

Hypertrees, projections, and moduli of stable rational curves

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Abstract. We give a conjectural description for the cone of effective divisors of the Grothendieck–Knudsen moduli space $\overline{M}_{0,n}$ of stable rational curves with n marked points. Namely, we introduce new combinatorial structures called hypertrees and show that they give exceptional divisors on $\overline{M}_{0,n}$ with many remarkable properties.

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1. Introduction

A major open problem inspired by the pioneering work of Harris and Mumford [HM] on the Kodaira dimension of the moduli space of stable curves, is to understand the geometry of its birational models, and in particular to describe its cone of effective divisors and a decomposition of this cone into Mori chambers [HK], encoding ample divisors on birational models.

Parts of this paper were written while the first author was visiting the Max-Planck Institute in Bonn, Germany, and while both authors were members at MSRI, Berkeley. The first author was partially supported by the NSF grant DMS-1001157. The second author was partially supported by the NSF grants DMS-0701191 and DMS-1001344 and by the Sloan research fellowship.

Here we study the genus zero case. The moduli spaces $\overline{M}_{0,n}$ parametrize stable rational curves, i.e., nodal trees of \mathbb{P}^1 's with n marked points and without automorphisms. For any subset I of marked points, $\overline{M}_{0,n}$ has a natural boundary divisor δ_I whose general element parametrizes stable rational curves with two irreducible components, one marked by points in I and another marked by points in I^c . We will introduce new combinatorial objects called *hypertrees* with an eye towards the following

Conjecture 1.1. *The effective cone of $\overline{M}_{0,n}$ is generated by boundary divisors and by divisors D_Γ (defined below) parametrized by irreducible hypertrees.*

Definition 1.2. A *hypertree* $\Gamma = \{\Gamma_1, \dots, \Gamma_d\}$ on a set N is a collection of subsets of N such that the following conditions are satisfied:

- any subset Γ_j has at least three elements,
- any $i \in N$ is contained in at least two subsets Γ_j ,
- (convexity axiom)

$$(\ddagger) \quad \left| \bigcup_{j \in S} \Gamma_j \right| - 2 \geq \sum_{j \in S} (|\Gamma_j| - 2) \quad \text{for any } S \subset \{1, \dots, d\},$$

- (normalization)

$$(\dagger) \quad |N| - 2 = \sum_{j \in \{1, \dots, d\}} (|\Gamma_j| - 2).$$

A hypertree Γ is *irreducible* if (\ddagger) is a strict inequality for $1 < |S| < d$.

Remark 1.3. The most common hypertrees are composed of triples. In this case, (\dagger) becomes $d = n - 2$ and (\ddagger) becomes

$$\left| \bigcup_{j \in S} \Gamma_j \right| \geq |S| + 2 \quad \text{for any } S \subset \{1, \dots, n - 2\},$$

i.e., Γ is sufficiently capacious. If we consider pairs instead of triples, and change 2 to 1 in (\dagger) and (\ddagger) , then it is easy to see that Γ will be a connected tree on vertices $\{1, \dots, n\}$. This explains our term ‘‘hypertree’’.

Definition 1.4. For any irreducible hypertree Γ on the set $\{1, \dots, n\}$, let $D_\Gamma \subset \overline{M}_{0,n}$ be the closure of the locus in $M_{0,n}$ obtained by

- choosing a *planar realization* of Γ : a configuration of different points $p_1, \dots, p_n \in \mathbb{P}^2$ such that, for any subset $S \subset \{1, \dots, n\}$ with at least three points, $\{p_i\}_{i \in S}$ are collinear if and only if $S \subset \Gamma_j$ for some j ,

- projecting p_1, \dots, p_n from a point $p \in \mathbb{P}^2$ to points $q_1, \dots, q_n \in \mathbb{P}^1$,

- representing the datum $(\mathbb{P}^1; q_1, \dots, q_n)$ by a point of $M_{0,n}$.

