_{g,n})$ as follows:

$$\begin{aligned} Z_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) & := \frac{f_1 - (r - n - 2)f_2}{r} DR_g \left(\tilde{m}_{-d} \tilde{m}_{f_1} m_{f_2} \prod_{l=3}^{n+1} m_{f_l} \right) \\ & + \frac{f_2 - (r - n - 2)f_1}{r} DR_g \left(\tilde{m}_{-d} \tilde{m}_{f_2} m_{f_1} \prod_{l=3}^{n+1} m_{f_l} \right) \\ & + \frac{f_2 - f_1}{r} \sum_{l=3}^{n+1} DR_g \left(\tilde{m}_{-d} \tilde{m}_{f_l} m_{f_2} \prod_{p=3}^{n+1} m_{f_p + \delta_{p,l} (f_1 - f_p)} \right), \end{aligned}$$

where $r := 2g+n+1$ and $d := \sum_{i=1}^{n+1} f_i$. Suppose that $d \neq 0$. Define the cycle $V_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) \in R^{g-2}(\mathcal{M}_{g,n})$ by

$$V_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) := \frac{f_2}{r} \left[\left(r - n - 2 + \frac{f_1}{d} \right) DR_g \left(\tilde{m}_{-d} \tilde{m}_{f_1} \prod_{l=2}^{n+1} m_{f_l} \right) - \left(1 + \frac{f_1}{d} \right) \sum_{l=2}^{n+1} DR_g \left(\tilde{m}_{-d} \tilde{m}_{f_l} \prod_{p=2}^{n+1} m_{f_p + \delta_{p,l}(f_1 - f_p)} \right) \right].$$

Note that the cycle Z_g is a linear combination of double ramification cycles of the same degree. Thus, the degree of the cycle Z_g is well defined. The same is true for the cycle V_g .

From the definition it immediately follows that

$$V_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) = 0, \quad \text{if } f_2 = 0. \quad (6.10)$$

Lemma 4.4 implies that

$$Z_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) = 0, \quad \text{if } \sum f_i = 0. \quad (6.11)$$

It is not hard to show that

$$V_g \left(m_{f_1} m_{f_2} \prod_{i=3}^{n+1} m_{f_i} \right) + V_g \left(m_{f_2} m_{f_1} \prod_{i=3}^{n+1} m_{f_i} \right) \stackrel{\text{mod } K}{=} -Z_g \left(\prod_{i=1}^{n+1} m_{f_i} \right).$$

Using Lemma 4.3 we can easily derive the following relations:

$$f_i V_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) + f_2 V_g \left(m_{f_1} m_{f_i} \prod_{k=3}^{n+1} m_{f_k + \delta_{i,k}(2-k)} \right) \in K, \quad \text{if } 3 \leq i \leq n+1; \quad (6.12)$$

$$V_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) + V_g \left(m_{f_1} m_{f_2} \prod_{k=3}^{n+1} m_{f_k + \delta_{i,k}(j-k) + \delta_{j,k}(i-k)} \right) \in K, \quad \text{if } 3 \leq i < j \leq n+1; \quad (6.13)$$

$$V_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) \stackrel{\text{mod } K}{=} V_g \left(m_{-d} \prod_{i=2}^{n+1} m_{f_i} \right), \quad \text{if } f_1 \neq 0; \quad (6.14)$$

$$V_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) \stackrel{\text{mod } K}{=} Z_g \left(m_{f_1} m_{-d} \prod_{i=3}^{n+1} m_{f_i} \right). \quad (6.15)$$

Also from (4.1) it follows that

$$V_g \left(\prod_{i=1}^{n+1} m_{f_i} \right) = -V_g \left(\prod_{i=1}^{n+1} m_{-f_i} \right). \quad (6.16)$$

Lemma 6.1. *The space $R^{g-2}(\mathcal{M}_{g,n})/K$ is spanned by cycles $V_g(\prod_{i=1}^{n+1} m_{f_i})$ with positive f_i 's.*

