GENUS TWO STABLE MAPS, LOCAL EQUATIONS AND MODULAR RESOLUTIONS

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Abstract. We geometrically describe a canonical sequence of modular blowups of the relative Picard stack over the Artin stack of genus two weighted curves. The resulted stack locally diagonalizes certain tautological derived objects. This implies a resolution of the primary component of the moduli space of genus two stable maps to projective space and meanwhile makes the entire space admit only normal crossing singularities. Our approach should extend to higher genera.

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1. Introduction

Moduli problems are of central importance in algebraic geometry. Among them, the moduli spaces $\overline{M}_{g,k}(\mathbb{P}^n, d)$ of genus $g$ degree $d$ stable maps into projective space with $k$ marked points are particularly important. For example, the Gromov-Witten theory is an intersection theory on these fundamental spaces (introduced and constructed in [11, 1, 2]).

This article focuses on the deep geometry of the moduli space $\overline{M}_{g,k}(\mathbb{P}^n, d)$. By Murphy’s law of Vakil ([13]), the moduli space $\overline{M}_{g,k}(\mathbb{P}^n, d)$ is arbitrarily singular: every singularity of finite type over $\mathbb{Z}$ appears for some $g$ and $d$. The resolution of singularity is arguably one of the hardest problems in algebraic geometry ([3, 11, 10]). To date, the problem remains open for positive characteristics. However, several moduli problems offer platforms for geometric solutions, and $\overline{M}_{g,k}(\mathbb{P}^n, d)$ is one of them (this is the pivotal motivation for us to study the moduli $\overline{M}_{g,k}(\mathbb{P}^n, d)$). When the genus $g$ is 0, the moduli space $\overline{M}_{0,k}(\mathbb{P}^n, d)$ is smooth. For $g = 1$, the moduli space $\overline{M}_{1,k}(\mathbb{P}^n, d)$ is singular and the resolution of the primary component of $\overline{M}_{1,k}(\mathbb{P}^n, d)$ was
constructed by Vakil and Zinger in [14], followed by an algebraic approach to the entire moduli $\overline{M}_1(\mathbb{P}^n, d)$ (without marked points) by Hu and Li [5].

Our current article begins to treat the more difficult cases of general genera. We start with the moduli space $\overline{M}_2(\mathbb{P}^n, d)$; for conciseness and without loss of generality in terms of singularity, we still work with curves without marked points. The goal of this paper is to geometrically describe a canonical sequence of blowups of $\overline{M}_2(\mathbb{P}^n, d)$ such that the resulted stack admits only normal crossing singularities and every of its irreducible components is smooth. This is the best that one can hope for as far as smoothness is concerned.

In the subsequent works [7, 8], the first and third named authors plan to prove that resulted blowup stacks in both [5] and the current article are moduli stacks. This approach has the benefit that it is almost ready for a generalization to arbitrary genus.

Although not a primary motivation of this series of works, the smooth blowup of $\overline{M}_2(\mathbb{P}^n, d)$ obtained in this paper can be used, for instance, to prove the “hyperplane” property of the Gromov-Witten invariants of quintic Calabi-Yau threefolds conjectured in [12] (along with other possible calculations). This is also a reason that we work with unmarked curves. Further, the method provided in this paper may also be helpful for the resolution of other singular moduli used in the recent progresses in mirror symmetry.

To state our main results, we denote by $\mathbb{M}_2$ the Artin stack of genus 2 nodal curves $C$ and by $\mathbb{P}_2$ the relative Picard stack over $\mathbb{M}_2$: its objects are pairs $(C, L)$, where $C$ are genus 2 weighted curves and $L$ are line bundles over $C$. Let

$$\tau : \overline{M}_2(\mathbb{P}^n, d) \longrightarrow \mathbb{P}_2; \quad [C, u] \rightarrow (C, u^*\mathcal{O}_{\mathbb{P}^n}(1)).$$

be the representable morphism.

We denote by

$$\pi : C \longrightarrow \overline{M}_2(\mathbb{P}^n, d), \quad \xi : C \longrightarrow \mathbb{P}^n$$

the universal family of the moduli $\overline{M}_2(\mathbb{P}^n, d)$. The main technical goal of this article is to locally diagonalize the derived objects $R\pi_*\xi^*\mathcal{O}_{\mathbb{P}^n}(k), k \geq 1$.

**Theorem 1.** There is a canonical sequence of blowups $\mathcal{P}_2 \rightarrow \mathbb{P}_2$ such that for all integer $k \geq 1$, the pullback of the derived object $R\pi_*\xi^*\mathcal{O}_{\mathbb{P}^n}(k)$ to

$$\widetilde{\mathcal{M}}_2(\mathbb{P}^n, d) = \overline{M}_2(\mathbb{P}^n, d) \times_{\mathbb{P}_2} \mathcal{P}_2$$

becomes locally diagonalizable.

Theorem 1 is proved in [5] see Theorem 5.1.1. We remark here that in order to make, for example, $R\pi_*\xi^*\mathcal{O}_{\mathbb{P}^n}(5)$ locally diagonalizable (hence to make $\pi_N^*\xi_N^*\mathcal{O}_{\mathbb{P}^n}(5)$ locally free), it suffices to perform a part of the blowups mentioned in Theorem 1.

The primary components of $\overline{M}_2(\mathbb{P}^n, d)$ and $\mathcal{M}_2(\mathbb{P}^n, d)$ are respectively the irreducible components whose general points are stable maps with smooth
domain curves. The $k = 1$ case of Theorem 1 leads to the following conclusion.

**Corollary 2.** For $d > 2$, $\widetilde{M}_2(\mathbb{P}^n, d)$ has normal crossing singularities, and its primary component is smooth and of the expected dimension $d(n+1)-n+3$.

Corollary 2 is proved in [6] see Theorem 6.2.2. Theorem 1 also gives rise to the following statement on the desingularization of the sheaves $\pi_*f^*O_{\mathbb{P}^n}(k)$.

**Corollary 3.** Let $N$ be a fixed irreducible component of $\widetilde{M}_2(\mathbb{P}^n, d)$, $d > 2$, and $(\pi_N, f_N)$ be the pullback to $N$ of the universal family $(\pi, f)$. Then the direct image sheaf $\pi_*f_*O_{\mathbb{P}^n}(k)$ is locally free for all $k \geq 1$. It is of rank $kd - 1$ if $N$ is the primary component of $\widetilde{M}_2(\mathbb{P}^n, d)$.

Our approach improves the technique of [5] and combines with the idea of the derived modular blowups in [6]. To explain this, we introduce the Artin stack $M_{\text{div}}^2$ of pairs $(C, D)$, where $C$ are genus 2 nodal curves and $D$ are effective divisors supported on the smooth loci of $C$. The stack $M_{\text{div}}^2$ is equipped with a universal curve $\rho : C \to M_{\text{div}}^2$ and a universal divisor $D$.

There is a canonical morphism

$$M_{\text{div}}^2 \longrightarrow \mathbb{P}_2, \quad (C, D) \mapsto (C, O_C(D));$$

via this morphism, we study the parallel diagonalization problem of the derived object $\rho_*O_C(D)$. Locally over a smooth chart $V$, the object $\rho_*O_C(D)|_V$ can be represented by a two term structural homomorphism

$$(1.2) \quad \varphi : O_V^{\oplus m+1} \longrightarrow O_V^{\oplus 2},$$

where $m$ is the degree of $D$.

We provide a detailed analysis of this homomorphism in terms of local modular parameters in [2] and [5]. The analysis of $\varphi$ suggests our construction of the modular blowups in [4]. The procedure involves three rounds, the first and the last of which further contain several phases. When the degree $d$ is fixed, each round or phase consists of finitely many steps. For conciseness, we hereafter write

$$(1.3) \quad r_i, \quad p_j, \quad s_\ell$$

respectively for the $i$-th round, the $j$-th phase, and the $\ell$-th step whenever applicable. We point out here that in order to locally diagonalize $R\pi_*f^*O_{\mathbb{P}^n}(k)$ with $k \geq 2$, $r_1p_5$ and $r_3p_4$ can be omitted; to locally diagonalize $R\pi_*f^*O_{\mathbb{P}^n}(k)$ with $k \geq 3$, $r_3p_4$ can be omitted as well.

Many sequences of our blowups are performed in the Artin stack $M_{\text{wt}}^2$ of weighted curves of genus 2 (i.e. genus 2 nodal curves whose irreducible components are decorated by weights in $\mathbb{Z}_{\geq 0}$; cf. [2.3]). There is a canonical morphism

$$\mathbb{P}_2 \longrightarrow M_{\text{wt}}^2, \quad (C, L) \mapsto (C, c_1(L))$$
and a canonical representable morphism
\begin{equation}
\varrho : \overline{M}_2(\mathbb{P}^n, d) \to \mathcal{M}_{\overline{2}}^\text{wt}, \quad [u, C] \to (C, c_1(u^* \mathcal{O}_{\mathbb{P}^n}(1)))
\end{equation}
that factors through (1.1). Each blowup \( \widetilde{\mathcal{M}}' \to \mathcal{M}_{\overline{2}}^\text{wt} \) determines the blowup \( \widetilde{\mathcal{M}}' = \mathcal{M} \times_{\mathcal{M}_{\overline{2}}^\text{wt}} \mathcal{M}_{\overline{2}} \) of \( \mathcal{M} \).

**The first round of blowups.** We first blow up \( \mathcal{M}^\text{wt} \) successively along the proper transforms of the substacks that are illustrated in Figure 1 and described in §4.3. The description of these substacks are “topological”; they are determined by the dual graphs and the distribution of weights.

When \( r_1 \) terminates, we denote the final stack by \( \mathcal{M}^r_1 \). Every point of \( \mathcal{M}^r_2 \) has a neighborhood \( \mathcal{V} \) so that the pullback \( \varphi^* \) of the structural homomorphism \( \varphi \) of (1.2) to \( \mathcal{V}^r_1 = \mathcal{V} \times_{\mathcal{M}^r_2} \mathcal{M}_{\overline{2}} \) has one row that contains an element that divides all other entries of \( \varphi^* \) evenly. However, \( \varphi^* |_{\mathcal{V}^r_1} \) may \text{not} be diagonalizable (c.f. Definition 2.1.1) due to the existence of (1) some distinguished directions in the exceptional divisors obtained in \( r_1 \) and/or (2) the Weierstrass and conjugate points of genus 2 curves.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The first round \( (r_1) \) of the modular blowups}
\end{figure}

**The second round of blowups.** The blowup loci of \( r_2 \) lie in the proper transforms of the exceptional divisors obtained in \( r_1 \), hence are more complicated. They are illustrated in Figure 2 and described in §4.4. We blow up \( \mathcal{M}^r_1 \) successively along these substacks and obtain \( \mathcal{M}^r_2 \). After this round, the only
obstacle to the pullback of $\varphi$ being locally diagonalizable is the existence of the Weierstrass and conjugate points. They will be dealt with in the next (i.e. the last) round of blowups.

The third round of blowups. This round is divided into four phases that are described in §4.5-4.8. The blowup loci of $r_3p_1$ (resp. $r_3p_2$) lie in the proper transforms of the exceptional divisors of $r_1p_1$ (resp. $r_2$). The description of these two phases is similar to that of $r_2$, but slightly more complicated because of the conjugate points (resp. Weierstrass points).

In the last two phases of $r_3$, we work on the relative Picard stack $\mathcal{P}_2$ rather than $\mathcal{M}^w_2$, because there is no obvious morphism $\mathcal{M}^w_2(\mathbb{P}^n,d) \to \mathcal{M}_2^{\text{div}}$ that (1.4) factors through. In $r_3p_3$, let $\mathcal{H}_k (k \geq 0)$ be the closed substack of $\mathcal{P}_2$ whose general points are pairs $(C,L)$ with $F$ denoting the core of $C$ (i.e. the smallest genus 2 subcurve of $C$; c.f. [2,2]) such that $\deg L|_F = 2$, $h^0(L|_F) = 2$, and $F$ has $k$ rational tails attached to it. We blow up the stack $\mathcal{P}_2 \times_{\mathcal{M}^w_2} \mathcal{M}^{r_3p_2}$ along the proper transforms of $\mathcal{H}_0 \times_{\mathcal{M}^w_2} \mathcal{M}^{r_3p_2}, \cdots, \mathcal{H}_k \times_{\mathcal{M}^w_2} \mathcal{M}^{r_3p_2}, \cdots$ and obtain $\mathcal{M}^{r_3p_3}$. The description of $r_3p_4$ is more sophisticated; it is in a mixed fashion of $r_2$ and $r_3p_3$. The key fact is that the pullback of $\varphi$ becomes locally diagonalizable when $r_3$ terminates; c.f. Theorem 5.1.1.

We remark that the description of the modular blowups in §4 is global. However, it is crucial to understand how each round or phase of the modular blowups affects the moduli space locally, so as to study the local behavior of the structural homomorphism $\varphi$ in §5. We thus introduce the notion of locally tree-compatible blowups in §3, which provides the desired connection between the globally defined the blowups and their local properties.

Once Theorem 5.1.1 is established in §5, we apply the technique in §5 to obtain the local structure of $\tilde{\mathcal{M}}_2(\mathbb{P}^n,d)$ in §6.
Throughout the paper, we work over an algebraically closed field of characteristic zero.

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2. The structures of the tautological derived objects

We begin with the notion of the diagonalizable derived objects introduced in [6]. It is key to this article.

2.1. Diagonalizable homomorphism. Let \( \varphi : \mathcal{E}_1 \to \mathcal{E}_2 \) be a homomorphism of locally free sheaves of \( \mathcal{O}_U \)-modules on a DM stack \( U \).

Definition 2.1.1. We say \( \varphi \) is diagonalizable if there are integers \( r, l_1 \) and \( l_2 \in \mathbb{Z}_{\geq 0}, p_i \in \Gamma(\mathcal{O}_U) \) such that the ideals \( (p_i) \subset (p_{i+1}) \), and isomorphisms \( \mathcal{E}_i \cong \mathcal{O}_U^{\otimes r} \oplus \mathcal{O}_U^{\otimes l_1} \) such that

\[
\varphi = \text{diag}[p_1, \cdots, p_r] \oplus 0 : \mathcal{O}_U^{\otimes r} \oplus \mathcal{O}_U^{\otimes l_1} \to \mathcal{O}_U^{\otimes r} \oplus \mathcal{O}_U^{\otimes l_2},
\]

where \( \text{diag}[p_1, \cdots, p_r] : \mathcal{O}_U^{\otimes r} \to \mathcal{O}_U^{\otimes r} \) is the diagonal homomorphism and \( 0 : \mathcal{O}_U^{\otimes l_1} \to \mathcal{O}_U^{\otimes l_2} \) is the zero homomorphism. We say \( \varphi \) is locally diagonalizable if there is an \( \acute{e} \)tale cover \( U_\alpha \) of \( U \) such that \( \varphi \) is diagonalizable over \( U_\alpha \).

Definition 2.1.2. Let \( \mathcal{E} \) be a perfect derived object on a DM stack \( M \). We say \( \mathcal{E} \) is locally diagonalizable if there is an \( \acute{e} \)tale cover \( \{U\} \) of \( M \) such that \( \mathcal{E}|_U \) is quasi-isomorphic to \( \varphi : \mathcal{E}_1 \to \mathcal{E}_2 \), where \( \mathcal{E}_1 \) and \( \mathcal{E}_2 \) are locally free sheaves and \( \varphi \) is diagonalizable.

Using [6] Proposition 3.2] (the universality of diagonalization), one checks directly that the definition does not depend on the local representation of the object \( \mathcal{E} \). Here it is worth to point out that in Definition 2.1.1 if the requirement \( (p_{i+1}) \subset (p_i) \) is removed, then the "diagonalization" thus defined is not a property of the derived object but merely a property of a presentation of the object \( \mathcal{E} \).

The following result is a conclusion of [6, Corollary 4.1]. It is needed to deduce Corollary 3 from Theorem 1 in [1].

Proposition 2.1.3 ([6]). Let \( M \) and \( \tilde{M} \) be two DM stacks and \( \mathcal{E} \) be a perfect derived object on \( M \). Assume there is a birational morphism \( \psi : \tilde{M} \to M \) such that the pullback of \( \mathcal{E} \) is locally diagonalizable in the sense of Definition 2.1.1. Then, for any irreducible component \( N \) of \( \tilde{M} \) endowed with the reduced stack structure, \( \mathcal{H}^0(L\psi^*\mathcal{E}|_N) \) is locally free.
2.2. Nodal curves and their dual graphs. Let $C$ be a nodal curve. We call a node $q$ (resp. an irreducible component) of $C$ separating if $C\setminus q$ (resp. $C\setminus \Sigma$) is disconnected. We call other nodes of $C$ non-separating. A curve $C$ is said to be separable (resp. inseparable) if it contains at least one separating node (resp. contains no separating node). An inseparable component of $C$ is a smallest (via inclusion) inseparable subcurve of $C$.

If $C$ is of positive (arithmetic) genus $g$, we call the smallest connected genus $g$ subcurve $F$ of $C$ the core (of $C$). Removing $F$ from $C$ results in disjoint connected trees of rational curves, called the tails of $C$. Each tail is attached to the core $F$ at a separating node, called a pivotal node.

A node $q$ of $C$ is said to be principal (resp. non-principal) if $q$ is (resp. is not) a node of the core $F$ of $C$. Every (not necessarily smooth) point $x \in C \setminus F$ belongs to a unique tail, whose pivotal node is denoted by $\langle x \rangle$. For $x \in F$, let $\langle x \rangle = x$.

A non-separating (resp. separating) bridge $B$ of $F$ is a chain of rational curves in $F$ whose principal nodes are all non-separating (resp. separating). A bridge is maximal if it is not a strict subset of any other bridge. Every bridge $B$ is connected to its complement in $F$ at two distinct principal nodes $p$ and $q$. We sometimes denote $B$ by $B[p, q]$ to emphasize these nodes.

Let $\mathcal{W} \subset \overline{\mathcal{M}}_{2,1}$ be the locus of (stable) genus $2$ curves with one marked Weierstrass point. Using admissible double covers (c.f. [9, §3G]), we can identify $\overline{\mathcal{M}}_2$ with $\overline{\mathcal{M}}_{0,6}/S_6$, where $S_6$ is the symmetry group on 6 letters. Here, the 6 unordered markings on the target rational curve are the branch points of the hyperelliptic admissible double covers. With this identification, choosing a Weierstrass point in the domain curve is the same as specifying a distinguished marking out of the 6 unordered markings in the target rational curve. Hence, $\mathcal{W}$ is isomorphic to $\overline{\mathcal{M}}_{0,6}/S_5$, where the last marking is declared to be distinguished from the others. In particular, $\mathcal{W}$ is a smooth divisor in $\overline{\mathcal{M}}_{2,1}$.

For $1 \leq i \leq k$, let $\mathcal{W}_{k,i} \subset \overline{\mathcal{M}}_{2,k}$ be the locus of stable genus $2$ curves with $k$ marked points so that the $i$-th marked point is Weierstrass. Then, $\mathcal{W}_{k,i}$ is the pullback of $\mathcal{W}$ in $\overline{\mathcal{M}}_{2,k}$ via the forgetful morphism that forgets all but the $i$-th marked point. Since $\mathcal{W}$ is a Cartier divisor, so is every $\mathcal{W}_{k,i}$. We remark that the smoothness of $\mathcal{W}$ does not imply that $\mathcal{W}_{k,i}$ is smooth.

Let $\mathcal{K} \subset \overline{\mathcal{M}}_{2,2}$ be the locus of (stable) genus $2$ curves with two marked conjugate points. Similar to the above discussions, $\mathcal{K}$ is isomorphic to $\overline{\mathcal{M}}_{0,7}/S_6$, where the 7-th marking corresponds to the image of a pair of conjugate points. In particular, $\mathcal{K}$ is a smooth divisor in $\overline{\mathcal{M}}_{2,2}$. Similarly, let $\mathcal{K}_{k,i,j} \subset \overline{\mathcal{M}}_{2,k}$ be the locus of stable genus $2$ curves with $k$ marked points so that the $i$-th and the $j$-th marked points are conjugate. Then $\mathcal{K}_{k,i,j}$ is a Cartier divisor in $\overline{\mathcal{M}}_{2,k}$.

For a nodal curve $C$, we call a smooth point $p$ of $C$ a Weierstrass point if $[C, p] \in \mathcal{W}$. Similarly, we say a pair of smooth points $p_1$ and $p_2$ of $C$ to be conjugate if $[C, p_1, p_2] \in \mathcal{K}$. The terminology can be generalized to all
non-principal node(s) by considering the connected component of \( \tilde{C} \), the normalization of \( C \) at the given node(s), that contains the core \( F \).

### Basic Assumptions

2.3. **Basic setup.** Let \( \mathcal{M}_2^{\text{wt}} \) be the Artin stack of the stable pairs \( (C, \omega) \) of genus 2 nodal curves \( C \) with non-negative weights \( \omega \in H^2(C, \mathbb{Z}) \), meaning that \( \omega(\Sigma) \geq 0 \) for all irreducible components \( \Sigma \) of \( C \). Here \( (C, \omega) \) is said to be stable if every rational irreducible component of weight 0 contains at least three nodal points; c.f. [5] §2.1. The stability requirements guarantees that each connected component of \( \mathcal{M}_2^{\text{wt}} \) is of finite type.

Similarly, let \( \mathcal{M}_2^{\text{div}} \) be the Artin stack of the stable pairs \( (C, D) \) where \( C \) are genus 2 nodal curves and \( D \) are effective divisors on \( C \). Here \( (C, D) \) is said to be stable if every rational irreducible component disjoint from \( D \) contains at least three nodal points; c.f. [5] §2.3. The stability requirements guarantees that each connected component of \( \mathcal{M}_2^{\text{div}} \) is also of finite type.

In studying \( \mathcal{M}_2^{\text{div}}(\mathbb{P}^n, d) \) together with \( \pi_* \mathcal{O}_{\mathbb{P}^n}(k) \), we cover it by étale opens \( U \to \mathcal{M}_2^{\text{div}}(\mathbb{P}^n, d) \) and pick degree \( k \) hypersurfaces \( H \subset \mathbb{P}^n \) in general position so that for each \( [u, C] \in U \), \( u^{-1}(H) \subset C \) is a simple divisor lying in the smooth locus of \( C \). The assignment \( [u, C] \mapsto (C, u^{-1}(H)) \) defines morphisms

\[
\mathcal{M}_2^{\text{div}}(\mathbb{P}^n, d) \supset U \longrightarrow \mathcal{M}_2^{\text{div}}.
\]

We pick an affine étale \( V \to \mathcal{M}_2^{\text{div}} \) so that \( U \to \mathcal{M}_2^{\text{div}} \) factor through \( U \to V \).

Using the (local) morphism \( (2.1) \), it suffices to study a parallel problem on \( \mathcal{M}_2^{\text{div}} \). For a fixed \( (C, D) \in \mathcal{M}_2^{\text{div}} \) lying over \( (C, \omega) \in \mathcal{M}_2^{\text{wt}} \) with deg \( D = m \) for some positive integer \( m \), we pick an affine smooth chart \( V \to \mathcal{M}_2^{\text{div}} \) containing \( (C, D) \). Let \( \rho : C \to V \) and \( D \subset C \) be the universal family on \( V \). We find disjoint sections \( A_1, A_2, B \) of \( C/V \), disjoint from \( D \), called the auxiliary divisors. We list this package as

\[
(2.2) \quad \rho : C \to V (\to \mathcal{M}_2^{\text{div}}), \quad D \subset C; \quad \text{plus } A = A_1 + A_2, B \subset C.
\]

Let

\[ \mathcal{L} = \mathcal{O}_C(D), \quad \mathcal{M} = \mathcal{O}_C(A - B), \quad \text{and } \mathcal{O}_A(A) = \mathcal{O}_V(A) \otimes \mathcal{O}_C \mathcal{O}_A. \]

We consider the two term complex

\[
(2.3) \quad \rho_* \mathcal{L}(A) \longrightarrow \rho_* \mathcal{O}_A(A)
\]

via the evaluation homomorphism. These data will be fixed throughout the paper.

**Basic Assumptions.** Possibly after an étale base change and a shrinking of \( V \), we assume

\begin{itemize}
  \item[(A)] \( a_i = A_i \cap C \) and \( b = B \cap C \) lie in the core \( F \) of \( C \) and are in general position; in case \( F \) is separable, then \( a_1 \) and \( a_2 \) lie on different genus-one inseparable components of \( F \);
  \item[(B)] \( D = D_1 + \cdots + D_m \) is a union of \( m \) disjoint sections \( D_i \) of \( C \to V \);
  \item[(C)] Assumptions \([A]\) and \([B]\) hold for all fibers of \( C \to D \).
\end{itemize}
Lemma 2.4.1. We have (1). Show that it is injective. The injectivity follows from that \( \rho_m \) and \( \rho \) and Lemma 4.10; we omit the details. We now prove (3). Since both \( \rho \) and \( \rho_m \) has the form \( \rho_m \) and the induced inclusions

\[
\eta_i : \rho_m \mathcal{M}(D_i) \hookrightarrow \rho_m \mathcal{M}(D) = \mathcal{O}_C(D + A - B),
\]

and the induced inclusions

\[
\eta_i : \rho_m \mathcal{M}(D_i) \hookrightarrow \rho_m \mathcal{M}(D).
\]

Because of the Basic Assumptions, the above terms are locally free. By Riemann-Roch Theorem, \( \rho_m \mathcal{M}(D_i) \) is invertible and \( \rho_m \mathcal{M}(D) \) has rank \( m \). Let

\[
\varphi : \rho_m \mathcal{M}(D) \longrightarrow \rho_m \mathcal{O}_A(A) \quad \text{and} \quad \varphi_i : \rho_m \mathcal{M}(D_i) \longrightarrow \rho_m \mathcal{O}_A(A)
\]

be the evaluation homomorphisms; then \( \varphi_i = \varphi \circ \eta_i \). We denote their sum by

\[
(\eta_i) : \oplus_{i=1}^m \rho_m \mathcal{M}(D_i) \longrightarrow \rho_m \mathcal{M}(D),
\]

\[
(\varphi_i) : \oplus_{i=1}^m \rho_m \mathcal{M}(D_i) \longrightarrow \rho_m \mathcal{O}_A(A).
\]

Lemma 2.4.1. We have (1). \( \rho_m \mathcal{L} \cong \mathcal{O}_V \oplus \rho_m \mathcal{L}(-B) \); (2). \( \rho_m \mathcal{L}(-B) \cong \ker \varphi \); (3). \( (\eta_i) \) is an isomorphism, and (4). \( (\varphi_i) = \varphi \circ (\eta_i) \). Consequently,

\[
\rho_m \mathcal{L} \cong \mathcal{O}_V \oplus \ker \{(\varphi_i)\}.
\]

Proof. The proofs of (1) and (2) are the same as for the genus 1 case, [5, Lemma 4.10]; we omit the details. We now prove (3). Since both \( \rho_m \mathcal{M}(D_i) \) and \( \rho_m \mathcal{M}(D) \) are locally free, we only need to show that for any closed \( z \in V, \oplus_{i=1}^m \rho_m \mathcal{M}(D_i)|_z \rightarrow \rho_m \mathcal{M}(D)|_z \) is an isomorphism. By base change, it suffices to show that the tautological homomorphism

\[
\bigoplus_{i=1}^m \eta_i(z) \oplus H^0(\mathcal{O}_C(D_i + A - B)) \longrightarrow H^0(\mathcal{O}_C(D + A - B))
\]

is an isomorphism. Because both sides are of equal dimensions, it suffices to show that it is injective. The injectivity follows from that \( D_1 \cap C_z, \ldots, D_m \cap C_z \) are distinct in \( C_z \). The item (4) is a tautology. This proves the lemma.

This proves that the homomorphism \( \varphi \) in (2.4) is equivalent to the homomorphism \( (\varphi_i) \), via the isomorphism \( (\eta_i) \).

We will call either \( \varphi \) or \( (\varphi_i) \) a structural homomorphism. Note that each \( \varphi_i \) has the form

\[
(\varphi_i) = \varphi_1 \oplus \varphi_2 : \rho_m \mathcal{M}(D_i) \longrightarrow \rho_m \mathcal{O}_{A_1}(A_1) \oplus \rho_m \mathcal{O}_{A_2}(A_2).
\]

These homomorphisms will be our focus in this section.
2.5. The structural homomorphism.} By the deformation theory of nodal curves, for each node $q \in C$ there is a regular function $\zeta_q \in \Gamma(\mathcal{O}_Y)$ so that $\Sigma_q = \{ \zeta_q = 0 \}$ is the locus where the node $q$ is not smoothed; the divisor $\Sigma_q$ is a smooth divisor. We will refer to $\zeta_q$ as a modular parameter.

To proceed, we introduce the notation of a node lying between two points (or components). We say a separating node $q$ separates (or lies between) two points $x$ and $y$ of $C$ if either $x = q$, or $y = q$, or $x$ and $y$ lie in different connected components of $C \setminus \{q\}$. If we replace $y$ by a connected subcurve $C'$ of $C$, we say $q$ lies between $x$ and $C'$ if either $x = q$ or $x$ and $C' \setminus \{q\}$ lie in different connected components of $C \setminus \{q\}$. We denote by $N_{[x,y]}$ (resp. $N_{[x,C]}$) the set of the separating nodes lying between $x$ and $y$ (resp. $C'$).

If $B = B[q_1,q_2]$ is a non-separating bridge on $F$, then for every $x \in B$, we define $N_{[x,q_1]}$ (resp. $N_{[x,q_2]}$) in the same fashion with $C$ replaced by the normalization of $C$ at $q_2$ (resp. at $q_1$).

Now back to the family $C \to V$ with $C = C \times V \mathbb{0}$ the central fiber mentioned before. For $1 \leq i \leq m$ and $1 \leq i \leq 2$, let
\[ \delta_i = D_i \cap C \quad \text{and} \quad A_s = A_s \cap C. \]
For $x,y \in C$, we define
\begin{equation}
\zeta_{[x,y]} = \prod_{q \in N_{[x,y]}} \zeta_q, \quad \text{and} \quad \zeta_x = \prod_{q \in N_{[x,F]}} \zeta_q.
\end{equation}
(Here as always, $F$ is the core of $C$.) In case $N_{[x,a_s]} = \emptyset$, we set $\zeta_{[x,a_s]} = 1$.

If $T$ is a tail and $x,y \in T$, let $x \wedge y$ be the (non-principal) node so that
\[ \zeta_{[x \wedge y]} = \prod_{q \in N_{[x,F] \cap N_{[y,F]}}} \zeta_q. \]
If $x \wedge y$ does not exist, i.e. $N_{[x,F]} \cap N_{[y,F]} = \emptyset$, we simply set $\zeta_{[x \wedge y]} = 1$.

We fix trivializations
\begin{equation}
\rho_s \cdot \mathcal{M}(D_i) \cong \mathcal{O}_Y, \quad \rho_s \cdot \mathcal{O}_{A_s}(A_s) \cong \mathcal{O}_Y; \quad 1 \leq i \leq m, \quad 1 \leq s \leq 2,
\end{equation}
and the induced trivialization $\rho_s \cdot \mathcal{O}_A(A) \cong \mathcal{O}_Y^{\otimes 2}$ throughout this section.

**Proposition 2.5.1.** After fixing (2.7), the evaluation homomorphism
\begin{equation}
\varphi_{s_i} : \rho_s \cdot \mathcal{M}(D_i) \longrightarrow \rho_s \cdot \mathcal{O}_{A_s}(A_s)
\end{equation}
is given by the multiplication
\[ \varphi_{s_i} = c_{s_i} \cdot \zeta_{[\delta_i,a_s]} : \mathcal{O}_Y \longrightarrow \mathcal{O}_Y, \quad c_{s_i} \in \Gamma(\mathcal{O}_Y^+). \]

**Proof.** The proof is parallel to that of [5 Prop. 4.13] and is thus omitted. \qed

2.6. A technical proposition on rational curves.} We now focus on a maximal chain $R \subset C$ of smooth rational curves $R = R_1 \cup \cdots \cup R_h$ of $C$ attached to a smooth point of the core $F \subset C$.

We fix some notation. First, we index the irreducible components of $R$ so that $R_1$ is attached to $F$, and $R_{j+1}$ is attached to $R_j$. Let
\[ q_1 = F \cap R_1, \quad q_{j+1} = R_j \cap R_{j+1} \quad \forall \ 1 \leq j \leq h-1. \]
with the node \( q \) the restriction homomorphism. Recall the modular parameter associated as stated above. Then after choosing suitable trivialization (2.7)

\[
\phi = \bigoplus_{\delta \in D \cap R} \rho_* \mathcal{M}(D) \to \rho_* \mathcal{O}(A)
\]

the restriction homomorphism. Recall the modular parameter associated with the node \( q_j \) is denoted by \( \zeta_{q_j} \).

**Proposition 2.6.1.** Let \( R \) be a maximal chain of rational curves in \((C,D)\) as stated above. Then after choosing suitable trivialization

\[
\bigoplus_{\delta \in D \cap R} \rho_* \mathcal{M}(D) \cong \mathcal{O}_V^B[D \cap R]
\]

and (2.7), the homomorphism \( \phi^R \) takes the form

\[
\phi^R = \left[ \begin{array}{cccc}
\hat{c}_{11} & \hat{c}_{12} & \hat{c}_{13} & \cdots \\
\hat{c}_{21} & \hat{c}_{22} & \hat{c}_{23} & \cdots \\
\hat{c}_{31} & \hat{c}_{32} & \hat{c}_{33} & \cdots \\
\vdots & \vdots & \vdots & \ddots \\
\end{array} \right]
\]

with \( \hat{c}_{11} = c_{11}, \hat{c}_{21} = c_{21} \in \Gamma(\mathcal{O}_V), \hat{c}_{ij} \in \Gamma(\mathcal{O}_V) \forall j > 1, \)

where \( c_{11} \) and \( c_{21} \) are as in Proposition 2.5.1. Moreover, with

\[
\theta_{ij} \equiv \det \left[ \begin{array}{cc}
\hat{c}_{ij} & \hat{c}_{ij} \\
\hat{c}_{ij} & \hat{c}_{ij} \\
\end{array} \right] \in \Gamma(\mathcal{O}_V) \quad \forall 1 \leq i < j \leq m,
\]

(1) if \( q_1 \) is not Weierstrass, then \( \theta_{12} \in \Gamma(\mathcal{O}_V) \);

(2) if \( q_1 \) is Weierstrass, then \( \theta_{12} \) vanishes to the first order along the locus on which \( D_1 \) and \( D_2 \) are conjugate;

(3) if \( q_1 \) is Weierstrass and is not on any bridge of \( F \), then \( \theta_{13} \in \Gamma(\mathcal{O}_V) \);

(4) if \( q_1 \) is on a maximal non-separating bridge \( B[p,r] \) of \( F \), then for every \( z \in V \), if there exist \( p_1 \in N[q_1,p] \) and \( r_1 \in N[q_1,r] \) such that

\[
\zeta_{q_1}(z) = \zeta_{p_1}(z) = \zeta_{r_1}(z) = 0,
\]

then \( \theta_{1j}(z) = 0 \) for all \( 3 \leq j \leq r \); moreover, the zero loci \( \{\theta_{1i} = 0\}, 2 \leq i \leq r \), are transverse to each other.

Note that in Part 3 of Proposition 2.6.1, the node \( q_1 \) is automatically Weierstrass. In addition, if \( q_1 \) is on a separating bridge of \( F \), then it cannot be Weierstrass. Thus, the last two parts of Proposition 2.6.1 cover all possibilities of the Weierstrass \( q_1 \).

**Proof.** Let \( \zeta_{q_j} \) be the modular function associated with \( q_j \). Since \( q_j \) is separating,

\[
\mathcal{C} \times \mathcal{V} (\zeta_{q_j} = 0) = \mathcal{G}_j \cup \mathcal{R}_j
\]
is a union of two families of nodal curves over \((\zeta_{a_{ij}} = 0)\) intersecting (i.e. glued along) a section of nodes \(\Sigma_j = G_j \cap R_j\), such that \(\Sigma_j \cap C = q_j\) and \(R_j \cap C = R_{j+1} \cup \cdots \cup R_h\).

Let \(M_{2, ss}\) be the Artin stack of semi-stable genus two nodal curves. (A nodal curve is semi-stable if its smooth rational subcurves contain at least two nodes of the nodal curve.) By (successively) contracting rational subcurves that contain only one node of the ambient curves, we obtain a semi-stablization \(M_2 \longrightarrow M_{2, ss}\). Possibly after shrinking and base changing \(V\), we can assume that there is a smooth chart \(V \rightarrow M_{2, ss}\) with \(X \rightarrow V\) its universal family so that the composite \(V \rightarrow M_{2, ss}^{\text{div}} \rightarrow M_{2, ss}\) lifts to a \(g\) together with a semi-stable contraction \(\bar{g}\) as shown

\[
\begin{align*}
V & \longrightarrow M_{2, ss}^{\text{div}} \\
\bar{V} & \longrightarrow M_{2, ss}
\end{align*}
\]

(2.13)

(Note that \(\bar{g}\) contracts all rational tails of the curves in the family \(C \rightarrow V\).)

Let \(D_i = \bar{g}(D_i)\), which are family of smooth divisors of \(\bar{C} \rightarrow V\), and let

\[
\mathcal{D}_R = \sum_{i=1}^r D_i \subset C, \quad \mathcal{D}_R = \sum_{i=1}^r D_i \subset \bar{C}.
\]

Let \(\bar{\rho} : \bar{C} \rightarrow V\) be the second projection of (2.13). By construction, the divisors \(R_1, \ldots, R_h\) are contracted under the morphism \(\bar{g}\), and

\[
(2.14) \quad \bar{g}^{-1}(D_i) = R_1 + \cdots + R_{e(i)} + D_i,
\]

where \(e\) is the index function (2.10).

Let \(r_i\) be the number of points in \(R_i \cap D\); thus \(\sum_{i=1}^h r_i = r\). We set \(R = \sum_{i=1}^h (r_i + \cdots + r_h)R_i\); then

\[
(2.15) \quad \bar{g}^* \mathcal{O}_C(\mathcal{D}_R + \mathcal{A} - \mathcal{B}) = \mathcal{O}_C(R + \mathcal{D}_R + \mathcal{A} - \mathcal{B}).
\]

Then we have

\[
(2.16) \quad \rho^a \mathcal{O}_C(\mathcal{D}_R + \mathcal{A} - \mathcal{B}) \longrightarrow \rho^a \mathcal{O}_C(R + \mathcal{D}_R + \mathcal{A} - \mathcal{B}) = \bar{\rho}^a \mathcal{O}_C(\mathcal{D}_R + \mathcal{A} - \mathcal{B}).
\]

Here the identity follows from combining (2.15) and the identities

\[
\rho^a \bar{g}^* \mathcal{O}_C(\mathcal{D}_R + \mathcal{A} - \mathcal{B}) = \bar{\rho}^a \bar{g}^* \mathcal{O}_C(\mathcal{D}_R + \mathcal{A} - \mathcal{B}) = \bar{\rho}^a \mathcal{O}_C(\mathcal{D}_R + \mathcal{A} - \mathcal{B}),
\]

where the last equality holds since both \(C\) and \(\bar{C}\) are smooth, \(\bar{g} : C \rightarrow \bar{C}\) is a proper divisorial contraction.

As before, we write \(a_i = F \cap A_i\), \(a = a_1 + a_2\), and \(b = F \cap B\). Since they are in general position (the basic assumptions), we have \(H^1(\mathcal{O}_F(\rho p_1 + a-b)) = 0\). Thus \(\bar{\rho}^a \mathcal{O}_C(\mathcal{D}_R + \mathcal{A} - \mathcal{B})\) is a free \(\Gamma(\mathcal{O}_V)\)-module. For convenience, we denote

\[
\mathcal{M} := \Gamma(\rho^a \mathcal{O}_C(\mathcal{D}_R + \mathcal{A} - \mathcal{B})) \subset \mathcal{M} := \Gamma(\bar{\rho}^a \mathcal{O}_C(\mathcal{D}_R + \mathcal{A} - \mathcal{B})).
\]
We now pick a basis of $\overline{M}$. Since $a$ and $b$ are in general positions, by a simple vanishing argument, we see that $H^j(\mathcal{O}_F(a-b)) = 0$ for all $j$. Hence, the restriction homomorphism

$$H^0(\mathcal{O}_F(rq_1 + a - b)) \rightarrow H^0(\mathcal{O}_F(rq_1)|_{rq_1})$$

is an isomorphism. Therefore, we can pick a basis $s_1, \ldots, s_r$ of the vector space $H^0(\mathcal{O}_F(rq_1 + a - b))$ so that $s_i$ has vanishing order $(r - i)$ at $q_1$.

Next, let $\mathcal{H}_i = (\zeta_{q_i} = 0) \subset V$, and let $\mathcal{H} = \bigcup_{i=1}^r \mathcal{H}_i$. Let

$$\bar{\rho}_H: \mathcal{H} := \mathcal{C} \times_V \mathcal{H} \rightarrow \mathcal{H}$$

be the projection; let $\Sigma_i = \bar{\gamma}(\Sigma_i)$, where $\Sigma_i = \zeta_i \cap \mathcal{R}_i$. For the same reason, $\overline{\mathcal{M}} = (\bar{\rho}_H)_*(\mathcal{O}_{\mathcal{C}}(\overline{D}_R + \overline{A} - \overline{B}))$ is a free $\Gamma(\mathcal{O}_{\mathcal{C}})$-module, and has a basis $S_{\mathcal{H}_i,1}, \ldots, S_{\mathcal{H}_i,r}$ extending the basis $s_1, \ldots, s_r$ along general directions so that $\bar{S}_{\mathcal{H}_i,i}$ lifts to $\bar{S}_{\mathcal{H}_i,i} \in \Gamma(\mathcal{O}_{\mathcal{C}}(\overline{D}_R + \overline{A} - \overline{B}(-r-i)\Sigma_i))$ such that $\bar{S}_{\mathcal{H}_i,i}$ are non-vanishing along $\Sigma_i$.

By shrinking $V$ if necessary, we can extend $\bar{S}_{\mathcal{H}_i,i}$ to $\bar{S}_i \in \overline{\mathcal{M}}$ along general directions so that $\overline{\mathcal{M}}$ (as a free $\Gamma(\mathcal{O}_{\mathcal{C}})$-module) is generated freely by $S_1, \ldots, S_r$. Thus by (2.16), $\bar{\gamma}^* S_1, \ldots, \bar{\gamma}^* S_r$ freely generate the free $\Gamma(\mathcal{O}_{\mathcal{C}})$-module $\Gamma(\mathcal{O}_{\mathcal{C}}(\mathcal{R} + \mathcal{D}_R + \mathcal{A} - \mathcal{B}))$.

**Sublemma.** Recall $\gamma_{[\zeta]} = \prod_{i=1}^r [\zeta_{q_i}]$, and let $S_i = \zeta_{[\zeta]} \cdot \bar{\gamma}^* S_i$. Then the submodule $M \subset \overline{M}$ is a free rank $r$ $\Gamma(\mathcal{O}_{\mathcal{C}})$-module generated by $S_1, \ldots, S_r$.

**Proof of Sublemma.** We begin with more convention. Let $U_i \subset \mathcal{C}$ be an affine open that contains the generic point $\xi_i$ of $\mathcal{R}_i$. Let $u_i \in \Gamma(\mathcal{O}_{U_i})$ be so that $\mathcal{R}_i \cap U_i = (u_i = 0) \subset U_i$. Since $\mathcal{R}_i \rightarrow \mathcal{H}_i$ is a family of rational curves and has general fibers isomorphic to $\mathbb{P}^1$, we can find a rational function $v_i$ on $U_i \cap \mathcal{R}_i$ so that $v_i$ restricts to general fibers of $\mathcal{R}_i \cap U_i \rightarrow \mathcal{H}_i$ are birational maps to $\mathbb{P}^1$. We next let $\xi'_i$ be the generic point of $\Sigma_i$. Since $\bar{\gamma}(\xi_i) = \xi'_i$, the field $K_i = \mathcal{O}_{\xi_i}$ contains $K'_i = \mathcal{O}_{\xi'_i}$ as its subfield. Because of our choice of $v_i$, we have $K_i = K'_i(v_i)$.