If Γ is an irreducible hypertree on a subset $K \subset \{1, \dots, n\}$, we abuse notation and let $D_\Gamma \subset \overline{M}_{0,n}$ be the pull-back of $D_\Gamma \subset \overline{M}_{0,K}$ with respect to the forgetful map $\overline{M}_{0,n} \rightarrow \overline{M}_{0,K}$.

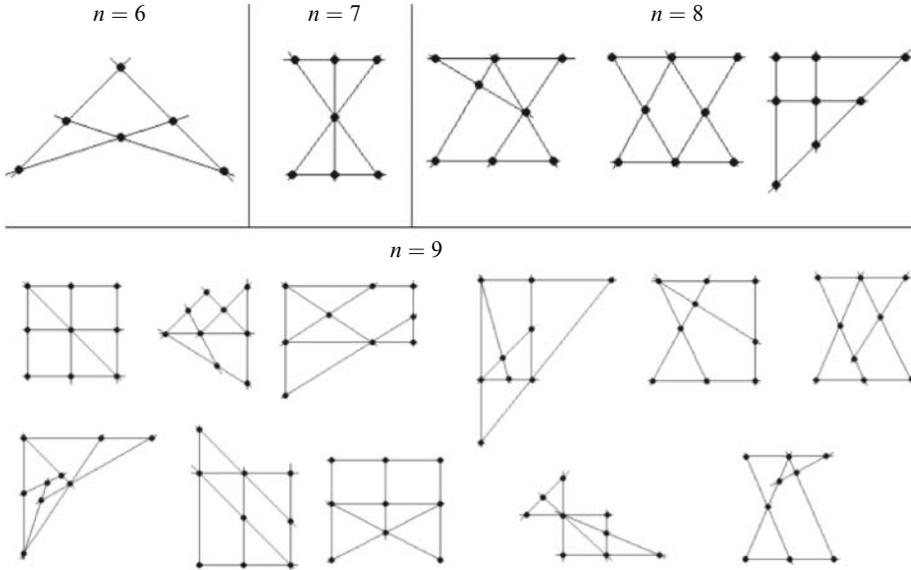


Figure 1. Irreducible hypertrees for $n < 10$. Points correspond to elements of N and lines correspond to $\Gamma_1, \dots, \Gamma_d$.

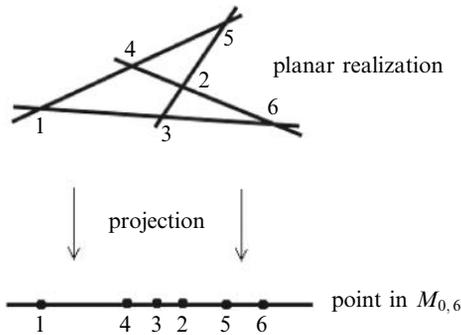


Figure 2. Hypertree divisor as the locus of projections.

Here is our first result:

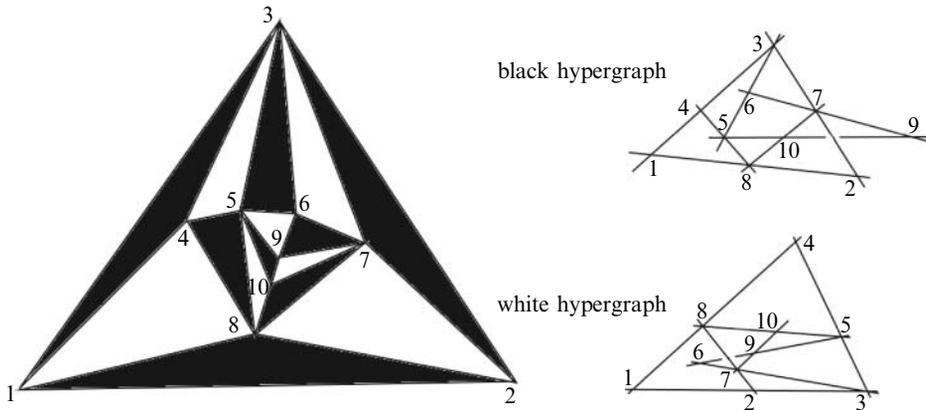
Theorem 1.5. *For any irreducible hypertree Γ , the locus $D_\Gamma \subset \overline{M}_{0,n}$ is a non-empty irreducible divisor, which generates an extremal ray of the effective cone of $\overline{M}_{0,n}$. Moreover, this divisor is exceptional: there exists a birational contraction*

$$\overline{M}_{0,n} \dashrightarrow X_\Gamma$$

onto a normal projective variety X_Γ (see Theorem 1.10), and D_Γ is the irreducible component of its exceptional locus that intersects $M_{0,n}$.