Proof. Lemmas 4.3 and 4.5 imply that the space $R^{g-2}(\mathcal{M}_{g,n})/K$ is spanned by double ramification cycles of the form

$$DR_g \left(\tilde{m}_{-d} \tilde{m}_b \prod_{i=1}^n m_{a_i} \right),$$

where a_1, \dots, a_n and b are positive integers and $d = b + \sum a_i$. For $1 \leq k \leq n+1$, let

$$\alpha_k := DR_g \left(\tilde{m}_{-d} \tilde{m}_{f_k} \prod_{p=2}^{n+1} m_{f_p + \delta_{p,k}(f_1 - f_p)} \right),$$

$$\beta_k := V_g \left(\prod_{i=k}^{n+1} m_{f_i} \prod_{j=1}^{k-1} m_{f_j} \right).$$

From the definition of cycles V_g it is easy to compute that $\beta_i \stackrel{\text{mod } K}{=} \sum_{j=1}^{n+1} g_{i,j} \alpha_j$, where

$$g_{i,j} = \begin{cases} (-1)^{(i-1)n+1+\delta_{j,1}} \frac{f_{i+1}}{r} \left(r - n - 2 + \frac{f_i}{d} \right), & \text{if } i = j; \\ (-1)^{(i-1)n+1+\delta_{j,1}} \frac{f_{i+1}}{r} \left(1 + \frac{f_i}{d} \right), & \text{if } i \neq j. \end{cases}$$

Here we, by definition, put $f_{n+2} := f_1$. We see that it is sufficient to prove that the matrix $G := (g_{i,j})$ is non-degenerate. Consider the matrix $\tilde{G} := (\tilde{g}_{i,j})$ defined by

$$\tilde{g}_{i,j} = \begin{cases} r - n - 2 + \frac{f_i}{d}, & \text{if } i = j; \\ 1 + \frac{f_i}{d}, & \text{if } i \neq j. \end{cases}$$

Denote by D the diagonal matrix with the entries $(-1)^{(i-1)n+1} \frac{f_{i+1}}{r}$ on the diagonal. It is clear that the matrices G and \tilde{G} are related by

$$G = D \cdot \tilde{G} \cdot \text{diag}(-1, 1, 1, \dots, 1).$$

Therefore, it is sufficient to prove that the matrix \tilde{G} is non-degenerate. It is easy to compute that $\det \tilde{G} = (r - n - 3)^n (r - 1) \neq 0$, so the lemma is proved. \square

6.3.3 Main relation

Let us consider the same triple $((b_1, b_2, b_3), b_4, (a_1, a_2, \dots, a_{n-1}))$, as in Section 6.3.1. Choose an arbitrary $1 \leq p \leq n-1$ and consider four basic relations corresponding to the following triples:

$$\begin{aligned} & ((b_1, b_2, b_3), b_4, (a_1, a_2, \dots, a_{n-1})), \\ & ((b_1, b_2, a_p), b_4, (a_1, \dots, a_{p-1}, b_3, a_{p+1}, \dots, a_{n-1})), \\ & ((b_1, a_p, b_3), b_4, (a_1, \dots, a_{p-1}, b_2, a_{p+1}, \dots, a_{n-1})), \\ & ((a_p, b_2, a_3), b_4, (a_1, \dots, a_{p-1}, b_1, a_{p+1}, \dots, a_{n-1})). \end{aligned}$$

Let us sum these relations with the coefficients $\left(1 - \frac{a_p}{b_4}\right)$, $\left(1 - \frac{b_3}{b_4}\right)$, $\left(1 - \frac{b_2}{b_4}\right)$ and $\left(1 - \frac{b_1}{b_4}\right)$ correspondingly. We get the following:

$$\sum_{\substack{\{i,j,k,l\}=\{1,2,3,4\} \\ i < j}} \left[(c_i + c_j) \left(1 - \frac{c_k}{b_4}\right) DR_g \left(\tilde{m}_{b_4} \tilde{m}_{c_l} m_{c_i+c_j} \prod_{q=1}^{n-1} m_{a_q+\delta_{q,p}(c_k-a_q)} \right) \right. \\ \left. + (c_j - c_i) DR_g \left(\tilde{m}_{b_4+c_i} \tilde{m}_{c_k} m_{c_i} \prod_{q=1}^{n-1} m_{a_q+\delta_{q,p}(c_j-a_q)} \right) \right] \in K, \quad (6.17)$$

where $c_i = b_i$, for $1 \leq i \leq 3$, and $c_4 = a_p$. Consider the sum of relations (6.17), for $p = 1, 2, \dots, n-1$. If we subtract this sum, divided by r , from (6.9), we get

$$\sum_{\substack{\{i,j,k\}=\{1,2,3\} \\ i < j}} \left[V_g \left(m_{b_k} m_{b_i+b_j} \prod_{l=1}^{n-1} m_{a_l} \right) + Z_g \left(m_{b_i} m_{b_j} \prod_{l=1}^{n-1} m_{a_l} \right) \right] \in K. \quad (6.18)$$

This relation will be called the main relation.