Let $\hat{\mathcal{O}}_{U_i}$ be the formal completion of $\mathcal{O}_{U_i}$ along $\xi_i$. Then $\hat{\mathcal{O}}_{U_i} = K_i[[u_i]]$, where $\hat{u}_i$ is the image of $u_i$ in $\hat{\mathcal{O}}_{U_i}$. (For any $f \in \Gamma(\mathcal{O}_{\mathcal{C}})$, we denote by $[f]$ its image in $\hat{\mathcal{O}}_{U_i}$ via the pullback $\mathcal{O}_{\mathcal{C}} \rightarrow \mathcal{O}_{U_i}$ and the completion map.)

We next pick an open $U'_i \subset \mathcal{C}$ that contains the generic point $\xi'_i$ of $\Sigma_i$. By shrinking $U_i$ if necessary, we can assume $\bar{\gamma}(U_i) \subset U'_i$. We then fix a trivialization $\bar{\mathcal{O}}_{U'_i}(\overline{D}_R + \overline{A} - \overline{B}) \cong \bar{\mathcal{O}}_{U'_i}$, and form the induced trivialization

$$\mathcal{O}_{U_i}((\mathcal{R} + \mathcal{D}_R + \mathcal{A} - \mathcal{B})) \cong \mathcal{O}_{U'_i}((\mathcal{R} + \mathcal{D}_R + \mathcal{A} - \mathcal{B})) \cong \mathcal{O}_{U_i}.$$

Using this trivialization, we can identify any section in $\Gamma(\mathcal{O}_{U_i}((\mathcal{R} + \mathcal{D}_R + \mathcal{A} - \mathcal{B}))$ with a regular function in $\Gamma(\mathcal{O}_{U_i})$, thus obtaining its image in $\hat{\mathcal{O}}_{U_i}$. We denote this process by $\gamma \in \Gamma(\mathcal{O}_{U_i}((\mathcal{R} + \mathcal{D}_R + \mathcal{A} - \mathcal{B})) \mapsto [\gamma] \in \mathcal{O}_{U_i}((\mathcal{R} + \mathcal{D}_R + \mathcal{A} - \mathcal{B})) \otimes \mathcal{O}_{U_i} \hat{\mathcal{O}}_{U_i} \cong \hat{\mathcal{O}}_{U_i}$. 


Note that by our choice of $\vec{s}_j$, (i.e. its vanishing along $\Sigma_j$,) $\vec{g}^\alpha \vec{s}_j|\mathcal{U}_i$ has vanishing order $r - j$ along $\mathcal{R}_i$; thus $[\vec{g}^\alpha \vec{s}_j] = e_j(\vec{u}_i)^{r - j}$, where $e_j \neq 0 \in \mathcal{O}_{\mathcal{U}_i} = K_1[\vec{u}_i]$ such that $\vec{u}_i$ does not divide $e_j$.

We now prove the Sublemma. Let $F' \in \Gamma(\rho_\alpha \mathcal{O}_C(\mathcal{R} + \mathcal{D}_R + \mathcal{A} - \mathcal{B}))$. By (2.16), it lies in $\mathcal{M}$ if and only if

$$F'|_{\mathcal{R}} = 0 \in \Gamma(\mathcal{O}_{\mathcal{R}}(\mathcal{R} + \mathcal{D}_R + \mathcal{A} - \mathcal{B})).$$

Let $\vec{r}_i = r_i + \cdots + r_h$; it is the multiplicity of $\mathcal{R}_i$ in $\mathcal{R}$. Since $\vec{g}^\alpha \vec{s}_j$ has vanishing order $r - j$ along $\mathcal{R}_i$, and since $\frac{\alpha}{q_i}$ has vanishing order $\max(0, j - (r - \vec{r}_i))$ along $\mathcal{R}_i$, $S_j = \frac{\alpha}{q_i} \cdot \vec{g}^\alpha \vec{s}_j$ has vanishing order $(r - j) + (j - r + \vec{r}_i) = \vec{r}_i$ along $\mathcal{R}_i$. Thus $S_j$ lies in $\mathcal{M}$.

We now prove that $\mathcal{M}$ is generated by $S_j$'s. Let $F \in \mathcal{M}$. Using (2.16), we denote its image in $\Gamma(\rho_\alpha \mathcal{O}_C(\mathcal{R} + \mathcal{D}_R + \mathcal{A} - \mathcal{B}))$ by $F'$. Using the isomorphism below (2.16), and that $\mathcal{M}$ is a free $\Gamma(\mathcal{O}_\mathcal{V})$-module generated freely by $S_j$, $F'$ can be uniquely expressed as

$$F' = f_1 \cdot \vec{g}^\alpha \vec{s}_1 + \cdots + f_r \cdot \vec{g}^\alpha \vec{s}_r, \quad f_i \in \Gamma(\mathcal{O}_\mathcal{V}).$$

By (2.18), $F'|_{\mathcal{R}} = 0$. In particular, $(u_i)^{\vec{r}_i}$ divides $F'|_{\mathcal{U}_i}$.

We claim that for any positive integer $\alpha$, $u_i^\alpha$ divides $F'|_{\mathcal{U}_i}$ if and only if for all $1 \leq j \leq r$, $f_j|_{\mathcal{U}_i}$ has vanishing order at least $\max(0, \alpha - r - j)$ along $\mathcal{R}_i$. As the if direction is trivial, we prove the only if part. Taking their respective images in $\mathcal{O}_{\mathcal{U}_i}$, $u_i^\alpha$ dividing $F'|_{\mathcal{U}_i}$ implies that

$$(\hat{u}_i)^\alpha \text{ divides } [F'] = \hat{f}_1 \cdot [\vec{g}^\alpha \vec{s}_1] + \cdots + \hat{f}_r \cdot [\vec{g}^\alpha \vec{s}_r] \in K_i[\hat{u}_i].$$

By replacing $u_i$ by $v_i^{-1}$ if necessary, we can assume that $\hat{\zeta}_i = c_i \hat{u}_i v_i$, where $c_i \neq 0 \in K_i^\alpha$. Let $\alpha_j$ be the order of which $f_j|_{\mathcal{U}_i}$ is divisible by $\zeta_i$, then $\hat{f}_j = c_j^{\alpha_j} (\hat{\zeta}_i)^{\alpha_j}$, where $c_j^{\alpha_j} \neq 0 \in K_i^\alpha$. (The case $\hat{f}_j = 0$ is trivially true and is ignored.)

Adding that $[\vec{g}^\alpha \vec{s}_j] = e_j(\hat{u}_i)^{r - j}$ mentioned earlier, (2.19) translates to that $(\hat{u}_i)^\alpha$ divides

$$\sum_{j=1}^r \hat{f}_j \cdot [\vec{g}^\alpha \vec{s}_j] = \sum_{j=1}^r c_j^{\alpha_j} (c_i \hat{u}_i v_i)^{\alpha_j} \cdot e_j(\hat{u}_i)^{r - j} = \sum_{k \geq 0} v_i^k \sum_{\alpha_j = k} (c_j^{\alpha_j} e_j)(\hat{u}_i)^{k + r - j}$$

in $K_i[\hat{u}_i] = K_i[\zeta_i](u_i)$. As $\hat{u}_i$ does not divide $c_j^{\alpha_j} e_j$, this divisibility holds if and only if $(\hat{u}_i)^{\alpha_j}$ divides each individual $v_i^k(\hat{u}_i)^{k + r - j}$, which holds if and only if $\alpha \leq \alpha_j + r - j$ for each $j$ where $f_j \neq 0$. This proves the claim.

Applying the claim to $\alpha = \vec{r}_i$, we conclude that $(u_i)^{\vec{r}_i}$ dividing $F'|_{\mathcal{U}_i}$ implies that $\alpha_j \geq \vec{r}_i - r + j$. This proves that $f_j/\zeta_i[\bar{v}_i]$ is a meromorphic function on $\mathcal{V}$, regular over an open subset of $\mathcal{V}$ containing the generic point of $\mathcal{H}_i$, for each $1 \leq i \leq r$. Since $f_j/\zeta_i[\bar{v}_i]$ is regular over $\mathcal{V} - \cup_i \mathcal{H}_i$, by Hartogs Lemma, it is regular over $\mathcal{V}$.

This proves that $F$ lies in the $\Gamma(\mathcal{O}_\mathcal{V})$ span of $S_1, \cdots, S_r$. Since $\mathcal{M}$ is a rank $r$ free $\Gamma(\mathcal{O}_\mathcal{V})$-modules, it is freely generated by $S_1, \cdots, S_r$. This proves the Sublemma. \qed
We continue the proof of Proposition 2.6.1. Let
\[ b_{ij} = \tilde{S}_j|_{A_i} \in \Gamma(p_\ast \mathcal{O}_{A}(A_i) \cong \Gamma(\mathcal{O}_Y)). \]
Then under \( \{ S_1, \ldots, S_r \} \) and (2.4), \( \varphi^R \) takes the form
\[ B = \begin{bmatrix} b_{11} \zeta_{[a_1]} & b_{12} \zeta_{[a_1]} \zeta_{[b_2]} & b_{13} \zeta_{[a_1]} \zeta_{[b_2]} \zeta_{[c_3]} & \cdots \\ b_{21} \zeta_{[a_1]} & b_{22} \zeta_{[a_1]} \zeta_{[b_2]} & b_{23} \zeta_{[a_1]} \zeta_{[b_2]} \zeta_{[c_3]} & \cdots \end{bmatrix}. \]
By Proposition 2.5.1 under a basis change of \( \mathbf{M} \), \( \varphi^R \) also takes the form
\[ A = \begin{bmatrix} a_{11} \zeta_{[a_1]} & a_{12} \zeta_{[a_1]} \zeta_{[b_2]} & a_{13} \zeta_{[a_1]} \zeta_{[b_2]} \zeta_{[c_3]} & \cdots \\ a_{21} \zeta_{[a_1]} & a_{22} \zeta_{[a_1]} \zeta_{[b_2]} & a_{23} \zeta_{[a_1]} \zeta_{[b_2]} \zeta_{[c_3]} & \cdots \end{bmatrix}, \]
where \( a_{ij} \in \Gamma(\mathcal{O}_Y^e) \). Therefore, \( B = A(\mu_{ij}) \) for a \( (\mu_{ij}) \in GL(r, \mathcal{O}_Y) \). Since \( \zeta_{[q_1,a_1]} \) divides the first row of \( (2.21) \), it divides the first row of \( (2.20) \) as well. Since \( \zeta_{[q_1,a_1]} \) are coprime with \( \zeta_{[b_r]} \) for all \( 1 \leq j \leq r \), we conclude \( \zeta_{[q_1,a_1]} \) divides \( b_{ij} \). Hence, we can write
\[ b_{ij} = \hat{c}_{1j} \zeta_{[q_1,a_1]} \quad \forall \ 1 \leq j \leq r. \]
Let \( (\nu_{ij}) = (\mu_{ij})^{-1} \). Then,
\[ a_{11} \zeta_{[a_1,a_1]} = \nu_{11} \hat{c}_{11} \zeta_{[a_1,a_1]} + \nu_{21} \hat{c}_{12} \zeta_{[a_1,a_1]} \zeta_{[b_2]} + \cdots. \]
Hence, \( a_{11} \neq \nu_{11} \hat{c}_{11} + \nu_{21} \hat{c}_{12} \zeta_{[b_2]} + \cdots. \) Thus \( 0 \neq a_{11}(0) = \nu_{11}(0) \hat{c}_{11}(0). \)
Shrinking \( \mathcal{V} \) if necessary, we can assume \( \hat{c}_{11} \in \Gamma(\mathcal{O}_Y^e) \). This brings the first row of \( (2.20) \) to the desired form. Similar arguments can be applied to the second row. This proves the form in (2.12).

Since \( s_1, s_2 \in H^0(\mathcal{O}_F(q_1 + a - b)) \) have vanishing order \( r - 1 \) and \( r - 2 \) respectively at \( q_1 \), one verifies directly that the image of \( H^0(\mathcal{O}_F(2q_1 + a - b)) \) in \( H^0(\mathcal{O}_F(q_1 + a - b)) \) (via the inclusion) is the subspace spanned by \( s_1 \) and \( s_2 \). By identifying the image of \( H^0(\mathcal{O}_F(2q_1 + a - b)) \) with this subspace, we obtain a homomorphism
\[ H^0(\mathcal{O}_F(2q_1 + a - b)) \overset{s_{12}}{\longrightarrow} k^2, \]
where \( s_{12} = [s_1(a_1) \ s_2(a_1)] = [\hat{c}_{11} \ \hat{c}_{12}] (0) \). Thus, \( \text{rank} \begin{bmatrix} \hat{c}_{11} & \hat{c}_{12} \\ \hat{c}_{21} & \hat{c}_{22} \end{bmatrix} (0) = 1 \)
if and only if \( h^0(\mathcal{O}_F(2q_1 - b)) = 1 \). Since \( b \) is a general point, the evaluation homomorphism at the point \( b, H^0(\mathcal{O}_F(2q_1)) \to k \), is surjective. By the exact sequence
\[ 0 \longrightarrow H^0(\mathcal{O}_F(2q_1 - b)) \longrightarrow H^0(\mathcal{O}_F(2q_1)) \longrightarrow k \longrightarrow 0, \]
h^0(\mathcal{O}_F(2q_1 - b)) = 1 is equivalent to \( h^0(\mathcal{O}_F(2q_1)) = 2 \), which is further equivalent to that \( q_1 \) is a Weierstrass point. Thus, \( \theta_{12}(0) = 0 \) if and only if \( q_1 \) is Weierstrass, which implies \( \delta_1 \) and \( \delta_2 \) are conjugate. We may further require \( \mathcal{S}_j \) extending \( s_j, j = 1, 2 \) so that \( \theta_{12} \) vanishes along the the locus on which \( D_1 \) and \( D_2 \) are conjugate. Mimicking the proof of Proposition 4.13 of [5], one can show that the vanishing order of \( \theta_{12} \) is 1. This proves Parts (1) and (2) We omit further details.
Likewise, for each \( 2 \leq \ell \leq r \), the natural image of \( H^0(\mathcal{O}_F(\ell q_1 + a - b)) \) in \( H^0(\mathcal{O}_F(\ell q_1 + a - b)) \) is the subspace spanned by \( s_1, \ldots, s_\ell \). Assume that rank \( \begin{bmatrix} \hat{c}_{11} & \cdots & \hat{c}_{1\ell} \\ \hat{c}_{21} & \cdots & \hat{c}_{2\ell} \end{bmatrix} (0) \leq 1 \). The argument in the previous paragraph implies \( h^0(\mathcal{O}_F(\ell q_1 - b)) = \ell - 1 \), and consequently \( h^0(\mathcal{O}_F(\ell q_1)) = \ell \). However, by the Riemann-Roch Theorem, \( h^0(\mathcal{O}_F(\ell q_1)) \leq \ell \) with the equality holds if and only if \( q_1 \) is on a non-separating bridge. This shows Parts (3).

Obviously the argument in the above paragraph applies not only to the center \( 0 \in \mathcal{V} \), but also to any \( z \in \mathcal{V} \) satisfying the displayed equalities in Part (4). This implies the former statement of Part (4). Parallel to the proof of Part (2), for any \( 3 \leq j \leq r \), if \( \theta_j \) vanishes at 0, it vanishes at the first order. The latter statement of Part (4) then follows from the assumption that \( \tilde{S}_i \) extends \( s_i, 3 \leq i \leq r \), in general directions. This completes the proof of Proposition 2.6.1 \( \square \)

2.7. Further relations. In this section, assume \( \delta_u, \delta_v, \delta_w \in D \) so that there does not exist any maximal tail rational chain containing a pair of the three points. Each of them may belong to the core \( F \) or a tail component. If \( \delta_u \) lies on a tail, we make the following assumptions.

(D1) We assume \( \delta_u \) is the first marked point in \( D \) on one (and thus all) maximal tail rational chain containing \( \delta_u \), with respect to the order (2.9).

(D2) If a maximal tail rational chain contains marked points in \( D \) other than \( \delta_u \), we denote by \( \delta_v \) the second marked point of the chain with respect to the order (2.9).

We make analogous assumptions to \( \delta_v \) and \( \delta_w \) if they are not on the core.

By Proposition 2.5.1 \( \square \) under the trivializations \( \rho_* \mathcal{M}(D_u) \cong \mathcal{O}_\mathcal{V} \), \( \rho_* \mathcal{M}(D_v) \cong \mathcal{O}_\mathcal{V} \) and \( \rho_* \mathcal{O}_{\mathcal{A}_s}(\mathcal{A}_s) \cong \mathcal{O}_\mathcal{V} \), \( s = 1, 2 \), the restriction homomorphism

\[ \varphi_{uv} : \rho_* \mathcal{M}(D_u) \oplus \rho_* \mathcal{M}(D_v) \rightarrow \rho_* \mathcal{O}_{\mathcal{A}}(\mathcal{A}) \]

can be represented by a matrix

\[ \begin{bmatrix} \phi_{1u} & \phi_{1v} \\ \phi_{2u} & \phi_{2v} \end{bmatrix}, \]

where \( \phi_{iu} \) and \( \phi_{iv} \) are as in Proposition 2.5.1

Set

\[ \lambda_{uv} = \det \begin{bmatrix} \phi_{1u} & \phi_{1v} \\ \phi_{2u} & \phi_{2v} \end{bmatrix} \in \Gamma(\mathcal{O}_\mathcal{V}). \]

Corollary 2.7.1. Assume that \( \langle \delta_u \rangle = \langle \delta_v \rangle = q_1 \) but \( \delta_u, \delta_v \) do not belong to any common maximal tail rational chain.

(1) If \( q_1 \) is not Weierstrass, then \( \lambda_{uv} \sim \zeta_{[\delta_u \wedge \delta_v]} \).

(2) If \( q_1 \) is Weierstrass, there then exists \( \theta_{w,uv} \in \Gamma(\mathcal{O}_\mathcal{V}) \) vanishing to the first order along the locus on which \( D_u \) and \( D_v \) are conjugate such that \( \lambda_{uv} = \theta_{uv,\delta_v} \zeta_{[\delta_u \wedge \delta_v]} \). Moreover, with \( \delta_{v'}, \delta_{v'} \) as in (D2) and \( \theta_{u,v'}, \theta_{v,v'} \) as in Proposition 2.6.1 \( \square \) the zero loci of \( \theta_{uv}, \theta_{u,v'}, \theta_{v,v'} \) are transverse.
(3) If \( q_1 \) is on a maximal non-separating bridge \( B[p, r] \) of \( F \), then the function \( \theta_{uv} \) in Part \([2]\) satisfies the following property: for every \( z \in \mathcal{V} \), if there exist \( p_1 \in \mathcal{N}_{[q_1, p]} \) and \( r_1 \in \mathcal{N}_{[q_1, r]} \) such that \( \zeta_{p_1}(z) = \zeta_{r_1}(z) = 0 \), then \( \theta_{uv}(z) = 0 \).

**Proof.** We follow the notation in the proof of Proposition \( 2.6.1 \).

Let \( R_u \) and \( R_v \) be respectively maximal tail rational chains containing \( \delta_u \) and \( \delta_v \), and \( R'_u \) and \( R'_v \) be respectively the subchains as the closures of \( R_u \backslash (R_u \cap R_v) \) and \( R_v \backslash (R_u \cap R_v) \). We take \( \mathcal{V} \) to be obtained from \( \mathcal{V} \) by collapsing the subchains \( R'_u \) and \( R'_v \), and call the resulting chain \( \mathcal{R}_{uv} \). The image of \( D \cap (R_u \cup R_v) \) in \( \mathcal{F}_{uv} \) is denoted by \( \mathcal{D}_{uv} \). For each \( \delta \in D \cap (R_u \cup R_v) \), its image in \( \mathcal{D}_{uv} \) is denoted by \( \delta \). Note that the node \( q_{uv} = \delta_u \land \delta_v \)

lies on the smooth rational curve \( C_{uv} \) that contains \( \mathcal{D}_{uv} \) and separates it from the core \( F \).

By Proposition \( 2.5.1 \) over the chart \( \mathcal{V} \),

\[
\varphi^{\mathcal{R}_{uv}} = \begin{bmatrix}
c_{1u}\zeta_{[\delta_u, a_1]} & c_{1v}\zeta_{[\delta_v, a_1]} & \cdots \\
c_{2u}\zeta_{[\delta_u, a_2]} & c_{2v}\zeta_{[\delta_v, a_2]} & \cdots 
\end{bmatrix}.
\]

If \( q_1 \) is not Weierstrass, by Part \([1]\) of Proposition \( 2.6.1 \) we observe that

\[
\det \begin{bmatrix}
c_{1u} & c_{1v} \\
c_{2u} & c_{2v}
\end{bmatrix} \sim \zeta_{[q_{uv}]} \in \Gamma(\mathcal{O}_P).
\]

Pulling \( \varphi^{\mathcal{R}_{uv}} \) back to \( \mathcal{V} \), we obtain

\[
\varphi^{R_u \cup R_v} = \begin{bmatrix}
c_{1u}\zeta_{[\delta_u, a_1]} & c_{1v}\zeta_{[\delta_v, a_1]} & \cdots \\
c_{2u}\zeta_{[\delta_u, a_2]} & c_{2v}\zeta_{[\delta_v, a_2]} & \cdots 
\end{bmatrix}, \quad \lambda_{uv} \sim \zeta_{[q_{uv}]} = \zeta_{[\delta_u \land \delta_v]},
\]

where \( \lambda_{uv} \) is as in \( 2.23 \). This completes Part \([1]\). Part \([2]\) follows from Proposition \( 2.6.1 \) and Part \([1]\). Part \([3]\) holds because for every \( z \) satisfying the assumption of \([3]\) \( \langle D_u(z) \rangle \) and \( \langle D_v(z) \rangle \) are on the same non-separating bridge of the core of \( z \), hence are conjugate to each other. \( \square \)

**Corollary 2.7.2.** Assume \( \langle \delta_u \rangle = \langle \delta_v \rangle = \langle \delta_w \rangle = q_1 \) so that each pair among \( \delta_u, \delta_v, \) and \( \delta_w \) do not belong to any common maximal tail rational chain. If \( q_1 \) is Weierstrass, then with \( \theta_{uv}, \theta_{uw} \) as in Part \([2]\) of Corollary \( 2.7.1 \) there exist \( f_{uvw}, g_{uvw} \in \Gamma(\mathcal{O}_P) \) such that

\[
\theta_{uv} \sim f_{uvw}\theta_{uv} + g_{uvw}\zeta_{[\delta_u \land \delta_w]}.
\]

Moreover, if \( q_1 \) does not lie on any bridge of the core \( F \), then \( g_{uvw} \in \Gamma(\mathcal{O}_P) \); if \( q_1 \) lies on a non-separating bridge of \( F \), the zero loci of \( \theta_{uv} \) and \( g_{uvw} \) are then transverse.

**Proof.** Let \( R_u, R_v, \) and \( R_w \) be maximal tail rational chains containing \( \delta_u, \delta_v, \) and \( \delta_w \), respectively. We denote by \( R'_u, R'_v, \) and \( R'_w \) respectively the subchains as the closure of \( R_u \backslash (R_u \cap R_v \cap R_w), \ R_v \backslash (R_u \cap R_v \cap R_u), \) and
$R_w \setminus (R_u \cap R_v \cap R_w)$. We take $\mathcal{V}$ to be obtained from $\mathcal{V}$ by collapsing the subchains $R_u'$, $R_v'$, and $R_w'$, and call the resulting chain $\overline{R}_{uvw}$.

The rest of proof is analogous to that of Corollary 2.7.1 but in addition to the application of Parts (1) and (2) of Proposition 2.6.1, Parts (3) and (4) of the same proposition are also needed. We omit further details. □

**Corollary 2.7.3.** Assume that $\langle \delta_u \rangle \neq \langle \delta_v \rangle$, i.e. no tail contains both $\delta_u$ and $\delta_v$.

1. If $\delta_u$ is not conjugate to $\delta_v$, then $\lambda_{uv} \in \Gamma(\partial^*_V)$.

2. If $\delta_u$ is conjugate to $\delta_v$, then $\lambda_{uv}$ vanishes to the first order along the locus on which $D_u$ and $D_v$ are conjugate. Moreover, with $\delta_{v'}$, $\delta_{v''}$ as in (D2) and $\theta_{u,v'}$, $\theta_{v,v''}$ as in Proposition 2.6.1, the zero loci of $\lambda_{uv}$, $\theta_{u,v'}$, and $\theta_{v,v''}$ are transverse.

3. If $\delta_u$ is conjugate to $\delta_v$, and $\langle \delta_u \rangle$ is on a maximal non-separating bridge $B[p,r]$ of $F$, then so is $\langle \delta_v \rangle$. Moreover, for every $z \in \mathcal{V}$, if there exist $p_1 \in N_{[0,1]}$ and $r_1 \in N_{[0,1]}$ such that $\zeta_{p_1}(z) = \zeta_{r_1}(z) = 0$, then $\lambda_{uw}(z) = 0$. Furthermore,

- if $\langle \delta_u \rangle = \langle \delta_w \rangle$, and $\delta_u$, $\delta_w$ do not belong to any common maximal tail rational chain, then with $\theta_{uw}$ as in Corollary 2.7.1 the zero loci of $\lambda_{uw}$ and $\theta_{uw}$ are transverse;
- if $\langle \delta_u \rangle$, $\langle \delta_v \rangle$, and $\langle \delta_w \rangle$ are pairwise distinct and belong to the same non-separating bridge, then the zero loci of $\lambda_{uw}$ and $\lambda_{uw}$ are transverse.

**Proof.** The statements follow from a semi-stable reduction argument parallel to the proof of Proposition 2.6.1. □

**2.8. Weierstrass and conjugate loci vs. modular parameters.** Let $\mathcal{W}_{k,i}$ and $\mathcal{K}_{k,i,j}$ be the Weierstrass and the conjugate loci in $\overline{\mathcal{M}}_{2,k}$, respectively; c.f. [2.2]. We have shown that they are Cartier divisors, and for $k = 1$ (resp. $k = 2$), $\mathcal{W}_{1,1} = \mathcal{W}$ (resp. $\mathcal{K}_{2,1,2} = \mathcal{K}$) is also smooth.

For $k \geq 1$, 1, the locus $\mathcal{W}_{k,i}$ is the pullback of $\mathcal{W}_{1,1}$ via the forgetful map $\pi_{k,i} : \overline{\mathcal{M}}_{2,k} \to \overline{\mathcal{M}}_{2,1}$. Each $\mathcal{W}_{k,i}$ is possibly singular along the closed locus $\mathcal{W}^{n-s}_{k,i}$ where the $i$-th marked point is on a non-separating bridge; it is smooth on $\mathcal{W}_{k;i} \setminus \mathcal{W}^{n-s}_{k,i}$. More precisely, for $x = (C; t_1, \ldots, t_n) \in \mathcal{W}^{n-s}_{k,i}$ ($\subset \mathcal{W}_{k,i}$), let $B = B[p,q] \subset C$ be the maximal non-separating bridge containing the marked point $t_i$. The complement of $B$ in $C$ is an elliptic curve $C_1$. We denote by $x' = (C'; t'_i)$ the image of $x$ in $\mathcal{W}_{1,1}$. Then, $C'$ consists of an inseparable elliptic curve $C'_1$ and a smooth rational curve $B'$ containing $t'_i$ such that $C'_1 \cap B' = \{p', q'\}$.

Since $\mathcal{W}_{1,1}$ is smooth, there exist a smooth chart $\mathcal{V} \subset \overline{\mathcal{M}}_{2,1}$ containing $x'$ and a local parameter $\lambda'$ on $\mathcal{V}$ such that

$$\mathcal{W}_{1,1} \cap \mathcal{V} = \{\lambda' = 0\}.$$
Let \( \{ \zeta'_p \} \) be a set of modular parameters on \( \mathcal{V}' \) as in \( \ref{2.5} \) centered at \( x' \). Then,
\[
\mathcal{W}_{1,1}^{n-s} \cap \mathcal{V}' = \{ \zeta'_p = \zeta'_q = 0 \}.
\]
This implies \( \lambda' = 0 \) whenever \( \zeta'_p = \zeta'_q = 0 \), so there exist \( f, g \in \Gamma(\mathcal{O}_{\mathcal{V}'}) \) so that
\[
\lambda' = f \zeta'_p + g \zeta'_q.
\]
Since \( \lambda' \) is a local parameter, by symmetry we have
\[
f|_{\mathcal{W}_{1,1}^{n-s} \cap \mathcal{V}'} \, g|_{\mathcal{W}_{1,1}^{n-s} \cap \mathcal{V}'} \in \Gamma(\mathcal{O}_{\mathcal{W}_{1,1}^{n-s} \cap \mathcal{V}'})).
\]
Thus, shrinking \( \mathcal{V}' \) if necessary, we can use \( f \zeta'_p \) and \( g \zeta'_q \) as new modular parameters instead of \( \zeta'_p \) and \( \zeta'_q \), respectively, and obtain
\[
(2.24)
\]
Lemma 2.8.1. With notation as above, there exist a smooth chart \( \mathcal{V} \) containing \( x \) and a set of modular parameters \( \{ \zeta_q \} \) on \( \mathcal{V} \) centered at \( x \) so that
\[
\mathcal{W}_{k;i} \cap \mathcal{V} = \{ \zeta_{[t_i,p]} + \zeta_{[t_j,q]} = 0 \}.
\]
Proof. Notice that up to a nowhere vanishing function, the modular parameter \( \zeta'_p \) (resp. \( \zeta'_q \)) pulls back to the product \( \zeta_{[t_i,p]} \) (resp. \( \zeta_{[t_j,q]} \)) on \( \mathcal{V} \). This, along with (2.24), establishes Lemma 2.8.1. \( \square \)

Analogously, when \( k > 2 \), the locus \( \mathcal{K}_{k;i,j} \) is the pullback of \( \mathcal{W}_{2,1,2} \) via the forgetful map \( \pi_{k;i,j} : \mathcal{M}_{2,k} \to \mathcal{M}_{2,2} \). Each \( \mathcal{K}_{k;i,j} \) is possibly singular along the closed locus \( \mathcal{K}_{k;i,j}^{n-s} \subset \mathcal{K}_{k;i,j} \) where the \( i, j \)-th marked points are on a same non-separating bridge; it is smooth on \( \mathcal{K}_{k;i,j} \setminus \mathcal{K}_{k;i,j}^{n-s} \). The following statement is parallel to Lemma 2.8.1 so is its proof.

Lemma 2.8.2. Given \( x = (C; t_1, \ldots, t_k) \in \mathcal{K}_{k;i,j}^{n-s} \), let \( B = B[p, q] \subset C \) be the maximal non-separating bridge containing the marked points \( t_i \) and \( t_j \). W.l.o.g. assume that \( N_{[t_i,p]} \subset N_{[t_j,p]} \). Then there exist a smooth chart \( \mathcal{V} \) containing \( x \) and a set of modular parameters \( \{ \zeta_q \} \) on \( \mathcal{V} \) centered at \( x \) so that
\[
\mathcal{K}_{k;i,j} \cap \mathcal{V} = \{ \zeta_{[t_i,p]} + \zeta_{[t_j,q]} = 0 \}.
\]

3. Local properties of sequences of blowups

In this section, we describe the local models of the globally defined modular blowups in \( \ref{3} \).

The following notation will be assumed throughout \( \ref{3} \). For all \( j, k \in \mathbb{Z}_{>0} \), we write
\[
[j, k] = \{ j, j+1, \ldots, k \}, \quad [k] = [1, k]
\]
for conciseness. Given an affine smooth chart \( \mathcal{V} \) of a stack \( \mathfrak{M} \) and \( f, g \in \Gamma(\mathcal{O}_\mathcal{V}) \), we write
\[
f \sim g \quad \text{if} \quad f/g \in \Gamma(\mathcal{O}_\mathcal{V}^*).
\]
3.1. **Local parameters.** Let \( V \) be an affine smooth chart of a stack \( \mathcal{M} \) with local parameters \( z_1, \ldots, z_r \). Assume \( Z \subseteq \mathcal{M} \) is a closed codimension \( \ell \) substack locally given by

\[
z_1 = \cdots = z_\ell = 0.
\]

Let \( \mathcal{M} \) be the blowup of \( \mathcal{M} \) along \( Z \), \( \pi: \mathcal{M} \to \mathcal{M} \) be the projection, and \( E \) be the exceptional divisor. If \( \mathfrak{M} \) is a substack of \( \mathcal{M} \), we denote by

\[
\mathfrak{M} = \text{PT}(\mathfrak{M}) = \pi^{-1}(\mathfrak{M} \setminus Z) \quad \text{and} \quad \mathfrak{M} = \pi^{-1}(\mathfrak{M})
\]

the proper transform and the pullback of \( \mathfrak{M} \) in \( \mathcal{M} \), respectively. Set

\[
E(3.3) \quad \Delta_r
\]

Every \( x \in E \cap \pi^{-1}(V) \) is in the form

\[
\tilde{x} = (0, \ldots, 0, \tilde{z}_{r+1}, \ldots, \tilde{z}_r; [x_1, \ldots, x_\ell]).
\]

Let

\[
\Delta_x = \{ k \in [\ell] : x_k \neq 0 \} \subset [\ell].
\]

Since \( \tilde{x} \in E \), the entries \( x_1, \ldots, x_\ell \) cannot be zero simultaneously. Thus, \( \Delta_x \neq \emptyset \).

For each nonempty \( S \subset [\ell] \), let

\[
E(S) = \{ x \in E \cap \pi^{-1}(V) : \Delta_x \subset S \} \subset E \cap \pi^{-1}(V).
\]

Such defined \( E(S) \) is smooth, closed, and of codimension \( \ell - |S| + 1 \) in \( \pi^{-1}(V) \).

**Lemma 3.1.1.** **For every** \( \tilde{x} \in E \cap \pi^{-1}(V) \), **there is an affine smooth chart** \( \tilde{V}_x \subset \pi^{-1}(V) \) **containing** \( \tilde{x} \) **so that**

\[
\tilde{z}_i \mid \tilde{z}_j, \quad \text{PT}\{z_j = 0\} \cap \tilde{V}_x = \left\{ \tilde{z}_j = 0 \right\} \quad \forall \ i \in \Delta_x, \ j \in [\ell].
\]

Moreover, if \( i \in \Delta_x \) and \( j \in [\ell] \setminus \Delta_x \), then \( \tilde{z}_j / \tilde{z}_i \) is a regular function on \( \tilde{V}_x \).

**Proof.** Every point in \( \tilde{V}_x \) is in the form \( (\tilde{z}_1, \ldots, \tilde{z}_r; [y_1, \ldots, y_\ell]) \) so that

\[
\tilde{z}_i y_j = \tilde{z}_j y_i \quad \forall \ i, j \in [\ell].
\]

Shrinking \( \tilde{V}_x \) if necessary, we may assume \( y_i \) does not vanish on \( \tilde{V}_x \) for all \( i \in \Delta_x \). Thus, \( \tilde{z}_j = (y_j / y_i) \tilde{z}_i \) for all \( j \in [\ell] \). This leads to the two statements in the display. The last statement follows from a direct check. \( \square \)

Let \( \tilde{V}_x \) be as in Lemma 3.1.1. For each \( i \in \Delta_x \), the zero locus of \( \tilde{z}_i \) on \( \tilde{V}_x \) is the same as \( E \cap \tilde{V}_x \). We select an arbitrary \( i \in \Delta_x \) and set

\[
\varepsilon = \tilde{z}_i \mid \tilde{V}_x \in \Gamma(\mathcal{O}_{\tilde{V}_x}).
\]

**Corollary 3.1.2.** **Let** \( \tilde{V}_x \) **be the affine smooth chart in Lemma 3.1.1.** **Then,**

\[
\varepsilon; \quad \tilde{z}_j = \frac{\varepsilon_j}{\varepsilon}, \ j \in [\ell] \setminus \Delta_x; \quad \tilde{z}_k, \ k \in [\ell + 1, r],
\]

form a subset of a family of local parameters on \( \tilde{V}_x \).
Proof. By Lemma 3.1.1, $\varepsilon$ and $\tilde{z}_j$, $j \in [\ell] \setminus \Delta x$ can be considered as local parameters. In addition, it follows from a direct check that on $\pi^{-1}(V)$,
\[
\{ \tilde{z}_k = 0 \} = \text{PT} \{ z_k = 0 \} \quad \forall \ k \in [\ell+1, r].
\]
We point out that $\tilde{\nu}_x$ contains other local parameters describing the positions of points in $\nu \in \nu_x$:
\[
\Delta_{\nu} \subset \nu_x.
\]
We will always denote by $\tilde{z}_j$, $j \in [\ell] \setminus \Delta_x$, the pullback of $z_j$ as in (3.2), and by $\tilde{z}_j$, $j \in [\ell] \setminus \Delta_x$, the proper transform of $z_j$ as in (3.5).

3.2. Locally tree-compatible blowups. Given a connected graph $\gamma$, we denote by $\text{Ver} \gamma$ and $\text{Edg} \gamma$, and $\text{Edg} \gamma$, respectively. If $\text{Ver} \gamma = \emptyset$, we denote the empty graph by $\emptyset$.

If in addition $\gamma$ is a rooted tree with the root $o$, then $\text{Ver} \gamma$ is endowed with a natural partial order $<$, called the tree order, so that $v < v'$ if and only if $v \neq v'$ and $v$ belongs to a path between $o$ and $v'$. Each edge $e \in \text{Edg} \gamma$ has two endpoints $v_e^-$ and $v_e^+$ in $\text{Ver} \gamma$ so that
\[
v_e^- < v_e^+.
\]
This induces a partial order $<$ on $\text{Edg} \gamma$, also called the tree order, so that
\[
e < e' \quad \iff \quad v_e^- < v_e^+.
\]
For each $E \subset \text{Edg} \gamma$, we write
\[
E^< = \bigcup_{e \in E} \{ e' \in \text{Edg} \gamma : e' < e \}, \quad E^\leq = E^< \sqcup E,
\]
\[
E^> = \bigcup_{e \in E} \{ e' \in \text{Edg} \gamma : e' > e \}, \quad E^\geq = E^> \sqcup E.
\]

The root $o$ is the unique minimal element of $\text{Ver} \gamma$; each of the minimal elements of $\text{Edg} \gamma$, called a pivotal edge, contains $o$ as an endpoint. We denote by $E_o(\gamma)$ the collection of the pivotal edges. When the context is clear, we write
\[
E_o = E_o(\gamma).
\]
For each $e \in \text{Edg} \gamma$, let $\langle e \rangle \in E_o$ be such that
\[
\langle e \rangle \leq e.
\]
The maximal elements of $\text{Ver} \gamma$ and $\text{Edg} \gamma$ are respectively called terminal vertices and terminal edges; they form the subsets
\[
\text{Ver} \gamma^t \subset \text{Ver} \gamma \quad \text{and} \quad \text{Edg} \gamma^t \subset \text{Edg} \gamma,
\]
respectively.

For each $e \in \text{Edg} \gamma$, there is a unique induced subgraph $\gamma_e$ of $\gamma$ satisfying
\[
\text{Edg} \gamma_e = \{ e' \in \text{Edg} \gamma : e' > e \} \subset \text{Edg} \gamma.
\]
Such defined $\gamma_e$ is a rooted tree with the root $v^+_e$; we call $\gamma_e$ a \textit{branch} of $\gamma$. If in addition $e \in E_0$, we call $\gamma_e$ a \textit{pivotal branch}.

A subset $E \subseteq \text{Edg}(\gamma)$ is called a \textit{traverse section} of $\gamma$ if for each $v \in \text{Ver}(\gamma)^t$, each path between $o$ and $v$ contains exactly one element of $E$. The collection of all traverse sections of $\gamma$ is denoted by $\text{ET}(\gamma)$; it is endowed with a partial order $\prec$ such that for any $E, E' \in \text{ET}(\gamma)$,

\begin{equation}
E \prec E' \iff \{ E \neq E' \} \text{ and } (\forall \ e' \in E', \exists \ e \in E \text{ s.t. } e \preceq e').
\end{equation}

The unique minimal element of $\text{ET}(\gamma)$ is $E_0$.

Let $\gamma$ be a rooted tree and $\mathcal{V}$ be an affine smooth chart of a stack $\mathfrak{M}$. If there exists a collection of local parameters on $\mathcal{V}$ so that a subset of which can be written as

\begin{equation}
\{ z_e \in \Gamma(\mathcal{O}_\mathcal{V}) : e \in \text{Edg}(\gamma) \},
\end{equation}

then \textbf{(3.8)} is called a $\gamma$-\textit{labeled subset of local parameters} on $\mathcal{V}$. We set

\begin{equation}
z_{[e]} = \prod_{\ell \leq e} z_{e'}, \ \forall e \in \text{Edg}(\gamma).
\end{equation}

Every nonempty subset $E$ of $\text{Edg}(\gamma)$ determines a closed locus $Z_E$ in $\mathcal{V}$ by

\begin{equation}
Z_E = \{ x \in \mathcal{V} : z_e(x) = 0 \ \forall \ e \in E \}.
\end{equation}

In addition, we set

\begin{equation}
Z_\gamma = Z_{\text{Edg}(\gamma)}, \quad Z_{\emptyset} = \emptyset.
\end{equation}

With notation as above, let

\begin{equation}
\pi : \widehat{\mathfrak{M}} \longrightarrow \mathfrak{M} \quad \text{ and } \quad \pi(k) : \widehat{\mathfrak{M}}(k) \longrightarrow \mathfrak{M}, \quad k \in \llbracket \ell \rrbracket,
\end{equation}

be the blowup of $\mathfrak{M}$ successively along the proper transforms of a sequence of closed substacks

\begin{equation}
Z_1, \ldots, Z_\ell \subset \mathfrak{M}
\end{equation}

and the same blowup of $\mathfrak{M}$ after the $k$-th step, respectively.

\textbf{Definition 3.2.1.} The blowup $\pi$ in \textbf{(3.10)} is said to be $\gamma$-\textit{compatible} on $\mathcal{V}$ if there exist a partition of $\text{ET}(\gamma)$:

\begin{equation}
\text{ET}(\gamma) = \bigsqcup_{k=1}^\ell \text{ET}(\gamma)_k = \bigsqcup_{k=1}^\ell \{ E_1^k, \ldots, E_n^k \}
\end{equation}

and a $\gamma$-labeled subset of local parameters on $\mathcal{V}$ such that

\begin{enumerate}[(C1)]
\item for each $k \in \llbracket \ell \rrbracket$,
\end{enumerate}

\begin{equation}
Z_k \cap \mathcal{V} = Z_{E_1^k} \cup \cdots \cup Z_{E_n^k};
\end{equation}

\begin{enumerate}[(C2)]
\item if $E' \in \text{ET}(\gamma)_k$, $E'' \in \text{ET}(\gamma)_k$, and $E' \prec E''$, then $k' < k''$.
\end{enumerate}

Note that \textbf{(C1)} implies that if $\text{ET}(\gamma)_k = \emptyset$ for some $k$ (i.e. $n_k = 0$), then $Z_k$ is disjoint from $\mathcal{V}$ because $Z_{\emptyset} = \emptyset$. Therefore, adding (resp. deleting) arbitrarily many blowup loci that are disjoint from $\mathcal{V}$ to (resp. from) an existing sequence of blowups does not affect the $\gamma$-compatibility on $\mathcal{V}$. 
The condition *(C2)* has two immediate conclusions. First, a sequence of blowups \( \gamma \)-compatible on \( \mathcal{V} \) must begin with \( Z_{E_0} \). The second conclusion is the next lemma.