Notice that a priori it is not at all clear that an irreducible hypertree has a planar realization, but we will show that this is always the case. Moreover, any irreducible hypertree on any subset $K \subset N$ gives rise, by pull-back via the forgetful map π_K , to an effective divisor which generates an extremal ray of the effective cone of $\overline{M}_{0,n}$ (see Lemma 7.8).

1.6. Spherical hypertrees. We discovered that any even (i.e., bicolored) triangulation of a 2-sphere gives a hypertree. Any such triangulation has a collection of “black” faces and a collection of “white” faces. We will show that each of these collections is a hypertree.



These *spherical hypertrees* are irreducible unless the triangulation is a connected sum of two triangulations obtained by removing a white triangle from one triangulation, a black triangle from another, and then gluing along the cuts.

One can ask if different hypertrees can give the same divisor of $\overline{M}_{0,n}$. This turns out to be a difficult question. We can prove the following

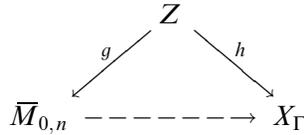
Theorem 1.7. *Let Γ and Γ' be generic hypertrees (see Definition 7.6). Then*

$$D_\Gamma = D_{\Gamma'}$$

if and only if Γ and Γ' are the black and white hypertrees of an even triangulation of a sphere that is not a connected sum.

Roughly speaking, the map $\Gamma \rightarrow D_\Gamma$ is generically injective, and a pair $\{\Gamma_1, \Gamma_2\}$ such that $D_{\Gamma_1} = D_{\Gamma_2}$ is associated to a bicolored triangulation of the 2-sphere. Outside of this “generic locus”, the map $\Gamma \rightarrow D_\Gamma$ can be more complicated. For example, in Section 9 we study the triangulation of a bipyramid, when many hypertrees give the same divisor. This is an interesting case because the corresponding divisor D_Γ is a pull-back of the classical Brill–Noether “gonality” divisor on \overline{M}_{2k+1} used by Harris and Mumford [HM].

We would like to explain why the divisors D_Γ are exceptional, i.e., how to construct a contracting birational map $f : \overline{M}_{0,n} \dashrightarrow X_\Gamma$ in Theorem 1.5. The map is called *contracting* if for one (and hence for any) resolution



g -exceptional divisors are also h -exceptional. A typical example is a composition of a small modification and a morphism.

To explain the idea, take a general smooth curve Σ of genus g . By Brill–Noether theory [ACGH], the variety G_{g+1}^1 , parameterizing pencils of divisors of degree $g + 1$ on Σ , is smooth. We have a natural morphism

$$v : G_{g+1}^1 \rightarrow W_{g+1}^1 \simeq \text{Pic}^{g+1}(\Sigma),$$

which assigns to a pencil of divisors its linear equivalence class. By Brill–Noether theory, v is birational, and has an exceptional divisor D over

$$W_{g+1}^2 = \{L \in \text{Pic}^{g+1}(\Sigma) \mid h^0(L) \geq 3\},$$

which is non-empty and has codimension 3 in $\text{Pic}^{g+1}(\Sigma)$. So, for example, it is immediately clear that D is an extremal ray of $\text{Eff}(G_{g+1}^1)$.¹⁾

Generically, G_{g+1}^1 parameterizes globally generated pencils, i.e., it contains a scheme of degree $g + 1$ morphisms $\Sigma \rightarrow \mathbb{P}^1$ (modulo automorphisms) as an open subset. So D generically parameterizes pencils that can be obtained by choosing a “planar realization”, i.e., a morphism $\Sigma \rightarrow \mathbb{P}^2$, and then taking composition with the projection from a general point.