Remark 6.2. In the subsequent sections we want to work with relations between cycles $V_g \left(\prod_{i=1}^{n+1} m_{f_i} \right)$ and $Z_g \left(\prod_{i=1}^{n+1} m_{f_i} \right)$, where $f_i \neq 0$ and $\sum f_i \neq 0$. At first glance, relation (6.18) contains the other cycles as well, because in the first summand the multiplicity $b_i + b_j$ can be equal to zero, and in the second summand the sum of the multiplicities $b_i + b_j + \sum a_l = -b_4 - b_k$ can be equal to zero. Happily, these extra terms vanish due to properties (6.10) and (6.11).

Remark 6.3. In the case $n \geq 2$ our proof of Proposition 3.3 is based only on the main relation (6.18) and relations (6.12)-(6.16). The case $n = 1$ is exceptional, because we also have to use Lemma 4.4.

6.3.4 Proof of Proposition 3.3: the case $n = 1$

Let $v_{i,j} := V_g(m_i m_j)$ and $z_{i,j} := Z_g(m_i m_j)$. By Lemma 6.1, it is sufficient to prove that $v_{i,j} \in K$, for $i, j \geq 1$.

First of all let us write relations (6.14), (6.15) and (6.16) in this case:

$$v_{i,j} \stackrel{\text{mod } K}{=} v_{-(i+j),j}, \quad v_{i,j} \stackrel{\text{mod } K}{=} z_{i,-(i+j)}, \quad v_{i,j} \stackrel{\text{mod } K}{=} -v_{-i,-j}. \quad (6.19)$$

Let a_1, a_2, a_3 be positive integers and $d = a_1 + a_2 + a_3$. Let us write relation (6.18) for $b_1 = a_1, b_2 = a_2, b_3 = a_3$ and $b_4 = -d$:

$$\sum_{i=1}^3 v_{a_i, d-a_i} + \sum_{i < j} z_{a_i, a_j} \in K. \quad (6.20)$$

Let a_1, a_2 and c_1, c_2 be positive integers such that $a_1 + a_2 = c_1 + c_2$. Let us write relation (6.18) for $b_1 = a_1, b_2 = a_2, b_3 = -c_1$ and $b_4 = -c_2$. We get a linear combination of cycles $z_{i,j}$ and $v_{k,l}$, where indices i, j, k, l can be negative. If we apply relations (6.19) in order to make all indices positive, we get

$$z_{a_1, a_2} - z_{c_1, c_2} - \sum_{a_i > c_j} v_{c_j, a_i - c_j} + \sum_{c_i > a_j} v_{a_j, c_i - a_j} \in K. \quad (6.21)$$

From Lemma 5.2 it follows that, for any $d \geq 2$, there is a class $\alpha_d \in R^{g-2}(\mathcal{M}_{g,1})$ such that

$$v_{i,j} \stackrel{\text{mod } K}{=} \left(\frac{i}{i+j} - \frac{1}{3} \right) \alpha_{i+j} + \left(\frac{1}{3} - \frac{i+j}{i} \right) \alpha_i + \frac{1}{3} \alpha_j. \quad (6.22)$$

Here we, by definition, put $\alpha_1 := 0$.