**Lemma 3.2.2.** Let \( \pi: \tilde{\mathcal{M}} \to \mathcal{M} \) be \( \gamma \)-compatible on \( \mathcal{V} \) as in Definition 3.2.1. Then for each \( k \in \mathbb{N} \), the proper transforms of \( Z_{E_1}, \ldots, Z_{E_n} \) after the first \( k-1 \) steps are pairwise disjoint and smooth. Therefore, the proper transform of \( Z_k \cap \mathcal{V} \) after the first \( k-1 \) steps consists of one or more smooth connected components.

**Proof.** For distinct \( i, j \in \mathbb{N}_k \), notice that \( E^i_k \) and \( E^j_k \) are not comparable. With \( E^i_k \) and \( E^j_k \) denoting the greatest common predecessor of \( E^i_k \) and \( E^j_k \) with respect to the order \( \preceq \) in (3.7), we have

\[ E \prec E^i_k, \quad E \prec E^j_k, \quad Z_{E^i_k} \cap Z_{E^j_k} \subset Z_E. \]

By *(C2)*, there is a unique \( h \in \mathbb{N}_k \) such that \( E \in \text{ET}(\gamma)_h \). It is then a direct check that the proper transforms of \( Z_{E^i_k} \) and \( Z_{E^j_k} \) are smooth after every step, and they become disjoint after step \( h \); see [14, Lemma 2.3 & Corollary 2.4] for more details. \( \square \)

By Lemma 3.2.2, the effect of a blowup that is \( \gamma \)-compatible on \( \mathcal{V} \) is the same as blowing up \( \mathcal{V} \) successively along the proper transforms of

\[ Z_E, \quad E \in \text{ET}(\gamma) \]

with respect to any total order on \( \text{ET}(\gamma) \) extending the partial order \( \prec \) in (3.7). Hence the exceptional divisor \( \mathcal{E}_{Z_k} \) obtained in the \( k \)-th step has \( n_k \) connected components

\[ (3.11) \quad \mathcal{E}_{E^1_k}, \ldots, \mathcal{E}_{E^n_k} \]

on \( \pi^{-1}_E(V) \). Each \( \mathcal{E}_{E^i_k} \) is obtained by blowing up \( \pi^{-1}_{(k-1)_i}(V) \) along the proper transform of \( Z_{E^i_k} \). Thus for each \( E \in \text{ET}(\gamma) \), (3.11) determines the exceptional divisor

\[ (3.12) \quad \mathcal{E}_E \subset \pi^{-1}_E(V) \quad \text{if} \quad E \in \text{ET}(\gamma)_k. \]

Moreover, it is a direct check that \( \mathcal{E}_E \) is transverse to the proper transforms of \( Z_{E^i} \) for all \( E^i \in \text{ET}(\gamma)_k, k' > k \). Thus, the proper transform of \( \mathcal{E}_E \) in \( \pi^{-1}(V) \) is the same as its pullback, i.e.

\[ (3.13) \quad \check{\mathcal{E}}_E = \mathcal{E}_{\pi^{-1}(\mathcal{E}_E)} \quad \forall \ E \in \text{ET}(\gamma). \]

Finally, we comment that the notions of \( \mathcal{E}_E \) and \( \check{\mathcal{E}}_E \) are intrinsic to \( \mathcal{V} \) and \( \gamma \). They are independent of the choice of the \( \gamma \)-compatible blowup on \( \mathcal{V} \).

**Remark 3.2.3.** Definition 3.2.1 applies to the empty graph \( \gamma = \emptyset \) trivially. A sequence of blowups \( \emptyset \)-compatible on \( \mathcal{V} \) is equivalent to that the blowup loci do not intersect \( \mathcal{V} \).
Definition 3.2.4. The blowup \( \pi : \hat{M} \to M \) in (3.10) is said to be locally tree-compatible if \( M \) has an étale cover of affine smooth charts \( \{ V \} \) so that each \( V \) is associated with a graph \( \gamma_V \) that is either a rooted tree or the empty graph, and \( \pi \) is \( \gamma_V \)-compatible on \( V \) for all \( V \in \{ V \} \).

Lemma 3.2.2 gives rise to the following smoothness statement.

Corollary 3.2.5. If the blowup \( \pi : \hat{M} \to M \) in (3.10) is locally tree-compatible, then for each \( k \in \mathbb{N} \), the proper transform of \( Z_k \) after the first \( k-1 \) steps is smooth.

Remark 3.2.6. An example of locally tree-compatible blowups is the desingularization of \( M = \mathcal{M}_1(\mathbb{P}^n, d) \), via either the symplectic approach in [14] or the algebraic approach in [5]. The subtle difference is the (idealized) blowup in [14] is on \( M_1(\mathbb{P}^n, d) \) directly, whereas in [5], the blowup is applied to the Artin stack \( \mathcal{M}_1^{\text{wt}} \) and a fiber product is taken at the end. Nonetheless the blowup in either approach is locally tree-compatible.

Consider the approach in [5] for example. The blowup loci \( \Theta_k \) described in [5, §1] can be illustrated by the substacks

\[
Z_k \equiv \mathcal{M}_{(1,k+1)}
\]

in Figure 1 but with the genus-2 core replaced by a genus-1 core. For every \( x \in \mathcal{M}_1^{\text{wt}} \), let \( \gamma \) be its terminally weighted tree in the sense of [5, Paragraph 3.16]; also see [4, §1]. Then there exists an affine smooth chart \( V \) containing \( x \) so that the collection of modular parameters \( \{ \zeta_e \}_{e \in \text{Edg}(\gamma)} \) (corresponding to node-smoothing) is a \( \gamma \)-labeled subset of local parameters on \( V \). Each \( Z_k \) as above satisfies

\[
Z_k \cap V = \bigcup_{E \in \text{ET}(\gamma)} Z_E.
\]

It is a direct check that the blowup successively along the proper transforms of \( Z_1, \ldots, Z_d \) is \( \gamma \)-compatible on \( V \), which indicates the sequential blowup in [5] is locally tree-compatible.

![Figure 3. Rooted trees](image)

For a concrete example, consider the tree \( \gamma \) illustrated in the second diagram of Figure 3. The sequential blowup described in the previous paragraph determines

\[
\text{ET}(\gamma) = \{ E_1^1 \equiv \{ e_a, e_b \} \} \cup \{ E_2^1 \equiv \{ e_a, e_c, e_d \} , E_2^2 \equiv \{ e_b, e_f, e_g \} \} \\
\cup \{ E_3^1 \equiv \{ e_f, e_g, e_c, e_d \} \}
\]
such that
\[ Z_1 \cap V = Z_{E_1}, \quad Z_2 \cap V = Z_{E_1} \cup Z_{E_2}, \quad Z_3 \cap V = Z_{E_3}, \quad E_1^1 < E_2^1, E_2^2 < E_3^1, \]
thus \([C1]\) and \([C2]\) in Definition 3.2.1 are satisfied. We remark here that \(Z_2 \cap V\) is singular: the two smooth loci \(Z_{E_1}^1 \cap Z_{E_2}^1\) meet at \(Z_{E_1}^1 \cap Z_{E_2}^1\). Nonetheless, after blowing up along \(Z_1\), the proper transforms of \(Z_{E_1}^1 \cap Z_{E_2}^1\) are smooth and meet the exceptional divisor \(E_{E_1} \cap \tilde{V} = E_{E_1}^1\) at the loci \([\zeta_0, \zeta_0] = [0, 1]\) and \([\zeta_0, \zeta_0] = [1, 0]\), respectively, hence are disjoint.

At the end of this subsection, we describe a sequential blowup induced from a \(\gamma\)-compatible sequential blowup on \(V\). This is related to the modular blowups in \(r_3\).

Given a rooted tree \(\gamma\) with the root \(o\), let \(\gamma'\) be the rooted tree with the same root \(o\) and an extra vertex \(v\) directed connected to \(o\), i.e.

\[ \text{Ver}(\gamma') = \text{Ver}(\gamma) \cup \{v\}, \quad \text{Edg}(\gamma') = \text{Edg}(\gamma) \cup \{e\}, \quad v^+ = v, \quad v^- = o. \]

Assume that \(V\) contains a \(\gamma\)-labeled subset of local parameters.

Let \(\pi : \tilde{M} \to M\) be \(\gamma\)-compatible on \(V\). A blowup

\[ \pi_+ : \tilde{M}_+ \to M \]
successively along the proper transforms of closed substacks \(Z_{1,+}, \ldots, Z_{r,+}\) of \(M\) is said to be supplementary to \(\pi\) on \(V\) if

\[ Z_{k,+} \cap V = Z_{E_{k+}^1 \cup \{e\}} \cup \cdots \cup Z_{E_{k+}^n \cup \{e\}} \quad \forall k \leq [r]. \]

A blowup \(\emptyset\)-compatible on \(V\) is supplementary to any blowup \(\emptyset\)-compatible on \(V\).

Over the entire stack \(M\) instead of locally on \(V\), \(\pi_+\) is said to be supplementary to \(\pi\) if \(\pi_+\) is locally tree-compatible with an étale cover \(\{V\}\) as in Definition 3.2.4 so that \(\pi_+\) is supplementary to \(\pi\) on all \(V \in \{V\}\).

The construction of \(\gamma_+\) leads to the following statement immediately.

**Lemma 3.2.7.** Let \(\pi : \tilde{M} \to M\) and \(\pi_+ : \tilde{M}_+ \to M\) be two sequential blowups. If \(\pi\) is \(\gamma\)-compatible on \(V\) and \(\pi_+\) is supplementary to \(\pi\) on \(V\), then \(\pi_+\) is \(\gamma_+\)-compatible on \(V\). If \(\pi_+\) is supplementary to \(\pi\) on \(M\), then \(\pi_+\) is locally tree-compatible.

### 3.3. Ascending sequences and dominant edges.
We continue with the notation from §3.2. Assume the blowup \(\pi : \tilde{M} \to M\) is \(\gamma\)-compatible on \(V\) as in Definition 3.2.1. For each \(E \in \text{ET}(\gamma)\), we still use \(\tilde{E}\) to denote the proper transform of the exceptional divisor \(E\) in (3.12). By (3.13), it is the same as the pullback of \(E\).

By Lemma 3.2.2, given

\[ \tilde{x} \in \pi^{-1}(Z_{\gamma}) \subset \pi^{-1}(V), \]

there exists a unique maximal sequence \( E = (E_1, \ldots, E_t) \) of elements of \( ET(\gamma) \) such that

\[
E_1 < \cdots < E_t, \quad \bar{x} \in \bar{E}_1 \cap \cdots \cap \bar{E}_t.
\]

By Definition 3.2.1 and the maximality of \( E \),

\[
\bigcup_{i=1}^{k} E_i = E_k^< \quad \forall k \in [t];
\]

c.f. (3.6) for notation. We call \( E \) the ascending sequence of \( r_x \).

Recall that \( \pi_{(k)} : \mathcal{M}(k) \to \mathcal{M} \) denotes the blowup after the \( k \)-th step. Given \( i \in \mathbb{I} \), there exists a unique step \( k = k(i) \) of the sequential blowup in which

\[
E_i \subset \mathcal{E}_{Z_k} \cap \pi_{(k)}^{-1}(\mathcal{V}).
\]

Let \( \bar{x}_{(i)} \) be the image of \( \bar{x} \) in \( \mathcal{M}(k) \). The latter condition in (3.14) implies that

\[
\bar{x}_{(i)} \in E_i.
\]

We can thus define \( \Delta_{\bar{x}, i} \subset E_i \) analogously to (3.3), with \( \bar{x} \) and \( [t] \) in (3.3) replaced by \( \bar{x}_{(i)} \) and \( E_i \), respectively. By (3.14),

\[
\Delta_{\bar{x}, i} = E_i \setminus E_{i+1} \quad \forall i \in [t-1].
\]

When \( i = t \), the maximality of \( E \) implies

\[
\Delta_{\bar{x}, t} \cap \text{Edg}(\gamma)^t \neq \emptyset \quad \text{(} \implies E_t \cap \text{Edg}(\gamma)^t \neq \emptyset \text{)}.
\]

**Definition 3.3.1.** The edges in

\[
\text{Dom}(\bar{x}) = \Delta_{\bar{x}, t} \cap \text{Edg}(\gamma)^t
\]

are called dominant edges of \( \bar{x} \). A branch of \( \gamma \) that contains at least one dominant edge is called a dominant branch of \( \bar{x} \). If a dominant branch is also pivotal, it is called a dominant pivotal branch.

With notation as above, we set

\[
\begin{align*}
\text{DP}(\bar{x}) &= \text{DP}_\gamma(\bar{x}) = \{e : e \in \text{Dom}(\bar{x})\} \subset E_\alpha(\gamma), \\
\text{DPN}(\bar{x}) &= \text{DPN}_\gamma(\bar{x}) = \{q_e : e \in \text{DP}(\bar{x})\}.
\end{align*}
\]

The latter is the collection of the (pivotal) nodes of \( \pi(\bar{x}) \) labeled by \( \text{DP}(\bar{x}) \).

The dominant pivotal branches of \( \bar{x} \) are indexed by \( \text{DP}(\bar{x}) \).

By (3.14), each \( e \in E_{\bar{x}, i}^< \) is contained in at least one \( E_i \) with \( i \in [t] \); let

\[
s(e) = \max \{ i \in [t] : e \in E_i \}.
\]

This implies \( e \in \Delta_{\bar{x}, s} \).

For each \( i \in [t] \), the exceptional divisor \( \mathcal{E}_{E_i} \) is the zero locus of a local parameter \( \bar{\varepsilon}_i \) on an affine smooth chart \( \mathcal{V}_{\bar{x}, i} \) containing \( \bar{x}_{(i)} \). The proper transform \( \bar{\mathcal{E}}_{E_i} \) is thus the zero locus of a local parameter \( \bar{\varepsilon}_i \) on an affine smooth chart \( \mathcal{V}_{\bar{x}} \) containing \( \bar{x} \).
Lemma 3.3.2. Let $\gamma, \mathcal{V},$ and $\pi: \tilde{\mathcal{M}} \to \mathcal{M}$ be as in Lemma 3.2.2, $\tilde{x} \in \pi^{-1}(\mathcal{Z})$, and $E = (E_1, \ldots, E_t)$ be the ascending sequence of $\tilde{x}$. Then,  
(1) for each $i \in [t-1]$, $\varepsilon_i$ can be taken to be the pullback $\tilde{z}_e \in \Gamma(\mathcal{O}_{\tilde{\mathcal{V}}})$ of $z_e \in \Gamma(\mathcal{O}_{\mathcal{V}})$ with an arbitrary $e \in E_i - E_{i+1}$; the function $\varepsilon_t$ can be taken to be any $\tilde{z}_e$ with $e \in \Delta_{\tilde{x},t}$; 
(2) for each $i \in [t]$, $\tilde{z}_i$ can be taken as the pullback $\tilde{z}_i$ of $\varepsilon_i$; 
(3) there is an affine smooth chart $\hat{\mathcal{V}}_{\tilde{x}} \subset \pi^{-1}(\mathcal{V})$ containing $\tilde{x}$ such that 
$$\tilde{z}_1, \ldots, \tilde{z}_t; \quad \tilde{z}_e, \quad e \in E_t \setminus \Delta_{\tilde{x},t}; \quad \tilde{z}_e, \quad e \in E_t^-$$
are part of a family of local parameters on $\hat{\mathcal{V}}_{\tilde{x}}$.

Proof. The statements (1) and (3) can be deduced from Corollary 3.1.2. The statement (2) follows from (3.13). \hfill \Box

The next statement plays a crucial role in analyzing the change of the structural homomorphism $\varphi$ throughout $[\tilde{\mathcal{M}}]$. Let $\gamma, \mathcal{V}, \pi, \tilde{x}, E,$ and $\hat{\mathcal{V}}_{\tilde{x}}$ be as in Lemma 3.3.2. For each $e \in E_i^\mathcal{V}$ and each $i \in [t]$, we denote by $\langle e \rangle_i$ the unique edge satisfying

\begin{equation}
\langle e \rangle_i \in E_i \quad \text{and} \quad \langle e \rangle_i \leq_i \varepsilon_i.
\end{equation}

With the functions $z_{[e]}$ as in (3.9), we set
$$\tilde{z}_{[e]} = z_{[e]} \circ \pi \in \Gamma(\mathcal{O}_{\hat{\mathcal{V}}_{\tilde{x}}}) \quad \forall \ e \in \text{Edg}(\gamma).$$

Proposition 3.3.3. For every $\tilde{x} \in \pi^{-1}(\mathcal{Z})$ with the ascending sequence $E = (E_1, \ldots, E_t)$ as in (3.14), there exists an affine smooth chart $\hat{\mathcal{V}}_{\tilde{x}} \subset \pi^{-1}(\mathcal{V})$ containing $\tilde{x}$ so that

$$\tilde{z} |_d \sim \tilde{z}_1 \cdot \tilde{z}_t, \quad \tilde{z} |_e \sim \tilde{z}_1 \cdot \tilde{z}_t \cdot \tilde{z}_e \cdot \prod_{\langle e \rangle_i < e' \leq_e} \tilde{z}_{e'}$$

for all $d \in \text{Dom}(\tilde{x})$ and all $e \in \text{Edg}(\gamma) \setminus \Delta_{\tilde{x},t}$.

Proof. Applying Lemma 3.3.2 and the middle equation in (3.5) repeatedly along the ascending sequence $E$, we obtain 
$$\tilde{z} |_d \sim \tilde{z}_1 \cdots \tilde{z}_t \quad \forall \ e \in \Delta_{\tilde{x},t}, \quad \tilde{z} |_e \sim \tilde{z}_1 \cdots \tilde{z}_t \cdot \tilde{z}_e \quad \forall \ e \in E_t \setminus \Delta_{\tilde{x},t}.$$ 

The former leads to the first displayed formula in Proposition 3.3.3. The latter implies 
$$\tilde{z} |_d \sim \tilde{z}_1 \cdots \tilde{z}_t \cdot \tilde{z}_{\langle e \rangle_i} \cdot \prod_{\langle e \rangle_i < e' \leq_e} \tilde{z}_{e'} \quad \forall \ e \in \text{Edg}(\gamma) \setminus \Delta_{\tilde{x},t}.$$ 

This gives rise to the second displayed formula in Proposition 3.3.3. \hfill \Box

Remark 3.3.4. In Remark 3.2.6, we observe that the desingularization of $\tilde{\mathcal{M}}_i(\mathbb{P}^n, d)$ is locally tree-compatible. The statements of Proposition 3.3.3 are consistent with the displayed formulae in the paragraph after [5], (5.23), but are more precise. In [5], it suffices to know $\text{Dom}(\tilde{x}) \neq \emptyset$ and $\tilde{z} |_d \tilde{z} |_e$ for some $d \in \text{Dom}(\tilde{x})$ and all $e \in \text{Edg}(\gamma)$. 

3.4. **Terminally fused multi-rooted (TFMR) trees.** We continue with the notation from §3.2 and §3.3. Notice that in all the statements of §3.2 and §3.3, the relevant aspects of the rooted tree $\gamma$ are $(\text{Edg}(\gamma), <)$. Thus, the same statements may still hold for other types of (directed) graphs, hence may play an important role in the desingularization of the higher genera moduli spaces. In this subsection, we focus on the generalization of the notion of the rooted trees that is necessary for the genus 2 case.

Let $\{\gamma_i\}_{i \in I}$ be a nonempty collection of rooted trees and $\{V_j\}_{j \in J}$ be a possibly empty collection of vertices satisfying

$$V_j \subset \bigsqcup_{i \in I} \text{Ver}(\gamma_i) \quad \forall \ j \in J, \quad V_{j_1} \cap V_{j_2} = \emptyset \quad \forall \ j_1 \neq j_2.$$ 

Note that each $V_j$ may contain no vertex or several vertices of a given $\gamma_i$. Let $\gamma$ be the graph obtained by identifying the vertices in $V_j$ for each $j \in J$; this gives rise to a natural surjective graph homomorphism

$$\bigsqcup_{i \in I} \gamma_i \twoheadrightarrow \gamma.$$ 

The collections $\text{Ver}(\gamma)$ and $\text{Edg}(\gamma)$ carry partial orders, both denoted by $<$, that are inherited from the tree orders $<_i$’s of $\gamma_i$’s. The minimal elements of $\text{Ver}(\gamma)$ with respect to $<$ are the roots $o_i$’s of $\gamma_i$’s. We call such defined $\gamma$ a **terminally fused multi-rooted (TFMR) tree** with the roots $o_i, i \in I$, and call $<$ the **TFMR tree order** on $\gamma$. When the context is clear, we may simply call $<$ the tree order. Every rooted tree itself is a TFMR tree. In Figure 4, some examples and counterexamples of TFMR trees are illustrated.

**Figure 4.** Examples and Counterexamples of TFMR trees

It is straightforward to verify that all notions for rooted trees in §3.2 and §3.3 hold verbatim for TFMR trees. The following operations on TFMR trees will appear in §3.5.

**Lemma 3.4.1.** Let $\gamma$ be a TFMR tree and $e$ be an edge of $\gamma$. The graph obtained from $\gamma$ by contracting all the edges $e'$ with $e' > e$ is a TFMR tree. Moreover, if a non-terminal edge $e'$ satisfies $e' > e$, the graph obtained from $\gamma$ by contracting all the edges $e''$ with $e \leq e'' \leq e'$ is a TFMR tree.

Analogous to Definitions 3.2.1 and 3.2.4, we can define $\gamma$-compatible blowups on a local chart $\mathcal{V}$ and define **locally TFMR tree-compatible blowups** on $\mathcal{M}$. 
Proposition 3.4.2. Lemmas 3.2.2 and 3.3.2, Corollary 3.2.5, and Proposition 3.3.3 remain valid if \( \gamma \) is a TFMR tree.

Proof. Notice that the sets of vertices are irrelevant in the rooted trees of the above statements. Thus given a TFMR tree \( \gamma \), let \( \overline{\gamma} \) be the rooted tree obtained by identifying all the roots of \( \gamma \), removing all the terminal vertices of \( \gamma \), and then assigning each terminal edge of \( \gamma \) with a distinct terminal vertex. Obviously
\[
[\text{Edg}(\overline{\gamma}), \prec_{\overline{\gamma}}] = [\text{Edg}(\gamma), \prec].
\]
Since the statements in Proposition 3.4.2 hold for \( \overline{\gamma} \), so do they for \( \gamma \). \( \square \)

3.5. Compatible sequences of blowups. In this subsection, we analyze how one TFMR tree-compatible blowup affects others locally.

Let \( \gamma_1 \) and \( \gamma_2 \) be two TFMR trees. We say \( \gamma_1 \) and \( \gamma_2 \) have a collection of common branches indexed by \( E_\ast \) if there exists \( E_\ast \subset \text{Edg}(\gamma_1) \cap \text{Edg}(\gamma_2) \) such that the elements of \( E_\ast \) are not comparable, and the intersection of \( \gamma_1 \) and \( \gamma_2 \) consists of branches \( \gamma_e, e \in E_\ast \). This implies
\[
\text{Edg}(\gamma_1) \cap \text{Edg}(\gamma_2) = E_\ast^c;
\]
c.f. (3.6) for notation. Let
\[
\{ z_e : e \in \text{Edg}(\gamma_1) \cup \text{Edg}(\gamma_2) \}.
\]
Assume there are two families of closed substacks
\[
Z_{1,1}, \ldots, Z_{1,d_1} \subset \mathcal{M} \quad \text{and} \quad Z_{2,1}, \ldots, Z_{2,d_2} \subset \mathcal{M}
\]
such that the sequential blowups
\[
\pi_1 : \widehat{\mathcal{M}}_1 \to \mathcal{M} \quad \text{and} \quad \pi_2 : \widehat{\mathcal{M}}_2 \to \mathcal{M}
\]
successively along the proper transforms of the first and the second families are \( \gamma_1 \)- and \( \gamma_2 \)-compatible on \( \mathcal{V} \), respectively.

Definition 3.5.1. We say \( \pi_1 \) and \( \pi_2 \) in (3.18) are compatible on \( \mathcal{V} \) if \( \gamma_1 \) and \( \gamma_2 \) have a (possibly empty) collection of common branches.

We first apply the sequential blowup \( \pi_1 \) to \( \mathcal{M} \) and obtain the proper transforms \( \tilde{Z}_{2,i}, i \in [\ell_2] \), of the blowup loci of \( \pi_2 \) in \( \widehat{\mathcal{M}}_1 \). Let
\[
(3.19) \quad \tilde{\pi}_2 : \widehat{\mathcal{M}}_{12} \to \widehat{\mathcal{M}}_1
\]
be the sequential blowup of \( \widehat{\mathcal{M}}_1 \) sucessively along the proper transforms of \( \tilde{Z}_{2,i}, i \in [\ell_2] \), called the proper transform of \( \pi_2 \). In the remainder of this subsection, we analyze \( \tilde{\pi}_2 \) locally.

Given
\[
\tilde{x} \in \pi_1^{-1}(Z_{\gamma_1} \cap Z_{\gamma_2}) \subset \pi_1^{-1}(\mathcal{V}),
\]
let \( E = (E_1, \ldots, E_t) \) be the ascending sequence of \( \tilde{x} \) and \( \tilde{V}_2 \subset \pi_1^{-1}(V) \) be the smaller chart containing \( \tilde{x} \) as in Lemma 3.3.2. We emphasize that
\[
E_i \in ET(\gamma_1) \quad \forall \; i \in [t].
\]
A priori Dom(\( \tilde{x} \)) \( \subset \) Edg(\( \gamma_1 \)). Set
\[
\hat{E}_a = \{ \langle e \rangle_a : e \in \text{Dom}(\tilde{x}) \cap E_a^\infty \} \quad ( \subset E_a),
\]
\[
\tilde{E}_a = \bigcup_{e \in E_a} \{ e' \in \text{Edg}(\gamma_2) : v_{e'} = v_e \} \quad ( \subset \text{Edg}(\gamma_2)),
\]
\[
\hat{E}_a = E_a \setminus \tilde{E}_a \quad ( \subset E_a \setminus \hat{E}_a).
\]
The definition of \( \hat{E}_a \) implies \( \hat{E}_a \subset \tilde{E}_a \) and \( \hat{E}_a \cap \tilde{E}_a = \emptyset \).
Recall \( E_o(\gamma_2) \) denotes the collection of the pivotal edges in \( \gamma_2 \). If
\[
(3.20) \quad \hat{E}_a \cap E_o(\gamma_2) = \emptyset,
\]
we construct a TFMR tree \((\gamma_2)_{\tilde{x}}\) from \( \gamma_2 \) as follows.
(a) For each \( e \in (E_t \setminus \Delta_{\tilde{x}, t}) \cap \hat{E}_a^\infty \), we contract all the edges \( e' \in \text{Edg}(\gamma_2) \) satisfying \( \langle e \rangle_a \leq e' < e \).
(b) For each \( e \in \Delta_{\tilde{x}, t} \cap \hat{E}_a^\infty \quad ( = (E_t \cap \Delta_{\tilde{x}, t}) \cap \hat{E}_a^\infty) \), notice that \( e \) is not a terminal edge, for otherwise it would be in Dom(\( \tilde{x} \)) and hence in \( \hat{E}_a^\infty \). We contract all the edges \( e' \in \text{Edg}(\gamma_2) \) satisfying \( \langle e \rangle_a \leq e' \leq e \).
(c) For each \( e \in \hat{E}_a \), we contract all the edges \( e' \in \text{Edg}(\gamma_2) \) satisfying \( e' \geq e \).

The assumption \((3.20)\) implies \( \hat{E}_a \cap E_o(\gamma_2) = \emptyset \), thus each \( e \in \hat{E}_a \) has an immediate predecessor \( e_{-1} \in \text{Edg}(\gamma_2) \) with respect to \( < \). Hence Step (c) is equivalent to contracting all \( e' \in \text{Edg}(\gamma_2) \) satisfying \( e' > e_{-1} \). By Lemma 3.4.1, \((\gamma_2)_{\tilde{x}}\) is a TFMR tree. In particular, if \( E_a^\infty \cap E_t = \emptyset \), the above construction implies \((\gamma_2)_{\tilde{x}} = \gamma_2 \).
Keeping track of the edges of \( \gamma_2 \) that are contracted in Steps (a) (c), we obtain
\[
\text{Edg}(\gamma_2)_{\tilde{x}} = (\text{Edg}(\gamma_2) \setminus (E_a \cup \hat{E}_a)^\infty) \cup ((E_t \cap \Delta_{\tilde{x}, t})^\infty \cap \hat{E}_a^\infty) \cup (\Delta_{\tilde{x}, t}^\infty \cap \hat{E}_a^\infty) = (\text{Edg}(\gamma_2) \setminus (E_a \cup \hat{E}_a)^\infty) \cup ((E_t \cap \Delta_{\tilde{x}, t}) \cap \hat{E}_a^\infty) \cup (E_a^\infty \cap \hat{E}_a^\infty).
\]
This implies
\[
(3.21) \quad \text{Edg}(\gamma_2)_{\tilde{x}}^t = \text{Edg}(\gamma_2)^t \setminus \hat{E}_a.
\]
We define \( \hat{E}_t \in ET(\gamma_1) \) to be
\[
(3.22) \quad \hat{E}_t = \left( E_t \setminus (\Delta_{\tilde{x}, t} \setminus \text{Edg}(\gamma_1)^t) \right) \cup \bigcup_{e \in \Delta_{\tilde{x}, t} \setminus \text{Edg}(\gamma_1)^t} \{ e' \in \text{Edg}(\gamma_1) : v_{e'} = v_e^t \}.
\]
Then, Edg((γ₂)ₓ) can also be written as

\[(3.23) \quad \text{Edg}((\gamma_2)_x) = (\text{Edg}(\gamma_2) \cup (E_s \cup \tilde{E}_s)^\circ) \cup (\tilde{E}_t^\circ \cap \tilde{E}_s^\circ).\]

**Proposition 3.5.2.** With notation as above,

1. if (3.20) does not hold, then \(\bar{\pi}_2 : \bar{M}_{12} \to \bar{M}_1\) is \(\emptyset\)-compatible on \(\tilde{V}_x\) (i.e., \(\bar{\pi}_2\) does not affect \(\tilde{V}_x\));
2. if (3.20) holds, then there exists a \((γ_2)_x\)-labeled subset of local parameters on \(\tilde{V}_x\) given by

\[
z_e^{(γ_2)x} \equiv z_e, \quad e \in (E_t \setminus \Delta_{x,i}) \cap \tilde{E}_s^\circ; \quad z_e^{(γ_2)x} \equiv z_e, \quad e \in E_t^\circ \cap \tilde{E}_s^\circ
\]

as in Lemma 3.3.2, along with

\[
z_e^{(γ_2)x} \equiv z_e, \quad e \in \text{Edg}(γ_2) \cup (E_s \cup \tilde{E}_s)^\circ.
\]

In addition, \(\bar{x} \in Z_{(γ_2)}\). Furthermore, \(\bar{\pi}_2\) is \((γ_2)_x\)-compatible on \(\tilde{V}_x\).

**Proof.** For each \(E \in \text{ET}(γ_2)\), keeping track of the proper transforms of the zero locus \(Z_E\) along the sequential blowups \(π_1\), we observe that \(\bar{x}\) lies in the final proper transform \(\bar{Z}_E\) of \(Z_E\) when \(π_1\) terminates if and only if

\[(3.24) \quad E \cap \Delta_{x,i} = \emptyset \quad \forall \ i \in [l].\]

If (3.20) does not hold, then there exists \(e_2 \in \text{Edg}(γ_2)^1 \cap \text{Dom}(\bar{x})\) such that each \(e \leq e_2\) (in \(γ_2\)) belongs to some \(E_i\) of the ascending sequence of \(\bar{x}\). Since each \(E \in \text{ET}(γ_2)\) contains an edge \(e' \leq e_2\), we conclude that \(\bar{x}\) is disjoint from all blowup loci of \(\bar{\pi}_2\). This shows Part (1).

In Part (2), the first two statements follow directly from Lemma 3.3.2 and Corollary 3.1.2. The last statement is obtained by the comparison of the traverse sections of \(γ_2\) satisfying (3.24) and all the traverse sections of \((γ_2)_x\) (c.f. (3.23)).

We say the sequential blowups \(π_1\) and \(π_2\) in (3.18) are **compatible on** \(M\) if \(M\) has an étale cover of affine smooth charts \(\{V\}\) so that \(π_1\) and \(π_2\) are compatible over each \(V \in \{V\}\). The assumption of \(π_1\) and \(π_2\) being compatible automatically implies they are both locally TFMR tree-compatible.

**Proposition 3.5.2** leads to the following conclusion.

**Corollary 3.5.3.** Let \(π_1\) and \(π_2\) be as in (3.18) and \(\bar{\pi}_2\) be the proper transform of \(π_2\) as in (3.19). If \(π_1\) and \(π_2\) are compatible, then \(\bar{\pi}_2\) is locally TMFR tree-compatible. If in addition there is another sequential blowup \(π_3 : \bar{M}_3 \to \bar{M}\) that is compatible with both \(π_1\) and \(π_2\), then when \(π_1\) terminates, the proper transform \(\bar{\pi}_3 : \bar{M}_{13} \to \bar{M}_1\) of \(π_3\) is compatible with \(\bar{\pi}_2\).

**Example 3.5.4.** Let \(γ_1\) and \(γ_2\) be the first graph in Figure 3 and the first graph in Figure 5, respectively. They share a common branch \(γ_e_b\). In this case,

\[
E_s = \{e_b\}, \quad E_s^\circ = \{e_b, e_c, e_d\} = \text{Edg}(γ_1) \cap \text{Edg}(γ_2).
\]
Let \( \tilde{x} \) be in the pullback of
\[ Z_{\gamma_1} \cap Z_{\gamma_2} = \{ z_a = z_b = z_c = z_d = z_p = z_q = z_r = 0 \} \]
after the sequential blowup \( \pi_1 \) as in Remark 3.2.6.

(1) If \( \hat{E} = \{ e_a, e_b \} \) and \( \Delta_{\tilde{x}, t} = \{ e_a \} \), then
\[
 t = 1, \quad E_1 = \{ e_a, e_b \}, \quad \text{Dom}(\tilde{x}) = \{ e_a \}, \quad \hat{E}_a = \hat{E}_b = \emptyset, \quad \hat{E}_a = \{ e_b \}.
\]
The TFMR tree \((\gamma_2)_{\tilde{x}}\) is isomorphic to \(\gamma_2\).

(2) If \( \hat{E} = \{ e_a, e_b \}, \Delta_{\tilde{x}, t} = \{ e_a, e_b \}, \text{and Dom}(\tilde{x}) = \{ e_a \} \), then
\[
 t = 1, \quad E_1 = \{ e_a, e_b \}, \quad \hat{E}_a = \hat{E}_b = \emptyset, \quad \hat{E}_a = \{ e_b \}.
\]
By Step \([b]\) the edge \( e_b \) is contracted, hence the TFMR tree \((\gamma_2)_{\tilde{x}}\) is given by the right graph in Figure 5.

(3) If \( \hat{E} = \{ e_a, e_b \}, \{ e_a, e_c, e_d \} \) and \( \text{Dom}(\tilde{x}) = \{ e_a \} \), then
\[
 t = 2, \quad E_2 = \{ e_a, e_c, e_d \}, \quad \Delta_{\tilde{x}, t} = \{ e_a \}, \quad \hat{E}_a = \hat{E}_b = \emptyset, \quad \hat{E}_a = \{ e_b \}.
\]
By Step \([a]\) the edge \( e_b \) is contracted, hence the TFMR tree \((\gamma_2)_{\tilde{x}}\) is given by the right graph in Figure 5.

(4) If \( \text{Dom}(\tilde{x}) \cap \{ e_c, e_d \} \neq \emptyset \), then
\[
 t = 2, \quad E_1 = \{ e_a, e_b \}, \quad E_2 = \{ e_a, e_c, e_d \},
\]
\[
 \Delta_{\tilde{x}, t} = \text{Dom}(\tilde{x}), \quad \hat{E}_a = \{ e_b \}, \quad \hat{E}_b = \{ e_q, e_b \}, \quad \hat{E}_a = \emptyset.
\]
By Step \([c]\) \((\gamma_2)_{\tilde{x}}\) consists of two vertices: the root \( o \) and another vertex \( v \), as well as two edges connecting \( o \) and \( v \).

3.6. Derived blowups. In this subsection, we construct a new sequential blowup on the pullback of \( \mathcal{V} \) after a special type of sequential blowup that is TFMR-tree compatible on \( \mathcal{V} \) terminates. Such blowup (or its supplementary blowup) provides a local model of the modular blowups in \( r_2, r_3p_2 \), and \( r_3p_4 \).

We continue with the notation from the previous subsections. Let \( \gamma \) be a TFMR tree, \( \mathcal{V} \) be an affine smooth chart with a collection of coordinate functions labeled by \( \gamma \) as in \((3.8)\), and \( \pi: \tilde{\mathcal{M}} \to \mathcal{M} \) be the blowup successively along the proper transforms of \( Z_1, \ldots, Z_t \) that is \( \gamma \)-compatible on \( \mathcal{V} \).

Consider the following subset of \( \text{Edg}(\gamma) \times ET(\gamma) \times \text{Edg}(\gamma) \):
\[
 \mathcal{D}(\gamma) = \{ \mathcal{E} = (E, e, E') \in ET(\gamma) \times \text{Edg}(\gamma) \times ET(\gamma) : E \preceq E', \ e \in E \cap E' \}.
\]
We define a partial order $<$ on $\mathcal{D}_1(\gamma)$ so that $(E_1, e_1, E'_1) < (E_2, e_2, E'_2)$ if and only if
\[(3.25) \quad \text{either } (E_1 < E_2) \text{ or } (E_1 = E_2, \, e_1 = e_2, \, E'_1 < E'_2).\]
For a terminal edge $e \in \text{Edg}(\gamma)^\dagger$, set
\[\mathcal{D}_1(\gamma; e) = \{(E, e, E') \in \mathcal{D}_1(\gamma) : e \leq e\}.
\]
The order (3.25) induces a partial order $<$ on $\mathcal{D}_1(\gamma; e)$ for every $e \in \text{Edg}(\gamma)^\dagger$.

For each $E \in \mathcal{ET}(\gamma)$, let $k \in \mathbb{I}^\ell$ be such that $E \in \mathcal{ET}(\gamma)_k$; c.f. Definition 3.2.1. For each nonempty subset $E_0$ of $E$, we define the locus
\[\mathcal{E}(E_0) \subset \mathcal{E}_E \quad (\subset \pi^{-1}(\mathcal{V}))\]
analogous to (3.4), where $\pi_{(k)}: \mathcal{M}_{(k)} \to \mathcal{M}$ denotes the blowup after the $k$-th step as always. For each $E \in \mathcal{D}_1(\gamma)$, let
\[Y_E = \mathcal{E}(\{e\} \cup (E \setminus E')) \cap \bigcap_{e' \in E \setminus E} \{z_{e'} = 0\} \quad (\subset \mathcal{E}_E).
\]

**Lemma 3.6.1.** With notation as above, $Y_E$ is closed, smooth, and of codimension $|E'|$ in the corresponding pullback $\pi_{(k)}^{-1}(\mathcal{V})$ of $\mathcal{V}$.

**Proof.** For every $y \in Y_E$, there is a chart $\mathcal{V}_y \supset \pi_{(k)}^{-1}(\mathcal{V})$ containing $y$ such that
\[Y_E \cap \mathcal{V}_y = \{\varepsilon_k = 0\} \cap \bigcap_{e' \in E \setminus E} \{z_{e'} = 0\} \cap \bigcap_{e' \in (E \setminus E) \setminus \{e\}} \{z_{e'} = 0\}. \quad \square\]

For each $E \in \mathcal{D}_1(\gamma)$, we denote by
\[\mathcal{Y}_E \subset \pi^{-1}(\mathcal{V}) \subset \mathcal{M}\]
the proper transform of $Y_E$.

**Remark 3.6.2.** We point out that if $\gamma = \emptyset$, then $\mathcal{D}_1(\gamma), Y()_{}, \mathcal{Y}_{()} = \emptyset$.

Let $\pi': \mathcal{M}' \to \mathcal{M}$ be the blowup of $\mathcal{M}$ successively along the proper transforms of a family of closed substacks
\[\mathcal{Y}_1, \ldots, \mathcal{Y}_r \subset \mathcal{M}.
\]

**Definition 3.6.3.** Assume $\pi: \mathcal{M} \to \mathcal{M}$ is $\gamma$-compatible on $\mathcal{V}$ and $\pi': \mathcal{M}' \to \mathcal{M}$ is as above. We say $\pi'$ is derived from $\pi$ on $\pi^{-1}(\mathcal{V}) \subset \mathcal{M}$ if $\mathcal{D}_1(\gamma)$ can be written as
\[\mathcal{D}_1(\gamma) = \bigsqcup_{k=1}^r \mathcal{D}_1(\gamma)_k \quad \text{s.t.}
\]

**(C1)** for each $k \in \mathbb{I}^\ell$,
\[\mathcal{Y}_k \cap \pi^{-1}(\mathcal{V}) = \bigcup_{E \in \mathcal{D}_1(\gamma)_k} \mathcal{Y}_E ;
\]

**(C2)** if $E_1 \in \mathcal{D}_1(\gamma)_{k_1}, E_2 \in \mathcal{D}_1(\gamma)_{k_2}$, and $E_1 < E_2$, then $k_1 < k_2$. \]
For a fixed $e \in \text{Edg}(\gamma)^i$, we say $\pi'$ is partially derived from $\pi$ (along $e$) on $\pi^{-1}(V)$ if in the above definition, $D_1(\gamma)$ is replaced by $D_1(\gamma; e)$.

Given $\tilde{x} \in \pi^{-1}(Z, \gamma)$, let $E = \{E_1, \ldots, E_t\}$ be the ascending sequence of $\tilde{x}$. Assume that $\tilde{x}$ has a unique dominant pivotal branch, i.e.

\[(3.26) \langle e \rangle = \langle e' \rangle \quad \forall \ e, e' \in \text{Dom}(\tilde{x}).\]

We then set

\[(3.27) e_* = \max\{ e \in \text{Edg}(\gamma) : e \leq e' \forall e' \in \text{Dom}(\tilde{x}) \} \in \text{Edg}(\gamma).\]

Since $\text{Dom}(\tilde{x}) \subset E_t$, we have $e_* \in E_t^\leq$. Let

\[s = s(e_*) \in [t];\]

c.f. (3.16). This implies $e_* \in \Delta_{\tilde{x}, s}$.

Recall that for each edge $e$ satisfying $\langle e \rangle = \langle e_* \rangle$, we denote by $e_* \land e$ the greatest (w.r.t. $<$) common predecessor of $e_*$ and $e$. This in turn determines an index $s(e_* \land e) \in [s]$ by (3.16). If $\langle e \rangle \neq \langle e_* \rangle$, we set $s(e_* \land e) = 0$.

Next, we construct a TFMR tree $\gamma'_x$ for $\tilde{x}$ satisfying (3.26).

(a) Let $[o, v_s]$ be the simple path with vertices and edges $v_0 = o < v_1 < \cdots < v_s$ and $e_1 < \cdots < e_s$, respectively.

(b) For each $e \in (E_t \setminus \Delta_{\tilde{x}, t}) \setminus \{e_*\}^\leq$,

we connect the root $v_e^+$ of the branch $\gamma_e$ and the vertex $v_{s(e_* \land e)}$ of the path $[o, v_s]$ by an edge.