From (4.6) it follows that $v_{ai, aj} = a^{2g+1} v_{i,j}$. Hence, $v_{d,d} = d^{2g+1} v_{1,1}$. Using (6.22) we obtain

$$\alpha_{2d} \stackrel{\text{mod } K}{=} 8\alpha_d + d^{2g+1} \alpha_2. \quad (6.23)$$

We have $v_{2d-2, 2} = 2^{2g+1} v_{d-1, 1}$. Using (6.22) we get

$$\begin{aligned} & \left(\frac{d-1}{d} - \frac{1}{3} \right) \alpha_{2d} + \left(\frac{1}{3} - \frac{d}{d-1} \right) \alpha_{2d-2} + \frac{\alpha_2}{3} \\ & \stackrel{\text{mod } K}{=} 2^{2g+1} \left(\left(\frac{d-1}{d} - \frac{1}{3} \right) \alpha_d + \left(\frac{1}{3} - \frac{d}{d-1} \right) \alpha_{d-1} \right). \end{aligned}$$

If we combine this equation with (6.23), we get

$$\begin{aligned} & \left(\frac{d-1}{d} - \frac{1}{3} \right) (8 - 2^{2g+1}) \alpha_d + \left(\frac{1}{3} - \frac{d}{d-1} \right) (8 - 2^{2g+1}) \alpha_{d-1} + \\ & + \left(\left(\frac{d-1}{d} - \frac{1}{3} \right) d^{2g+1} + \left(\frac{1}{3} - \frac{d}{d-1} \right) (d-1)^{2g+1} + \frac{1}{3} \right) \alpha_2 \in K. \end{aligned} \quad (6.24)$$

Relation (6.24) allows to compute all α_d , for $d \geq 3$, in terms of α_2 . It is not hard to check that this recursion has the following solution:

$$\alpha_d \stackrel{\text{mod } K}{=} \frac{d^3 - d^{2g+1}}{2^3 - 2^{2g+1}} \alpha_2.$$

Therefore, we have

$$v_{i,j} \stackrel{\text{mod } K}{=} \left[\left(\frac{i}{i+j} - \frac{1}{3} \right) (i+j)^{2g+1} + \left(\frac{1}{3} - \frac{i+j}{i} \right) i^{2g+1} + \frac{j^{2g+1}}{3} \right] \alpha_2. \quad (6.25)$$

From Lemma 4.4 it follows that the class $DR_g(\tilde{m}_a\tilde{m}_b m_{-a-b})$ is a homogeneous polynomial of degree $2g$ in the variables a and b . Moreover, this polynomial is divisible by ab . Hence, we have

$$\lim_{a \rightarrow \infty} \frac{1}{a^{2g}} DR_g(\tilde{m}_a\tilde{m}_1 m_{-a-1}) = 0. \quad (6.26)$$

It is easy to compute that

$$\frac{(r-1)(r-4)}{r-3} DR_g(\tilde{m}_i\tilde{m}_j m_{-i-j}) \stackrel{\text{mod } K}{=} \frac{r}{r-3} \frac{iv_{i,j} + jv_{j,i}}{ij} + \frac{r}{i+j} (v_{i,j} + v_{j,i}).$$

If we substitute here the expression (6.25) for $v_{i,j}$, we get

$$\lim_{a \rightarrow \infty} \frac{1}{a^{2g}} DR_g(\tilde{m}_a\tilde{m}_1 m_{-a-1}) \stackrel{\text{mod } K}{=} \frac{r}{(r-1)(r-4)} \frac{4g-4}{3} \alpha_2.$$

From (6.26) it now follows that $\alpha_2 \in K$. This completes the proof of the proposition in the case $n = 1$.

6.3.5 Proof of Proposition 3.3: the case $n = 2$

Let $v_{i,j,k} := V_g(m_i m_j m_k)$ and $z_{i,j,k} := Z_g(m_i m_j m_k)$. By Lemma 6.1, it is sufficient to prove that $v_{i,j,k} \in K$ for $i, j, k \geq 1$. The problem here is that relations (6.18), that involve only these terms, are not enough. So we have to consider also classes $v_{i,j,k}$ with negative indices.

In this section we consider cycles $v_{i,j,k}$ and $z_{i,j,k}$ as elements of $R^{g-2}(\mathcal{M}_{g,n})/K$. So, instead of writing $v_{i,j,k} \stackrel{\text{mod } K}{=} 0$, we will simply write $v_{i,j,k} = 0$.