(c) For each $e \in \Delta_{\tilde{x}, t} \setminus \{e_*\}^\leq$,

the definition of $e_*$ implies $e$ is not a terminal edge. We connect the root $v_e^+$ of the branch $\gamma_e$ and the vertex $v_{s(e_* \land e)}$ of the path $[o, v_s]$ by an edge, and then contract this new edge.

By Lemma 3.4.1, $\gamma'_x$ is still a TFMR tree with the root $o$. We call it the derived TFMR tree (or simply the derived tree when the context is clear) of $\gamma$ at $\tilde{x}$. Notice that

\[\text{Edg}(\gamma'_x) = \{e_1, \ldots, e_s\} \cup ((E_t \setminus \Delta_{\tilde{x}, t})^\leq \setminus \{e_*\}^\leq) \cup (\Delta_{\tilde{x}, t}^\leq \setminus \{e_*\}^\leq)\]

\[= \{e_1, \ldots, e_s\} \cup ((E_t \setminus \Delta_{\tilde{x}, t})^\leq \setminus \{e_*\}^\leq) \cup (E_t^\leq \setminus \{e_*\}^\leq).\]

With $\hat{E}_t$ as in (3.22), we can also write

\[(3.28) \text{Edg}(\gamma'_x) = \{e_1, \ldots, e_s\} \cup (\hat{E}_t^\leq \setminus \{e_*\}^\leq).\]

The following statement follows from Lemma 3.3.2 and Corollary 3.1.2 directly.
Lemma 3.6.4. Given $\bar{x} \in \pi^{-1}(Z_\gamma)$ satisfying (3.26), there exists an affine smooth chart $\bar{\mathcal{V}}_x \subset \pi^{-1}(\mathcal{V})$ such that

$$z_{e_i}^\gamma = \bar{z}_e, \quad \text{for} \quad [e]; \quad z_{e_i}^\varsigma = \bar{z}_e, \quad e \in (E_1 \setminus \Delta_{x,e}) \{e_*\}^\gamma; \quad z_{e_i}^\gamma = \bar{z}_e, \quad e \in E_1 \setminus \{e_*\}^\gamma$$

as in Lemma 3.3.2 form a $\gamma$-labeled subset of local parameters on $\bar{\mathcal{V}}_x$. Moreover, $\bar{x} \in Z_{\gamma_1}$.

Remark 3.6.5. Given $\bar{x}$ satisfying (3.26) and $e \in \text{Edg}(\gamma)^1$, we replace $e_*$ and $s = s(e_*)$ in the construction of $\gamma_{\bar{x}}^1$ by

$$e_* \equiv e \wedge e_*, \quad \text{and} \quad s = s(e_*),$$

respectively and call the resulting TFMR tree $\gamma'_{\bar{x}, e}$ the partially derived (TFMR) tree of $\gamma$ along $e$ at $\bar{x}$. It is a direct check that $\text{Edg}(\gamma'_{\bar{x}, e}) \subset \text{Edg}(\gamma')$, hence the analogue of Lemma 3.6.4 for $\gamma'_{\bar{x}, e}$ naturally holds.

For $\hat{E}_i$ in (3.22), we notice that

$$(\{E \setminus \{e\}\} \cup (\hat{E}_i \cap \{e\})^\gamma) \in \mathcal{E}(\gamma) \quad \forall \ E' \in \mathcal{E}(\gamma), \ e \in E'.$$

Lemma 3.6.6. Given $\bar{x} \in \pi^{-1}(Z_\gamma)$, there exists an affine smooth chart $\bar{\mathcal{V}}_x \subset \pi^{-1}(\mathcal{V})$ such that for each $\mathcal{E} = (E, e, E') \in \mathcal{D}_1(\gamma)$,

1. if $\bar{x}$ satisfies (3.26), $E = E_0 \in \{E_1, \ldots, E_s\}$, $e \leq e_*$, and

$$((E \setminus \{e\}) \cup (\hat{E}_i \cap \{e\})^\gamma) \geq \hat{E}_i,$$

then $\bar{\mathcal{Y}}_\mathcal{E} \cap \bar{\mathcal{V}}_\mathcal{E}$ is given by

$$\{\bar{z}_e = 0\} \cup \bigcap_{e' \in (E' \setminus E) \cap E_0} \{\bar{z}_e = 0\} \cup \bigcap_{e' \in (E' \setminus E) \cap (E \setminus \Delta_{x,e})} \{\bar{z}_{e'} = 0\};$$

2. otherwise, $\bar{\mathcal{Y}}_\mathcal{E} \cap \bar{\mathcal{V}}_\mathcal{E} = \emptyset$.

Proof. For each $\mathcal{E} \in \mathcal{D}_1(\gamma)$, the explicit local expression of $Y_\mathcal{E}$ is given in the proof of Lemma 3.6.1. Keeping track of the proper transforms of $Y_\mathcal{E}$, we observe that $\bar{x} \in \bar{Y}_\mathcal{E}$ if and only if the assumptions in Part (1) hold.

Lemma 3.6.7. Let $\pi_1' : \widetilde{\mathcal{M}}_1' \to \widetilde{\mathcal{M}}$ and $\pi_2' : \widetilde{\mathcal{M}}_2' \to \widetilde{\mathcal{M}}$ be two sequential blowups that are both derived (or both partially derived along the same $e \in \text{Edg}(\gamma)^1$) from the $\gamma$-compatible blowup $\pi : \widetilde{\mathcal{M}} \to \mathcal{M}$ on $\pi^{-1}(\mathcal{V})$. Then the pullbacks of $\pi^{-1}(\mathcal{V})$ in $\widetilde{\mathcal{M}}_1'$ and $\widetilde{\mathcal{M}}_2'$ are isomorphic.

Proof. The proof is parallel to Lemma 3.2.2 and the paragraph after it.

Proposition 3.6.8. Let $\pi : \widetilde{\mathcal{M}} \to \mathcal{M}$ and $\pi' : \widetilde{\mathcal{M}}' \to \mathcal{M}$ be two sequential blowups. Assume $\pi$ is $\gamma$-compatible on $\mathcal{V}$.

1. If $\pi'$ is derived from $\pi$ on $\pi^{-1}(\mathcal{V})$, then for every $\bar{x} \in \pi^{-1}(Z_\gamma)$, there exists an affine smooth chart $\bar{\mathcal{V}}_x \subset \pi^{-1}(\mathcal{V})$ containing $\bar{x}$ such that $\pi'$ is $\gamma_{\bar{x}}^1$-compatible on $\bar{\mathcal{V}}_x$ if $\bar{x}$ satisfies (3.26) and $\emptyset$-compatible otherwise.
(2) If $\pi'$ is partially derived from $\pi$ along $\varepsilon$ on $\pi^{-1}(V)$, then for every $\bar{x} \in \pi^{-1}(Z)$, there exists an affine smooth chart $\tilde{V}_x \subset \pi^{-1}(V)$ containing $\bar{x}$ such that $\pi'$ is $\gamma'_{\bar{x}}$-compatible on $\tilde{V}_x$ if $\bar{x}$ satisfies (3.26) and $\emptyset$-compatible otherwise.

Proof. The statements follow from Definition 3.6.3 and the comparison of the local expression of $\tilde{Y}_\varepsilon$ in Lemma 3.6.6 and the traverse sections of $\gamma'_x$ (c.f. (3.28)).

If $\pi : \tilde{M} \rightarrow M$ is locally TFMR tree-compatible, let $\{V\}$ be the étale cover of affine smooth charts associated with $\pi$ as in Definition 3.2.4. A sequential blowup $\pi' : \tilde{M}' \rightarrow \tilde{M}$ is said to be derived from $\pi$ if for each $V \in \{V\}$, $\pi'$ is derived from $\pi$ on $\pi^{-1}(V)$. It is said to be partially derived from $\pi$ if for each $V \in \{V\}$, $\pi'$ is partially derived from $\pi$ on $\pi^{-1}(V)$.

The following statement follows immediately from Proposition 3.6.8.

Corollary 3.6.9. Let $\pi : \tilde{M} \rightarrow M$ be locally TFMR tree-compatible and $\pi' : \tilde{M}' \rightarrow \tilde{M}$ be a sequential blowup derived (or partially derived) from $\pi$. Then, $\pi'$ is locally TFMR tree-compatible.

Example 3.6.10. Let $\gamma$ be the first graph in Figure 3 and $\bar{x} \in \pi^{-1}(Z)$ be fixed. Recall in Remark 3.2.6, we see that $\gamma$ has two traverse sections:

$$E_1 = \{e_a, e_b\} < E_2 = \{e_a, e_c, e_d\}.$$  

It is straightforward that $\mathcal{D}_1(\gamma) = \{\mathcal{C}_1, \ldots, \mathcal{C}_6\}$, where

$$\mathcal{C}_1 = (E_1, e_a, E_1), \quad \mathcal{C}_2 = (E_1, e_a, E_2), \quad \mathcal{C}_3 = (E_2, e_a, E_2),$$  

$$\mathcal{C}_4 = (E_1, e_b, E_1), \quad \mathcal{C}_5 = (E_2, e_c, E_2), \quad \mathcal{C}_6 = (E_2, e_d, E_2).$$

The partial order on $\mathcal{D}_1(\gamma)$ is given by

$$\mathcal{C}_1 < \mathcal{C}_2 < \mathcal{C}_3, \quad \mathcal{C}_4 < \mathcal{C}_5, \quad \mathcal{C}_4 < \mathcal{C}_6.$$

(1) If $\operatorname{Dom}(\bar{x}) = \{e_a\}$ and $E' = (E_1, E_2)$, then

$$e_* = e_a, \quad s = t = 2, \quad \Delta_{\bar{x},1} = \{e_b\}, \quad \Delta_{\bar{x},2} = \{e_a\}, \quad \hat{E}_2 = E_2.$$

The derived tree $\gamma'_x$ is the first graph of Figure 6. Locally near $\bar{x}$, the relevant $\tilde{Y}_\varepsilon$ are

$$\tilde{Y}_{\mathcal{C}_2} = \{\tilde{z}_1 = \tilde{z}_c = \tilde{z}_d = 0\} \quad \text{and} \quad \tilde{Y}_{\mathcal{C}_3} = \{\tilde{z}_2 = \tilde{z}_c = \tilde{z}_d = 0\}.$$
(2) If Dom(\(\bar{x}\)) = \{e_a\}, \(E = (E_1, E_2)\), and \(\Delta_{\bar{x}, 1} = \{e_a, e_b\}\), then
\[ e_* = e_a, \quad s = t = 1, \quad \hat{E}_2 = E_2. \]
The derived tree \(\gamma'_{\bar{x}}\) is the second graph of Figure 6. Locally near \(\bar{x}\), the relevant \(\tilde{Y}_e\) is
\[ \tilde{Y}_{e_2} = \{\tilde{z}_1 = \tilde{z}_c = \tilde{z}_d = 0\}. \]
(3) If Dom(\(\bar{x}\)) = \{e_a\}, \(E = (E_1, E_2)\), and \(\Delta_{\bar{x}, 1} = \{e_a\}\), then
\[ e_* = e_a, \quad s = t = 1, \quad \hat{E}_2 = E_1. \]
The derived tree \(\gamma'_{\bar{x}}\) is the third graph of Figure 6. Locally near \(\bar{x}\), the relevant \(\tilde{Y}_e\) are
\[ \tilde{Y}_{e_1} = \{\tilde{z}_1 = \tilde{z}_b = 0\} \quad \text{and} \quad \tilde{Y}_{e_2} = \{\tilde{z}_2 = \tilde{z}_c = \tilde{z}_d = 0\}. \]
(4) If Dom(\(\bar{x}\)) = \{e_c, e_d\}, then \(E = (E_1, E_2)\),
\[ e_* = e_b, \quad s = 1, \quad t = 2, \quad \Delta_{\bar{x}, 1} = \{e_b\}, \quad \Delta_{\bar{x}, 2} = \{e_c, e_d\}, \quad \hat{E}_2 = E_2. \]
The derived tree \(\gamma'_{\bar{x}}\) is the fourth graph of Figure 6. Locally near \(\bar{x}\), the relevant \(\tilde{Y}_e\) is
\[ \tilde{Y}_{e_1} = \{\tilde{z}_1 = \tilde{z}_a = 0\}. \]
(5) If Dom(\(\bar{x}\)) = \{e_c\}, then \(E = (E_1, E_2)\),
\[ e_* = e_c, \quad s = t = 2, \quad \Delta_{\bar{x}, 1} = \{e_b\}, \quad \Delta_{\bar{x}, 2} = \{e_c\}, \quad \hat{E}_2 = E_2. \]
The derived tree \(\gamma'_{\bar{x}}\) is the last graph of Figure 6. Locally near \(\bar{x}\), the relevant \(\tilde{Y}_e\) are
\[ \tilde{Y}_{e_1} = \{\tilde{z}_1 = \tilde{z}_a = 0\} \quad \text{and} \quad \tilde{Y}_{e_2} = \{\tilde{z}_2 = \tilde{z}_a = \tilde{z}_d = 0\}. \]

The case that Dom(\(\bar{x}\)) = \{e_d\} is parallel.

3.7. Bi-dominantly derived blowups. This subsection is similar to the previous subsection. We construct another sequential blowup on the pull-back of \(\mathcal{V}\) after a sequential blowup that is TFMR-tree compatible on \(\mathcal{V}\) terminates. It provides a local model of the modular blowups in \(\text{r3p1}\).

Let \(\gamma\), \(\mathcal{V}\), and \(\pi: \tilde{\mathcal{M}} \to \mathcal{M}\) be as in \([3.6]\). Consider the following subset of \(\text{ET}(\gamma) \times \text{Edg}(\gamma) \times \text{Edg}(\gamma) \times \text{ET}(\gamma)\):
\[ \mathcal{D}_2(\gamma) = \{ \mathcal{F} = (E, e_1, e_2, E') \in \text{ET}(\gamma) \times \text{Edg}(\gamma) \times \text{Edg}(\gamma) \times \text{ET}(\gamma) : E \leq E', \quad e_1 \neq e_2, \quad \{e_1, e_2\} \subset E \cap E' \}. \]
Thus, \(e_1\) and \(e_2\) are not comparable if \((E, e_1, e_2, E') \in \mathcal{D}_2(\gamma)\). We define a partial order \(<\) on \(\mathcal{D}_2(\gamma)\) so that \((E, e_1, e_2, E') < (E', \hat{E}_1, \hat{E}_2, \hat{E}')\) if and only if either \((E < \hat{E})\) or \((E = \hat{E}, (e_1, e_2) = (\hat{e}_1, \hat{e}_2), E' < \hat{E}')\).

For each \(\mathcal{F} \in \mathcal{D}_2(\gamma)\), let \(k\) be such that \(E \in \text{ET}(\gamma)_k\), and let
\[ Y_\mathcal{F} = \mathcal{E}(\{e_1, e_2\} \cup (E \setminus E')) \cap \bigcap_{e' \in E \setminus E} \{\tilde{z}_{e'} = 0\} \subset \mathcal{E}_E. \]
The following statement is the analogue of Lemma 3.6.1 under the current setup; we omit its proof.

**Lemma 3.7.1.** With notation as above, $Y_{\delta}$ is closed, smooth, and of codimension $|E| - 1$ in the corresponding pullback $\pi_1^{-1}(V)$ of $V$.

For each $\delta \in D_2(\gamma)$, we denote by
\[ \bar{Y}_{\delta} \subseteq \pi_1^{-1}(V) \subseteq \tilde{M} \]
the proper transform of $Y_{\delta}$.

**Remark 3.7.2.** We point out that if $\gamma = \emptyset$, then $D_2(\gamma), Y_{\delta}, \bar{Y}_{\delta} = \emptyset$.

Let
\[ \pi' : \tilde{M}' \rightarrow \tilde{M} \quad \text{and} \quad \pi^{(2)} : \tilde{M}' \rightarrow \tilde{M} \]
be respectively the blowup derived from $\pi : \tilde{M} \rightarrow M$ and the blowup of $\tilde{M}$ successively along the proper transforms of a family of closed substacks
\[ \Upsilon^1_1, \ldots, \Upsilon^r_1 \subseteq \tilde{M}. \]
We denote by
\[ \bar{\pi}^{(2)} : \tilde{M}^{(2)} \rightarrow \tilde{M}' \]
blowup of $\tilde{M}'$ successively along the proper transforms of $\Upsilon^1_1, \ldots, \Upsilon^r_1$ after $\pi'$ and call it the proper transform of $\pi^{(2)}$.

**Definition 3.7.3.** Assume $\pi : \tilde{M} \rightarrow M$ is $\gamma$-compatible on $V$ and $\bar{\pi}^{(2)} : \tilde{M}^{(2)} \rightarrow \tilde{M}'$ is as above. We say $\bar{\pi}^{(2)}$ is bi-dominantly derived from $\pi$ on $(\pi')^{-1}(\pi^{-1}(V)) \subseteq \tilde{M}'$ if $D_2(\gamma)$ can be written as
\[ D_2(\gamma) = \bigsqcup_{k=1}^{r} D_2(\gamma)_k \quad \text{s.t.} \]
\[ (C1) \text{ for each } k \in [r], \quad \Upsilon^k_1 \cap \pi^{-1}(V) = \bigcup_{\delta \in D_2(\gamma)_k} \bar{Y}_{\delta}; \]
\[ (C2) \text{ if } \delta_1 \in D_2(\gamma)_{k_1}, \delta_2 \in D_2(\gamma)_{k_2}, \text{ and } \delta_1 < \delta_2, \text{ then } k_1 < k_2. \]

Let $\bar{x}$ and $E$ be as in §3.6. If there exist $e_1, e_2 \in Edg(\gamma)$ such that they are not comparable and
\[ (3.29) \quad \text{Dom}(\bar{x}) = D_1 \cup D_2, \quad \emptyset \neq D_i \subseteq \text{Edg}(\gamma_{e_i}), \quad i = 1, 2, \]
we then set
\[ e_i^* = \max \{ e \in Edg(\gamma) : e \leq e' \forall e' \in D_i \} \in Edg(\gamma), \quad i = 1, 2. \]
Since $\text{Dom}(\bar{x}) \subseteq E$, we observe that $e_1^*, e_2^* \in E^{\leq}_i$, although $s(e_1^*)$ may not equal $s(e_2^*)$; c.f. (3.16). Set
\[ \varsigma = \min \{ s(e_1^*), s(e_2^*) \} \in [t], \quad \varsigma_0 = s(e_1^* \land e_2^*) \in \{0 \} \cup [t]. \]
By definition, $\varsigma_0 < \varsigma$. Recall that $s(e \cap e') = 0$ whenever $\langle e \rangle \neq \langle e' \rangle$. Hence if $\langle e_1 \rangle \neq \langle e_2 \rangle$, then $\varsigma_0 = 0$.

Let $e_1, e_2 \in E_\varsigma$ be such that

$$e_i \leq e_0, \quad i = 1, 2.$$  

For each $e \in \text{Edg}(\gamma)$, define

$$\sigma(e) = \max \{ s(e_1 \cap e), s(e_2 \cap e), \varsigma_0 \}.$$  

This implies $\varsigma_0 \leq \sigma(e) \leq \varsigma$ for all $e \in \text{Edg}(\gamma)$.

We construct a rooted tree $\tau_{\hat{x}}$ following the steps below.

(a) Let $[d', v'_s]$ be the simple path with vertices and edges

$$v'_0 = d' < v'_1 < \cdots < v'_s$$  

and $\gamma_{\sigma(e)}$ be the derived tree of $\gamma_e$ and the vertex $v'_s$ of the path $[d', v'_s]$ by an edge.

(b) For each

$$e \in (E_e \setminus \Delta_{\hat{x}, t}) \setminus \{e_1, e_2\}_e$$  

we connect the root $v_e^+$ of the branch $\gamma_e$ and the vertex $v'_s$ of the path $[d', v'_s]$ by an edge.

(c) For each

$$e \in \Delta_{\hat{x}, t} \setminus \{e_1, e_2\}_e$$  

the definition of $e_\varsigma$ implies $e$ is not a terminal edge. We connect the root $v_e^+$ of the branch $\gamma_e$ and the vertex $v'_s$ of the path $[d', v'_s]$ by an edge, and then contract this new edge.

Analogous to the derived tree as in $[3.6]$ the graph $\tau_{\hat{x}}$ is still a TFMR tree. If $\text{Dom}(\hat{x})$ is contained in exactly two pivotal branches, i.e. the edges $e_1, e_2$ in $[3.26]$ belong to $E_\varsigma$, then $\pi': \tilde{M'} \to \tilde{M}$ does not affect a neighborhood of $\hat{x}$. Moreover, $\varsigma_0 = 0$. Let $\tilde{x}' = (\pi')^{-1}(\hat{x})$. We set

$$\gamma_\tilde{x}' (2) = \tau_{\hat{x}}$$  

and call it the bi-dominantly derived TFMR tree of $\gamma$ at $\tilde{x}'$.

Next, we consider the case in which $\text{Dom}(\hat{x})$ is contained in a unique pivotal branch, i.e. $[3.26]$ holds. Let $\gamma_{\hat{x}}$ be the derived tree of $\gamma$ at $\hat{x}$. When the derived blowup $\pi': \tilde{M'} \to \tilde{M}$ terminates, for every lift $\tilde{x}'$ of $\hat{x}$, there are two possibilities when $\gamma_{\hat{x}} (2)$ can be defined:

(S1) $\text{Dom}(\tilde{x}) = \{ e_s \}$ and meanwhile $[3.29]$ holds for $\text{Dom}(\tilde{x})$;

(S2) there exists $e \in \text{Edg}(\gamma_{\hat{x}}) \setminus \{e_1, \ldots, e_s\}$ such that $e \leq e'$ for all $e' \in \text{Dom}(\tilde{x}')$ (thus $e_s \notin \text{Dom}(\tilde{x}')$).

For Possibility (S1) notice that $\tau_{\hat{x}}$ is well-defined and $\varsigma_0 = s$. We set

$$\gamma_{\tilde{x}', 2} = (\tau_{\hat{x}})_{\tilde{x}'}$$  

and call it the bi-dominantly derived TFMR tree of $\gamma$ at $\tilde{x}'$; see $[3.5]$ for notation.
For Possibility \([S2]\), we construct the TFMR tree \(\gamma^{(2)}_{\bar{x}'}\) out of \(\gamma'_{\bar{x}}\), mimicking the construction of \(\tau_{\bar{x}}\) with \(\text{Dom}(\bar{x})\) in (3.29) replaced by \(\text{Dom}(\bar{x}') \cup \{x\}\). We still call \(\gamma^{(2)}_{\bar{x}'}\) the bi-dominantly derived TFMR tree of \(\gamma\) at \(\bar{x}'\).

The following statements are parallel to Lemma \(3.6.7\) and Proposition \(3.6.8\), respectively.

**Lemma 3.7.4.** Let \(\pi_{1}: \tilde{\mathcal{M}}_{1}^{(2)} \rightarrow \tilde{\mathcal{M}}^{(2)}\) and \(\pi_{2}: \tilde{\mathcal{M}}_{2}^{(2)} \rightarrow \tilde{\mathcal{M}}^{(2)}\) be two sequential blowups that are both bi-dominantly derived from the \(\gamma\)-compatible blowup \(\pi: \tilde{\mathcal{M}} \rightarrow \tilde{\mathcal{M}}\) on \(\pi^{-1}(\mathcal{V})\). Then the pullbacks of \((\pi')^{-1}(\pi^{-1}(\mathcal{V}))\) in \(\tilde{\mathcal{M}}_{1}^{(2)}\) and \(\tilde{\mathcal{M}}_{2}^{(2)}\) are isomorphic.

**Proposition 3.7.5.** Let \(\pi: \tilde{\mathcal{M}} \rightarrow \tilde{\mathcal{M}}^{(2)}\) be \(\gamma\)-compatible on \(\mathcal{V}\), \(\pi': \tilde{\mathcal{M}}^{(2)} \rightarrow \tilde{\mathcal{M}}^{(2)}\) be derived from \(\pi\) on \(\pi^{-1}(\mathcal{V})\), and \(\tilde{\mathcal{M}}^{(2)}\) be bi-dominantly derived from \(\pi\) on \((\pi')^{-1}(\pi^{-1}(\mathcal{V}))\). Then, for every \(\bar{x}' \in (\pi')^{-1}(\pi^{-1}(\mathcal{V}))\), there exists an affine smooth chart \(\tilde{\mathcal{V}}_{\bar{x}'}\) containing \(\bar{x}'\) such that \(\tilde{\pi}(\bar{x}')\) is \(\gamma_{\bar{x}'}\)-compatible on \(\tilde{\mathcal{V}}_{\bar{x}'}\) if \(\tilde{\pi}(\bar{x}')\) exists and is \(\mathcal{O}\)-compatible on \(\tilde{\mathcal{V}}_{\bar{x}'}\) otherwise.

If \(\pi: \tilde{\mathcal{M}} \rightarrow \tilde{\mathcal{M}}^{(2)}\) is locally TFMR tree-compatible, let \(\{\mathcal{V}\}\) be the étale cover of affine smooth charts associated with \(\pi\) as in Definition \(3.2.4\) and \(\pi': \tilde{\mathcal{M}}^{(2)} \rightarrow \tilde{\mathcal{M}}^{(2)}\) be derived from \(\pi\). A sequential blowup \(\tilde{\pi}_{2}: \tilde{\mathcal{M}}^{(2)} \rightarrow \tilde{\mathcal{M}}^{(2)}\) is said to be bi-dominantly derived from \(\pi\) if for each \(\mathcal{V} \in \{\mathcal{V}\}\), \(\tilde{\pi}_{2}\) is bi-dominantly derived from \(\pi\) on \((\pi')^{-1}(\pi^{-1}(\mathcal{V}))\). The following statement is parallel to Corollary \(3.6.9\).

**Corollary 3.7.6.** Let \(\pi: \tilde{\mathcal{M}} \rightarrow \tilde{\mathcal{M}}^{(2)}\) be locally TFMR tree-compatible, \(\pi': \tilde{\mathcal{M}}^{(2)} \rightarrow \tilde{\mathcal{M}}^{(2)}\) be derived from \(\pi\), and \(\tilde{\pi}_{2}: \tilde{\mathcal{M}}^{(2)} \rightarrow \tilde{\mathcal{M}}^{(2)}\) be bi-dominantly derived from \(\pi\). Then, \(\tilde{\pi}_{2}\) is locally TFMR tree-compatible.

4. **Description of the Modular Blowups**

In this section, we introduce the three-round modular blowups of \(\mathcal{M}_{2}^{\text{sm}}\). The first two rounds are respectively described in \(4.3\) and \(4.4\). The last round is more sophisticated (due to the existence of conjugate and Weierstrass points for genus 2 curves), hence is divided into four phases described in \(4.5\) and \(4.8\). Throughout this section, the proper transform of a substack along the way is decorated with the corresponding step as the superscript.

4.1. **Weighted graphs.** We summarize the combinatorial notation for several TFMR trees related to a weighted curve \((C, w) \in \mathcal{M}_{2}^{\text{sm}}\) in this subsection.

Let \(\gamma\) be an arbitrary graph. Contracting all the edges in a subset \(E\) of \(\text{Edg}(\gamma)\) results in a new graph, which we denote by \(\gamma|_{E}\), along with a surjective map

\[
\pi|_{E}: \text{Ver}(\gamma) \longrightarrow \text{Ver}(\gamma|_{E}).
\]

A pair \((\gamma, w)\) consisting of a graph \(\gamma\) and a function

\[
w: \text{Ver}(\gamma) \longrightarrow \mathbb{Z}_{\geq 0}
\]
is called a weighted graph with the weight function $w$. For each $E \subset \text{Edg}(\gamma)$, the weight function $w$ on $\gamma$ induces a function

$$w_{\lfloor E \rfloor} : \text{Ver}(\gamma_{\lfloor E \rfloor}) \rightarrow \mathbb{Z}_{\geq 0}, \quad w_{\lfloor E \rfloor}(v) = \sum_{v' \in \gamma_{\lfloor E \rfloor}(v)} w(v'),$$

which makes $(\gamma_{\lfloor E \rfloor}, w_{\lfloor E \rfloor})$ a weighted graph. We call $w_{\lfloor E \rfloor}$ the induced weight on $\gamma_{\lfloor E \rfloor}$.

If in addition $\gamma$ is a TFMR tree with the tree order $<$, let $(\gamma^b, w^b)$ be the weighted TFMR tree so that

$$\gamma^b = \gamma_{\lfloor E' \rfloor}, \quad \text{where} \quad E' = \left\{ e \in \text{Edg}(\gamma) : \left( \sum_{e' < e} w(v_{e'}^+) \right) > 0 \right\},$$

and $w^b$ be the induced weight on $\gamma^b$. We call $(\gamma^b, w^b)$ the terminally weighted TFMR tree of $(\gamma, w)$, because every positively weighted vertex of $\gamma^b$ is either a terminal vertex or a root.

Let $C$ be a nodal curve. We denote by $\gamma^*$ the dual graph of $C$. There is a natural partition of $\text{Edg}(\gamma^*)$ given by

$$\text{Edg}(\gamma^*) = \text{Edg}_{cr}(\gamma^*) \cup \text{Edg}_{pv}(\gamma^*) \cup \text{Edg}_{tl}(\gamma^*)$$

corresponding to the principal nodes, the pivotal nodes, and the nodes of the tails, respectively. Recall a weighted curve is a pair $(C, w)$ consisting of a nodal curve $C$ and an element $w \in H^2(C; \mathbb{Z})$, which can be considered as a function

$$w : \text{Ver}(\gamma^*) \rightarrow \mathbb{Z}_{\geq 0}.$$

Thus, $(\gamma^*, w)$ is a weighted graph.

With notation as above, we set

$$\hat{\gamma} = \gamma^*_{\lfloor E_{cr}(\gamma^*) \rfloor}.$$

The graph $\hat{\gamma}$ is a rooted tree whose root $o$ corresponds to the core $F$. By definition,

$$\text{Edg}(\hat{\gamma}) = \text{Edg}_{pv}(\gamma^*) \cup \text{Edg}_{tl}(\gamma^*) = E_o(\hat{\gamma}) \cup \text{Edg}_{tl}(\gamma^*),$$

where $E_o(\hat{\gamma})$ denotes the collection of the minimal edges of $\hat{\gamma}$. As in [5], $\hat{\gamma}$ is called the reduced dual tree of $C$ and

$$\gamma = \gamma^b$$

the terminally weighted tree of $C$.

Each subcurve $F'$ of $F$ determines a subgraph $\gamma_{F'}$ of $\gamma^*$. We write

$$\text{Ver}(F') = \text{Ver}(\gamma_{F'}), \quad \text{Edg}(F') = \text{Edg}(\gamma_{F'})$$

for conciseness. Let

$$E_{pv,F'}(\gamma^*) = \text{Edg}_{pv}(\gamma^*)$$

be the subset of the pivotal edges that each has an endpoint in $\text{Ver}(F')$. Set

$$E_{F'} = \text{Edg}(F') \cup \bigcup_{e \in E_{pv,F'}(\gamma^*)} \{ e \}^\geq,$$

(4.1)

(4.2)

(4.3)
where $<$ on the right-hand side denotes the tree order on $\gamma$.

If the core $F$ is separable, it contains two genus 1 inseparable components $F_1$ and $F_2$. In the weighted graph $\gamma_{[\operatorname{Edg}(F_2) \cup E^c_{F_1}]^t}$, $F_1$ and $F_2$ respectively correspond to two vertices $o_1$ and $o_2$. This weighted graph can be considered as a rooted tree with the root $o_2$. With respect to the induced tree order, let

$$\gamma_{\nu} = \gamma_{\nu,F_2} = (\gamma_{[\operatorname{Edg}(F_2) \cup E^c_{F_1}]^t})^b,$$

which is still a rooted tree with the root $o_2$. It is obvious that $o_1 \in \operatorname{Ver}(\gamma_{\nu})^t$.

with respect to the induced tree order.

If in addition $F$ contains a (not necessarily maximal) separating bridge $B$, then in the weighted graph $\gamma_{[\operatorname{Edg}(F_1) \cup \operatorname{Edg}(F_2) \cup E^c_{B}]^t}$, once again $F_1$ and $F_2$ respectively correspond to two vertices $o_1$ and $o_2$. This weighted graph can be considered as a TFMR tree with $o_1$ and $o_2$ as the roots and the bridge $B$ corresponding to a terminal vertex. With respect to the induced tree order, we set

$$\gamma_{\wedge} = \gamma_{\wedge,B} = (\gamma_{[\operatorname{Edg}(F_1) \cup \operatorname{Edg}(F_2) \cup E^c_{B}]^t})^b,$$

which is still a TFMR tree with the roots $o_1$ and $o_2$. The bridge $B$ (along with the irreducible components of $C$ in the tails attached to $B$) corresponds to the unique terminal vertex

$$v_B \in \operatorname{Ver}(\gamma_{\wedge})^t$$

that is the common endpoint of two distinct terminal edges

$$e_1, e_2 \in \operatorname{Edg}(\gamma_{\wedge})^t.$$

If $F$ contains a non-separating bridge $B$, let $B'$ be the maximal non-separating bridge of $F$ containing $B$. We denote by $C_2$ the closure of $F \backslash B'$ in $F$, which is a genus 1 subcurve. In the weighted graph $\gamma_{[\operatorname{Edg}(C_2) \cup E^c_{B}]^t}$, $C_2$ corresponds to a vertex $\overline{o}_2$. This weighted graph can be considered as a TFMR tree with $\overline{o}_2$ as the root and the bridge $B$ corresponding to a terminal vertex. With respect to the induced tree order, we set

$$\gamma_{\wedge} = \gamma_{\wedge,B} = (\gamma_{[\operatorname{Edg}(C_2) \cup E^c_{B}]^t})^b,$$

which is still a TFMR tree with the root $\overline{o}_2$. The bridge $B$ (along with the irreducible components of $C$ in the tails attached to $B$) corresponds to the unique terminal vertex

$$v_B \in \operatorname{Ver}(\gamma_{\wedge})^t$$

that is the common endpoint of two distinct terminal edges

$$e_1, e_2 \in \operatorname{Edg}(\gamma_{\wedge})^t.$$


4.2. A stratification of $\mathcal{M}_2^{\text{wt}}$. In this section, we describe a stratification of $\mathcal{M}_2^{\text{wt}}$ consisting of the following strata

$$\mathcal{M}_{(1,k)}, \mathcal{M}_{(2,k)}, \mathcal{M}_{(3,k)}, \mathcal{M}_{(4,k)}, \mathcal{M}_{(5,k)}, \quad k \in \mathbb{Z}_{>0},$$

of $\mathcal{M}_2^{\text{wt}}$. Recall we denote by $F$ the core of a curve $C$. For each $k$,

- $(C, w) \in \mathcal{M}_{(1,k)}$ if $F$ is a smooth genus 2 curve of weight 0 and the tails of $C$ are $k$ smooth rational curves of positive weights.
- $(C, w) \in \mathcal{M}_{(2,k)}$ if $F$ consists of two smooth genus 1 curves of weight 0 and one smooth rational curve of positive weight, and the tails of $C$ are $(k-1)$ smooth rational curves of positive weights;
- $(C, w) \in \mathcal{M}_{(3,k)}$ if $F$ consists of one smooth genus 1 curve of weight 0 and one smooth rational curve of positive weight, and the tails of $C$ are $(k-1)$ smooth rational curves of positive weights;
- $(C, w) \in \mathcal{M}_{(4,k)}$ if $F$ consists of one smooth genus 1 curve of weight 0 and one smooth genus 1 curve of positive weight, and the tails of $C$ are $(k-1)$ smooth rational curves of positive weights;
- $(C, w) \in \mathcal{M}_{(5,k)}$ if $F$ is a smooth genus 2 curve of weight 1 and the tails of $C$ are $k$ smooth rational curves of positive weights.

For each pair $(i, k)$, let $\mathcal{M}_{(i,k)}$ be the closure of $\mathcal{M}_{(i,k)}$ in $\mathcal{M}_2^{\text{wt}}$ and $S_{(i,k)}$ be the symmetric group of the dual graph corresponding to $\mathcal{M}_{(i,k)}$. In Figure 1 we illustrate $\mathcal{M}_{(i,k)}$ with $k \leq 3$. An unshaded irreducible component indicates the weight is 0.

The strata $\mathcal{M}_{(i,k)}$ are the images of natural node-identifying surjective immersions from smooth domains as follows. Given a finite set $S$, let $\overline{M}_{g,S}$ be the moduli space of genus $g$ stable curves whose marked points are indexed by $S$. Let $\overline{M}_g^{\text{wt};+}$ be the Artin stack of stable pairs $(C, w)$ of genus $g$ nodal curves $C$ whose marked points are indexed by $S$ and weights $w \in H^2(C; \mathbb{Z})$ satisfying $w(C) > 0$ and $w(\Sigma) \geq 0$ for all irreducible $\Sigma \subset C$. Here $(C, w)$ is said to be stable if any smooth rational irreducible component of weight 0 contains at least three nodal and/or marked points. With $[k]$ and $[j , k]$ as in (3.1), we define

$$\mathcal{M}_{(1,k)} = \overline{M}_2, [k] \times \prod_{i \in [k]} \overline{M}_0, [i],$$

$$\mathcal{M}_{(2,k)} = \bigcup_{\ell=1}^{k} \left( \overline{M}_1, [\ell-1] \cup \{\ell_+\} \times \overline{M}_1, [\ell+1] \cup \{\ell_-\} \times \overline{M}_0, [\ell_+, \ell_-] \times \prod_{i \in [k], i \neq \ell} \overline{M}_0, [i] \right),$$

$$\mathcal{M}_{(3,k)} = \overline{M}_1, [k-1] \cup \{k_+, k_-\} \times \overline{M}_0, [k_+, k_-] \times \prod_{i \in [k-1]} \overline{M}_0, [i],$$

$$\mathcal{M}_{(4,k)} = \overline{M}_1, [k] \times \overline{M}_1, [k] \times \prod_{i \in [k-1]} \overline{M}_0, [i],$$

$$\mathcal{M}_{(5,k)} = \overline{M}_2, [k] \times \prod_{i \in [k]} \overline{M}_0, [i].$$
For each \((i,k) \in [5] \times \mathbb{Z}_{>0}\), there is a natural node-identifying immersion
\[
\iota_{(i,k)} : \widehat{\mathcal{M}}_{(i,k)} \longrightarrow \overline{\mathcal{M}}_{(i,k)} \subset \mathcal{M}_2^{\text{wt}}
\]
obtained by identifying the marked points that share the same index. Such \(\iota_{(i,k)}\) is surjective onto \(\overline{\mathcal{M}}_{(i,k)}\) and descends to the quotient
\[
(4.7) \quad \overline{\iota}_{(i,k)} : \widehat{\mathcal{M}}_{(i,k)}/\mathcal{S}_{(i,k)} \longrightarrow \overline{\mathcal{M}}_{(i,k)} \subset \mathcal{M}_2^{\text{wt}},
\]
where \(\mathcal{S}_{(i,k)}\) is the symmetric group of the dual graph of \(\mathcal{M}_{(i,k)}\). Notice that \(\iota_{(i,k)}\) is generally not an isomorphism to its image; c.f. [14, Figure 3] with the genus 1 component replaced by a genus 2 curve, as well as the example at the end of Remark 3.2.6. Thus \(\overline{\mathcal{M}}_{(i,k)}\) is generally not smooth.

By the topology of \(\mathcal{M}_2^{\text{wt}}\), \(\overline{\mathcal{M}}_{(i,k)} \cap \overline{\mathcal{M}}_{(j,\ell)} = \emptyset\) whenever \((j,\ell) > (i,k)\) (w.r.t. the lexicographical order). Let
\[
\overline{\mathcal{M}}_{(i)} = \bigcup_{k \geq 1} \overline{\mathcal{M}}_{(i,k)}, \quad \overline{\mathcal{M}}_{(i)}^{\text{mn}} = \overline{\mathcal{M}}_{(i)} \ominus \left( \bigcup_{\ell \in \mathbb{Z}_{[-1]}^*} \overline{\mathcal{M}}_{(i,\ell)} \right), 1 \leq i \leq 4;
\]
(4.8)
\[
\overline{\mathcal{M}}_2^{\text{wt}} = \bigcup_{i = 4} \overline{\mathcal{M}}_{(i)}^{\text{mn}} \cup \bigcup_{i = 1} \overline{\mathcal{M}}_{(i)}^{\text{mn}}.
\]
In particular, \(\overline{\mathcal{M}}_{(1)}^{\text{mn}} = \overline{\mathcal{M}}_{(1)}\). Then we obtain a partition of \(\mathcal{M}_2^{\text{wt}}\):
\[
\mathcal{M}_2^{\text{wt}} = \overline{\mathcal{M}}_{(2)}^{\text{mn}} \sqcup \overline{\mathcal{M}}_{(3)}^{\text{mn}} \sqcup \overline{\mathcal{M}}_{(4)}^{\text{mn}} \sqcup \overline{\mathcal{M}}^{\text{mn}}.
\]
Notice that \(\overline{\mathcal{M}}_{(2)} \cap \overline{\mathcal{M}}_{(3)} \subset \overline{\mathcal{M}}_{(1)}\), thus
\[
(4.9) \quad \overline{\mathcal{M}}_{(3)}^{\text{mn}} \cap \overline{\mathcal{M}}_{(2)}^{\text{mn}} = \emptyset, \quad \overline{\mathcal{M}}_{(3)}^{\text{mn}} = \overline{\mathcal{M}}_{(3)} \ominus \overline{\mathcal{M}}_{(1)}^{\text{mn}}.
\]

4.3. The first round \((r_1)\). In \(r_1\), \(\mathcal{M}_2^{\text{wt}}\) is blown up successively along the proper transforms of \(\overline{\mathcal{M}}_{(i,k)}\) with respect to the lexicographical order on \((i,k)\):
\[
\overline{\mathcal{M}}_{(i,k)} < \overline{\mathcal{M}}_{(j,\ell)} \iff i < j \text{ or } (i = j, k < \ell),
\]
as is illustrated in Figure [1]. Since each connected component of \(\mathcal{M}_2^{\text{wt}}\) is of finite type, the sequential blowup \(r_1\) on this component will terminate after finitely many steps.

Each row (resp. element) of Figure [1] is called a phase (resp. step) of \(r_1\). As in [13], the \(k\)-th step of the \(i\)-th phase of \(r_1\) is denoted by \(r_1 p_i s_k\). The proper transform of a substack \(\mathcal{N}\) after \(r_1 p_i s_k\) (resp. after \(r_1\)) is denoted by \(\overline{\mathcal{N}}_{r_1 p_i s_k}\) (resp. \(\overline{\mathcal{N}}_{r_1}\)). We write
\[
\overline{\mathcal{M}}_{r_1 p_i s_k} = (\mathcal{M}_2^{\text{wt}})_{r_1 p_i s_k}, \quad \overline{\mathcal{M}}_{r_1} = (\mathcal{M}_2^{\text{wt}})_{r_1}.
\]
The exceptional divisor obtained in \(r_1 p_i s_k\) is denoted by \(\mathcal{E}_{(i,k)}\), which lies in \(\overline{\mathcal{M}}_{r_1 p_i s_k}\).