Let us write relations (6.12), (6.14), (6.15) and (6.16) in this case:

$$kv_{i,j,k} + jv_{i,k,j} = 0, \quad (6.27)$$

$$v_{i,j,k} = v_{-(i+j+k),j,k}, \quad (6.28)$$

$$v_{i,j,k} = z_{i,-(i+j+k),k}, \quad (6.29)$$

$$v_{i,j,k} = -v_{-i,-j,-k}. \quad (6.30)$$

From these relations it follows that any class $v_{a,b,c}$, where $a, b, c \neq 0$ and $a + b + c \neq 0$, can be expressed in terms of classes $v_{i,j,k}$ with $i, j, k \geq 1$ or classes $v_{i,j,-k}$ with $i, j, k \geq 1$ and $k < i + j$. Therefore, we have to prove that

$$v_{i,j,k} = 0, \text{ where } i, j, k \geq 1, \quad (6.31)$$

$$v_{i,j,-k} = 0, \text{ where } i, j, k \geq 1 \text{ and } k < i + j. \quad (6.32)$$

We prove it by induction on the degree d . In (6.31) the degree of $v_{i,j,k}$ is $i + j + k$ and in (6.32) the degree of $v_{i,j,-k}$ is $i + j$. The smallest possible degree is 2 and the class $v_{1,1,-1}$

if the only class of degree 2. We have $v_{1,1,-1} \stackrel{\text{by (6.27)}}{=} v_{1,-1,1} \stackrel{\text{by (6.28)}}{=} v_{-1,-1,1} \stackrel{\text{by (6.30)}}{=} -v_{1,1,-1}$. Thus, $v_{1,1,-1} = 0$.

Suppose that $d \geq 3$. In the main relation (6.18) the numbers b_i and a_j can be positive or negative. In Section 6.3.6 we write explicitly the relations, that we have, depending on the numbers of positive b_i 's and a_j 's. Using the induction assumption we ignore the terms with the smaller degree. Then in Section 6.3.7 we prove (6.31) and in Section 6.3.8 we prove (6.32).

6.3.6 Relations

Let c_1, c_2, c_3, a be positive integers such that $c_1 + c_2 + c_3 + a = d$. Then, if we put $b_1 = c_1, b_2 = c_2, b_3 = c_3, b_4 = -d$ and $a_1 = a$ in (6.18), we get

$$\sum_{\substack{\{i,j,k\}=\{1,2,3\} \\ i < j}} v_{c_k, c_i + c_j, a} = 0. \quad (6.33)$$

Let c_1, c_2, c_3, c_4, a be positive integers such that $c_1 + c_2 + a = c_3 + c_4 = d$. Putting $b_1 = c_1, b_2 = c_2, b_3 = -c_3, b_4 = -c_4$ and $a_1 = a$ in (6.18), we get

$$v_{-c_3, c_1 + c_2, a} + z_{c_1, c_2, a} = 0.$$

Applying relations (6.29) and (6.30), we get

$$z_{c_1, c_2, a} - z_{c_3, c_4, -a} = 0. \quad (6.34)$$

Let c_1, c_2, c_3, c_4, a be positive integers such that $c_1 + c_2 + c_3 = a + c_4 = d$. Then, if we put $b_1 = c_1, b_2 = c_2, b_3 = c_3, b_4 = -c_4$ and $a_1 = -a$ in (6.18), we get

$$\sum_{\substack{\{i,j,k\}=\{1,2,3\} \\ i < j}} v_{c_k, c_i + c_j, -a} = 0. \quad (6.35)$$

6.3.7 Proof of (6.31)

We have relations (6.27) and (6.33), therefore, we can apply Lemma 5.3. By this lemma, the cases $d = 3, 4$ are done. Suppose $d \geq 5$, then there exists a class $\alpha \in R^{g-2}(\mathcal{M}_{g,n})/K$ such that

$$v_{i,j,k} = \left(\frac{i}{d-1} - \frac{1}{3} \right) \left(\delta_{k,1} - \frac{1}{k} \delta_{j,1} \right) \alpha.$$

By (6.34), we have $z_{d-2,1,1} = z_{d-3,2,1}$. Therefore, we get

$$0 = z_{d-2,1,1} - z_{d-3,2,1} = - \left(\frac{1}{d-1} - \frac{1}{3} \right) \alpha + \frac{\alpha}{3} = \left(-\frac{1}{d-1} + \frac{2}{3} \right) \alpha.$$

Since the coefficient $\left(-\frac{1}{d-1} + \frac{2}{3} \right)$ is not equal to zero, we have $\alpha = 0$. This completes the proof of (6.31).