**Lemma 4.3.1.** \(r_1 p_1\) is locally tree-compatible.
Proof. Let \( x \in \mathcal{M}_x^\text{aff} \).

If \( x \in \mathcal{M}_x^{\text{mm}_{(1)}} \), then \( x \) has a neighborhood \( \mathcal{V} \) such that \( r_1 \mathcal{P}_1 \) is \( \gamma \)-compatible on \( \mathcal{V} \), where \( \gamma \) is the terminally weighted tree of \( x \). This follows from the same reasoning as in the densingularization of \( \mathcal{M}_1(P^n, d) \) [15][14]; c.f. the second paragraph of Remark 3.2.6. If \( x \notin \mathcal{M}_x^{\text{mm}_{(1)}} \), then \( x \) has a neighborhood \( \mathcal{V} \) not affected by \( r_1 \mathcal{P}_1 \), thus \( r_1 \mathcal{P}_1 \) is \( \emptyset \)-compatible on \( \mathcal{V} \). In sum, \( r_1 \mathcal{P}_1 \) is locally tree-compatible. \( \square \)

**Lemma 4.3.2.** \( r_1 \mathcal{P}_2 \) is locally TFMR tree-compatible.

**Proof.** Let \( x \in \mathcal{M}_x^\text{aff} \).

If \( x \in \mathcal{M}_x^{\text{mm}_{(2)}} \), then the core of \( x \) contains a minimal separating bridge \( B \) so that \( \deg D \cap F = \deg D \cap B \). Let \( \gamma_\lambda \) be the TFMR tree as in (4.5) so that \( B \) corresponds to the fused vertex \( v_B \). It is straightforward that there is an affine smooth chart \( \mathcal{V} \) containing \( x \) so that the collection of modular parameters \( \{ \zeta \}_e \in \text{Ed}_{\lambda}(\gamma, \lambda) \) is a \( \gamma_\lambda \)-labeled subset of local parameters on \( \mathcal{V} \) and

\[
(4.10) \quad \mathcal{M}(1,k) \cap \mathcal{V} = \emptyset, \quad \mathcal{M}(2,k) \cap \mathcal{V} = \bigcup_{E \in \mathcal{T}(\gamma, \lambda)} Z_E \quad \forall \, k \in \mathbb{Z}_{>0}.
\]

Thus, \( r_1 \mathcal{P}_1 \) and \( r_1 \mathcal{P}_2 \) are \( \emptyset \)- and \( \gamma_\lambda \)-compatible on \( \mathcal{V} \), respectively.

If \( x \in \mathcal{M}_x^{\text{mm}_{(2)}} \cap \mathcal{M}_x^{(1)} \), then the core of \( x \) contains a (non-degenerate) maximal separating bridge \( B_M \). After \( r_1 \mathcal{P}_1 \), let \( y \) be a lift of \( x \) and DPN\((y)\) be as in (3.15). If DPN\((y) \notin B_M \), then \( y \) is not in the proper transform of any \( \mathcal{M}(2,k) \), hence \( r_1 \mathcal{P}_2 \) is \( \emptyset \)-compatible on \( \mathcal{V}_y \). If DPN\((y) \subset B_M \), we denote by \( B \subset B_M \) the minimal separating bridge containing DPN\((y)\). With \( \gamma_\lambda \) as in the previous paragraph, we observe that \( r_1 \mathcal{P}_2 \) is \( (\gamma_\lambda)_y \)-compatible on an affine smooth \( \mathcal{V}_y \) containing \( y \).

If \( x \notin \mathcal{M}_x^{(2)} \), then \( r_1 \mathcal{P}_2 \) is \( \emptyset \)-compatible on the pullback of \( \mathcal{V} \) after \( r_1 \mathcal{P}_1 \). In sum, \( r_1 \mathcal{P}_2 \) is locally TFMR tree-compatible. \( \square \)

**Lemma 4.3.3.** \( r_1 \mathcal{P}_3 \) is locally TFMR tree-compatible.

**Proof.** By (4.9), the proof is almost identical to that of Lemma 4.3.2 but with the separating bridge \( B \) and the TFMR tree \( \gamma_\lambda \) replaced by the non-separating bridge \( \tilde{B} \) and the TFMR tree \( \gamma_\circ \) of (4.6), respectively. \( \square \)

**Lemma 4.3.4.** \( r_1 \mathcal{P}_4 \) is locally tree-compatible.

**Proof.** The approach in the proof of Lemma 4.3.2 can as well be applied to the current case.

To be precise, if \( x \in \mathcal{M}_x^{\text{mm}_{(4)}} \), let \( \gamma_\circ \) be as in (4.4) so that \( D \cap F = D \cap F_1 \). Mimicking the paragraph containing (4.10), we conclude that \( r_1 \mathcal{P}_1 - r_1 \mathcal{P}_3 \) are all \( \emptyset \)-compatible on an affine smooth \( \mathcal{V} \) containing \( x \), whereas \( r_1 \mathcal{P}_4 \) is \( \gamma_\circ \)-compatible on \( \mathcal{V} \).

If \( x \in \mathcal{M}_x^{(4)} \cap \mathcal{M}_x^{\text{mm}_{(3)}} \), let \( y \) be a lift of \( x \) after \( r_1 \mathcal{P}_3 \), \( \gamma_\circ \) be as in (4.6), and DPN\(_{\gamma_\circ}(y) \) be as in (3.15). The core \( F \) is still separable; w.l.o.g. assume \( D \cap F = D \cap F_1 \). If DPN\(_{\gamma_\circ}(y) \cap F_2 \neq \emptyset \), then \( y \) is not in the proper transform
of any $\overline{\mathcal{M}}_{(4,k)}$, hence $r_1p_4$ is $\emptyset$-compatible on an affine smooth chart $\mathcal{V}_y$ of $y$. If $\text{DPN}_{\gamma}(y) \cap F_2 = \emptyset$, then by Proposition 3.5.2, $r_1p_4$ is $(\gamma_y)_y$-compatible on an affine smooth chart $\mathcal{V}_y$ containing $y$.

If $x \in \overline{\mathcal{M}}_{(4)} \cap \overline{\mathcal{M}}_{(2)}^{\text{mm}}$, let $y$ be a lift of $x$ after $r_1p_2$ (hence after $r_1p_3$ by (4.5)), $\gamma_\Lambda$ be as in (4.5), and $\text{DP}_{\gamma}(y)$ be as in (3.15). If there exist edges in $\text{DP}_{\gamma}(y)$ that are respectively connected to the roots $o_1$ and $o_2$, then $y$ is not in the proper transform of any $\overline{\mathcal{M}}_{(4,k)}$, hence $r_1p_4$ is $\emptyset$-compatible on a chart $\mathcal{V}_y$ of $y$. If all the edges in $\text{DP}_{\gamma}(y)$ are over one root of $\gamma_\Lambda$, say $o_1$, then by Proposition 3.5.2, $r_1p_4$ is $(\gamma_y)_y$-compatible on an affine smooth chart $\mathcal{V}_y$ containing $y$.

If $x \notin \overline{\mathcal{M}}_{(4)}$, then $r_1p_4$ is $\emptyset$-compatible on the pullback of $\mathcal{V}$ after $r_1p_3$. In sum, $r_1p_4$ is locally TFMR tree-compatible. □

**Lemma 4.3.5.** $r_1p_5$ is locally tree-compatible.

**Proof.** The approach in the proofs of Lemmas 4.3.2, 4.3.3 can as well be applied to the current case.

To be precise, let $x \in \overline{\mathcal{M}}_{(2)}^{\text{et}}$. If $x \in \overline{\mathcal{M}}_{(5)}^{\text{mm}}$, then $\deg D \cap F = 1$, hence $r_1p_1-r_1p_4$ are all $\emptyset$-compatible on an affine smooth $\mathcal{V}$ containing $x$, whereas $r_1p_5$ is $\gamma$-compatible on $\mathcal{V}$.

If $x \in \overline{\mathcal{M}}_{(5)} \cap \overline{\mathcal{M}}_{(4)}^{\text{mm}}$, let $\gamma_y$ be as in (4.4) so that $D \cap F \subseteq F_1$ and $e_1 \in \text{Edg}(\gamma_y)^t$ be such that $q_{e_1}$ is the node on $F_1$ separating $F_1$ from $F_2$. Let $y$ be a lift of $x$ after $r_1p_4$. If $\text{Dom}(y) = \{e_1\}$ (resp. $\text{Dom}(y) \neq \{e_1\}$), then $r_1p_5$ is $\gamma_y$-compatible (resp. $\emptyset$-compatible) on an affine smooth $\mathcal{V}_y$ containing $y$.

If $x \in \overline{\mathcal{M}}_{(5)} \cap \overline{\mathcal{M}}_{(3)}^{\text{mm}}$, let $B$ be the irreducible component containing the only point of $D \cap F$. Since $x \in \overline{\mathcal{M}}_{(5)}^{\text{mm}}$, $B$ belongs to a non-separating bridge. Let $\gamma_\Lambda$ be as in (4.6) and $e_1, e_2 \in \text{Edg}(\gamma_\Lambda)^t$ be such that $q_{e_1}, q_{e_2}$ are the two principal nodes on $B$. Let $y$ be a lift of $x$ after $r_1p_3$. If $\text{Dom}(y) \subseteq \{e_1, e_2\}$, then $r_1p_5$ is $\emptyset$-compatible on the pullback after $r_1p_3$ of an affine smooth $\mathcal{V}_y$ containing $y$. If $\text{Dom}(y) \subseteq \{e_1, e_2\}$ and $F$ is inseparable, then $r_1p_4$ and $r_1p_5$ are $\emptyset$- and $\gamma_y$-compatible on $\mathcal{V}_y$, respectively. If $\text{Dom}(y) \subseteq \{e_1, e_2\}$ and $F$ is separable, then the argument is analogous to the $x \in \overline{\mathcal{M}}_{(5)} \cap \overline{\mathcal{M}}_{(4)}^{\text{mm}}$ case.

If $x \in \overline{\mathcal{M}}_{(5)} \cap \overline{\mathcal{M}}_{(2)}^{\text{mm}}$, let $B$ be the irreducible component containing the only point of $D \cap F$. Since $x \in \overline{\mathcal{M}}_{(2)}^{\text{mm}}$, $B$ belongs to a separating bridge. Let $\gamma_\Lambda$ be as in (4.5) and $e_1, e_2 \in \text{Edg}(\gamma_\Lambda)^t$ be such that $q_{e_1}$ and $q_{e_2}$ are the two principal nodes on $B$ separating $B$ from $F_1$ and $F_2$, respectively. Let $y$ be a lift of $x$ after $r_1p_2$. If $\text{Dom}(y) \subseteq \{e_1, e_2\}$, then $r_1p_5$ is $\emptyset$-compatible on the
pullback after $r_1p_4$ of an affine smooth $V_y$ containing $y$. If $\text{Dom}(y) = \{\xi_1, \xi_2\}$, then $r_1p_3$ and $r_1p_4$ are $\emptyset$-compatible on $V_y$, whereas $r_1p_5$ is $\gamma_y$-compatible on $V_y$, respectively. If $\text{Dom}(y) \subseteq \{\xi_1, \xi_2\}$, say $\text{Dom}(y) = \{\xi_1\}$, then $r_1p_3$ is $\emptyset$-compatible on $V_y$. The remaining argument is analogous to the $x \in \overline{\mathcal{M}}(5) \cap \mathcal{M}^{\text{mn}}(4)$ case.

If $x \in \overline{\mathcal{M}}(5) \cap \mathcal{M}^{\text{mn}}(1)$, let $y$ be a lift of $x$ after $r_1p_1$. If $|\text{Dom}(y)| > 1$ or $\text{Dom}(y) = e$ but $|D \cap C_{y_1}| > 1$, then $r_1p_4$ is $\emptyset$-compatible on the pullback after $r_1p_4$ of an affine smooth $V_y$ containing $y$. It remains to consider the case when $\text{Dom}(y) = e$ but $|D \cap C_{y_1}| = 1$. If in addition $\langle e \rangle$ lies on a bridge of $F$, then the argument is similar to one of the two preceding paragraphs. If $\langle e \rangle$ is not contained in any bridge of $F$, then $r_1p_2$ and $r_1p_3$ do not affect an affine smooth $V_y$ containing $y$. If $F$ is inseparable, then $r_1p_5$ is $(\gamma_{\{e\} \times y})_y$-compatible on $V_y$. If $F$ is separable, the remaining argument is analogous to the $x \in \overline{\mathcal{M}}(5) \cap \mathcal{M}^{\text{mn}}(4)$ case.

If $x \notin \overline{\mathcal{M}}(5)$, then $r_1p_5$ is $\emptyset$-compatible on the pullback of $V$ after $r_1p_4$. In sum, $r_1p_5$ is locally TFMR tree-compatible.

Lemmas 4.3.1-4.3.5 along with Corollary 3.2.5 and Proposition 3.4.2 imply the following statement.

**Corollary 4.3.6.** The blowup locus at every step of $r_1$ is closed and smooth.

4.4. **The second round** ($r_2$). The blowup loci of $r_2$ lie in the proper transforms $\mathcal{E}^{r_1p_3}_{(1,k)}$ of the exceptional divisors $\mathcal{E}_{(1,k)}$ obtained in $r_1p_1$. We first construct the corresponding loci in $\mathcal{E}_{(1,k)}^{r_1p_1}$ and show the sequential blowup along these loci is derived from $r_1p_1$. We then take their proper transform after $r_1p_5$.

The following terminology is consistent with [14, Section 3.1]. For an arbitrary stack $\hat{\mathcal{M}}$, denote by $T\hat{\mathcal{M}}$ and $TC\hat{\mathcal{M}}$ its Zariski tangent space and its tangent cone, respectively. If $X$ is a smooth stack, a morphism $\iota_X: X \rightarrow T\hat{\mathcal{M}}$ is an immersion if its differential

$$d\iota_X: TX \rightarrow \iota_X^*TC\hat{\mathcal{M}}$$

is injective at every point of $X$. Let

$$N_{\iota_X} \equiv \iota_X^*TC\hat{\mathcal{M}}/\text{Im}d\iota_X$$

be the normal cone of $\iota_X$ in $T\hat{\mathcal{M}}$.

For $k \geq 1$, the normal cone of the immersion $\iota_{(1,k)}: \hat{\mathcal{M}}_{(1,k)} \rightarrow \mathcal{M}^{\text{tw}}_{(1,k)}$ is the direct sum of $k$ line bundles:

$$N_{\iota_{(1,k)}} = \bigoplus_{i \in \mathbb{Z}[k]} \left( \text{pr}_{1,i}^* N_{i} \otimes \text{pr}_{2,i}^* \mathcal{L} \right) = \bigoplus_{i \in \mathbb{Z}[k]} \hat{L}_{k;i} \rightarrow \hat{\mathcal{M}}_{(1,k)}$$

where $\mathcal{L}_{k;i}$ and $\mathcal{L}$ are respectively the universal tangent line bundle at the marked point of $\mathcal{M}_{(1,k)}$ labeled by $i$ and the marked point of $\hat{\mathcal{M}}_{0,\{\xi\}}$,
is locally tree compatible. Let \( j \) step. For successively along the proper transforms of the proof of Lemma 4.3.1, we conclude that the sequential blowup of marked curves that has exactly onto components.

\[
\ell_{(1,k)} : \mathcal{M}^{\overline{r}_{1}p_{1}\overline{s}_{j}}_{(1,k)} \to \mathcal{N}^{r_{0}t_{1}/i}, \quad i \in [k],
\]

are the projections onto components.

The immersion \( \tau_{(i,k)} \) in (4.7) induced by \( \ell_{(i,k)} \) is generally not an isomorphism to its image. For \( j < k \), the immersion \( \ell_{(1,k)} \) induces an immersion and the corresponding quotient:

\[
\ell_{(1,k)}^{r_{1}p_{1}s_{j}} : \mathcal{M}^{r_{1}p_{1}s_{j}}_{(1,k)} \longrightarrow \mathcal{M}^{r_{1}p_{1}s_{j}}_{(1,k)} = \mathcal{M}^{r_{1}p_{1}s_{j}}_{(1,k)} / S_{(k)},
\]

\[
(4.12)
\]

The domain \( \mathcal{M}^{r_{1}p_{1}s_{j}}_{(1,k)} \) is constructed by applying [14 Lemma 3.3.(1)] repeatedly. It is analogous to the smooth variety introduced in [14 Section 2.3]. To be precise, for an arbitrary finite set \( S \), let \( \mathcal{M}_{2,s,j} \subset \mathcal{M}_{2,S} \) be consisting of marked curves that has exactly \( j \) special points (pivotal nodes and marked points) on its core. We denote by \( \mathcal{M}_{2,s,j} \) its closure in \( \mathcal{M}_{2,S} \). Mimicking the proof of Lemma 4.3.1, we conclude that the sequential blowup of \( \mathcal{M}_{2,S} \) successively along the proper transforms of

\[
\mathcal{M}_{2,S,1}, \ldots, \mathcal{M}_{2,S|S|-1}
\]
is locally tree compatible. Let \( \mathcal{M}^{s}_{2,j} \) be the blowup of \( \mathcal{M}_{2,S} \) after the \( j \)-th step. For \( S = [k] \) and \( j \in [k-1] \), let

\[
\mathcal{M}^{r_{1}p_{1}s_{j}}_{(1,k)} = \mathcal{M}^{s}_{2,k} \times \prod_{i \in [k]} \mathcal{M}^{r_{0}t_{1}/i},
\]

which is smooth by Corollary 3.2.5. For \( j = 0 \), set \( \ell_{(i,k)}^{r_{1}p_{1}s_{0}} = \ell_{(i,k)} \).

The immersion \( \tau_{(1,k)}^{r_{1}p_{1}s_{k-1}} \) in (4.12) is an embedding. This follows from [14 Lemma 3.3.(2)] repeatedly; c.f. [14 §4.3 (I13)]. The normal cone of \( \tau_{(1,k)}^{r_{1}p_{1}s_{k-1}} \) is still a direct sum of \( k \) line bundles:

\[
\mathcal{N}_{(1,k)}^{r_{1}p_{1}s_{k-1}} = \bigoplus_{j \in [k]} L_{K_{j}} \longrightarrow \mathcal{M}^{r_{1}p_{1}s_{k-1}}_{(1,k)};
\]

(4.14)

c.f. [14 Lemma 3.5]. Each line bundle \( L_{K_{j}} \) above is the pullback of \( \hat{L}_{K_{j}} \) twisted by some exceptional divisors of previous steps. The immersion \( \tau_{(1,k)}^{r_{1}p_{1}s_{k-1}} \) induces an immersion

\[
\ell_{(1,k)}^{r_{1}p_{1}s_{k-1}} : \mathbb{P} \mathcal{N}_{(1,k)}^{r_{1}p_{1}s_{k-1}} \longrightarrow \mathcal{E}_{(1,k)} = \mathbb{P} \mathcal{N}_{M}^{r_{1}p_{1}s_{k-1}} \subset \mathcal{M}^{r_{1}p_{1}s_{k}},
\]

which in turn determines an isomorphism

\[
\tau_{(1,k)}^{r_{1}p_{1}s_{k-1}} : \mathbb{P} \mathcal{N}_{(1,k)}^{r_{1}p_{1}s_{k-1}} \longrightarrow \mathcal{E}_{(1,k)}.
\]

Next, consider the index sets

\[
\hat{D}_{l}(m) = \{ (J,J',S,I = \bigcup_{i \in S} I_{i}) : I \cup J \subset [m], \ |J'| = l, \}
\]

(4.17)

\[
\mathcal{D}_{1}(m) = \{ ([k],\{j\},S,I) \in \hat{D}_{1}(m) : k \in [m] \} \quad ( \subset \hat{D}_{1}(m)).
\]
For each $\rho=(J,J',S,I)\in\hat{\mathcal{D}}(m)$, set
\[
\kappa(\rho) = |J|, \quad \sigma(\rho) = I \cup (J \setminus S),
\]
(4.18) \[
\hat{M}_\rho = \mathcal{M}_{2,J} \times \prod_{i\in S} \mathcal{M}_{0,\{i\} \cup I_i} \times \prod_{h\in \sigma(\rho)} \mathcal{M}_{0,\{h\}},
\]
(4.19) \[
\hat{M}_\rho \subset \hat{M}(1,\kappa(\rho))
\]
For each $\rho\in\mathcal{D}_1(m)$, let
(4.20) \[
\hat{M}_\rho \subset \hat{M}(1,\kappa(\rho))
\]
be the image of $\hat{M}_\rho$ in $\hat{M}(1,\kappa(\rho))$ by identifying the marked points labeled by $I$. With $\hat{M}(1,\kappa(\rho))$ as in (4.12), we denote by \[
\hat{M}_\rho^{r_1p_1s_1(\rho)^-1} \subset \hat{M}(1,\kappa(\rho))
\]
the proper transform of $\hat{M}_\rho$ in $\hat{M}(1,\kappa(\rho))$. Set
(4.21) \[
\hat{X}_\rho = \mathbb{P}\left(\left(\bigoplus_{i\in \{j\} \cup S} L_{\kappa(\rho)}:i\right)|_{\hat{M}_\rho^{r_1p_1s_1(\rho)^-1}} \subset \mathbb{P}\mathcal{M}_{(1,\kappa(\rho))}^{r_1p_1s_1(\rho)^-1},
\]
(4.22) \[
X_\rho = \iota_{(1,\kappa(\rho))}^*\left(\hat{X}_\rho\right) = \tau_{(1,\kappa(\rho))}^*\left(\hat{X}_\rho/\mathcal{M}(1,\kappa(\rho))\right) \subset \mathcal{E}(1,\kappa(\rho)).
\]
If $\rho\in\mathcal{D}_1(m)$ satisfies $S=\emptyset$, then $\hat{X}_\rho$ and $X_\rho$ are isomorphic to $\hat{M}_\rho^{r_1p_1s_1(\rho)^-1}$ and $\hat{M}_\rho^{r_1p_1s_1(\rho)^-1}$, respectively. Some of these loci are illustrated in Figure 2. In each diagram of Figure 2, the proper transform $\hat{M}_\rho^{r_1p_1s_1(\rho)^-1}$ is abbreviated as $\hat{M}_\rho^*$ (to save space).

We are ready to describe a sequential blowup derived from $r_1p_1$. Let \[
\text{Ad}_1(m) = \{(k,k')\in\mathbb{Z}\times\mathbb{Z} : 1 \leq k \leq k' \leq m\}
\]
be endowed with the lexicographical order. For each $(k,k')\in\text{Ad}_1(m)$, set
(4.23) \[
\mathcal{D}_1(k,k') = \{\rho\in\mathcal{D}_1(m) : \kappa(\rho) = k, \ |\sigma(\rho)| = k'\}, \quad X_{k,k'} = \bigcup_{\rho\in\mathcal{D}_1(k,k')} X_\rho.
\]
Following the notation in [4.3], we denote by $X_{k,k'}^{r_1p_1}$ the proper transform of $X_{k,k'}$ after $r_1p_1$.

Let \[
\pi : \hat{M}^{r_1p_1} \to \hat{M}_{2,t}^{r_1p_1} \quad \text{and} \quad \pi' : \hat{M} \to \hat{M}^{r_1p_1}
\]
be respectively the sequential blowup of $r_1p_1$ and the blowup of $\hat{M}^{r_1p_1}$ successively along the proper transforms of $X_{k,k'}^{r_1p_1}$, $1 \leq k \leq k'$, with respect to the lexicographical order. For each connected component of $\hat{M}_{2,t}^{r_1p_1}$ with the total weight $m$, the relevant blowup loci $X_{k,k'}^{r_1p_1}$ are indexed by the finite set $\text{Ad}_1(m)$, hence $\pi'$ on this component will terminate after finitely many steps.

**Lemma 4.4.1.** With notation as above, $\pi'$ is derived from $\pi$. 

Proof. Given \( x \in \mathcal{M}_2^{\text{wt}} \), if \( x \notin \mathcal{M}_{(1)} = \mathcal{M}_2^{\text{mn}}(1) \), then \( \pi \) is \( \mathcal{O} \)-compatible on a chart \( \mathcal{V} \) containing \( x \). We may assume \( \mathcal{V} \) is sufficiently small so that every \( E^{(1)}_{(1,k)} \) is disjoint from \( \mathcal{V} \). Hence \( \pi' \) is \( \mathcal{O} \)-compatible on \( \pi^{-1}(\mathcal{V}) \). By Remark 3.6.2 this implies \( \pi' \) is derived from \( \pi \) on \( \mathcal{V} \).

If \( x \in \mathcal{M}_2^{\text{mn}}(1) \), let \( \gamma \) be its terminally weighted tree. The splitting of \( \mathcal{D}_1(m) \) into \( \mathcal{D}_1(k,k') \), \( (k,k') \in \text{Ad}_{1}(m) \), induces a splitting of \( \mathcal{D}_1(\gamma) \) into \( \mathcal{D}_1(\gamma)_{k,k'} \), \( (k,k') \in \text{Ad}_{1}(m) \), given by

\[
\mathcal{D}_1(\gamma)_{k,k'} = \{ \mathcal{E} = (E,e,E') \in \mathcal{D}_1(\gamma) : |E| = k, |E'| = k' \}.
\]

To each \( \mathcal{E} \in \mathcal{D}_1(\gamma)_{k,k'} \), we assign a bijection \( 1_{\mathcal{E}} : E \to [k] \). Then \( \mathcal{E} \) uniquely determines

\[
\left( \{k\}, \left\{ 1_{\mathcal{E}}(e) \right\}, E \setminus E', E' \setminus E \right) \in \mathcal{D}_1(k,k').
\]

By (4.20) and (4.19),

\[
\bigcup_{\rho \in \mathcal{D}_1(k,k')} X^{(1)}_{\rho} \cap \pi^{-1}(\mathcal{V}) = \bigcup_{\mathcal{E} \in \mathcal{D}_1(\gamma)_{k,k'}} Y_{\mathcal{E}} \quad \forall \ (k,k') \in \text{Ad}_{1}(m).
\]

This shows \( \pi' \) satisfies (C1) of Definition 3.6.3.

Given \( \mathcal{E}_i \in \mathcal{D}_1(\gamma)_{k_i,k_i'} \), \( i = 1, 2 \), with \( \mathcal{E}_1 < \mathcal{E}_2 \), by (3.25), either \( E_1 < E_2 \), which implies \( k_1 < k_2 \) and hence \( (k_1,k_1') < (k_2,k_2') \), or \( E_1 = E_2 \), \( e_1 = e_2 \), and \( E_1' < E_2' \), which implies \( k_1 = k_2 \) and \( k_1' < k_2' \), and thus \( (k_1,k_1') < (k_2,k_2') \). Therefore, the condition (C2) of Definition 3.6.3 is also satisfied.

In \( r_2 \), the stack \( \widetilde{\mathcal{M}}^{(1)} \) is blown up successively along the proper transforms of \( X^{(1)}_{k,k'} \), \( 1 \leq k \leq k' \), with respect to the lexicographical order; c.f. Figure 2.

As explained before Lemma 4.4.1, the sequential blowup \( r_2 \) will terminate after finitely many steps on each connected component of \( \widetilde{\mathcal{M}}^{(1)} \). In each diagram of Figure 2 we illustrate (the preimage under (4.15) of) a typical element of \( X_{k,k'} \). Note that the only non-empty \( X^{(1)}_{1,1} \) is the divisor \( X^{(1)}_{1,1} \); blowing up along it does not change anything. Thus in Figure 2 the first diagram is for \( X_{2,2} \).

The proper transform of a substack \( \mathcal{N} \) (of either the original stack \( \mathcal{M}_2^{\text{wt}} \) or its blowup after any intermediate step) after the step \( r_2 k,k' \) (resp. after \( r_2 \)) is denoted by \( \mathcal{N}^{r_2 k,k'} \) (resp. \( \mathcal{N}^{r_2} \)). We write

\[
\widetilde{\mathcal{M}}^{r_2 k,k'} = (\mathcal{M}_2^{\text{wt}})^{r_2 k,k'}, \quad \widetilde{\mathcal{M}}^{r_2} = (\mathcal{M}_2^{\text{wt}})^{r_2}.
\]

The exceptional divisor in the step \( r_2 k,k' \) is denoted by \( \mathcal{E}_{k,k'} \) (\( \subset \widetilde{\mathcal{M}}^{r_2 k,k'} \)).

It is a direct check that (the proper transform of) \( \pi' \) in Lemma 4.4.1 is compatible with each sequential blowup of \( r_{1 p_j} \), \( 2 \leq j \leq 5 \). Applying Corollary 3.5.3 repeatedly, we thus obtain the following statement.

**Lemma 4.4.2.** \( r_2 \) is locally tree-compatible.

**Lemma 4.4.2** and Corollary 3.2.5 lead to the following conclusion.

**Corollary 4.4.3.** The blowup locus at every step of \( r_2 \) is closed and smooth.
4.5. **The first phase of the third round** \( (r_3p_1) \). The blowup loci of \( r_3p_1 \) lie in the proper transforms \( E_{(1,k)}^p \) of the exceptional divisors \( E_{(1,k)} \) obtained in \( r_1p_1 \). We first construct the corresponding loci in \( E_{(1,k)}^{r_1p_1} \) and take its proper transform after \( r_2 \). We then show the blowup along these loci is *supplementary* to the proper transform of a sequential blowup \( bi-dominantly \) derived from \( r_1p_1 \) (c.f. \( \S 3.2 \) and \( \S 3.7 \) for terminology).

Given a finite set \( S \) and distinct \( i_1, i_2 \in S \), we denote by \( K_{S,i_1,i_2} \) the locus in \( \overline{M}_{g,n} \) so that the marked points indexed by \( i_2 \) and \( i_2 \) are conjugate. As in \( \S 2.2 \), it is a Cartier divisor. Consider the index set

\[
D_2(m) = \{ ([k], \{j_1, j_2\}, S, I) \in \hat{D}_2(m) : k \in [2, m] \} \quad (\subset \hat{D}_2(m)),
\]

where \( \hat{D}_2(m) \) is as in \( (4.17) \). For each \( \rho = ([k], \{j_1, j_2\}, S, I) \in D_2(m) \), let

\[
\hat{K}_\rho = K_{[k]; j_1, j_2, I} \times \prod_{I \in S} \overline{M}_{0, \{i\} \cup I} \times \prod_{P \in \overline{M}_{0, \{h\}}} (\subset \hat{M}_\rho).
\]

Then, \( \hat{K}_\rho \) is a Cartier divisor of \( \hat{M}_\rho \); see \( (4.18) \) for notation.

For \( \rho \in D_2(m) \), we denote by

\[
(4.23) \quad \hat{\mathcal{M}}_\rho \quad \text{and} \quad \hat{K}_\rho \subset \hat{\mathcal{M}}_{(1,\kappa(\rho))}
\]

the images of \( \hat{M}_\rho \) and \( \hat{K}_\rho \) in \( \hat{\mathcal{M}}_{(1,\kappa(\rho))} \) by identifying the marked points labeled by \( I \), respectively. With \( \hat{\mathcal{M}}_{(1,\kappa(\rho))}^{r_1p_1s_{\kappa(\rho)}^{-1}} \) as in \( (4.12) \), we denote by

\[
\hat{\mathcal{M}}_\rho^{r_1p_1s_{\kappa(\rho)}^{-1}} \quad \text{and} \quad \hat{K}_\rho^{r_1p_1s_{\kappa(\rho)}^{-1}} \subset \hat{\mathcal{M}}_{(1,\kappa(\rho))}^{r_1p_1s_{\kappa(\rho)}^{-1}}
\]

the proper transforms of \( \hat{\mathcal{M}}_\rho \) and \( \hat{K}_\rho \) in \( \hat{\mathcal{M}}_{(1,\kappa(\rho))}^{r_1p_1s_{\kappa(\rho)}^{-1}} \), respectively. Set

\[
\hat{K}_\rho \equiv \mathbb{P} \left( \bigoplus_{I \in [j_1, j_2]} L_{(\kappa(\rho); i)} \right)_{\hat{\mathcal{M}}_\rho^{r_1p_1s_{\kappa(\rho)}^{-1}}}
\]

\[
\subset \hat{X}_\rho^{(2)} \equiv \mathbb{P} \left( \bigoplus_{I \in [j_1, j_2]} L_{(\kappa(\rho); i)} \right)_{\hat{\mathcal{M}}_\rho^{r_1p_1s_{\kappa(\rho)}^{-1}}} \quad (\subset \mathbb{P} \mathcal{N}_{(1,\kappa(\rho))}^{r_1p_1s_{\kappa(\rho)}^{-1}}),
\]

\[
K_\rho = \ell_{(1,\kappa(\rho))}(\hat{K}_\rho) \subset \hat{X}_\rho^{(2)}(\equiv \ell_{(1,\kappa(\rho))}(\hat{X}_\rho^{(2)}) \subset \mathcal{E}_{(1,\kappa(\rho))}.
\]

Similarly, \( K_\rho \) is a Cartier divisor of \( X_\rho^{(2)} \).

We next describe a sequence of blowups \( bi-dominantly \) derived from the modular blowups in \( r_1p_1 \). Let

\[
Ad_2(m) \equiv \{ (k, k') \in \mathbb{Z} \times \mathbb{Z} : 2 \leq k \leq k' + 1 \leq m \}
\]

For each \( (k, k') \in Ad_2(m) \), set

\[
D_2(k, k') = \{ \rho \in D_2(m) : \kappa(\rho) = k, \sigma(\rho) = k' \},
\]

\[
X_{k,k'}^{(2)} = \bigcup_{\rho \in D_2(k, k')} X_\rho^{(2)}, \quad K_{k,k'} = \bigcup_{\rho \in D_2(k, k')} K_\rho.
\]
Following the notation in §4.3, we denote by $X^{(2); r_1 p_1}$ and $K^{r_1 p_1}_{k, k'}$ the proper transforms of $X_{k, k'}$ and $K_{k, k'}$ after $r_1 p_1$, respectively.

Let $\pi : \mathcal{M}^{r_1 p_1} \to \mathcal{M}^{\text{wt}}_{2}$ and $\pi' : \mathcal{M}' \to \mathcal{M}^{r_1 p_1}$ be as in (4.22), and $\varphi^{(2)} : \mathcal{M}^{(2)} \to \mathcal{M}'$ be the blowup of $\mathcal{M}'$ successively along the proper transforms of $X^{(2); r_1 p_1}$, $2 \leq k \leq k'$, with respect to the lexicographical order. For each connected component of $\mathcal{M}^{\text{wt}}_2$ with the total weight $m$, the relevant blowup loci $X^{(2); r_1 p_1}$ are indexed by the finite set $\text{Ad}_2(m)$, hence $\varphi^{(2)}$ on this component will terminate after finitely many steps. The following statement is parallel to Lemma 4.4.1, we omit its proof.

**Lemma 4.5.1.** With notation as above, $\varphi^{(2)}$ is bi-dominantly derived from the blowup $\pi$, and the proper transform of $\varphi^{(2)}$ is compatible with $r_1 p_2 - r_2$.

In $r_3 p_1$, we blow up $\mathcal{M}^{r_2}$ successively along the proper transforms of $K^{r_1 p_1}_{k, k'}$, $2 \leq k \leq k'$, with respect to the lexicographical order. As explained before Lemma 4.5.1, the sequential blowup $r_3 p_1$ will terminate after finitely many steps on each connected component of $\mathcal{M}^{r_2}$. The proper transform of a substack $\mathcal{N}$ (of either the original stack $\mathcal{M}^{\text{wt}}_2$ or its blowup after any intermediate step) after the step $r_3 p_1 s_{k, k'}$ (resp. after $r_3 p_1$) is denoted by $\mathcal{N}^{r_3 p_1 s_{k, k'}}$ (resp. $\mathcal{N}^{r_3 p_1}$). We write

$$\mathcal{M}^{r_3 p_1 s_{k, k'}} = (\mathcal{M}^{r_2}_{\text{wt}})^{r_3 p_1 s_{k, k'}}, \quad \mathcal{M}^{r_3 p_1} = (\mathcal{M}^{r_2}_{\text{wt}})^{r_3 p_1}.$$

**Lemma 4.5.2.** $r_3 p_1$ is locally tree-compatible.

**Proof.** Let $\mathcal{R}^{n-s}_p$ be the closed locus in $\mathcal{R}_p$ where the nodes labeled by $j_1$ and $j_2$ are on a same non-separating bridge. Notice that $\mathcal{R}_p$ is possibly singular only along $\mathcal{R}^{n-s}_p$. Given $x \in \mathcal{R}^{n-s}_p$, w.l.o.g. we assume the nodes $q_{j_1}$ and $q_{j_2}$ are on a maximal non-separating bridge $B[p, q]$ such that $N[q_{j_1}, p] \subset N[q_{j_2}, p]$. Lemma 2.8.2 then implies there exist a smooth chart $\mathcal{V} \subset \mathcal{M}_p$ containing $x$ and modular parameters $\{\zeta_q\}$ corresponding to the nodes of $B[p, q]$ so that $\mathcal{R}_p \cap \mathcal{V} = \{\zeta[q_{j_1}, p] + \zeta[q_{j_2}, q] = 0\}$.

For any lift $\bar{x}$ of $x$ after $r_1 p_2$ that lies in the proper transform $\mathcal{R}^{r_1 p_3}_p$, we see that $\zeta[q_{j_1}, p]$ and $\zeta[q_{j_2}, q]$ pull back to $\bar{v}_1 \cdots \bar{v}_t \cdot u_1 \cdots u_{h_1}$ and $\bar{v}_1 \cdots \bar{v}_t \cdot v_1 \cdots v_{h_2}$, respectively, where $\bar{v}_1, \ldots, \bar{v}_t$ are the local parameters as in Lemma 3.3.2 whose vanishing loci are the proper transforms of the exceptional divisors of $r_3 p_2$, and $u_1, \ldots, u_{h_1}, v_1, \ldots, v_{h_2}$ are distinct nowhere vanishing local parameters corresponding to the positions of the images of $\bar{x}$ in the relevant exceptional divisors. Thus, $\mathcal{R}^{r_1 p_3}_p$ is locally given by $u_1 \cdots u_{h_1} + v_1 \cdots v_{h_2} = 0$. 
It is straightforward that $\hat{\mathcal{C}}_{\rho, p_1}^{r_2 p_3}$ is smooth near $x$.

In sum, we have shown that the proper transform of $\hat{x}_\rho$ is a smooth Cartier divisor of $\hat{\mathcal{M}}_\rho$ after $r_1 p_3$. This, along with Lemma 4.5.1 implies that $r_2 p_1$ is supplementary to the proper transform of $\hat{x}^{(2)}$, hence is locally tree-compatible.

Lemma 4.5.2 and Corollary 3.2.5 lead to the following conclusion.

**Corollary 4.5.3.** The blowup locus at every step of $r_3 p_1$ is closed and smooth.

4.6. The second phase of the third round ($r_3 p_2$). The blowup loci of $r_3 p_2$ lie in the proper transforms $\mathcal{E}^{r_3 p_1}_{k, k'}$ of the exceptional divisors $\mathcal{E}_{k, k'}$, $(k, k') \in \text{Ad}_1(m)$, obtained in $r_2$. We first construct the corresponding loci in $\mathcal{E}^{r_2}_{k, k'}$ and show the blowup along these loci is supplementary to a sequential blowup partially derived from $r_2$ (c.f. 3.2 and 3.6 for terminology). We then take its proper transform after $r_3 p_1$.

Given a finite set $J$ and $j \in J$, we denote by $\mathcal{W}_{\rho, j}$ the locus in $\hat{\mathcal{M}}_{\rho, J}$ so that the marked point labeled by $j$ is Weierstrass. As shown in 3.2, it is a Cartier divisor.

For $\rho = ([k], \{j\}, S, I) \in \mathcal{D}_1(m)$, let

$$\mathcal{N}(\rho) = \{ (\hat{j}, \{j\}, \hat{S}, \hat{I}) \in \hat{\mathcal{D}}_1(m) : \hat{j} = \sigma(\rho) \} \subset \hat{\mathcal{D}}_1(m).$$

For each $\hat{\rho} = (\sigma(\rho), \{j\}, \hat{S}, \hat{I}) \in \mathcal{N}(\rho)$, set

$$\tilde{W}_{\rho, \hat{\rho}} = W_{[k], j} \times \prod_{i \in S} \mathcal{M}_{0, \{i\} \cup I_i} \times \prod_{t \in S} \mathcal{M}_{0, \{t\} \cup I_t} \times \prod_{h \in \sigma(\rho)} \mathfrak{m}_{[0], [h]}^{\text{wt} + 1}.$$

Let $\tilde{W}_{\rho, \hat{\rho}}$ be the image of $\tilde{W}_{\rho, \hat{\rho}}$ in $\hat{\mathcal{M}}_\rho$ of (4.18) by identifying the marked points labeled by $\hat{I}$. As in (4.13), we set

$$\hat{\mathcal{M}}_{\rho, \hat{\rho}}^{r_1 p_1 s(\rho) - 1} = \mathcal{M}_{2, [\rho]}^{s(\rho) - 1} \times \prod_{i \in S} \mathcal{M}_{0, \{i\} \cup I_i} \times \prod_{h \in \sigma(\rho)} \mathfrak{m}_{[0], [h]}^{\text{wt} + 1},$$

which in turn determines $\hat{W}_{\rho, \hat{\rho}}^{r_1 p_1 s(\rho) - 1} \subset \hat{\mathcal{M}}_{\rho, \hat{\rho}}^{r_1 p_1 s(\rho) - 1}$. With

$$\nu_{\rho} : \hat{\mathcal{M}}_{\rho, \hat{\rho}} \to \hat{\mathcal{M}}_{\rho},$$

denoting the node identifying immersion in (4.19) and $\hat{X}_{\rho}$ denoting the pullback of $\hat{X}_{\rho}$ of (4.20) to $\hat{\mathcal{M}}_\rho$, let

$$\hat{X}_{\rho, \hat{\rho}} = \hat{X}_{\rho} \big|_{\hat{W}_{\rho, \hat{\rho}}^{r_1 p_1 s(\rho) - 1}}.$$

We next analyze the exceptional divisors $\mathcal{E}_{k, k'}$ of $r_2$. With the line bundles $L_{k, i}$ as in (4.14), for each non-empty $J \subset [k]$, let

$$\gamma_{k, J} \to \mathbb{P}\left( \bigoplus_{i \in J} L_{k, i} \right).$$
be the tautological line bundle. For each \( \rho \in \mathcal{O}_1(m) \), let

\[
\iota_{\rho} = \iota_{(1, \kappa(\rho))}^\nu \circ \nu_{\rho} : X_{\rho} \to X_\rho \subset \widehat{\mathbb{P}}^{r_1p_1s_{\kappa(\rho)}},
\]

\[
\tau_{\rho} = \tau_{(1, \kappa(\rho))}^\nu \circ \nu_{\rho} : X_{\rho}/G_\rho \to X_\rho \subset \widehat{\mathbb{P}}^{r_1p_1s_{\kappa(\rho)}},
\]

where \( \iota_{(1, \kappa(\rho))}^\nu \) and \( \tau_{(1, \kappa(\rho))}^\nu \) are as in (4.15) and (4.16), respectively, and \( G_\rho \) is the symmetry group of the dual graph of a general element of \( \hat{M}_\rho \). By (4.14) and (4.20), the normal cone of \( \iota_{\rho} \) can be written explicitly as

\[
\mathcal{N}_{\iota_{\rho}} \cong \nu_\rho^* \gamma_{\kappa(\rho), \{j\}} \cup S \bigoplus \bigoplus_{i \in I} \hat{L}_{\rho;i} \bigoplus \nu_\rho^* \left( \gamma_{\kappa(\rho), \{j\}} \cup S \bigoplus \left( \bigoplus_{i \in [k]} L_{\kappa(\rho);i} \right) \right),
\]

where \( \hat{L}_{\rho;i} \), \( i \in I \), are line bundles corresponding to the smoothing of the nodes labeled by \( I \); they are analogous to the line bundles in (4.11). We set

\[
\nu_\rho^* \hat{L}_{\rho;j} = \gamma_{\kappa(\rho), \{j\}} \cup S, \quad \hat{L}_{\rho;j} = \nu_\rho^* \left( \gamma_{\kappa(\rho), \{j\}} \cup S \bigoplus L_{\kappa(\rho);i} \right) \quad \forall \; i \in k \setminus \{ \{ j \} \cup S \}.
\]

Then \( \mathcal{N}_{\iota_{\rho}} = \bigoplus_{i \in \sigma(\rho)} \hat{L}_{\rho;i} \).

For each \((k, k') \in \text{Ad}_1(m)\), we denote by \((k, k') \rceil \) its immediate predecessor with respect to the lexicographical order on \( \text{Ad}_1(m) \). After \( r_2s_{(k, k')}^{-1} \), the immersion \( \iota_{\rho} \) with \( \rho \in \mathcal{O}_1(k, k') \) induces the immersion

\[
\tau_{\rho}^{r_2s_{(k, k')}^{-1}} : \hat{X}_{\rho}^{r_2s_{(k, k')}^{-1}} \to X_{\rho}^{r_2s_{(k, k')}^{-1}} \subset \mathcal{E}_{(1, k)}^{r_2s_{(k, k')}^{-1}} \subset \widehat{\mathbb{P}}^{r_2s_{(k, k')}^{-1}},
\]

where \( \hat{X}_{\rho}^{r_2s_{(k, k')}^{-1}} \) is obtained by blowing up \( \hat{X}_\rho \) successively along some smooth substacks analogously to the construction of \( \widehat{\mathbb{P}}^{r_1p_1s_j} \) in (4.13). The key fact is that the normal cone of \( \tau_{\rho}^{r_2s_{(k, k')}^{-1}} \) is still in the form

\[
\mathcal{N}_{\tau_{\rho}^{r_2s_{(k, k')}^{-1}}} = \bigoplus_{i \in \sigma(\rho)} \hat{L}_{\rho;i}.
\]

Each line bundle \( L_{\rho;j} \) above is the pullback of \( \hat{L}_{\rho;j} \) twisted by some exceptional divisors of previous steps. Furthermore, the immersion \( \tau_{\rho}^{r_2s_{(k, k')}^{-1}} \) determines

\[
\tau_{\rho}^{r_2s_{(k, k')}^{-1}} : \hat{X}_{\rho}^{r_2s_{(k, k')}^{-1}}/G_\rho \to X_{\rho}^{r_2s_{(k, k')}^{-1}} \subset \widehat{\mathbb{P}}^{r_2s_{(k, k')}^{-1}},
\]

which is isomorphic to its image. Thus, the immersion

\[
\iota_{\rho}^\epsilon : \mathbb{P}\mathcal{N}_{\tau_{\rho}^{r_2s_{(k, k')}^{-1}}} \to \mathcal{E}_{k, k'}
\]

determines an isomorphism

\[
\tau_{\rho}^\epsilon : \mathbb{P}\mathcal{N}_{\tau_{\rho}^{r_2s_{(k, k')}^{-1}}} \to \mathcal{E}_{k, k'}.
\]

For each \( \rho \in \mathcal{O}_1(k, k') \) and each \( \hat{\rho} \in \kappa(\rho) \), we set

\[
\hat{W}_{\rho, \hat{\rho}} = \mathbb{P}\left( \bigoplus_{i \in \{ j \} \cup S} L_{\rho;i} \right) \big|_{\hat{X}_{\rho}^{r_2s_{(k, k')}^{-1}}} \subset \mathbb{P}\mathcal{N}_{\tau_{\rho}^{r_2s_{(k, k')}^{-1}}},
\]

\[
W_{\rho, \hat{\rho}} = \iota_{\rho}^\epsilon(\hat{W}_{\rho, \hat{\rho}}) = \tau_{\rho}^\epsilon(\hat{W}_{\rho, \hat{\rho}}/G_\rho) \subset \mathcal{E}_{k, k'}.
\]
Let $W$ be endowed with the lexicographical order. For each $(k', k'') \in \text{Ad}_w(m)$, set

$$W_{k,k',k''} = \bigcup_{(\rho, \rho') \in D_w(k, k', k'')} W_{p, \rho, \rho'}.$$ 

Following the notation in §4.3, we denote by $W_{k,k',k''}^r$ the proper transform of $W_{k,k',k''}$ after $r$.

In $r_3p_2$, we blow up $\widetilde{M}^{r_3p_1}$ successively along the proper transforms of $W_{k,k',k''}^r$, $1 \leq k \leq k''$, with respect to the lexicographical order. For each connected component of $M^{rt}_2$ with the total weight $m$, the relevant blowup loci of $r_3p_2$ are indexed by the finite set $\text{Ad}_w(m)$, hence $r_3p_2$ will terminate after finitely many steps on each connected component of $M^{rt}_2$. The proper transform of a substack $\mathcal{R}$ (of either the original stack $M^{rt}_2$ or its blowup after any intermediate step) after the step $r_3p_2$ is denoted by $\widetilde{\mathcal{R}}_{k,k',k''}^r$ (resp. after $r_3p_2$) is denoted by $\widetilde{\mathcal{R}}_{k,k',k''}^{r_3p_2}$. We write

$$\widetilde{\mathcal{R}}_{k,k',k''}^{r_3p_2} = (\widetilde{\mathcal{R}}_{k,k',k''}^{r_3p_2})_{k,k',k''}.$$

**Lemma 4.6.1.** $r_3p_2$ is locally tree-compatible.

**Proof.** The proof is parallel to that of Lemma 4.5.2 except the local equation should be deduced from Lemma 2.8.1 instead of Lemma 2.8.2. We omit further details.

**Lemma 4.6.1** and Corollary 3.2.5 lead to the following conclusion.

**Corollary 4.6.2.** The blowup locus at every step of $r_3p_2$ is closed and smooth.

4.7. **The third phase of the third round** $(r_3p_3)$. The blowup loci of $r_3p_3$ lie in the relative Picard stack $\mathfrak{P}_2$ over $M^{rt}_2$ instead of the stack $M^{rt}_2$ itself. For a general point $(C, L) \in \mathfrak{P}_2$ with $\deg L = 2$, we observe that $h^0(L) = 1$; the locus

$$\mathcal{H}_1 = \{(C, L) \in \mathfrak{P}_2 : \deg L = 2, \ h^0(L) = 2\}$$

is a Cartier divisor of $\mathfrak{P}_2$. For $k \geq 0$, let $\mathcal{H}_k$ be the closed substack of $\mathfrak{P}_2$ whose general points are pairs $(C, L)$ with $F$ denoting the core of $C$ such that $(F, L|_F) \in \mathcal{H}_1$ and $C$ has $k$ tails attached to $F$. Note that if $(C, D) \in M^{rt}_2$ with $k$ tails satisfies

$$D \cap F = \{\delta_1, \delta_2\}, \quad \delta_1 \text{ is conjugate to } \delta_2,$$

then $(C, \mathcal{O}_C(D)) \in \mathcal{H}_k$.

When the modular blowups of $r_1$ terminates, let

$$\mathfrak{P}_1 = \mathfrak{P}_2 \times_{M^{rt}_2} \widetilde{\mathfrak{P}}_1, \quad \mathcal{H}_k' = \mathcal{H}_k \times_{M^{rt}_2} \widetilde{\mathfrak{P}}_1 \quad \forall \ k \geq 0.$$
We denote by $\pi^\dagger: \mathcal{P}_2 \to \tilde{\mathcal{P}}_{r_3}$ the sequential blowup successively along the proper transforms of $\mathcal{H}_{k}^{r_3}$, $k \geq 0$. Since each connected component of $\mathcal{M}_{2}^{\text{wt}}$ is of finite type, so is that of $\tilde{\mathcal{P}}_{r_3}$. The sequential blowup $\pi^\dagger$ on any connected component will thus terminate after finitely many steps.

**Lemma 4.7.1.** $\pi^\dagger$ is locally tree-compatible.

**Proof.** Given $(C, L) \in \mathcal{P}_2$, fix $(C, D) \in \mathcal{M}_2^{\text{div}}$ so that $L = \mathcal{O}_C(D)$. If $(C, L)$ is not contained in any $\mathcal{H}_k$, obviously $\pi^\dagger$ is $\mathcal{O}$-compatible on the pullback of a chart $\mathcal{V}$ containing $(C, L)$ after $r_1$. Hereafter we assume $(C, L)$ is contained in at least one of $\mathcal{H}_k$. In particular, this implies $\deg D \cap F \leq 2$.

If $\deg D \cap F = 2$ and $x = (C, c_1(L)) \in \mathcal{M}_2^{\text{wt}}$ is not contained in $\mathcal{M}(i)$ for any $i \in [5]$, then the entire $r_1$ does not affect a neighborhood of $x$. With $\gamma$ denoting the terminally weighted tree of $x$ as in (4.2), we observe that $\pi^\dagger$ is $\gamma_+^{+}$-compatible on a chart $\mathcal{V}$ containing $(C, L)$, where the extra edge corresponds to the normal direction of $\mathcal{V}$ in $\mathcal{P}_2$.

For all other possibilities of $(C, L)$, the proof is similar to that of Lemma 4.3.5 and/or Lemma 4.5.2 hence is omitted. \hfill \Box

After $r_3p_2$, let

$$
\tilde{\mathcal{P}}_{r_3}^p = \mathcal{P}_2 \times_{\mathcal{M}_2^{\text{wt}}} \tilde{\mathcal{P}}_{r_3}, \quad \mathcal{H}_{k}^{r_3} \equiv \mathcal{H}_k \times_{\mathcal{M}_2^{\text{wt}}} \tilde{\mathcal{P}}_{r_3} \quad \forall \ k \geq 0.
$$

In $r_3p_3$, we blow up the stack $\tilde{\mathcal{P}}_{r_3}^p$ successively along the proper transforms of $\mathcal{H}_k^{r_3}$. As explained before Lemma 4.7.1 the sequential blowup $r_3p_3$ will terminate after finitely many steps on each connected component of $\tilde{\mathcal{P}}_{r_3}^p$. The proper transform of a substack $\mathcal{N}$ (of either the original stack $\mathcal{P}_2$ or its blowup after any intermediate step) after the step $r_3p_3k$ (resp. after the phase $r_3p_3$) is denoted by $\mathcal{N}^{r_3p_3k}$ (resp. $\mathcal{N}^{r_3p_3}$).

It is a direct check that (the proper transform of) $\pi^\dagger$ in Lemma 4.7.1 is compatible with $r_2$-$r_3p_3$. Applying Corollary 3.5.3 repeatedly, we thus obtain the following statement.

**Lemma 4.7.2.** $r_3p_3$ is locally tree-compatible.

**Lemma 4.7.2** and Corollary 3.2.5 lead to the following conclusion.

**Corollary 4.7.3.** The blowup locus at every step of $r_3p_3$ is closed and smooth.

4.8. **The fourth phase of the third round** ($r_3p_4$). The process of $r_3p_4$ is analogous to the round $r_2$, but the blowup loci lie in the proper transforms of $\mathcal{P}_2$ instead of $\mathcal{M}_2^{\text{wt}}$.

Notice that the main difference between $\mathcal{M}(1)$ and $\mathcal{M}^{r_1p_4}$ in (4.8) is the weight of the core curve. Thus, the exceptional divisors obtained in the phases $r_1p_1$ and $r_1p_5$ share similar properties. In particular, we define

$$
X'_\rho \subset \mathcal{E}(5, k), \quad \rho \in \mathcal{D}_1(m),
$$
analogously to $X_\rho$ in (4.20). For each $\rho = ([k], \{j\}, S, I) \in D_1(m)$ and every $x \in X_\rho'$, we denote by $F_x$ the core of the curve $C_x$, by $q_x$ the node labeled by $j$, and by $p_x = \langle q_x \rangle$ the pivotal node corresponding to $q_x$. Let
\[ Q_\rho \subset \tilde{\mathcal{P}}_{r_1p_5s_e(\rho)}, \quad \rho \in D_1(m), \]
be the closed substack of $\tilde{\mathcal{P}}_{r_1p_5s_e(\rho)}$ whose general points are pairs $(x, L)$ satisfying
\[ x \in X_\rho', \quad (F_x, L |_{F_x} \otimes \mathcal{O}_{F_x}(q_x)) \in S. \]
We denote by $\pi^\dagger : \tilde{\mathcal{P}}^\dagger \to \tilde{\mathcal{P}}^*$ the sequential blowup successively along the proper transforms of
\[ Q_{k,k'} = \bigcup_{\rho \in D_1(k,k')} Q_\rho \left( \subset \tilde{\mathcal{P}}_{r_1p_5s_e} \right), \quad 1 \leq k \leq k', \]
with respect to the lexicographical order. Similarly, $\pi^\dagger$ on each connected component of $\tilde{\mathcal{P}}^\dagger$ will terminate after finitely many steps.

The following lemma follows from a combination of the proofs of Lemmas \[4.4.1\] and \[4.5.2\].

**Lemma 4.8.1.** $\pi^\dagger$ is supplementary to a sequential blowup derived from $r_1p_5$.

In $r_3p_4$, we blow up $\tilde{\mathcal{P}}_{r_3p_3}$ successively along the proper transforms of $Q_{k,k'}$, $1 \leq k \leq k'$. As explained before Lemma \[4.8.1\] the sequential blowup $r_3p_4$ will terminate after finitely many steps on each connected component of $\tilde{\mathcal{P}}_{r_3p_3}$. It is a direct check that (the proper transforms of) $\pi^\dagger$ is compatible with $r_2-r_3p_3$. Applying Corollary \[3.5.3\] repeatedly, we thus obtain the following statement.

**Lemma 4.8.2.** $r_3p_4$ is locally tree-compatible.

Lemma \[4.8.2\] and Corollary \[3.2.5\] lead to the following conclusion.

**Corollary 4.8.3.** The blowup locus at every step of $r_3p_4$ is closed and smooth.

Corollaries \[4.3.6\] \[4.4.3\] \[4.5.3\] \[4.6.2\] \[4.7.3\] and \[4.8.3\] together imply:

**Corollary 4.8.4.** The blowup locus at every step of the entire sequence of the modular blowups $\tilde{\mathcal{P}}_2 \to \mathcal{P}_2$ is closed and smooth. In particular, $\tilde{\mathcal{P}}_2$ is smooth.

5. **The structural homomorphism in the modular blowups**

5.1. **Main statement.** Throughout \[5\] $\tilde{\mathcal{P}}_2$ denotes the final stack after the three-round blowups and $\pi : \tilde{\mathcal{P}}_2 \to \mathcal{P}_2$ the projection. The following diagram shows the relation between the relevant stacks.
Given \((C, D) \in \mathcal{M}_2^\text{div}\), let \(\mathcal{V} \rightarrow \mathcal{M}_2^\text{div}\) be an affine smooth chart containing \((C, D)\). Then \(\mathcal{V}\) can also be considered as affine smooth charts of \((C, \sigma_C(D)) \in \mathcal{P}_2\) and of \((C, c_1(D)) \in \mathcal{M}_2^\text{wt}\), respectively. Set

\[
\tilde{\mathcal{V}} = \mathcal{V} \times_{\mathbb{P}_2} \mathbb{P}_2.
\]

For the blowup \(\pi^\ast: \mathbb{P}^\ast \rightarrow \mathbb{P}_2\) after an intermediate step, let \(\tilde{\mathcal{V}}^\ast = \mathcal{V} \times_{\mathbb{P}_2} \mathbb{P}^\ast\).

In this section, we investigate the pullback \(\tilde{\varphi}\) of the structural homomorphism \(\varphi\) locally on \(\tilde{\mathcal{V}}\). The main statement is as follows.

**Theorem 5.1.1.** For all integer \(k \geq 1\), the pullback of the derived object \(R\pi^\ast \varphi_{\pi_0}(k)\) to the moduli space \(\mathcal{M}_2(\mathbb{P}^n, d)\) is locally diagonalizable.

Theorem 5.1.1 follows immediately from Definition 2.1.2 and the statement below.

**Proposition 5.1.2.** For every \(\mathcal{x} \in \mathbb{P}_2\), there exists an affine smooth chart \(\tilde{\mathcal{V}}_x\) containing \(\mathcal{x}\) so that the pullback \(\tilde{\varphi}\) of the structural homomorphism \(\varphi\) to \(\tilde{\mathcal{V}}_x\) is diagonalizable.

Recall in (4.8), there is a partition of \(\mathcal{M}_2^\text{wt}\) into five disjoint substacks:

\[
\mathcal{M}_2^\text{wt} = \mathcal{M}_2^{\text{mn}(1)} \sqcup \mathcal{M}_2^{\text{mn}(2)} \sqcup \mathcal{M}_2^{\text{mn}(3)} \sqcup \mathcal{M}_2^{\text{mn}(4)} \sqcup \mathcal{M}_2^{\text{mn}}.
\]

Proposition 5.1.2 is proved in \(\S 5.2-5.6\) depending on which of the above substacks contains \(\varpi(\mathcal{x})\).

**Remark 5.1.3.** Throughout \(\S 5\), if we write out a matrix explicitly with some columns omitted as "* * *", it means each omitted column lies in the span of the shown columns. Since Proposition 5.1.2 is local, if the entries of a row or a column of the pullback of \(\varphi\) have a common factor that is nowhere vanishing on a chart \(\mathcal{V}\), we may omit the factor, because it does not affect the local diagonalizability.

### 5.2. The structural homomorphism around \(\mathcal{M}_2^{\text{mn}}\)

The main statement of this subsection is as follows.

**Proposition 5.2.1.** Proposition 5.1.2 holds if \(\varpi(\mathcal{x}) \in \mathcal{M}_2^{\text{mn}}\).

**Proof.** Fix \((C, D) \in \mathcal{M}_2^\text{div}\) so that \(\mathcal{x} = (C, \sigma_C(D))\). Let

\[
x = (C, c_1(D)) \in \mathcal{M}_2^{\text{mn}}
\]

and \(\gamma\) be the terminally weighted tree of \(x\) as in (4.2). By Basic Assumption (B) in \(\S 2.3\),

\[
D = \delta_1 + \cdots + \delta_m.
\]
The definition of $M_{mn}$ in (4.8) implies the core $F$ of $C$ satisfies $D \cap F \neq \emptyset$. Moreover, if $F'$ is a connected subcurve of $C$, then

$$[D \cap F' = D \cap F] \implies F' \supseteq F.$$ 

Based on the topology of $F$ and the locations of the points in $D$, we divide the proof into five cases, with the last being further divided into several subcases. Together they imply Proposition 5.2.1. In each case, it suffices to show that the pullback of $\varphi$ becomes diagonalizable on a chart containing the image of $\tilde{x}$ after some intermediate step of the three-round modular blowups.

Case 1. Assume $F$ is separable. Let $F_1$ and $F_2$ be the two genus 1 inseparable components of $F$. W.l.o.g. we assume $\delta_1, a_1 \in F_1, \delta_2, a_2 \in F_2$.

By Proposition 2.5.1, $\varphi_{11}$ and $\varphi_{22}$ do not vanish on $V$, whereas $\varphi_{12}$ and $\varphi_{21}$ vanish at $x$. The structural homomorphism $\varphi$ is thus diagonalizable on $V$.

Case 2. Assume $F$ is inseparable and $\deg D \cap F \geq 3$. There then exist $\delta, \delta' \in D \cap F$ that are not conjugate to each other. (Otherwise all the elements of $D \cap F$ would lie on a non-separating bridge of $F$, which would imply $x \in \mathcal{M}^{mn}_{(3)}$.) In addition, $F$ being inseparable implies that $\zeta_{r, e}, \zeta_{r, e} \in \Gamma(D^*)$ for $i = 1, 2$. Hence by Part (1) of Corollary 2.7.3, $\varphi$ is diagonalizable on $V$.

Case 3. Assume $F$ is inseparable, $\deg D \cap F = 2$, and the elements of $D \cap F$ are not conjugate to each other. The argument in Case 2 still holds verbatim.

Case 4. Assume $F$ is inseparable, $\deg D \cap F = 2$, and the elements of $D \cap F$ are conjugate to each other. W.l.o.g. we assume $D^* \subseteq D$. For otherwise $\delta_1$ and hence $\delta_2$ would be on a non-separating bridge, which would imply $x \in \mathcal{M}^{mn}_{(3)}$. Thus, $\varphi$ can be written as

$$\varphi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \lambda_{12} & \left( \zeta_{[e]} \right)_{e \in \text{Edg}(\gamma)}^* \\ \end{bmatrix}$$

under suitable trivialization. Since $\deg D \cap F = 2$, the modular blowups up to the end of $r_3p_2$ do not affect $V$. We thus do not distinguish $V$ and $\tilde{V}^{r_3p_2}$.

By Part (2) of Corollary 2.7.3, $\lambda_{12}$ and $\zeta_{e} \in \text{Edg}(\gamma)$, form a $\gamma_+$-labeled subset of local parameters on $\gamma'$. As in the proof of Lemma 1.7.1, $r_3p_3$ is $\gamma_+$-compatible on $V$. By Proposition 3.3.3, at least one of the pullbacks of the shown entries of the second row of (5.1) divides all the elements of the second row of $\varphi^{t_3p_3}$ evenly. Thus, $\varphi^{t_3p_3}$ is diagonalizable on $\tilde{V}^{t_3p_3}$.

Case 5. Assume $F$ is inseparable and $\deg D \cap F = 1$. W.l.o.g. we assume $D \cap F = \{\delta_1\}$. Since $\gamma$ is terminally weighted,

$$D \cap C_{\gamma_+} \neq \emptyset \quad \forall e \in \text{Edg}(\gamma)^*,$$
where $C_{v^+_v}$ refers to the irreducible component of $C$ labeled by the vertex $v^+_v$.

For each $e \in \text{Edg}(\gamma)^i$, we choose $\delta_e \in D \cap C_{v^+_v}$ and write $\lambda_{1_e} = \lambda_{1_1}$ if $\delta_e = \delta_1$. By Proposition 2.5.1,

$$\varphi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & \chi_{1_e} q_{\delta_1} \\ 0 & 0 & \chi_{1_e} q_{\delta_1} \end{bmatrix}_{e \in \text{Edg}(\gamma)^i} \left( \chi_{1_e} q_{\delta_1} \right)_{\delta_1 \in D \setminus \{\delta_1 \cup \{\delta_e \} \cup \text{Edg}(\gamma)^i}$$

where $\chi_{1_e} = \det \begin{bmatrix} c_{11} & c_{1i} \\ c_{21} & c_{2i} \end{bmatrix} \in \Gamma(\mathcal{O}_Y)$.

Since $x \in \mathcal{M}^{\infty}$ and $\deg D \cap F = 1$, the modular blowups up to the end of $r_1p_4$ do not affect $\mathcal{V}$. The functions $\zeta_{e_i, e_{1_e}} \in \text{Edg}(\gamma)$, form a $\gamma$-labeled subset of local parameters on $\mathcal{V}$, and the blowups in $r_1p_5$ are $\gamma$-compatible on $\mathcal{V}$. Thus, when $r_1p_5$ terminates, every lift $y$ of $x$ satisfies $\text{Dom}(y) \neq \emptyset$. Let $E = (E_1, \ldots, E_i)$ be the ascending sequence of $y$.

If $y$ has at least two dominant pivotal branches, take $e, e' \in \text{Dom}(y)$ so that they belong to distinct pivotal branches. Then at least one among $\{\delta_e, \delta_{e'}\}$, say, $\delta_e$, is not conjugate to $\delta_1$, for otherwise $\delta_1$ would lie on a non-separating bridge of $F$ and $x$ would be in $\mathcal{M}^{\infty}$. Hence $\lambda_{1_e} \in \Gamma(\mathcal{O}_Y)$. In addition, $e \in \text{Dom}(y)$ implies the pullback of $\zeta_{e_i}$ divides the pullbacks of all elements of the second row of (5.2) evenly. Thus $\tilde{\varphi}^{r_1p_5}$ is diagonalizable on a neighborhood of the pullback of $y$ in $\tilde{\mathcal{V}}^{r_1p_5}$.

If $y$ has only one dominant pivotal branch whose pivotal node $p$ is not conjugate to $\delta_1$, the argument in the previous paragraph still holds verbatim.

If $y$ has only one dominant pivotal branch whose pivotal node $p$ is conjugate to $\delta_1$, then $p$ is not Weierstrass and other pivotal nodes cannot be conjugate to $\delta_1$. Let $e_\bullet$ be as in (3.27) and $C_\bullet$ be the irreducible component of $C$ labeled by the vertex $v^+_v$. There are two possibilities:

(a) $|\text{Dom}(y)| \geq 2$, or $\text{Dom}(y) = \{e_\bullet\}$ and $\deg D \cap C_\bullet \geq 2$;
(b) $\text{Dom}(y) = \{e_\bullet\}$ and $\deg D \cap C_\bullet = 1$.

For Possibility (a) choose $e_2, e_3 \in \text{Dom}(y)$ and $\delta_2, \delta_3 \in D$ such that

$$e_2 \wedge e_3 = e_\bullet, \quad \delta_2 \in D \cap C_{v^+_v}, \quad \delta_3 \in D \cap C_{v^+_v}.$$

By Corollaries 2.7.1 and 2.7.3 (5.2) can be rewritten as

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \lambda_{1_e} q_{\delta_1} q_{\delta_1} \\ 0 & 0 & \chi_{1_e} q_{\delta_1} \end{bmatrix}_{e \in \text{Edg}(\gamma)^i} \left( \chi_{1_e} q_{\delta_1} \right)_{\delta_1 \in D \setminus \{\delta_1 \cup \{\delta_e \} \cup \text{Edg}(\gamma)^i}.$$

By Proposition 3.3.3 the second row of $\tilde{\varphi}^{r_1p_5}$ can be written as

$$\tilde{\varphi}_{[1]} \begin{bmatrix} 0, \tilde{\lambda}_{1_e}, \tilde{\zeta}_{[e]}, \bar{\Xi}_1, \bar{\Xi}_2, \bar{\Xi}_3 \end{bmatrix}, \quad \text{where}
\Xi_1 = \left\{ \tilde{\zeta}_{[\gamma(e_\bullet \wedge e_\bullet)]} \tilde{\zeta}_{[e_\bullet]} q_{\gamma(e_\bullet \wedge e_\bullet)} \mid_{e \in (\text{Edg}(\gamma)^i \setminus \{e_\bullet\})} \right\} \Delta_{\bar{y}, \bar{t}}^*; \Xi_2 = \left\{ \tilde{\zeta}_{[\gamma(e_\bullet \wedge e_\bullet)]} q_{\gamma(e_\bullet \wedge e_\bullet)} \right\} \Delta_{\bar{y}, \bar{t}}^*.$$

By Proposition 3.3.3 the second row of $\tilde{\varphi}^{r_1p_5}$ can be written as

$$\tilde{\varphi}_{[1]} \begin{bmatrix} 0, \tilde{\lambda}_{1_e}, \tilde{\zeta}_{[e]}, \bar{\Xi}_1, \bar{\Xi}_2, \bar{\Xi}_3 \end{bmatrix}, \quad \text{where}
\Xi_1 = \left\{ \tilde{\zeta}_{[\gamma(e_\bullet \wedge e_\bullet)]} \tilde{\zeta}_{[e_\bullet]} q_{\gamma(e_\bullet \wedge e_\bullet)} \mid_{e \in (\text{Edg}(\gamma)^i \setminus \{e_\bullet\})} \right\} \Delta_{\bar{y}, \bar{t}}^*; \Xi_2 = \left\{ \tilde{\zeta}_{[\gamma(e_\bullet \wedge e_\bullet)]} q_{\gamma(e_\bullet \wedge e_\bullet)} \right\} \Delta_{\bar{y}, \bar{t}}^*.$$
With $\gamma'_y$ denoting the derived tree of $\gamma$ at $y$ as in (3.6) and $\zeta'_y$ denoting the local parameters of Lemma 3.6.4, $\tilde{\varphi}_{r_1p_5}$ can then be rewritten as

$$
(5.3) \begin{bmatrix}
1 & 0 \\
0 & \tilde{\lambda}_{12} \begin{pmatrix} 0 & \zeta'_y \\ \zeta'_y & \cdot \cdot \cdot \end{pmatrix} \in \text{Edg}(\gamma'_y) \end{bmatrix}.
$$

Since $\deg D \cap F = 1$, the modular blowups from $r_2$ until the end of $r_3p_2$ do not affect a neighborhood $\tilde{V}_y$ of $y$. Moreover, the assumptions of Possibility (a) imply $r_3p_3$ do not affect $\tilde{V}_y$ either. By Lemma 4.8.2, the blowups in $r_3p_4$ are supplementary to a sequence of blowups derived from $r_1p_5$ on $\tilde{V}_y$. Proposition 3.6.8 then implies $r_3p_4$ is $\gamma'_y$-compatible on $\tilde{V}_y$, where the additional vertex in $\gamma'_y$ corresponds to $\tilde{\lambda}_{12}$. By Lemma 3.6.4 and Proposition 3.3.3 at least one of the pullbacks of the shown entries in (5.3) divides the rest evenly when $r_3p_4$ terminates. Thus, $\tilde{\varphi}$ is diagonalizable on a chart containing the pullback of $y$.

Possibility (b) is more complicated. We deal with it in Lemma 5.2.2 separately, which completes the proof of Proposition 5.2.1.

**Lemma 5.2.2.** Let $\tilde{\gamma}$ be as in Proposition 5.1.2, $x$ the image of $\tilde{x}$ in $\mathfrak{M}_2^{\text{wt}}$, and $y$ a lift of $x$ after $r_1p_5$ satisfying Case 3. Possibility (b) in the proof of Proposition 5.2.1. Then, $\tilde{\varphi}$ is diagonalizable on a neighborhood of the pullback of $y$.

**Proof.** With $\hat{\gamma}$ denoting the reduced rooted tree of $x$ as in (4.1), set

$$
\tau_2 = (\gamma_{|\{\epsilon_\bullet\}^1})^3.
$$

Let $E_\alpha \subset \text{Edg}(\gamma) \cap \text{Edg}(\tau_2)$ be as in (3.6) so that the common branches of $\gamma$ and $\tau_2$ are indexed by $E_\alpha$. The definition of $\tau_2$ implies that

$$
(5.4) \quad E_\alpha \cup \{e_\bullet\} \in \text{ET}(\gamma).
$$

W.l.o.g. we assume $D \cap C_\alpha = \{\delta_2\}$. Then by Part (1) of Proposition 2.6.1 (5.2) can be rewritten as

$$
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\lambda}_{12} \zeta_{e_\epsilon} \in \text{Edg}(\tau_2) \setminus E_\alpha \begin{pmatrix} 0 & \zeta_{e_\epsilon} \zeta_{e_\epsilon} \cdot \cdot \cdot \end{pmatrix} \in \text{Edg}(\tau_2) \setminus E_\alpha \end{bmatrix}.
$$

Here $\zeta_{e_\epsilon} = \zeta_e$ for all $e \in \text{Edg}(\tau_2)$, but the superscript indicates the product $\zeta_{e_\epsilon}$ is taken within $\tau_2$.

After $r_1p_5$, let $E = \langle E_1, \ldots, E_t \rangle$ be the ascending sequence of $y$. By Proposition 3.3.3 near $y$, $\tilde{\varphi}_{r_1p_5}$ can be written as

$$
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\lambda}_{12} \begin{pmatrix} 0 & \zeta_{e_\epsilon} \zeta_{e_\epsilon} \cdot \cdot \cdot \end{pmatrix} \in \text{Edg}(\tau_2) \setminus E_\alpha \end{bmatrix} \begin{bmatrix} 0 & 0 & \cdot \cdot \cdot \end{bmatrix},
$$

where

$$
\Xi_1 = \left[ \begin{array}{c} \tilde{\lambda}_{12} \zeta_{e_\epsilon} \zeta_{e_\epsilon} \cdot \cdot \cdot \in E_\alpha \setminus \Delta_{\tilde{\varphi}_{r_1p_5}}^y \\
\end{array} \right],
$$

$$
\Xi_2 = \left[ \begin{array}{c} \tilde{\lambda}_{12} \zeta_{e_\epsilon} \zeta_{e_\epsilon} \cdot \cdot \cdot \in E_\alpha \setminus \Delta_{\tilde{\varphi}_{r_1p_5}}^y \\
\end{array} \right].
$$
There are two relevant rooted trees after $r_3 p_3$: the proper transform $(\tau_2)_y$ of $\tau_2$ as in (3.5) and the rooted tree $\gamma'_y$ derived from $\gamma$ at $y$ as in (3.6). The assumptions of Possibility (b) implies $\hat{E}_a = \hat{E}_a = \emptyset$ and $\hat{E}_a = E_a$ for $\tau_2$. With $\hat{E}_t \in \text{ET}(\gamma)$ as in (3.22), we thus have

$$\text{Edg}((\tau_2)_y) = (\text{Edg}(\tau_2)_y) \setminus E^\infty_a \cup (\hat{E}^\infty_t \cap E^\infty_a).$$

We require the additional edges respectively in $(\tau_2)_y$ and in $\gamma'_y$ to be the same pivotal edge $e_+$. Let

$$E_s = \hat{E}_t \cap E^\infty_a \subset E^\infty_a, \quad E_{s,+} = E_s \cup \{e_+\}.$$  

The former equality in (5.5) implies

$$E^t_s = E^t_a.$$  

We observe that the common branches of $(\tau_2)_y$ and $\gamma'_y$ are indexed by $E_{s,+}$. The construction of the derived tree in (3.6) along with (5.4) and (5.5), implies the collection of the pivotal edges of $\gamma'_y$ satisfies

$$E_o(\gamma'_y) = \{e_1\} \cup (\hat{E}_t \setminus \{e_0\}) \cup \{e_+\}$$

$$= \{e_1\} \cup \{e \in \hat{E}_t \cap E^\infty_a : \langle e \rangle \neq \langle e_0 \rangle\} \cup \{e_+\}$$

$$(5.6) \quad = \{e_1\} \cup \{e \in \hat{E}_s : \langle e \rangle \neq \langle e_0 \rangle\} \cup \{e_+\}.$$  

With $\zeta^y_{e(\tau_2)}$ as in Proposition 3.5.2, $\zeta^y_{e(\tau_2)}$ as in Lemma 3.6.4 and $E_a$ as in (5.5), $\hat{\tau}_{r_3p_3}$ can then be rewritten as

$$(5.7) \quad \begin{bmatrix} 1 & 0 \\ 0 & \tilde{\tau} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \hat{\lambda}_{12} \end{bmatrix} \begin{bmatrix} 0 & \zeta^y_{e(\tau_2)} \\ \zeta^y_{e(\tau_2)} & 0 \end{bmatrix} \begin{bmatrix} 0 \\ \zeta^y_{e(\tau_2)} \end{bmatrix} \quad \quad \quad \quad \text{***}.$$  

Note that in (5.7),

$$(5.8) \quad \zeta^y_{e(\tau_2)} = \zeta^y_{e(\tau_2)} \quad \forall \ e \in E^\infty_a.$$  

Since $\deg D \cap F = 1$, the modular blowups from $r_2$ until the end of $r_3 p_2$ do not affect a neighborhood $\hat{V}_y$ of $y$. By Lemma 4.7.1 and Proposition 3.5.2, $r_3 p_3$ is $(\tau_2)_y$-compatible on $\hat{V}_y$. When $r_3 p_3$ terminates, fix a lift $\hat{y}$ of $y$, whose ascending sequence is denoted by $\hat{E} = (\hat{E}_1, \ldots, \hat{E}_u)$. We may then define

$$\hat{E}_{a,+} = \{\langle e \rangle_{E_{a,+}} : e \in \text{Dom}(\hat{y}) \cap E^\infty_{a,+}\} \subset E_{a,+},$$

$$\hat{E}_{a,+} = \bigcup_{e \in E_{a,+}} \text{Edg}(\gamma'_{y,+} : v_e' = v_e') \subset \text{Edg}(\gamma'_{y,+}), \quad \hat{E}_a = E_a \setminus \hat{E}_a \subset E_a$$

for $\gamma'_{y,+}$ as in (3.5).

If $\hat{E}_{a,+} \cap E_o(\gamma'_{y,+}) \neq \emptyset$, by (5.6) and (5.5), either $e_+$ or some $e \in E^t_a$ with $\langle e \rangle \neq \langle e_0 \rangle$ (i.e. $\zeta^y_{e(\tau_2)}$ does not vanish at $y$) becomes dominant after $r_3 p_3$. Thus by (5.7), $\hat{\tau}_{r_3p_3}$ is diagonalizable near $\hat{y}$. 
If \( \mathcal{E}_* \cap E_0(\gamma_{y,+}) = \emptyset \), then

\[
\text{Dom}(\gamma) \subseteq \text{Edg}(\gamma) \setminus \{ e \in E_0 : \langle e \rangle \neq \langle e_* \rangle \} \quad (\subset \text{Edg}(\gamma)).
\]

Hence every \( e \in \text{Dom}(\gamma) \) satisfies \( \langle e \rangle \gamma = \langle e_* \rangle \gamma \) in \( \hat{\gamma} \). Let

\[
e_* = \min\{ e_* \wedge e : e \in \text{Dom}(\gamma) \} \in \text{Edg}(\gamma).
\]

Obviously, \( e_* < e_\ast \), hence \( e_* \) is an edge in \( \hat{\gamma} \). Thus,

\[
\mathcal{E}_* = \mathcal{E}_* \setminus \{ e_* \} \supseteq \text{Edg}(\gamma) \setminus (\mathcal{E}_* \cup \mathcal{E}_*) = \{ e_1, \ldots, e_s(e_\ast) \},
\]

\[
\text{Edg}(\gamma) \setminus (\mathcal{E}_* \cup \mathcal{E}_*) = \{ e_1, \ldots, e_s(e_\ast) \} \cup (\mathcal{E}_* \cup \mathcal{E}_*) = \{ e_1, \ldots, e_s(e_\ast) \} \setminus \{ e_* \}.
\]

By (5.7), Proposition 3.3.3 and (5.8), near \( \gamma \), \( \varphi^{r_3\mathfrak{p}_3} \) can be written as

\[
\begin{bmatrix}
1 & 0 \\
0 & \widetilde{\zeta}[\theta]\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & \lambda_{12} & \zeta_{1^2} & \zeta_{2^2} & \zeta_{3^2}
\end{bmatrix}
\begin{bmatrix}
\mathcal{E}_1 \\
\mathcal{E}_2
\end{bmatrix}
\]

where

\[
\begin{bmatrix}
1 & 0 \\
0 & \widetilde{\zeta}[\theta]\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & \lambda_{12} & \zeta_{1^2} & \zeta_{2^2} & \zeta_{3^2}
\end{bmatrix}
\begin{bmatrix}
\mathcal{E}_1 \\
\mathcal{E}_2
\end{bmatrix}
\]

Here \( \tilde{e}_i, i \in [u] \), are the exceptional parameters associated with the ascending sequence \( \mathcal{E}_* \) of \( \gamma \). With \( \zeta^{\langle \gamma_{y,+} \rangle} \) as in Proposition 3.5.2, we rewrite \( \varphi^{r_3\mathfrak{p}_3} \) as

\[
\begin{bmatrix}
1 & 0 \\
0 & \widetilde{\zeta}[\theta]\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & \lambda_{12} & \zeta_{1^2} & \zeta_{2^2} & \zeta_{3^2}
\end{bmatrix}
\begin{bmatrix}
\mathcal{E}_1 \\
\mathcal{E}_2
\end{bmatrix}
\]

By Part (2) of Proposition 3.5.2 and Lemma 4.8.1, we conclude \( r_3\mathfrak{p}_4 \) is \( \langle \gamma_{y,+} \rangle \)-compatible on a neighborhood of \( \gamma \). Thus, the expression of \( \varphi^{r_3\mathfrak{p}_3} \) in the previous paragraph and Proposition 3.3.3 together imply \( \varphi = \varphi^{r_3\mathfrak{p}_4} \) is diagonalizable on the pullback of a neighborhood of \( \gamma \).

**Example 5.2.3.** Given \( (C, D) \in \mathfrak{P}_D^\text{inv} \) with the dual graph \( \gamma^* \) of \( C \) as in the first diagram in Figure 3, Assume

\[
D \cap F = \{ \delta_1 \}, \quad D \cap C_a = \{ \delta_2 \}, \quad D \cap C_i = \{ \delta_i, \delta_d, \ldots \}, \quad i = a, c, d.
\]

This implies the core \( F \) of \( C \) is smooth and \( x = (C, c_1(D)) \in \mathfrak{P}_F^\text{inv} \). Under suitable trivialization, \( \varphi \) on a chart \( V \) containing \( (C, D) \) can be written as

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & \lambda_{1a} & \lambda_{1b} & \lambda_{a^2} & \theta_{a^2} & \theta_{a^2} \zeta_{a^2} \zeta_{b^2} \zeta_{d^2} \zeta_{d^2} \zeta_{d^2}
\end{bmatrix}
\]

where \( \lambda_{1a}, \lambda_{1b} \) are as in Corollary 2.7.3 and \( \theta_{a^2}, \theta_{b^2}, \theta_{d^2} \) are as in Proposition 2.6.1. Since \( D \cap F \neq \emptyset \), the blowups in \( r_1\mathfrak{p}_1 \) and \( r_1\mathfrak{p}_4 \) do not affect \( V \). After \( r_1\mathfrak{p}_5 \), given a lift of \( x \), there are three possible cases: \( \text{Dom}(y) = \{ e_a, e_b \} \), \( \text{Dom}(y) = \{ e_a \} \), or \( \text{Dom}(y) = \{ e_b \} \). In each case, the ascending sequence of \( y \) consists of only one traverse section \( \{ e_a, e_b \} \) of \( \gamma^* \).

If \( \text{Dom}(y) = \{ e_a, e_b \} \), the pullbacks of \( \lambda_{1a} \) and \( \lambda_{1b} \) cannot vanish at \( y \) simultaneously, because \( \delta_1 \) cannot be conjugate to \( \delta_a \) and \( \delta_b \) simultaneously. Thus, the pullback \( \varphi^{r_1\mathfrak{p}_5} \) of \( \varphi \) near \( y \) can be rewritten as

\[
\begin{bmatrix}
1 & 0 \\
0 & \widetilde{\zeta}_1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & \lambda_{1a} & \lambda_{1b} & \lambda_{a^2} & \theta_{a^2} \zeta_{b^2} \zeta_{d^2}
\end{bmatrix}
\begin{bmatrix}
\mathcal{E}_1 \\
\mathcal{E}_2
\end{bmatrix}
\]

Thus, the pullback \( \varphi^{r_1\mathfrak{p}_5} \) of \( \varphi \) near \( y \) can be rewritten as
hence $\tilde{\varphi}^{r_1p_5}$ is diagonalizable near $y$.

In the second case (i.e. $\text{Dom}(y) = \{e_a\}$), the pullback of $\varphi$ near $y$ can be written as
\[
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\varepsilon}_1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & *** \\
0 & \tilde{\lambda}_{1a} & \tilde{\lambda}_{1b} & \tilde{\varepsilon}_1 & \tilde{\varepsilon}_2 & \tilde{\varepsilon}_3 & \tilde{\varepsilon}_4 & \tilde{\varepsilon}_5 & \tilde{\varepsilon}_6 & \tilde{\varepsilon}_7 & \tilde{\varepsilon}_8 & \tilde{\varepsilon}_9
\end{bmatrix}.
\]

As per our convention in §3.1, we use $\sim$ and $\tilde{}$ to denote the pullback of a function and the proper transform of a local parameter, respectively. If $\tilde{\lambda}_{1a}(y) \neq 0$, then $\tilde{\varphi}^{r_1p_5}$ is still diagonalizable near $y$. If $\tilde{\lambda}_{1a}(y) = 0$, then $\delta_a$ and $\delta_1$ are conjugate, hence the node $p_{e_a}$ on $C$ cannot be Weierstrass and consequently $\tilde{\theta}_{a,\epsilon}$ does not vanish near $y$. By Corollary 2.7.1, $\tilde{\lambda}_{1a}$ vanishes to the first order near $y$. Furthermore, $\tilde{\lambda}_{1b}$ does not vanish near $y$ because $\delta_b$ is not conjugate to $\delta_1$ whenever $\delta_a$ is. Thus, the pullback of $\varphi$ near $y$ can be rewritten as
\[
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\varepsilon}_1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & *** \\
0 & \tilde{\lambda}_{1a} & \tilde{\lambda}_{1b} & \tilde{\varepsilon}_1 & \tilde{\varepsilon}_2 & \tilde{\varepsilon}_3 & \tilde{\varepsilon}_4 & \tilde{\varepsilon}_5 & \tilde{\varepsilon}_6 & \tilde{\varepsilon}_7 & \tilde{\varepsilon}_8 & \tilde{\varepsilon}_9
\end{bmatrix}.
\]

It is then a direct check that $r_2$ through $r_3p_3$ do not affect a neighborhood of $y$, whereas the pullback of $\varphi$ becomes diagonalizable on the pullback of a chart containing $y$ after $r_3p_4$.