6.3.8 Proof of (6.32)

We have

$$v_{i,j,-k} \stackrel{\text{by (6.28)}}{=} v_{-(d-k),j,-k} \stackrel{\text{by (6.27)}}{=} \frac{j}{k} v_{-(d-k),-k,j} \stackrel{\text{by (6.30)}}{=} -\frac{j}{k} v_{d-k,k,-j}. \quad (6.36)$$

As a consequence, we get

$$v_{i,j,-j} = 0. \quad (6.37)$$

Suppose that $d = 3$. Then we have only four classes $v_{1,2,-1}$, $v_{1,2,-2}$, $v_{2,1,-1}$ and $v_{2,1,-2}$. By (6.37), $v_{1,2,-2} = v_{2,1,-1} = 0$. By (6.36), $v_{2,1,-2} = -\frac{1}{2}v_{1,2,-1}$. Finally, by (6.35), $v_{1,2,-1} = 0$.

Suppose that $d \geq 4$. From relations (6.35) and Lemma 5.1 it follows that, for any $1 \leq k \leq d-1$, there exists a class $\alpha_k \in R^{g-2}(\mathcal{M}_{g,n})/K$ such that

$$v_{i,j,-k} = \left(\frac{i}{d} - \frac{1}{3} \right) \alpha_k, \text{ if } 2 \leq j \leq d-1.$$

On the other hand, from (6.34) and (6.31) it follows that $z_{i,j,-k} = 0$, if $k \leq d-2$. If $i, j \geq 2$, then $z_{i,j,-k} = -\frac{\alpha_k}{3}$. Thus, $\alpha_k = 0$, if $1 \leq k \leq d-2$. Therefore $v_{i,j,-k} = 0$, if $j \geq 2$ and $k \leq d-2$. Since $v_{d-1,1,-k} = -z_{d-1,1,-k} - v_{1,d-1,-k}$, we conclude that $v_{i,j,-k} = 0$, if $k \leq d-2$.

It remains to prove that $v_{i,j,-(d-1)} = 0$. Applying (6.36), we get $v_{i,j,-(d-1)} = 0$, if $j \leq d-2$. Finally, by (6.37), $v_{1,d-1,-(d-1)} = 0$. This completes the proof of Proposition 3.3 in the case $n = 2$.

6.3.9 Proof of Proposition 3.3: the case $n \geq 3$

From Lemma 6.1 it follows that it is sufficient to prove that $V_g \left(\prod_{i=1}^{n+1} m_{a_i} \right) \in K$, if $a_i \geq 1$.

We proceed by induction on the degree $d = \sum_{i=1}^{n+1} a_i$. The smallest possible degree is $n+1$, then $V_g \left(\prod_{i=1}^{n+1} m_1 \right) \in K$, because of the property (6.12).

Suppose that $d \geq n+2$. From relations (6.18), (6.12) and Lemma 5.3 it follows that $V_g \left(\prod_{i=1}^{n+1} m_{a_i} \right) \in K$, if $a_2 \geq 2$ and $a_3 \geq 2$. Applying (6.12) and (6.13), we get that $V_g \left(\prod_{i=1}^{n+1} m_{a_i} \right) \in K$, if there exist $n+1 \geq j > i \geq 2$ such that $a_i, a_j \geq 2$. Suppose there exists at most one $i \geq 2$ such that $a_i \geq 2$. Since $n \geq 3$, there exist $n+1 \geq j > k \geq 2$ such that $a_j = a_k = 1$. If we again apply (6.12) or (6.13), we get $V_g \left(\prod_{i=1}^{n+1} m_{a_i} \right) \in K$. This completes the proof of Proposition 3.3 in the case $n \geq 3$.

Acknowledgments. The authors are grateful to C. Faber, M. Kazarian and R. Pandharipande for useful discussions. We would like to thank the anonymous referee for valuable remarks and suggestions that allowed us to improve the exposition of this paper.