In the third case (i.e. $\text{Dom}(y) = \{e_b\}$), the pullback of $\varphi$ near $y$ can be written as
\[
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\varepsilon}_1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & *** \\
0 & \tilde{\lambda}_{1a} & \tilde{\lambda}_{1b} & \tilde{\varepsilon}_1 & \tilde{\varepsilon}_2 & \tilde{\varepsilon}_3 & \tilde{\varepsilon}_4 & \tilde{\varepsilon}_5 & \tilde{\varepsilon}_6 & \tilde{\varepsilon}_7 & \tilde{\varepsilon}_8 & \tilde{\varepsilon}_9
\end{bmatrix}.
\]

If $\tilde{\lambda}_{1b}(y) \neq 0$, then $\tilde{\varphi}^{r_1p_5}$ is still diagonalizable near $y$. If $\tilde{\lambda}_{1b}(y) = 0$, analogous to the second case, the pullback of $\varphi$ can be written as
\[
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\varepsilon}_1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & *** \\
0 & \tilde{\lambda}_{1b} & \tilde{\lambda}_{1c} & \tilde{\varepsilon}_1 & \tilde{\varepsilon}_2 & \tilde{\varepsilon}_3 & \tilde{\varepsilon}_4 & \tilde{\varepsilon}_5 & \tilde{\varepsilon}_6 & \tilde{\varepsilon}_7 & \tilde{\varepsilon}_8 & \tilde{\varepsilon}_9
\end{bmatrix}.
\]

It is then a direct check that $r_2$ through $r_3p_2$ do not affect a neighborhood of $y$, and after $r_3p_3$, for every lift $\tilde{y}$ of $y$, either the pullback of $\varphi$ becomes diagonalizable near $\tilde{y}$, or it can be rewritten as
\[
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\varepsilon}_1\tilde{\varepsilon}_2
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & *** \\
0 & \tilde{\lambda}_{1b} & \tilde{\lambda}_{1c} & \tilde{\varepsilon}_1 & \tilde{\varepsilon}_2 & \tilde{\varepsilon}_3 & \tilde{\varepsilon}_4 & \tilde{\varepsilon}_5 & \tilde{\varepsilon}_6 & \tilde{\varepsilon}_7 & \tilde{\varepsilon}_8 & \tilde{\varepsilon}_9
\end{bmatrix}.
\]

thus becomes diagonalizable on the pullback of a chart containing $\tilde{y}$ after $r_3p_1$.

5.3. The structural homomorphism around $\mathcal{M}^{mn}_{(4)}$. The main statement of this subsection is as follows.

**Proposition 5.3.1.** Proposition 5.1.2 holds if $\varphi(x) \in \mathcal{M}^{mn}_{(4)}$.

**Proof.** As in the proof of Proposition 5.2.1, we fix $(C, D) \in \mathcal{M}^{\text{div}}_{(2)}$ so that $\tilde{x} = (C, \theta_C(D))$ and set
\[
\tilde{x} = (C, c_1(D)) \in \mathcal{M}^{mn}_{(2)}.
\]
We still assume $D = \delta_1 + \cdots + \delta_m$.

By the definition of $\mathcal{M}^{mn}_{(4)}$, the core $F$ of $x$ consists of two genus 1 inseparable components $F_1$ and $F_2$ as well as a (possibly degenerate) separating bridge $B$. W.l.o.g. we assume that

$$a_1 \in F_1, \quad a_2 \in F_2, \quad D \cap F \subset F_1 \cup B.$$ 

Let $C_1$ be the smallest connected genus 1 subcurve of $F$ containing $D \cap F$. Then $C_1$ contains a unique irreducible component $F_1'$ that is the closest to $F_2$. The definition of $\mathcal{M}^{mn}_{(4)}$ then implies $F_1'$ does not belong to any non-separating bridge and $D \cap F_1' \neq \emptyset$.

Let $\gamma$ be the terminally weighted tree of $x$ and $\gamma_\nu$ be the rooted tree as in (4.4). Recall that $F_1$ and $F_2$ correspond to the terminal vertex $o_1$ and the root $o_2$, respectively, in $\gamma_\nu$. Let $E_\ast \subset \text{Edg}(\gamma) \cap \text{Edg}(\gamma_\nu)$ be as in (3.5) so that the common branches of $\gamma$ and $\gamma_\nu$ are indexed by $E_\ast$. With $e_1 \in \text{Edg}(\gamma_\nu)$ denoting the edge such that $v_{e_1}^+ = o_1$, we see that

$$E_\ast \cup \{e_1\} \in ET(\gamma_\nu).$$

Similar to the proof of Proposition 5.2.1, we divide the proof of Proposition 5.3.1 into four cases.

Case 1. Assume $\deg D \cap F \geq 3$. W.l.o.g. we assume

$$\delta_1 \in D \cap F_1, \quad \delta_2 \in D \cap F_1', \quad \delta_3 \in D \cap C_1.$$ 

Switching $\delta_1$ and $\delta_3$ if necessary, we may assume that $\delta_1$ and $\delta_2$ are not conjugate, for otherwise these three points would lie on a non-separating bridge. By Proposition 2.5.1, $\varphi$ can be written as

$$\varphi = \begin{bmatrix} 1 & 0 \\ 0 & \zeta_{[e]}^{e \in \text{Edg}(\gamma_\nu)} v_{e_1}^+ \end{bmatrix}^{***}$$

on $\mathcal{V}$. Here $\zeta_{[e]}^{e \in \text{Edg}(\gamma_\nu)} = \zeta_e$ for all $e \in \text{Edg}(\gamma_\nu)$, but as in the proof of Lemma 5.2.2 the superscript indicates the product $\zeta_{[e]}^{e \in \text{Edg}(\gamma_\nu)}$ is taken in $\gamma_\nu$.

Since $x \in \mathcal{M}^{mn}_{(4)}$, the modular blowups up to the end of $r_1p_3$ do not affect $\mathcal{V}$. By the proof of Lemma 4.3.4, the blowups in $r_1p_4$ are $\gamma_\nu$-compatible on $\mathcal{V}$. By Proposition 3.3.3, at least one of the pullbacks of $\zeta_{[e]}^{e \in \text{Edg}(\gamma_\nu)}$, $e \in \text{Edg}(\gamma_\nu)$, divides all the elements of the second row of $\tilde{\varphi}_{r_1p_4}$ evenly. Thus $\tilde{\varphi}_{r_1p_4}$ is diagonalizable on $\tilde{\mathcal{V}}_{r_1p_4}$.

Case 2. Assume $\deg D \cap F = 2$ and the elements of $D \cap F$ are not conjugate to each other. The argument in Case 1 still holds verbatim.

Case 3. Assume $\deg D \cap F = 2$ and the elements $\delta_1$ and $\delta_2$ of $D \cap F$ are conjugate to each other. Then,

$$\delta_1, \delta_2 \in F_1' \subset F_1 = C_1.$$
By Proposition 2.5.1 Part (1) of Proposition 2.6.1 and Part (1) of Corollary 2.7.3, \( \varphi \) of \( \mathcal{V} \) can be written as

\[
(5.9) \quad \begin{pmatrix}
1 & 0 \\
0 & \lambda_{12} \tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} \begin{pmatrix}
\tilde{\zeta}_t^{-1} \zeta_i^\gamma \\
\tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} = \begin{pmatrix}
0 & 0 \\
0 & \tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} \; \text{for} \; \tilde{\zeta}_t^{-1} \zeta_i^\gamma \in \mathcal{E}_s^\gamma \backslash E_s^\gamma.
\]

As in Case 1, the modular blowups up to the end of \( r_1 p_3 \) do not affect \( \mathcal{V} \), and \( r_1 p_4 \) is \( \gamma^- \)-compatible on \( \mathcal{V} \). Thus, when \( r_1 p_4 \) terminates, every lift \( y \) of \( x \) satisfies \( \text{Dom}(y) \neq \emptyset \). Let \( E = (E_1, \ldots, E_t) \) be the ascending sequence of \( y \). There are two possibilities:

(a) \( \text{Dom}(y) \neq \{ e_1 \} \);
(b) \( \text{Dom}(y) = \{ e_1 \} \).

For Possibility (a), at least one edge \( e \in E_1 \) becomes dominant after \( r_1 p_4 \). By Proposition 3.3.3, the pullback of \( \zeta_i^\gamma \) then divides all elements of the second row of \( \tilde{\varphi}^{r_1 p_4} \) evenly. Hence \( \tilde{\varphi}^{r_1 p_4} \) is diagonalizable on a neighborhood of \( y \).

For Possibility (b) by Proposition 3.3.3 near \( y \), the second row of the pullback of (5.9) after \( r_1 p_4 \) can be written as

\[
\begin{pmatrix}
\tilde{\zeta}_t^{-1} \zeta_i^\gamma \\
\tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} = \begin{pmatrix}
0, \lambda_{12} \tilde{\zeta}_t^{-1} \zeta_i^\gamma \\
0, \lambda_{12} \tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} \in \mathcal{E}_s^\gamma \backslash E_s^\gamma, \quad \Xi_1, \Xi_2, ***
\]

where

\[
\Xi_1 = \tilde{\zeta}_t^{-1} \zeta_i^\gamma, \Xi_2 = \tilde{\zeta}_t^{-1} \zeta_i^\gamma.
\]

Note that after \( r_1 p_4 \),

\[
\tilde{E}_s = \hat{E}_s = \emptyset, \quad \hat{E}_s = E_s
\]

for \( \gamma \). Hence \( \gamma \) as in (3.5) satisfies

\[
\text{Edg}(\gamma) = (\text{Edg}(\gamma) \backslash E_s^\gamma) \cup (\hat{E}_s \cap E_s^\gamma).
\]

With \( \tilde{\zeta}_t^{-1} \) as in Proposition 3.5.2, \( \tilde{\varphi}^{r_1 p_4} \) can be rewritten as

\[
\begin{pmatrix}
1 & 0 \\
0 & \tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} \begin{pmatrix}
1 & 0 \\
0 & \tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} \; \text{for} \; \tilde{\zeta}_t^{-1} \zeta_i^\gamma \in \mathcal{E}_s^\gamma \backslash E_s^\gamma.
\]

Since \( \text{deg} D \cap F = 2 \) and \( \text{Dom}(y) = \{ e_1 \} \), the effect of the modular blowups from \( r_1 p_5 \) on a neighborhood of \( y \) is the same as that on a neighborhood of \( x \) in Case 4 of the proof of Proposition 5.2.1. Comparing the above expression of \( \tilde{\varphi}^{r_1 p_4} \) with (5.1), we conclude that the entire argument of Case 4 of the proof of Proposition 5.2.1 applies to this case.

Case 4. Assume \( \text{deg} D \cap F = 1 \). W.l.o.g. we assume \( D \cap F = \{ \delta_1 \} \). Then,

\[
\delta_1 \in F' \subset F_1 = C_1.
\]

Similar to (5.2), \( \varphi \) can be written as

\[
(5.10) \quad \begin{pmatrix}
1 & 0 \\
0 & \lambda_{1e} \tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} \begin{pmatrix}
\tilde{\zeta}_t^{-1} \zeta_i^\gamma \\
\tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} = \begin{pmatrix}
0 & 0 \\
0 & \lambda_{1e} \tilde{\zeta}_t^{-1} \zeta_i^\gamma
\end{pmatrix} \; \text{for} \; \tilde{\zeta}_t^{-1} \zeta_i^\gamma \in \mathcal{E}_s^\gamma \backslash E_s^\gamma,
\]

where

\[
\lambda_{1e} \tilde{\zeta}_t^{-1} \zeta_i^\gamma.
\]
where \( D' = D \setminus \{ \{ \delta_i \} \cup \{ \delta_j \} \in \text{Edg}(\gamma) \} \) and \( \chi_{1t} = \det \begin{bmatrix} c_{11} & c_{1t} \\ c_{21} & c_{2t} \end{bmatrix} \in \Gamma(\mathcal{O}_V) \).

As in Case 1, the modular blowups up to the end of \( r_1p_4 \) do not affect \( V \), whereas \( r_1p_4 \) is \( \gamma_V \)-compatible on \( V \). So when \( r_1p_4 \) terminates, every lift \( y \) of \( x \) satisfies \( \text{Dom}(y) \neq \emptyset \). Let \( E = (E_1, \ldots, E_t) \) be the ascending sequence of \( y \).

If \( \text{Dom}(y) \neq \{ e_1 \} \), since \( \tilde{x}_{1e} \) does not vanish at \( y \) for all \( e \in E_1 \), the argument in Possibility (a) of Case 3 holds here. If \( \text{Dom}(y) = \{ e_1 \} \), the argument in Possibility (b) of Case 3 implies that near \( y \), \( \tilde{\varphi}^{r_1p_4} \) can be written as

\[
\begin{bmatrix} 1 & 0 \\ 0 & \tilde{z}_{I_1} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ \tilde{x}_{1e}\gamma_{I_1} \end{bmatrix} \begin{bmatrix} 0 \\ \tilde{x}_{1e}\gamma_{I_1} \end{bmatrix} \begin{bmatrix} 0 \\ \tilde{x}_{1e}\gamma_{I_1} \end{bmatrix} \delta_{I_1} \in E'.
\]

Since \( \text{deg } D \cap \mathcal{C} = 1 \) and \( \text{Dom}(y) = \{ e_1 \} \), the effect of the modular blowups from \( r_1p_4 \) on a neighborhood of \( y \) is the same as that on a neighborhood of \( x \) in Case 3 of the proof of Proposition 5.2.1. Comparing the above expression of \( \tilde{\varphi}^{r_1p_4} \) with (5.2), we conclude that the entire argument of Case 3 of the proof of Proposition 5.2.1 applies to the current case. This completes Case 4 of the proof of Proposition 5.3.1.

5.4. The structural homomorphism around \( \mathcal{M}^{\text{mn}}_{(3)} \). The main statement of this subsection is as follows.

**Proposition 5.4.1.** Proposition 5.1.2 holds if \( \varphi(\tilde{x}) \in \mathcal{M}^{\text{mn}}_{(3)} \).

**Proof.** As in the proof of Proposition 5.2.1, we fix \( (C, D) \in \mathcal{M}^{\text{div}}_2 \) so that \( \tilde{x} = (C, \mathcal{O}_C(D)) \) and set

\[ x = (C, c_1(D)) \in \mathcal{M}^{\text{mn}}_{(3)}. \]

We still assume \( D = \delta_1 + \cdots + \delta_m \).

By the definition of \( \mathcal{M}^{\text{mn}}_{(3)} \), the core \( F \) of \( x \) contains a minimal non-separating bridge \( B = B[q_1, q_2] \) so that

\[ D \cap B = D \cap F. \]

We denote by \( C^+_1 \) and \( C^+_2 \) the irreducible components of \( B \) containing \( q_1 \) and \( q_2 \), respectively. Note that \( C^+_1 \) and \( C^+_2 \) may be the same.

Let \( \gamma \) be the reduced dual tree of \( x \) and \( \gamma_0 \) be the rooted tree as in (4.6) so that \( B \) corresponds to the fused vertex \( v_B \). Let \( E_\ast \subset \text{Edg}(\gamma) \cap \text{Edg}(\gamma_0) \) be as in (3.5) so that the common branches of \( \gamma \) and \( \gamma_0 \) are indexed by \( E_\ast \). With \( \epsilon_1, \epsilon_2 \in \text{Edg}(\gamma_0) \) denoting the edges such that

\[ v^+_{\epsilon_1} = v^+_{\epsilon_2} = v_B, \]

Then, \( E_\ast \cup \{ \epsilon_1, \epsilon_2 \} \in \text{ET}(\gamma_0) \).

If in addition \( F \) is separable, w.l.o.g. we assume \( F_1 \) and \( F_2 \) are the genus 1 inseparable components of \( F \) so that \( B \subset F_1 \). Let \( \gamma_\vee \) be the rooted tree as
in (4.4) so that \( F_1 \) and \( F_2 \) correspond to the terminal vertex \( o_1 \) and the root \( o_2 \), respectively. Let \( e_{o_1} \in \text{Edg}(\gamma_v)^t \) be such that
\[
\nu_{e_{o_1}} = o_1.
\]
Set \( E_\ast = E_\ast \cap \text{Edg}(\gamma_v) \). It is straightforward that
\[
\text{Edg}(\gamma) \cap \text{Edg}(\gamma_v) = \text{Edg}(\gamma_0) \cap \text{Edg}(\gamma_v) = \mathbb{E}_\ast^e.
\]
Moreover, the edges in \( E_\ast \) are not comparable because \( E_\ast \subset E_\ast \). Hence the common branches of \( \gamma \) and \( \gamma_v \) are indexed by \( E_\ast \); so are the common branches of \( \gamma_0 \) and \( \gamma_v \).

Similar to the proofs of Propositions 5.2.1 and 5.3.1 we divide the proof of Proposition 5.4.1 into six cases.

Case 1. Assume deg \( D \cap F \geq 3 \) and \( F \) is inseparable. W.l.o.g. we assume that
\[
\delta_1 \in D \cap F, \quad \delta_2 \in C_1^+, \quad \delta_3 \in C_2^+.
\]
By Proposition 2.5.1 and Corollary 2.7.3 \( \varphi \) on \( V \) can thus be written as
\[
(5.11) \quad \left[ \begin{array}{c} 1 \\
\lambda_1 \\
\end{array} \right]_{\delta \in D \cap F \setminus \{ \delta_1 \}} \left[ \begin{array}{c} 0 \\
\zeta_1 \\
\end{array} \right]_{e \in \text{Edg}(\gamma_0)^\dagger \setminus \{ \delta_1, \delta_2 \}} **
\]

Since \( x \in \mathfrak{M} \), the modular blowups up to the end of \( r_1 p_2 \) do not affect \( \mathcal{V} \). By the proof of Lemma 4.3.3, \( r_1 p_3 \) is \( \gamma_0 \)-compatible. Let \( y \) be a fixed lift of \( x \) after \( r_1 p_3 \) and \( E = (E_1, \ldots, E_t) \) be its ascending sequence.

If \( \text{Dom}(y) \notin \{ e_1, e_2 \} \), then by Proposition 3.3.3 and Corollary 2.7.3 at least one of the pullbacks of \( \zeta_{[e] \gamma_0}, e \in \text{Edg}(\gamma_0)^\dagger \setminus \{ e_1, e_2 \} \), divides all the elements of the second row of \( \tilde{\varphi}^{r_1 p_3} \) evenly. If \( \text{Dom}(y) \subseteq \{ e_1, e_2 \} \), then by Corollary 2.7.3 and the assumption on the location of \( \delta_2 \) and \( \delta_3 \), we conclude that
\[
(5.12) \quad \tilde{\lambda}_{1i} = \lambda_{1i} \tilde{\varepsilon}[t]
\]
does not vanish at \( y \) for at least one \( i \in \{ 2, 3 \} \). Thus \( \tilde{\varphi}^{r_1 p_3} \) is diagonalizable on \( \tilde{\varphi}^{r_1 p_3} \).

Case 2. Assume deg \( D \cap F \geq 3 \) and \( F \) is separable. We choose \( \delta_1, \delta_2, \delta_3 \in D \cap F \) as in Case 1. The structural homomorphism \( \varphi \) on \( V \) can be written as
\[
\left[ \begin{array}{c} 1 \\
\lambda_1 \zeta_{[e] \gamma_v} \\
\end{array} \right]_{\delta \in D \cap F \setminus \{ \delta_1 \}} \left[ \begin{array}{c} 0 \\
\zeta_{[e] \gamma_v} \\
\end{array} \right]_{e \in \text{Edg}(\gamma_v)^\dagger \setminus \{ \delta_1, \delta_2 \}} \left[ \begin{array}{c} 0 \\
\zeta_{[e] \gamma_v} \\
\end{array} \right]_{e \in \text{Edg}(\gamma_v)^\dagger \setminus \{ \delta_1, \delta_2 \}} **
\]

Note that \( \zeta_{[e] v} = \zeta_{[e] v} \) for all \( e \in \mathbb{E}_\ast^e \).

Similar to Case 1, \( r_1 p_1 \) and \( r_1 p_2 \) do not affect \( \mathcal{V} \), whereas \( r_1 p_3 \) is \( \gamma_0 \)-compatible. After \( r_1 p_3 \), fix a lift \( y \) of \( x \) and let \( E = (E_1, \ldots, E_t) \) be its ascending sequence.

If there is \( e \in \text{Dom}(y) \cap \mathbb{E}_\ast^e \) so that \( \langle e \rangle_{\gamma_v} \neq \langle e_{o_1} \rangle_{\gamma_v} \), then \( \zeta_{[e_{o_2} \wedge e]} \) does not vanish on \( V \) and the pullback of \( \zeta_{[e] v} \) divides all the elements of \( \tilde{\varphi}^{r_1 p_3} \) evenly. Hence \( \tilde{\varphi}^{r_1 p_3} \) is diagonalizable on \( \tilde{\varphi}^{r_1 p_3} \).
If \( \text{Dom}(y) \cap \{ e \in E'_* : \langle e \rangle_{y,v} \neq \langle e_{o(1)} \rangle_{y,v} \} = \emptyset \), let

\[
eq \min \left( \{ e_{o(1)} \} \cup \{ e_{o(1)} \wedge_{y,v} e : e \in \text{Dom}(y) \cap E'_* \} \right) \quad (e \in \text{Edg}(y,v)).
\]

Then,

\[
\tilde{E}_* = E_* \setminus \{ e_{o(1)} \}, \quad \text{Edg}(y,v) = \left( \text{Edg}(y,v) \setminus \left( E'_* \cup \{ e_{o(1)} \} \right) \right) \cup \left( \tilde{E}_* \cap \tilde{E}'_* \right).
\]

By the argument in Case 1 and by Proposition 3.3.3, \( \varphi_{\tilde{r}_0p_3} \) on a neighborhood of \( y \) can be rewritten as

\[
\begin{bmatrix}
1 & 0 \\
\tilde{e}[t] & \Sigma_1 & \Sigma_2 & \cdots & \cdots
\end{bmatrix}
\]

where

\[
\Sigma_1 = \left( \zeta_\gamma \{ e_{o(1)} \} \right)_{e \in E'_*} | \Sigma_2 = \left( \zeta_\gamma \{ e_{o(1)} \} \right)_{e \in E'_*} | \Delta_{y,v}. \]

With \( \zeta_\gamma \{ e_{o(1)} \} \) as in Proposition 3.5.2, we can rewrite \( \varphi_{\tilde{r}_0p_3} \) as

\[
\begin{bmatrix}
1 & 0 \\
\tilde{e}[t] & \zeta_\gamma \{ e_{o(1)} \} \end{bmatrix}
\]

The modular blowups in \( r_1p_4 \) is \( (y,v) \)-compatible on neighborhood of \( y \). By Proposition 3.3.3, \( \varphi_{\tilde{r}_1p_3} \) is diagonalizable on the pullback of a neighborhood of \( y \).

Case 3. Assume \( \deg D \cap F = 2 \) and \( F \) is inseparable. W.l.o.g. we assume \( D \cap F = \{ \delta_1, \delta_2 \} \). The structural homomorphism \( \varphi \) on \( V \) can be written as

\[
(5.13) \quad \begin{bmatrix}
1 & 0 \\
0 & \lambda_{12} \end{bmatrix}
\begin{bmatrix}
\zeta_{e} \{ e \} \in \text{Edg}(y,v) \backslash E'_* \end{bmatrix}
\begin{bmatrix}
0 \\
\zeta_{e} \{ e \} \in E'_* \end{bmatrix}
\begin{bmatrix}
0 \\
\chi_{12} \zeta_{e} \{ e \} \in E'_* \end{bmatrix}
\end{bmatrix}_{e \in D'}. \]

where \( D' = D \backslash \{ \{ \delta_1, \delta_2 \} \cup \{ e_{o(1)} \in \text{Edg}(y,v) \} \} \) and \( \chi_{12} = \det \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} = 1 \in \Gamma(O_\gamma) \).

Similar to Case 1, \( r_1p_1 \) and \( r_1p_2 \) do not affect \( V \), whereas \( r_1p_3 \) is \( \gamma_0 \)-compatible. After \( r_1p_3 \), fix a lift \( y \) of \( x \) and let \( E = \{ E_1, \ldots, E_l \} \) be its ascending sequence.

If \( \text{Dom}(y) \cap E'_* \neq \emptyset \), choose \( e \in \text{Dom}(y) \cap E'_* \). By Proposition 3.3.3, (5.13), and Corollary 2.7.3, the pullback of \( \zeta_{e} \{ e \} \) divides all the elements of the second row of \( \varphi_{\tilde{r}_1p_3} \), thus \( \varphi_{\tilde{r}_1p_3} \) is diagonalizable near \( y \).

If \( \text{Dom}(y) \subseteq \{ e_{1}, e_{2} \} \), then \( \lambda_{12} \) as in (5.12) has two possibilities: either it does not vanish at \( y \), which along with (5.13) and Proposition 3.3.3 implies \( \varphi_{\tilde{r}_1p_3} \) is diagonalizable on \( \tilde{V} \); or \( \lambda_{12}(y) = 0 \) and hence

\[
\tilde{\lambda}_{1e} \sim 1 \quad \forall e \in \text{Edg}(y,v) \backslash E'_*, \quad \tilde{e}[t] | \tilde{\lambda}_{1e} \quad \forall \, \delta_{i} \in \tilde{D}'.
\]

By (5.13), \( \varphi_{\tilde{r}_1p_3} \) on a neighborhood of \( y \) can be written as

\[
\begin{bmatrix}
1 & 0 \\
\tilde{e}[t] & \tilde{\lambda}_{12} \end{bmatrix}
\begin{bmatrix}
0 \\
\tilde{e}[t] \end{bmatrix}
\begin{bmatrix}
\tilde{e}[t] \end{bmatrix}
\begin{bmatrix}
0 \\
\tilde{e}[t] \end{bmatrix}
\end{bmatrix}_{e \in D'}. \]

where

\[
\begin{bmatrix}
1 & 0 \\
\tilde{e}[t] & \tilde{\lambda}_{12} \end{bmatrix}
\begin{bmatrix}
0 \\
\tilde{e}[t] \end{bmatrix}
\begin{bmatrix}
0 \\
\tilde{e}[t] \end{bmatrix}
\end{bmatrix}_{e \in D'}. \]
With \( \zeta \) as in Proposition 3.5.2, the above matrix can be rewritten as
\[
\begin{bmatrix}
1 & 0 \\
0 & \tilde{z}_{[t]}
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\lambda}_{12} \zeta_{[t]}^{y} \\
\end{bmatrix}_{\epsilon \in \text{Edg}(\gamma_{y})}.
\]

Since \( F \) is inseparable, \( r_{1} p_{4} \) does not affect a neighborhood of \( y \). Since \( \deg D \cap F = 2 \) and \( \text{Dom}(y) \subset \{ \epsilon_{1}, \epsilon_{2} \} \), the effect of the modular blowups starting \( r_{1} p_{5} \) on a neighborhood of \( y \) is the same as that on a neighborhood of \( x \) in Case 4 of the proof of Proposition 5.2.1. Comparing the above expression of \( \tilde{\phi}^{r_{1} p_{3}} \) with (5.1), we conclude that \( \tilde{\phi}^{r_{1} p_{3}} \) is diagonalizable on the pullback of a neighborhood of \( y \).

Case 4. Assume \( D \cap F = \{ \delta, \delta' \} \) and \( F \) is separable. Combining the arguments in Case 2 and Case 3, we see that either \( \tilde{\phi}^{r_{1} p_{3}} \) is diagonalizable, or the arguments in Case 1 or Case 3 of the proof of Proposition 5.3.1 apply to the current case.

Case 5. Assume \( \deg D \cap F = 1 \) and \( F \) is inseparable. In this case, \( B \) is a smooth rational curve. W.l.o.g. we assume \( D \cap F = \{ \delta \} \). Analogously to (5.13), \( \phi \) can be written as
\[
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\lambda}_{12} \zeta_{[t]}^{y} \\
\end{bmatrix}_{\epsilon \in \text{Edg}(\gamma^{r_{1} p_{3}})}.
\]

where \( D' = D \setminus \{ \{ \delta \} \cap \text{Edg}(\gamma^{r_{1} p_{3}}) \} \) and \( \chi_{11} = \det \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \in \Gamma(\mathcal{O}_{V}) \).

Similar to Case 1, \( r_{1} p_{1} \) and \( r_{1} p_{2} \) do not affect \( V \), whereas \( r_{1} p_{3} \) is \( \gamma_{y}^{r_{1} p_{3}} \)-compatible. After \( r_{1} p_{3} \), fix a lift \( y \) of \( x \) and let \( E = (E_{1}, \ldots, E_{t}) \) be its ascending sequence. If \( \text{Dom}(y) \cap E_{t} \neq \emptyset \), the corresponding argument in Case 3 still holds verbatim.

If \( \text{Dom}(y) \subset \{ \epsilon_{1}, \epsilon_{2} \} \), mimicking the argument in Case 3, we see that \( \tilde{\phi}^{r_{1} p_{3}} \) can be rewritten as
\[
\begin{bmatrix}
1 & 0 \\
0 & \tilde{z}_{[t]}
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & \tilde{\lambda}_{12} \zeta_{[t]}^{y} \\
\end{bmatrix}_{\epsilon \in \text{Edg}(\gamma^{r_{1} p_{3}})}.
\]

Since \( F \) is inseparable, \( r_{1} p_{4} \) does not affect a neighborhood of \( y \). Since \( \deg D \cap F = 1 \) and \( \text{Dom}(y) \subset \{ \epsilon_{1}, \epsilon_{2} \} \), the effect of the modular blowups starting \( r_{1} p_{5} \) on a neighborhood of \( y \) is the same as that on a neighborhood of \( x \) in Case 5 of the proof of Proposition 5.2.1. Comparing the above expression of \( \tilde{\phi}^{r_{1} p_{3}} \) with (5.2), we conclude that \( \phi = \tilde{\phi}^{r_{1} p_{4}} \) is diagonalizable on the pullback of a neighborhood of \( y \).

Case 6. Assume \( D \cap F = \{ \delta \} \) and \( F \) is separable. Combining the arguments in Case 2 and Case 5, we see that the argument in Case 5 or the arguments in Case 1, Case 3, or Case 4 of the proof of Proposition 5.3.1 applies to the current case.

**Example 5.4.2.** Given \((C, D) \in \mathcal{M}_{g}^{\text{div}} \) with the dual graph \( \gamma^{*} \) of \( C \) as in the third diagram of Figure 4. The edges are denoted by \( \epsilon_{1}, \epsilon_{2}, \) and \( e_{a} \) from left...
to right. Assume
\[ D \cap B = D \cap F = \{ \delta_1, \delta_2, \delta_3 \}, \quad D \cap C_a \neq \emptyset. \]
This implies \( x = (C, \phi_1(D)) \in \mathcal{M}_{(3)} \). Under suitable trivialization, \( \varphi \) on a chart \( V \) containing \( (C, D) \) can be written as
\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \lambda_{12} & \lambda_{13} & \zeta_a \\
0 & \widetilde{\lambda}_{12} & \widetilde{\lambda}_{13} & \widetilde{\zeta}_a
\end{bmatrix},
\]
where \( \lambda_{12}, \lambda_{13} \) are as in Corollary 2.7.3.
Since \( x \in \mathcal{M}_{(3)} \), the blowups up to \( r_1p_2 \) do not affect \( \varphi \) near \( x \). When \( r_1p_3 \) terminates, let \( y \) be a fixed lift of \( x \). If \( e_a \in \text{Dom}(y) \), then the pullback of \( \varphi \) becomes diagonalizable near \( y \). If \( e_a \notin \text{Dom}(y) \), then the pullback of \( \varphi \) can be rewritten as
\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \lambda_{12} & \lambda_{13} & \zeta_a \\
0 & \widetilde{\lambda}_{12} & \widetilde{\lambda}_{13} & \widetilde{\zeta}_a
\end{bmatrix}.\]
By Part (3) of Corollary 2.7.3 \( \lambda_{12}(y) \) and \( \lambda_{13}(y) \) cannot vanish simultaneously, hence the pullback of \( \varphi \) is diagonalizable near \( y \).

5.5. The structural homomorphism around \( \mathcal{M}^{\text{mn}}_{(2)} \). The main statement of this subsection is as follows.

**Proposition 5.5.1.** Proposition 5.1.2 holds if \( \varphi(\overline{x}) \in \mathcal{M}^{\text{mn}}_{(2)} \).

**Proof.** As in the proof of Proposition 5.2.1 we fix \( (C, D) \in \mathcal{M}_{2} \) so that \( \overline{x} = (C, \phi_c(D)) \) and set
\[ x = (C, \phi_1(D)) \in \mathcal{M}^{\text{mn}}_{(2)}. \]
We still assume \( D = \delta_1 + \cdots + \delta_m \).

By the definition of \( \mathcal{M}^{\text{mn}}_{(2)} \), the core \( F \) of \( x \) contains two genus 1 inseparable components \( F_1 \) and \( F_2 \), as well as a unique minimal separating bridge \( B = B_{\beta} \) so that
\[ D \cap F = D \cap B. \]
Let \( C_1 \) and \( C_2 \) be the irreducible components of \( B \) containing \( q_1 \) and \( q_2 \), respectively. Note that \( C_1 \) and \( C_2 \) may be the same.

Let \( \gamma \) be the reduced dual tree of \( x \), \( \gamma_\Lambda \) be the TFMR tree as in (4.5) so that \( B \) corresponds to the fused vertex \( v_B \), and \( \gamma_\Lambda \) be the root tree as in (4.4) with the root \( o_2 \). Although \( F_1 \) and \( F_2 \) respectively correspond to the vertices \( o_1 \) and \( o_2 \) in both \( \gamma_\Lambda \) and \( \gamma_\Lambda \), notice that \( o_1 \) is a root in \( \gamma_\Lambda \) but a terminal vertex in \( \gamma_\Lambda \). We set
\[ E^t_\Lambda, i = \{ e \in \text{Edg}(\gamma_\Lambda)_1^t : a_i \prec \gamma_\Lambda, v^+_e \} \quad i = 1, 2. \]
Then, \( \text{Edg}(\gamma_\Lambda)_1^t = E^t_\Lambda, 1 \cup E^t_\Lambda, 2 \).
Let \( E_\ast \subset \text{Edg}(\gamma) \cap \text{Edg}(\gamma_\Lambda) \) be as in (3.5) so that the common branches of \( \gamma \) and \( \gamma_\Lambda \) are indexed by \( E_\ast \). With \( e_1, e_2 \in \text{Edg}(\gamma_\Lambda)_1^t \) denoting the edges such that \( v^+_e = v_B = v^+_e \), we see that
\[ E_\ast \cup \{ e_1, e_2 \} \in \text{ET}(\gamma_\Lambda). \]
In addition, we set
\[ E_* = E_* \cap \text{Edg}(\gamma_y), \quad E_*^{\gamma} = E_* \cup \langle \epsilon_2 \rangle. \]

Here \( \langle \epsilon_2 \rangle \) is taken in \( \text{Edg}(\gamma_y) \) (and equivalently in \( \text{Edg}(\gamma_u) \)). It is straightforward that
\[ E_*^{t} = E_*^{t,2}, \quad \text{Edg}(\gamma) \cap \text{Edg}(\gamma_y) = E_*^{\gamma}, \quad \text{Edg}(\gamma_u) \cap \text{Edg}(\gamma_y) = E_*^{\gamma,2}. \]

The edges in \( E_* \) or \( E_*^{\gamma} \) are not comparable.

We divide the proof of Proposition 5.4.1 into four cases.

Case 1. Assume \( \deg D \cap F \geq 3 \). W.l.o.g. we assume \( \delta_1 \in C_1 \) and \( \delta_2 \in C_2 \). If \( \delta_1 \) is conjugate to \( \delta_2 \), then \( C_1 = C_2 = B \). By assumption, we may take another point in \( D \cap B \), which cannot be conjugate to \( \delta_2 \). Thus, w.l.o.g. we further assume \( \delta_1 \) and \( \delta_2 \) are not conjugate.

By Proposition 2.5.1, \( \phi \) is in the form
\[
\begin{bmatrix}
\begin{pmatrix}
0 \\
1 - \gamma^{t}_y
\end{pmatrix}
\end{bmatrix}_{e \in E_{\lambda,1}^{*}} \quad \begin{bmatrix}
\begin{pmatrix}
0 \\
1 - \gamma^{t}_y
\end{pmatrix}
\end{bmatrix}_{e \in E_{\lambda,2}^{*}}
\]
under suitable trivialization.

Since \( x \in \Omega_{\lambda}^{y} \), the modular blowups in \( r_1 P_1 \) do not affect \( \mathcal{V} \). By the proof of Lemma 4.3.2, the blowups in \( r_1 P_2 \) are \( \gamma_y \)-compatible. After \( r_1 P_2 \), fix a lift \( y \) of \( x \) and let \( E = (E_1, \ldots, E_t) \) be the ascending sequence of \( y \).

Since \( \text{Dom}(y) \neq \emptyset \), at least one of
\[ (5.14) \quad \text{Dom}(y) \cap E_{\lambda,1}^{*} \quad \text{and} \quad \text{Dom}(y) \cap E_{\lambda,2}^{*}, \]
say the former, is not empty. If both are not empty, Proposition 3.4.2 implies \( \tilde{\phi}^{r_1 P_2} \) is diagonalizable near \( y \).

If \( \text{Dom}(y) \subset E_{\lambda,1}^{*} \), \( \tilde{\phi}^{r_1 P_2} \) on a neighborhood of \( y \) can be rewritten as
\[
\begin{bmatrix}
\begin{pmatrix}
0 \\
\gamma^{(y)}_{y}
\end{pmatrix}
\end{bmatrix}_{e \in \text{Edg}(\gamma_y)^{1}}
\]
By (4.9), \( r_1 P_3 \) does not affect a neighborhood of \( y \). By the proof of Lemma 4.3.4, the blowups in \( r_1 P_4 \) are \( (\gamma_y)_{y} \)-compatible. Hence by Proposition 3.3.3, \( \tilde{\phi}^{r_1 P_4} \) is diagonalizable on the pullback of a neighborhood of \( y \).

Case 2. Assume \( \deg D \cap F = 2 \) and the elements of \( D \cap F \) are not conjugate. The argument in Case 1 still holds verbatim.

Case 3. Assume \( \deg D \cap F = 2 \) and the elements of \( D \cap F \) are conjugate. W.l.o.g. we assume \( D \cap F = \{ \delta_1, \delta_2 \} \). Then \( B = C_1 = C_2 \). The structural homomorphism \( \phi \) can then be written as
\[
\begin{bmatrix}
\begin{pmatrix}
\gamma^{t}_y
\end{pmatrix}
\end{bmatrix}_{e \in E_{\lambda}^{*}} \quad \begin{bmatrix}
\begin{pmatrix}
\gamma^{t}_y
\end{pmatrix}
\end{bmatrix}_{e \in E_{\lambda}^{*}} \quad \begin{pmatrix}
0 \\
\gamma^{t}_y
\end{pmatrix}_{e \in \text{Edg}(\gamma_y)^{1}}
\]
under suitable trivialization.
As in Case 1, \( r_1p_1 \) does not affect \( \mathcal{V} \), whereas \( r_1p_2 \) is \( \gamma_\lambda \)-compatible. After \( r_1p_2 \), fix a lift \( y \) of \( x \) and let \( E=(E_1,\ldots,E_t) \) be the ascending sequence of \( y \). One of the two sets in (5.14) is still non-empty.

If \( \text{Dom}(y) \not\subset \{e_1,e_2\} \), w.l.o.g. assume \( \text{Dom}(y) \cap E_1^* \neq \emptyset \). Then similar to Case 1, \( \varphi'^{r_1p_4} \) is diagonalizable on the pullback of a neighborhood of \( y \).

If \( \text{Dom}(y)=\{e_1,e_2\} \), then the blowups from \( r_1p_3 \) up to the end of \( r_3p_2 \) do not affect a neighborhood \( \mathcal{V}_y \) of \( y \), and \( \varphi'^{r_3p_2} \) on \( \mathcal{V}_y \) can be rewritten as

\[
\tilde{\varepsilon}[t] \begin{bmatrix} 1 & 0 \\ 0 & \tilde{\lambda}_{12} \end{bmatrix} \begin{bmatrix} 0 \\ \tilde{\zeta}[\gamma_y] \end{bmatrix} \begin{bmatrix} \varepsilon \in \text{Edg}(\gamma_y)^t \end{bmatrix} \]

under suitable trivialization. Comparing the above expression of \( \varphi'^{r_3p_3} \) and (5.1), we conclude that the argument in Case 3 of the proof of Proposition 5.2.1 applies to the current case.

If \( \text{Dom}(y) \) consists of only one element of \( \{e_1,e_2\} \), say, \( \text{Dom}(y)=\{e_1\} \), then the blowups in \( r_1p_3 \) do not affect a neighborhood \( \mathcal{V}_y \) of \( y \), and \( \varphi'^{r_1p_3} \) on \( \mathcal{V}_y \) can be rewritten as

\[
\tilde{\varepsilon}[t] \begin{bmatrix} 1 & 0 \\ 0 & \tilde{\lambda}_{12} \end{bmatrix} \begin{bmatrix} 0 \\ \tilde{\zeta}[\gamma_y] \end{bmatrix} \begin{bmatrix} \varepsilon \in \text{Edg}(\gamma_y)^t \end{bmatrix} \]

under suitable trivialization. Comparing the above expression of \( \varphi'^{r_1p_3} \) and (5.9), we conclude that the argument in Case 3 of the proof of Proposition 5.3.1 applies to the current case.

Case 4. Assume \( \text{deg} D \cap F = \{\delta_i\} \). Then \( B = C_1 = C_2 \). The structural homomorphism \( \varphi \) can then be written as

\[
\begin{bmatrix} 0 \\ \lambda_{1i} \end{bmatrix}_{\varepsilon \in E_y \setminus E_x^*} \begin{bmatrix} 1 \\ 0 \end{bmatrix}_{\varepsilon \in E_x^*} \begin{bmatrix} 0 \\ \zeta[\gamma_{y}] \end{bmatrix}_{\varepsilon \in \text{Edg}(\gamma_y)^t \setminus E^*_x} \begin{bmatrix} \chi_{1i} \end{bmatrix}_{\delta \in D'} \end{bmatrix},
\]

where \( D'=D \setminus \{(\delta_1) \cup \{\delta_i\}_{\varepsilon \in \text{Edg}(\gamma)^t} \geq 1 \} \) and \( \chi_{1i} = \text{det} \begin{bmatrix} c_{1i} & c_{11} \\ -c_{2i} & c_{21} \end{bmatrix} \in \Gamma(\mathcal{O}_x) \).

As in Case 3 when \( r_1p_2 \) terminates, every lift \( y \) of \( x \) satisfies \( \text{Dom}(y) \neq \emptyset \). Let \( E=(E_1,\ldots,E_t) \) be the ascending sequence of \( y \).

If \( \text{Dom}(y) \not\subset \{e_1,e_2\} \), then similar to Case 3, \( \varphi'^{r_1p_4} \) is diagonalizable on the pullback of a neighborhood of \( y \).

If \( \text{Dom}(y)=\{e_1,e_2\} \), then the blowups in \( r_1p_3 \) and \( r_1p_4 \) do not affect a neighborhood \( \mathcal{V}_y \) of \( y \), and \( \varphi'^{r_1p_4} \) on \( \mathcal{V}_y \) can be rewritten as

\[
\tilde{\varepsilon}[t] \begin{bmatrix} 1 & 0 \\ 0 & \tilde{\lambda}_{1i} \end{bmatrix} \begin{bmatrix} 0 \\ \chi_{1i} \end{bmatrix} \begin{bmatrix} \varepsilon \in \text{Edg}(\gamma_y)^t \end{bmatrix} \begin{bmatrix} \delta \in D' \end{bmatrix} \]

Comparing the above expression of \( \varphi'^{r_3p_4} \) and (5.2), we conclude that the argument in Case 3 of the proof of Proposition 5.2.1 applies to the current case.

If \( \text{Dom}(y) \) consists of only one element of \( \{e_1,e_2\} \), say, \( \text{Dom}(y)=\{e_1\} \), then the blowups in \( r_1p_3 \) do not affect a neighborhood \( \mathcal{V}_y \) of \( y \), and \( \varphi'^{r_1p_3} \) on
\( \mathcal{V}_y \) can be rewritten as
\[
\tilde{\varphi}[t] \left[ \begin{array}{cc}
1 & 0 \\
0 & \tilde{\lambda}_{1e} q_{[d]}(\gamma \gamma)_{y}^{[e_2]}_{[e_3]} \end{array} \right] \in \text{Edg}(\gamma)_{\delta} \quad F_{e_3}^{[e_2]} \left[ \begin{array}{c}
0 \\
0 \chi_{1e} q_{[d]}(\gamma \gamma)_{y}^{[e_2]}_{[e_3]} \end{array} \right] \delta \in D' \quad * * *
\]

Comparing the above expression of \( \tilde{\varphi}_{r1p3} \) and (5.10), we conclude that the argument in Case 4 of the proof of Proposition 5.3.1 applies to the current case. \( \Box \)

5.6. The structural homomorphism around \( M_{(1)} \). The main statement of this subsection is as follows.

**Proposition 5.6.1.** Proposition 5.1.2 holds if \( \varphi(\tilde{x}) \in M_{(1)}^{\text{min}} \).

**Proof.** As in the proof of Proposition 5.2.1, we fix \((C, D) \in M_2^{\text{div}} \) so that \( \tilde{x} = (C, \partial_C(D)) \) and set
\[
x = (C, c_1(D)) \in M_{(1)}^{\text{min}}.
\]
Let \( \gamma \) be the reduced dual tree of \( x \). We still assume \( D = \delta_1 + \cdots + \delta_m \). By the definition of \( M_{(1)}^{\text{min}} \), the core \( F \) of \( C \) satisfies \( D \cap F = \emptyset \).

It is straightforward that the functions \( \zeta_e, e \in \text{Edg}(\gamma) \), are coordinate functions labeled by \( \gamma \) on \( \mathcal{V} \), and \( r_1p_1 \) is \( \gamma \)-compatible on \( \mathcal{V} \). After \( r_1p_1 \), fix a lift \( y \) of \( x \) and let \( F = (E_1, \ldots, E_t) \) be the ascending sequence of \( y \). With \( \text{DPN}(y) \) as in (3.15), let \( F_y \) be the smallest connected subcurve of \( F \) containing \( \text{DPN}(y) \) and \( F_y^c \) be the closure of \( F \setminus F_y \) in \( F \). Notice that \( F_y^c \) may be disconnected.

We divide the proof of Proposition 5.6.1 into five cases. Case 1 is further divided into several subcases depending on the number and position of the dominant pivotal branches. Regarding the other three cases, we show that the pullback of \( \varphi \) either becomes locally diagonalizable or can be reduced to Case 1. As in the previous subsections, it suffices to show that in each case the pullback of \( \varphi \) becomes locally diagonalizable after some intermediate step of the three-round modular blowups.

**Case 1.** Assume that \( g_2(F_y^c) = 0 \). There are five subcases:

(a) \( |\text{DPN}(y)| \geq 3 \);
(b) \( \text{DPN}(y) = \{p_{e_1}, p_{e_2}\} \) and \( p_{e_1} \) is not conjugate to \( p_{e_2} \);
(c) \( \text{DPN}(y) = \{p_{e_1}, p_{e_2}\} \) and \( p_{e_1} \) is conjugate to \( p_{e_2} \);
(d) \( \text{DPN}(y) = \{p_{e_0}\} \) and \( p_{e_0} \) is not Weierstrass;
(e) \( \text{DPN}(y) = \{p_{e_0}\} \) and \( p_{e_0} \) is Weierstrass.

In Subcases (a) and (b), there exist \( p_{e_1}, p_{e_2} \in \text{DPN}(y) \) that are not conjugate. By Corollary 2.7.3, \( \tilde{\varphi}^{r1p1} \) near \( y \) can be written as
\[
\tilde{\varphi}[t] \left[ \begin{array}{cc}
1 & 0 \\
0 & 1 \\
* & * \\
* & *
\end{array} \right],
\]
where the first two columns correspond to some \( e_1, e_2 \in \text{Dom}(y) \) with \( \langle e_i \rangle = e_i, i = 1, 2 \).
In Subcase [(c)] let \( e_1, e_2, \xi_0, \eta, \) and \( \sigma(e) \) be as in \( \text{§3.7} \). Obviously \( \xi_0 = 0 \). If \( |\text{Dom}(y)| \geq 3 \) or \( |\text{Dom}(y)| = 2 \) and at least one \( e \in \text{Dom}(y) \) satisfies \( w(v^+_e) > 1 \), then \( \tilde{\varphi}^{\tau_1 p_1} \) can be written as

\[
\tilde{\varphi}[t] \begin{bmatrix}
    1 & 0 & 0 & 0 & 0 & \ast & \ast & \ast \\
    0 & \lambda_{12} & \tilde{\varphi}[e] & \Xi_1 & \Xi_2 & \ast & \ast & \ast \\
\end{bmatrix},
\]

where

\[
\Xi_1 = \left( \tilde{\varphi}[\sigma(e)] \bar{\zeta}(e, r, e) \right)_{e \in \text{Dom}(\gamma) \setminus \Delta_{p, e}}^{\gamma_{y, e}} ;
\]

\[
\Xi_2 = \left( \tilde{\varphi}[\sigma(e)] \bar{\zeta}(e, r, e) \right)_{e \in \text{Dom}(\gamma_2)^{\gamma_{y, e}}}.
\]

The modular blowups from \( r_1 p_2 \) up to the end of \( r_2 \) do not affect a neighborhood \( \mathcal{V}_y \) of \( y \), and \( r_3 p_1 \) is \( \gamma_{y, e}^{(2)} \)-compatible on \( \mathcal{V}_y \). With \( \gamma_{y, e}^{(2)} \) denoting the bi-dominantly derived tree at \( y \) as in \( \text{§3.7} \), \( \tilde{\varphi}^{\tau_2} \) can be rewritten as

\[
\tilde{\varphi}[t] \begin{bmatrix}
    1 & 0 & 0 & \ast & \ast & \ast & \ast & \ast \\
    0 & \lambda_{12} & \tilde{\varphi}[\gamma_{y, e}^{(2)}] & \Xi_1 & \Xi_2 & \ast & \ast & \ast \\
\end{bmatrix},
\]

By Proposition \( \text{§3.3.3} \), \( \tilde{\varphi}^{\tau_1 p_1} \) becomes diagonalizable on the pullback of \( \mathcal{V}_y \).

If \( \text{Dom}(y) = \{ e, e' \} \) with \( w(v^+_e) = w(v^+_e') = 1 \), then \( \zeta = t \). Set

\[
\tau_2 = (\gamma_{y, e}^{(1)} )^{\gamma_{y, e}^{(2)}}.
\]

Let \( E_s \subset \text{Edg}(\gamma) \cap \text{Edg}(\gamma_2) \) be as in \( \text{§3.5} \) so that the common branches of \( \gamma \) and \( \tau_2 \) are indexed by \( E_s \). Mimicking the argument in the paragraph above, we see that \( \tilde{\varphi}^{\tau_1 p_1} \) can be written as

\[
\tilde{\varphi}[t] \begin{bmatrix}
    1 & 0 & 0 & \ast & \ast & \ast & \ast & \ast \\
    0 & \lambda_{12} & \tilde{\varphi}[\gamma_{y, e}^{(2)}] & \Xi_1 & \Xi_2 & \ast & \ast & \ast \\
\end{bmatrix},
\]

where \( \Xi_1 \) and \( \Xi_2 \) are as in \( \text{(5.15)} \). Then either \( \tilde{\varphi}^{\tau_1 p_1} \) becomes diagonalizable as in the previous paragraph, or \( \tilde{\varphi}^{\tau_2 p_3} \) becomes diagonalizable as in the proof of Lemma \( \text{§5.2.2} \).

In Subcase [(d)] let \( e \) and \( s \) be as in \( \text{§3.6} \). We have the following two possibilities:

(d1) none of the pivotal nodes is conjugate to \( q_{(e, s)}^{(e)} ;
\]

(d2) there exists a pivotal node \( q_{e'} \) conjugate to \( q_{(e, s)} \).

For Possibility [(d1)] if either \( |\text{Dom}(y)| \geq 2 \), or \( \text{Dom}(y) = \{ e_1 \} \) and \( w(v^+_{e_1}) > 1 \), similar to the argument in Subcase [(c)] \( \tilde{\varphi}^{\tau_1 p_1} \) can be written as

\[
\tilde{\varphi}[t] \begin{bmatrix}
    1 & 0 & \ast & \ast & \ast & \ast \\
    0 & \lambda_{12} & \tilde{\varphi}[\gamma_{y, e}^{(2)}] & \Xi_1 & \Xi_2 & \ast \\
\end{bmatrix},
\]

where \( \gamma_{y, e}^{(2)} \) is the derived tree at \( y \) as in \( \text{§3.6} \) and \( \zeta_{e, e}^{(2)} \) is the local parameter of Lemma \( \text{§3.6.4} \). We see that \( r_1 p_2 \rightarrow r_1 p_5 \) do not affect \( \mathcal{V}_y \), whereas \( r_2 \) is \( \gamma_{y, e}^{(2)} \)-compatible on \( \mathcal{V}_y \). Thus, \( \tilde{\varphi}^{\tau_2} \) becomes diagonalizable. If \( \text{Dom}(y) = \{ e_1 \} \) with \( w(v^+_{e_1}) = 1 \), let \( \bar{y} \) be a fixed lift of \( y \) after \( r_1 p_5 \). Then either \( \tilde{\varphi}^{\tau_1 p_5} \) is already
diagonalizable near $\bar{y}$, or the previous argument in this paragraph applies to the current case with $y$ and $\gamma_y'$ replaced by $\bar{y}$ and $(\gamma_y')_{\bar{y}}$, respectively.

For Possibility (d2), once again we first assume $|\text{Dom}(y)| \geq 2$ or $\text{Dom}(y) = \{e_1\}$ and $w(v_e^+) > 1$. Let $\bar{y}$ be a fixed lift of $y$ after $r_2$. If $\text{Dom}(\bar{y})$ contains at least one edge $e'$ with $\langle e' \rangle \neq e'$, then by the preceding paragraph, $\bar{v}^{\tau_2}$ is still diagonalizable. If $\langle e' \rangle = e'$ for all $e' \in \text{Dom}(\bar{y})$, then by the argument in Subcase (e), $\bar{\varphi}^{\tau_2 \tau_1}$ becomes diagonalizable. If $\text{Dom}(y) = \{e\}$ with $w(v_e^+) = 1$, the argument is parallel to the scenario in Possibility (d1).

In Subcase (e), let $e_\ast$ and $s$ be as in §3.6 and $\gamma_y'$ be the derived tree at $y$. We first assume $\sum_{e \in \text{Dom}(y)} w(v_e^+) \geq 3$. This guarantees that $r_1p_2, r_1p_3$, and $r_3p_4$ do not affect the corresponding pullbacks of $V_y$. As in Subcase (d), $r_2$ is $\gamma_y'$-compatible on $V_y$. When $r_2$ terminates, we fix a lift $\bar{y}$ of $y$. We have the following two possibilities.

(e1) $\text{Dom}(\bar{y})$ contains at least one edge $e'$ such that $\langle e' \rangle_{\gamma_y'} \neq e_1$.
(e2) All edges $e' \in \text{Dom}(\bar{y})$ satisfy $\langle e' \rangle_{\gamma_y'} = e_1$.

In Possibility (e1), since $q_{\langle e' \rangle}$ cannot be conjugate to $a_{\ast \gamma}$, $\bar{v}^{\tau_2}$ is diagonalizable after $r_2$.

In Possibility (e2), the bi-dominantly derived tree $\gamma_y^{(2)}$ may or may not exist; c.f. (S1) and (S2) of §3.7. If $\gamma_y^{(2)}$ does not exist, then $r_3p_1$ does not affect $\mathcal{V}_{\bar{y}}$. By Proposition 2.6.1 and Corollaries 2.7.1-2.7.3, $\bar{v}^{\tau_2}$ near $\bar{y}$ can be rewritten as

$$\bar{v}[\bar{q}]_{\bar{v}[u]} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \theta_{12} & \bar{\zeta}_{[c]}^{\langle \gamma_y \rangle} \\ \bar{\zeta}_{[c]}^{\langle \gamma_y \rangle} & \bar{\zeta}_{[c]}^{\langle \gamma_y \rangle} & \ast & \ast & \ast \end{bmatrix},$$

where $(\gamma_y')_{e_\ast, \bar{y}}$ is the TFMR tree partially derived from $\gamma_y'$ along $e_\ast$ at $\bar{y}$ as in §3.6 and $\theta_{12}$ is as in Corollary 2.7.1. The sequential blowup $r_3p_2$ is $(\gamma_y')_{e_\ast, \bar{y}, +}$-compatible on a neighborhood of $y'$, thus $\bar{\varphi}^{\tau_2 \tau_1}$ is locally diagonalizable on the pullback of $V_{\bar{y}}$. If $\gamma_y^{(2)}$ exists, similar to the previous argument, we see that $r_3p_1$ is $\gamma_y^{(2)}$-compatible on $V_{\bar{y}}$; when $r_3p_1$ terminates, near a fixed lift $\bar{y}'$ of $\bar{y}$, either $\bar{v}^{\tau_2 \tau_1}$ is already diagonalizable, or $r_3p_2$ is $(\gamma_y')_{e_\ast, \bar{y}, +}$-compatible and $\bar{\varphi}^{\tau_2 \tau_1}$ is diagonalizable near $\bar{y}'$.

Regarding the special cases in which $\sum_{e \in \text{Dom}(y)} w(v_e^+) = 2$ or 1, $r_3p_3$ and $r_3p_4$ may become relevant. The argument is similar to that of Subcase (e) and of Possibility (d1), respectively. We omit further details.

Case 2. Assume that $g_y(F_y) = g_{\ast}(F_y) = 1$. Let $F_1$ and $F_2$ be the core of $F_y$ and $F_{y'}$ respectively. As before, we denote by $\gamma_{\ast \gamma}$ the rooted tree whose root is $o_2$; c.f. (4.4).

The definition of $F_y$ implies $r_1p_2$ and $r_1p_3$ do not affect $V_y$, whereas $r_1p_4$ is $(\gamma_y')_{y}$-compatible on $V_y$. When $r_1p_4$ terminates, for every lift $\bar{y}$ of $y$, either $\bar{v}^{\tau_1 \tau_4}$ is already diagonalizable near $\bar{y}$, or the argument in Case 1 applies to the current case with $y$ replaced by $\bar{y}$. 
Case 3. Assume that \( g_u(F_c^c) = 1, g_v(F_d) = 0, \) and \( F \) is inseparable. We denote by \( F_2 \) the core of \( F_c^c \). As before, let \( \gamma_0 \) be the TFMR tree with a single root \( o_2 \) such that \( F_d \) corresponds to the unique fused terminal vertex of \( \gamma_0 \); c.f. (4.6).

Similar to Case 2, \( r_1p_2 \) does not affect \( V_y \), whereas \( r_1p_3 \) is \( (\gamma_0)_y \)-compatible on \( V_y \). When \( r_1p_3 \) terminates, for every lift \( \tilde{y} \) of \( y \), either \( \tilde{\varphi}^{r_1p_3} \) is already diagonalizable near \( \tilde{y} \), or the argument in Case 1 applies to the current case with \( y \) replaced by \( \tilde{y} \).

Case 4. Assume that \( g_u(F_c^c) = 1, g_v(F_d) = 0, \) and \( F \) is separable. Analogous to Case 3, let \( F_2 \) be the core of \( F_c^c \). In addition to the TFMR tree \( \gamma_0 \) in Case 3, there is another relevant rooted tree \( \gamma_v \) whose root \( o_2 \) corresponds to \( F_2 \); c.f. (4.5) and (4.4).

As in Case 3, \( r_1p_3 \) is still \( (\gamma_0)_y \)-compatible on \( V_y \). When \( r_1p_3 \) terminates, for every lift \( y' \) of \( y \), either \( \tilde{\varphi}^{r_1p_3} \) is already diagonalizable near \( y' \), or \( r_1p_4 \) is \( (\gamma_v)_y \)-compatible on a neighborhood of \( y' \). When \( r_1p_4 \) terminates, for every lift \( \tilde{y} \) of \( y' \), either \( \tilde{\varphi}^{r_1p_4} \) is already diagonalizable near \( \tilde{y} \), or the argument in Case 1 applies to the current case with \( y \) replaced by \( \tilde{y} \).

Case 5. Assume that \( F_c^c \) consists of two genus 1 subcurves. We denote by \( F_1 \) and \( F_2 \) the cores of the connected components of \( F_c^c \). As before, let \( \gamma_\wedge \) be the TFMR tree with the roots \( o_1 \) and \( o_2 \) respectively corresponding to \( F_1 \) and \( F_2 \), and \( \gamma_v \) be the rooted tree with the root \( o_2 \) corresponding to \( F_2 \); c.f. (4.5) and (4.4).

The modular blowups in \( r_1p_2 \) are \( (\gamma_\wedge)_y \)-compatible on \( V_y \). When \( r_1p_2 \) terminates, for every lift \( y' \) of \( y \), either \( \tilde{\varphi}^{r_1p_2} \) is already diagonalizable near \( y' \), or \( r_1p_4 \) is \( (\gamma_v)_y \)-compatible on a neighborhood of \( y' \). When \( r_1p_4 \) terminates, for every lift \( \tilde{y} \) of \( y' \), either \( \tilde{\varphi}^{r_1p_4} \) is already diagonalizable near \( \tilde{y} \), or the argument in Case 1 applies to the current case with \( y \) replaced by \( \tilde{y} \). \( \square \)

**Example 5.6.2.** Let \( (C,D) \in M^\text{div}_3 \) be such that \( C \) has a smooth core \( F \) and two tails \( C_u \) and \( C_v \), each of which is a smooth rational curve, and

\[
D \cap F = \emptyset, \quad |D \cap C_i| \geq 2, \quad i = u, v;
\]

see the diagram for \( \overline{M}_{1,2} \) in Figure 1. The (pivotal) edges are denoted by \( e_u \) and \( e_v \), respectively. Then, \( x = (C, c_1(D)) \in \overline{M}^\text{max}_{1,2} \).

In Example 5.6.2 we assume that \( q_{e_u} \) and \( q_{e_v} \) are not conjugate, and neither of them is a Weierstrass point. Under suitable trivialization, \( \varphi \) on a chart \( \mathcal{V} \) containing \( (C, D) \) can then be written as

\[
(5.16) \quad \begin{bmatrix}
c_{1u} \zeta_u & c_{1v} \zeta_v & 0 & 0 & \ast & \ast & \ast \\
c_{2u} \zeta_u & c_{2v} \zeta_v & \zeta_u^2 & \zeta_v^2 & \ast & \ast & \ast
\end{bmatrix},
\]

where \( \zeta_u = \zeta_{e_u} \) and \( \zeta_v = \zeta_{e_v} \) are the modular parameters. By Proposition 2.5.1, \( c_{ij} \in \Gamma(D^+_x) \) for \( i = 1, 2 \) and \( j = u, v \). By Corollary 2.7.3

\[
\lambda_{uv} = \det \begin{bmatrix} c_{1u} & c_{1v} \\ c_{2u} & c_{2v} \end{bmatrix}
\]

is nowhere vanishing on \( \mathcal{V} \).
Let \( y \) be a lift of \( x \) after \( r_1 p_1 \) and \( \mathcal{V}_y \) be a chart containing \( y \). If \( \text{Dom}(y) = \{ e_u, e_v \} \), then \( \varphi^{r_1 p_1} \) can be rewritten as
\[
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}.
\]
Thus \( \varphi^{r_1 p_1} \) is diagonalizable on \( \mathcal{V}_y \). If \( \text{Dom}(y) = \{ e_u \} \), \( \varphi^{r_1 p_1} \) can be rewritten as
\[
\begin{bmatrix}
1 & 0 \\
0 & \zeta_v & \zeta_1
\end{bmatrix}.
\]

By the assumption of \((C, D)\), \( r_1 p_2 - r_1 p_5 \) do not affect \( \mathcal{V}_y \). Analyzing the derived tree \( \gamma' \), we see that locally \( \mathcal{V}_y \) is blown up along the locus \( \{ \zeta_1 = \zeta_v = 0 \} \) in \( r_2 \), thus \( \varphi^{r_2} \) becomes diagonalizable on the pullback on \( \mathcal{V}_y \).

**Example 5.6.3.** Let \((C, D) \in \mathcal{M}_2^{\text{div}} \) be the same as in Example 5.6.2 except \( q_{e_u} \) and \( q_{e_v} \) are conjugate. Then on a chart \( \mathcal{V} \) containing \((C, D)\), \( \varphi \) is still in the form of (5.16), but \( \lambda_{uv} = \det \begin{bmatrix} c_{1u} & c_{1v} \\ c_{2u} & c_{2v} \end{bmatrix} \) vanishes on the locus where \( q_{e_u} \) and \( q_{e_v} \) are conjugate by Corollary 2.7.3.

Let \( y \) be a lift of \( x = (C, c_1(D)) \) after \( r_1 p_1 \) and \( \mathcal{V}_y \) be a chart containing \( y \). If \( \text{Dom}(y) = \{ e_u, e_v \} \), then \( \varphi^{r_1 p_1} \) can be rewritten as
\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & \lambda_{uv} & \zeta_1
\end{bmatrix}.
\]
Thus \( \varphi^{r_1 p_1} \) is diagonalizable on \( \mathcal{V}_y \). The topology of \( C \) and the assumption on \( \text{Dom}(y) \) imply that \( r_1 p_2 - r_2 \) do not affect \( \mathcal{V}_y \). Analyzing the rooted tree \( \gamma_2^{(2)} \) supplementary to the bi-dominantly derived tree \( \gamma_y^{(2)} \), we see that locally \( \mathcal{V}_y \) is blown up along the locus \( \{ \zeta_1 = \lambda_{uv} = 0 \} \) in \( r_3 p_1 \), thus \( \varphi^{r_3 p_1} \) becomes diagonalizable on the pullback on \( \mathcal{V}_y \).

If \( \text{Dom}(y) = \{ e_u \} \), \( \varphi^{r_1 p_1} \) can be rewritten as
\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & \lambda_{uv} & \zeta_1
\end{bmatrix}.
\]
Similar to the preceding paragraph, for a fixed lift \( \bar{y} \) of \( y \) after \( r_2 \), either \( \varphi^{r_2} \) is diagonalizable on a chart \( \mathcal{V}_{\bar{y}} \), or \( \text{Dom}(\bar{y}) = \{ e_v \} \). In the latter situation, \( \varphi^{r_2} \) can be rewritten as
\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & \lambda_{uv} & \zeta_1
\end{bmatrix}.
\]
As shown in the preceding paragraph, \( \varphi^{r_3 p_1} \) thus becomes diagonalizable on the pullback on \( \mathcal{V}_y \).

**Example 5.6.4.** Let \((C, D) \in \mathcal{M}_2^{\text{div}} \) be such that the dual graph of \( C \) is the first graph in Figure 2, the core \( F \) is a smooth genus 2 curve, the irreducible components \( C_a, C_b, C_c, \) and \( C_d \) are all smooth rational curves, and

\[
D \cap (F \cup C_b) = \emptyset, \quad |D \cap C_i| \geq 3, \quad i = a, c, d.
\]
Assume that $q_{e_b}$ is a Weierstrass point. For a fixed lift $y$ of $x = (C, c_1(D))$ after $r_1p_1$, we further assume that $\text{Dom}(y) = \{e_b\}$. By Example 3.6.10, the derived tree $\gamma'_y$ at $y$ is the last graph in Figure 6.

Let $\mathcal{V}'_y$ be a chart containing $y$. Under suitable trivialization, $\varphi^{r_1p_1}$ on $\mathcal{V}_y$ can then be written as

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & * * * \\ 0 & \tilde{\theta}_c & \tilde{e}_2 & \tilde{\theta}_{cd} & \tilde{e}_1 & \tilde{\zeta}_{1} & \tilde{\zeta}_{d} & \tilde{\zeta}_{a} & * * * \end{pmatrix},$$

where $\theta_c$, $\theta_d$ are as in Proposition 2.6.1 and $\theta_{cd}$ is as in Corollary 2.7.1 satisfying

$$\theta_{cd} = f_1\theta_c + g_1\zeta_b = f_2\theta_d + g_2\zeta_b, \quad f_i, g_i \in \Gamma(O^*_y), \quad i = 1, 2, \quad \det \begin{pmatrix} f_1 & g_1 \\ f_2 & g_2 \end{pmatrix} \in \Gamma(O^*_y).$$

Similar to the previous two examples, $r_1p_2-r_1p_5$ do not affect $\mathcal{V}'_y$, and $r_2$ is $\gamma'_y$-compatible on $\mathcal{V}_y$. When $r_2$ terminates, fix a lift $\tilde{y}$ of $y$.

If $e_a \in \text{Dom}(\tilde{y})$, then obviously $\tilde{\mathcal{V}}^2$ becomes diagonalizable. If $e_a \notin \text{Dom}(\tilde{y})$, there are three possibilities for $\text{Dom}(\tilde{y})$: \{e_2, e_d\}, \{e_2\}, or \{e_d\}.

If $\text{Dom}(\tilde{y}) = \{e_2, e_d\}$, then on a chart $\mathcal{V}_y$ containing $\tilde{y}$, $\tilde{\mathcal{V}}^2$ can be rewritten as

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & * * * \\ 0 & \tilde{\theta}_c & \tilde{e}_2 & \tilde{\theta}_{cd} & \tilde{e}_1 & \tilde{\zeta}_{1} & \tilde{\zeta}_{d} & \tilde{\zeta}_{a} & * * * \end{pmatrix},$$

The assumption on $\text{Dom}(\tilde{y})$ implies $r_2p_1$ does not affect $\mathcal{V}'_y$. Analyzing the rooted tree $(\gamma'_y)_{e_2, \tilde{y}, \tilde{y}'}$ supplementary to the partially derived tree of $\gamma'_y$ at $\tilde{y}$ along $e_2$, we see that locally $\mathcal{V}_y$ is blown up along the locus $\{\tilde{\theta}_c = \tilde{e}_1 = \tilde{\zeta}_a = 0\}$ in $r_3p_2$, thus $\tilde{\mathcal{V}}^{r_3p_2}$ becomes diagonalizable on the pullback of $\mathcal{V}'_y$.

If $\text{Dom}(\tilde{y}) = \{e_2\}$, then the partially derived tree $(\gamma'_y)_{e_2, \tilde{y}}$ of $\gamma'_y$ along $e_2$ is isomorphic to $\gamma'_y$. On a chart $\mathcal{V}_y$ containing $\tilde{y}$, $\tilde{\mathcal{V}}^2$ can be rewritten as

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & * * * \\ 0 & \tilde{\theta}_c & \tilde{e}_2 & \tilde{\theta}_{cd} & \tilde{e}_1 & \tilde{\zeta}_{1} & \tilde{\zeta}_{d} & \tilde{\zeta}_{a} & * * * \end{pmatrix}. $$

Since $r_3p_1$ does not affect $\mathcal{V}_y$ and $r_3p_2$ is $(\gamma'_y)_{e_2, \tilde{y}, \tilde{y}'}$-compatible on $\mathcal{V}_y$, we see that locally $\mathcal{V}_y$ is blown up along the locus $\{\tilde{\theta}_c = \tilde{e}_2 = \tilde{\zeta}_d = \tilde{\zeta}_a = 0\}$ and then along the proper transform of $\{\tilde{\theta}_d = \tilde{e}_1 = \tilde{\zeta}_a = 0\}$ in $r_3p_2$, thus $\tilde{\mathcal{V}}^{r_3p_2}$ becomes diagonalizable on the pullback of $\mathcal{V}_y$.

If $\text{Dom}(\tilde{y}) = \{e_d\}$, on a chart $\mathcal{V}_y$ containing $\tilde{y}$, $\tilde{\mathcal{V}}^2$ can be rewritten as

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & * * * \\ 0 & \tilde{\theta}_{cd} & \tilde{e}_2 & \tilde{\theta}_d & \tilde{e}_1 & \tilde{\zeta}_{1} & \tilde{\zeta}_{a} & * * * \end{pmatrix}. $$

Similar to the preceding paragraphs, we observe that locally $\mathcal{V}_y$ is blown up along the locus $\{\tilde{\theta}_{cd} = \tilde{e}_2 = \tilde{\zeta}_a = 0\}$ in $r_3p_1$ and then along the proper transform of $\{\tilde{\theta}_d = \tilde{e}_1 = \tilde{\zeta}_a = 0\}$ in $r_3p_2$, thus $\tilde{\mathcal{V}}^{r_3p_2}$ becomes diagonalizable on the pullback of $\mathcal{V}_y$. 
Example 5.6.5. Let\((C, D)\in\mathbb{R}_2^{\text{div}}\) be such that its weighted tree is illustrated in Figure 7. Assume that the irreducible components of \(C\) are all smooth,

\[D \cap F = \emptyset, \quad |D \cap C_a| = |D \cap C_b| = 1, \quad |D \cap C_c| = |D \cap C_d| \geq 2,\]

and \(q_{e_a}\) and \(q_{e_b}\) are conjugate. For a fixed lift \(y = (C, c_1(D))\) after \(r_1p_1\), we further assume that \(\text{Dom}(y) = \{e_a\}\).

![Figure 7. The weighted tree in Example 5.6.5](image)

On a chart \(\mathcal{V}_y\) of \(y\), \(\varphi^r_{1p_1}\) can be written as

\[
\tilde{\varepsilon}_1 \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots \\ 0 & \tilde{\varepsilon}_1 \tilde{c}_c & \lambda_{ab} \tilde{c}_b & \tilde{\varepsilon}_1 \tilde{c}_b \tilde{c}_d & \cdots \end{bmatrix},
\]

where \(\lambda_{ab}\) is as in Corollary 2.7.3. The sequential blowups \(r_1p_2-r_1p_4\) do not affect \(\mathcal{V}_y\). In \(r_1p_5\), locally \(\mathcal{V}_y\) is blown up along the locus \(\{\tilde{\varepsilon}_1 = \tilde{\zeta}_b = 0\}\). After \(r_1p_5\), fix a lift \(\tilde{y}\) of \(y\). There are three possibilities for \(\text{Dom}(\tilde{y})\): \(\{e_c, e_b\}\), \(\{e_c\}\), or \(\{e_b\}\).

If \(\text{Dom}(\tilde{y}) = \{e_c, e_b\}\), on a chart \(\mathcal{V}_{\tilde{y}}\) containing \(\tilde{y}\), \(\tilde{\varphi}^r_{1p_5}\) can be rewritten as

\[
\tilde{\varepsilon}_1 \begin{bmatrix} 1 & 0 & 0 & \cdots \\ 0 & \tilde{\varepsilon}_1 \tilde{c}_c & \tilde{\lambda}_{ab} \tilde{c}_b & \cdots \end{bmatrix}.
\]

The assumption on \(\text{Dom}(\tilde{y})\) implies that \(r_2\) does not affect \(\mathcal{V}_{\tilde{y}}\). In \(r_3p_1\), locally \(\mathcal{V}_{\tilde{y}}\) is blown up along the locus \(\{\tilde{\varepsilon}_1 = \tilde{\lambda}_{ab} = 0\}\), thus \(\tilde{\varphi}^r_{3p_1}\) becomes diagonalizable on the pullback of \(\mathcal{V}_{\tilde{y}}\).

If \(\text{Dom}(\tilde{y}) = \{e_c\}\), on a chart \(\mathcal{V}_{\tilde{y}}\) containing \(\tilde{y}\), \(\tilde{\varphi}^r_{1p_5}\) can be rewritten as

\[
\tilde{\varepsilon}_1 \begin{bmatrix} 1 & 0 & 0 & \cdots \\ 0 & \tilde{\varepsilon}_1 \tilde{c}_c & \tilde{\lambda}_{ab} \tilde{c}_b & \cdots \end{bmatrix}.
\]

Locally \(\mathcal{V}_{\tilde{y}}\) is blown up along the locus \(\{\tilde{\varepsilon}_1 = \tilde{\zeta}_b = 0\}\) in \(r_2\). When \(r_2\) terminates, let \(\tilde{y}'\) be a lift of \(\tilde{y}\). If \(e_1\) is dominant, obviously \(\tilde{\varphi}^{r_2}\) is diagonalizable; otherwise, we observe that the blowup locus of \(r_3p_1\) near \(\tilde{y}'\) is given by \(\{\tilde{\varepsilon}_1 = \tilde{\lambda}_{ab} = 0\}\), thus \(\tilde{\varphi}^{r_3p_1}\) becomes diagonalizable on the pullback of \(\mathcal{V}_{\tilde{y}}\).

If \(\text{Dom}(\tilde{y}) = \{e_b\}\), on a chart \(\mathcal{V}_{\tilde{y}}\) containing \(\tilde{y}\), \(\tilde{\varphi}^r_{1p_5}\) can be rewritten as

\[
\tilde{\varepsilon}_1 \begin{bmatrix} 1 & 0 & 0 & \cdots \\ 0 & \tilde{\varepsilon}_1 \tilde{c}_c & \tilde{\lambda}_{ab} \tilde{c}_b & \tilde{\varepsilon}_1 \tilde{c}_b \tilde{c}_d & \cdots \end{bmatrix}.
\]

It is again a direct check that \(r_2\) does not affect a neighborhood of \(\tilde{y}\), and \(\mathcal{V}_{\tilde{y}}\) is blown up along the locus \(\{\tilde{\varepsilon}_1 = \tilde{\lambda}_{ab} = 0\}\) in \(r_3p_1\), then possibly along the proper transform of \(\{\tilde{\zeta}_c = \tilde{\lambda}_{ab} = \tilde{\zeta}_d = 0\}\) in \(r_3p_3\), and finally possibly along
the proper transform of \( \{ \zeta_c = \lambda_{ab} = \zeta_b = 0 \} \) in \( \mathcal{V}_3 \). In sum, \( \mathcal{V}_{3}^{2} \) becomes diagonalizable on the pullback of \( \mathcal{V}_3 \).

6. Local defining equations of \( \overline{M}_2(\mathbb{P}^n, d) \) and its blowups

6.1. The local open immersions. As in the first paragraph of \( \S 2.3 \) we cover \( \overline{M}_2(\mathbb{P}^n, d) \) by charts \( U/V \). Let \( \mathcal{E}_V \) be the total space of the vector bundle \( \rho_\ast \mathcal{L}(A)^{\otimes n} \) and let

\[
\rho : \mathcal{E}_V \to V
\]

be the projection. We also set

\[
\rho_\ast (\mathcal{L}(A)^{\otimes n}|_A) = \rho_\ast (\mathcal{L}(A)^{\otimes n}|_{A_1}) \oplus \rho_\ast (\mathcal{L}(A)^{\otimes n}|_{A_2}).
\]

Then the tautological restriction homomorphism

\[
(6.1) \text{rest} : \rho_\ast (\mathcal{L}(A)^{\otimes n}|_A) \to \rho_\ast (\mathcal{L}(A)^{\otimes n}|_A)
\]

lifts to a section

\[
(6.2) \Phi \in \Gamma(\mathcal{E}_V, \rho_\ast (\mathcal{L}(A)^{\otimes n}|_A)).
\]

By choosing suitable trivialization, the homomorphism “rest” of (6.1) can be identified with the homomorphism

\[
(6.3) (0 \oplus \varphi)^{\otimes n} : (\mathcal{E}_V \oplus \rho_\ast \mathcal{M}(D))^{\otimes n} \to (\rho_\ast \mathcal{O}_A(A))^{\otimes n},
\]

where \( \varphi \) is the structural homomorphism in (2.4). Then, the section \( \Phi \) of (6.2) is the lift of \( (0 \oplus \varphi)^{\otimes n} \) in (6.3).

**Theorem 6.1.1.** Let \( U = V \times \mathbb{P}^{\text{div}}_2 \). Then there is a canonical open immersion

\[
(6.4) \quad U \to (\Phi = 0) \subset \mathcal{E}_V.
\]

**Proof.** This theorem is the natural extension of [5, Theorem 2.17]; the proofs are also parallel. \( \square \)

**Corollary 6.1.2.** Let \( (C, D) \in \mathbb{P}^{\text{div}}_2 \) be such that its image in \( \mathbb{M}_2^{\text{wt}} \) lies in \( \mathbb{M}_2^{\text{nm}} \) and \( D \cap F \) contains a pair of non-conjugate points. Then by shrinking \( V \) if necessary, we have that \( U = V \times \mathbb{P}^{\text{div}}_2 \) is smooth. In particular, the primary component of \( \overline{M}_2(\mathbb{P}^n, d), d > 2 \), is generically smooth and of expected dimension.

**Proof.** We can trivialize \( \rho_\ast \mathcal{M}(D) \) and \( \rho_\ast \mathcal{O}_A(A) \) so that

\[
\mathcal{E}_V \cong V \times (\mathbb{A}^{d+1})^n.
\]

Let \( w^i_j \in \mathbb{A}^1 \) for all \( 1 \leq i \leq n \) and \( 0 \leq j \leq d \). Recall that the homomorphism “rest” of (6.1) can be identified with the homomorphism

\[
(0 \oplus \varphi)^{\otimes n} : (\mathcal{E}_V \oplus \rho_\ast \mathcal{M}(D))^{\otimes n} \to (\rho_\ast \mathcal{O}_A(A))^{\otimes n}.
\]

By Proposition 2.5.1 and Corollary 2.7.3, \( 0 \oplus \varphi \) can be represented by

\[
0 \oplus \varphi = [0, I_2, 0 \cdots, 0].
\]
Hence, the equation $\Phi = 0$ is equivalent to the following equations
\begin{equation}
(6.5) \quad w_i^1 = w_i^2 = 0 \quad \text{for all } 1 \leq i \leq n,
\end{equation}
which obviously implies that $\mathcal{U}$ is isomorphic to an open subset of $\mathcal{V} \times (\mathbb{A}^{d-1})^n$. Note that $\dim(\mathcal{V} \times (\mathbb{A}^{d-1})^n) = 3 + d + (d-1)n = d(n+1) - n + 3$ which is the expected dimension of $\overline{M}_2(\mathbb{P}^n, d)$. The assertion then follows. □

6.2. **Induced open immersions of the blowup.** We continue with the notation as in previous sections. Let $\mathcal{V} \times \mathbb{P}^2$. Then $E = \mathcal{V} \times \mathbb{P}^2$. Then
\begin{equation}
(6.6) \quad \tilde{\Phi} : \mathcal{E}_V \to \mathcal{V}
\end{equation}
is the total space of the pull back bundle $\beta^* \rho_* \mathcal{L}(A)^{\otimes n}$, where $\beta : \mathcal{V} \to \mathcal{V}$ denotes the projection. The tautological restriction homomorphism “rest” of \((6.1)\) pullbacks to give rise to
\begin{equation}
(6.7) \quad \tilde{\Phi} \in \Gamma(\mathcal{E}_V, \beta^* \rho_* \mathcal{L}(A)^{\otimes n}|_A),
\end{equation}
where $\tilde{\Phi} : \mathcal{E}_V \to \mathcal{V}$ denotes the projection. Set $\mathcal{U} = \mathcal{V} \times \mathcal{U}$. The immersion $\mathcal{U} \to \mathcal{E}_V$ of Theorem 6.1.1 then naturally induces an open immersion
\begin{equation}
(6.8) \quad \mathcal{U} \to (\tilde{\Phi} = 0) \subset \mathcal{E}_V.
\end{equation}

**Lemma 6.2.1.** With notation as above, $\mathcal{U}$ has normal crossing singularities, and its primary component is smooth.

**Proof.** First, we trivialize $\beta^* \rho_* \mathcal{M}(D)$ and $\beta^* \rho_* \mathcal{O}_A(A)$ so that
\[ \mathcal{E}_V \cong \mathcal{V} \times (\mathbb{A}^{d+1})^n. \]
Let $w_i^j \in \mathbb{A}^1$ for all $1 \leq i \leq n$ and $0 \leq j \leq d$.

By Proposition 5.1.2, $\mathcal{V}$ can be covered by $\{\mathcal{V}\}$ so that on each $\mathcal{V} \subset \mathcal{V}$, the homomorphism
\[ \beta^* \varphi : \beta^* \rho_* \mathcal{M}(D) \to \beta^* \rho_* \mathcal{O}_A(A) \]
can be diagonalized as
\[ \begin{bmatrix} z_1 & 0 & 0 & \cdots & 0 \\ 0 & z_2 & 0 & \cdots & 0 \end{bmatrix} \quad \text{with} \quad z_1 z_2 \in \Gamma(\mathcal{O}_{\mathcal{V}}). \]
Then the equation $\tilde{\Phi} = 0$ is equivalent to the following equations
\begin{equation}
(6.9) \quad z_1 w_i^j = 0, \quad z_2 w_i^j = 0 \quad \text{for all } 1 \leq i \leq n.
\end{equation}
Thus, $\mathcal{U}$ has normal crossing singularities.

Since the primary component of $\mathcal{U} = \mathcal{V} \times \mathcal{U}$ consists of general points with non-vanishing $z_1 z_2$, we see that the primary component is defined by
\begin{equation}
(6.10) \quad w_i^1 = w_i^2 = 0 \quad \text{for all } 1 \leq i \leq n.
\end{equation}
Thus, the primary component of $\mathcal{U}$ is smooth. □
Theorem 6.2.2. Assume $d > 2$. Then, $\widetilde{M}_2(\mathbb{P}^n, d)$ has normal crossing singularities and the primary component of $\widetilde{M}_2(\mathbb{P}^n, d)$ is smooth and of expected dimension.

Proof. The first two statements follows from Lemma 6.2.1. It remains to check the last statement about the dimension. Note that $\dim E_V = 3 + d + (d + 1)n$. Hence the dimension of the primary component of $\widetilde{U}$ is

$$\dim E_V = 3 + d + (d + 1)n - 2n = d(n + 1) - n + 3$$

which is the virtual dimension of $\overline{M}_2(\mathbb{P}^n, d)$. □

When $d = 2$, the interior of the primary component of $\overline{M}_2(\mathbb{P}^n, 2)$ consists of stable maps that are double covers of smooth rational curves, which is smooth and of dimension $2n + 4$. Since the virtual dimension of $\overline{M}_2(\mathbb{P}^n, 2)$ is $n + 5$, the primary component is of wrong dimension unless $n = 1$. The entire moduli can be treated by hand.

References


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