A. B. was supported by grant ERC-2012-AdG-320368-MCSK in the group of R. Pandharipande at ETH Zurich, by a Vidi grant of the Netherlands Organization for Scientific Research, Russian Federation Government grant no. 2010-220-01-077 (ag. no. 11.634.31.0005), the grants RFFI 13-01-00755, NSh-4850.2012.1, the Moebius Contest Foundation for Young Scientists and "Dynasty" foundation.

S. S. was supported by a Vidi and a Vici grants of the Netherlands Organization for Scientific Research.
D. Z. was supported by the grant ANR-09-JCJC-0104-01.

References

- [BS11] Buryak A., Shadrin S.: A new proof of Faber's intersection number conjecture. *Advances in Mathematics* **228** (2011), no. 1, 22-42.
- [BSSZ12] Buryak A., Shadrin S., Spitz L., Zvonkine D.: Integrals of ψ -classes over double ramification cycles. *American Journal of Mathematics* **137** (2015), no. 3, 699-737.
- [CMW11] Cavalieri R., Marcus S., Wise J.: Polynomial families of tautological classes on $\mathcal{M}_{g,n}^{rt}$. *Journal of Pure and Applied Algebra* **216** (2012), no. 4, 950-981.
- [Fab99] Faber C.: A conjectural description of the tautological ring of the moduli space of curves. In: *Moduli of Curves and Abelian Varieties*, 109-129, *Aspects Math.*, E33, Vieweg, Braunschweig, 1999.
- [Fab97] Faber C.: A nonvanishing result for the tautological ring of \mathcal{M}_g . arXiv:9711.219.
- [FP05] Faber C., Pandharipande R.: Relative maps and tautological classes. *Journal of the European Mathematical Society* **7** (2005), no. 1, 13-49.
- [GP98] Getzler E., Pandharipande R.: Virasoro constraints and the Chern classes of the Hodge bundle. *Nuclear Physics B* **530** (1998), no. 3, 701-714.
- [GJV11] Goulden I. P., Jackson M. D., Vakil R.: The moduli space of curves, double Hurwitz numbers, and Faber's intersection number conjecture. *Annals of Combinatorics* **15** (2011), no. 3, 381-436.
- [Hain11] Hain R.: Normal functions and the geometry of moduli spaces of curves. In: *Handbook of moduli. Vol. I*, 527-578, *Adv. Lect. Math. (ALM)*, 24, Int. Press, Somerville, MA, 2013.
- [Ion02] Ionel E.-N.: Topological recursive relations in $H^{2g}(\mathcal{M}_{g,n})$. *Inventiones Mathematicae* **148** (2002), no. 3, 627-658.
- [LX09] Liu K., Xu H.: A proof of the Faber intersection number conjecture. *Journal of Differential Geometry* **83** (2009), no. 2, 313-335.
- [Loo95] Looijenga E.: On the tautological ring of \mathcal{M}_g . *Inventiones Mathematicae* **121** (1995), no. 2, 411-419.
- [LM00] Losev A., Manin Y.: New moduli spaces of pointed curves and pencils of flat connections. *Michigan Mathematical Journal* **48** (2000), 443-472.

- [Mum83] Mumford D.: Towards an enumerative geometry of the moduli space of curves. In: *Arithmetic and Geometry, Vol. II*, 271-328, *Progr. Math.*, 36, Birkhauser Boston, Boston, MA, 1983.
- [OP06] Okounkov A., Pandharipande R.: Virasoro constraints for target curves. *Inventiones Mathematicae* **163** (2006), no. 1, 47-108.
- [Sha03] Shadrin S.: Geometry of meromorphic functions and intersections on moduli spaces of curves. *International Mathematical Research Notices* **2003**, no. 38, 2051-2094.
- [SZ08] Shadrin S., Zvonkine D.: Intersection numbers with Witten's top Chern class. *Geometry and Topology* **12** (2008), no. 2, 713-745.
- [Vak08] Vakil R.: The moduli space of curves and Gromov-Witten theory. In: *Enumerative Invariants in Algebraic Geometry and String Theory*, 143-198, *Lecture Notes in Math.*, 1947, Springer, Berlin, 2008.
- [Zvo12] Zvonkine D.: An introduction to moduli spaces of curves and their intersection theory. In: *Handbook of Teichmuller theory. Volume III*, 667716, *IRMA Lect. Math. Theor. Phys.*, 17, Eur. Math. Soc., Zurich, 2012.