Next we degenerate a smooth curve to a union of rational curves with combinatorics encoded in a hypertree.

Definition 1.8. We work with schemes over an algebraically closed field k . A curve Σ_Γ of genus

$$g = d - 1$$

is called a *hypertree curve* if it has d irreducible components, each isomorphic to \mathbb{P}^1 and marked by Γ_j , $j = 1, \dots, d$. These components are glued at identical markings as a scheme-theoretic push-out: at each singular point $i \in N$, Σ_Γ is locally isomorphic to the union of coordinate axes in \mathbb{A}^{v_i} , where v_i is the valence of i , i.e., the number of subsets Γ_j that contain i . We consider Σ_Γ as a marked curve (by indexing its singularities).

The most common case is when all Γ_j are triples. If this is not the case, then hypertree curves have moduli, namely

$$M_\Gamma := \prod_{j=1, \dots, d} M_{0, \Gamma_j}.$$

¹⁾ Other extremal rays can be found using methods of Bauer–Szemberg [BS].

Then we have to adjust our construction a little bit: Σ_Γ will be the universal curve over the moduli space M_Γ .

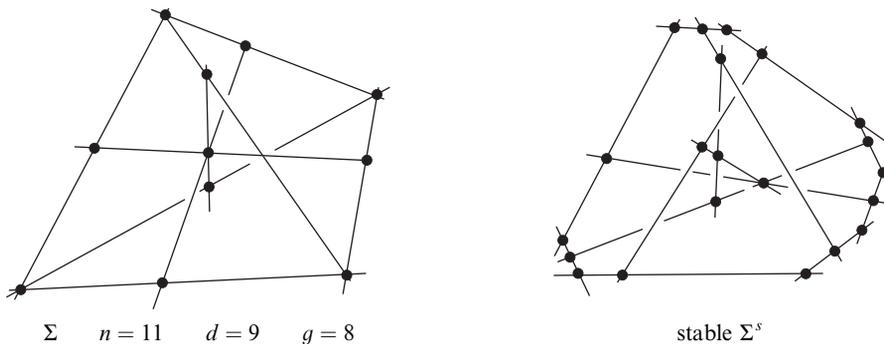
By the definition of push-out, $M_{0,n}$ can be identified with the variety of morphisms $f : \Sigma_\Gamma \rightarrow \mathbb{P}^1$ (modulo the free action of PGL_2) that send singular points p_1, \dots, p_n of Σ_Γ to different points $q_1, \dots, q_n \in \mathbb{P}^1$. This gives a morphism

$$(1.8.1) \quad v : M_{0,n} \rightarrow \mathrm{Pic}^1, \quad f \mapsto f^* \mathcal{O}_{\mathbb{P}^1}(1)$$

from $M_{0,n}$ to the (relative over M_Γ) Picard scheme Pic^1 of line bundles on Σ of degree 1 on each irreducible component. This is the analogue of the map $G_{g+1}^1 \rightarrow \mathrm{Pic}^{g+1}$ in the smooth case. The locus $D_\Gamma \subset M_{0,n}$ defined above corresponds to the divisor D in the smooth case.

We have to compactify the source and the target of the map v .

Definition 1.9. A nodal curve Σ_Γ^s , called a *stable hypertree curve*, is obtained by inserting a \mathbb{P}^1 with v_i markings instead of each singular point of Σ_Γ with $v_i > 2$. If $v_i > 3$,



then we do not allow extra moduli, instead we arbitrarily *fix* the cross-ratios of the marked points on the inserted \mathbb{P}^1 's. Let Pic^1 be the Picard scheme of invertible sheaves on Σ^s of degree 1 on each irreducible component coming from Σ and degree 0 on each component inserted at a non-nodal point of Σ .

Theorem 1.10. *Let Γ be an irreducible hypertree. Any sheaf in Pic^1 is Gieseker-stable w.r.t. the dualizing sheaf ω_{Σ^s} . Let X_Γ be the normalization of the main component in the compactified Jacobian of Σ^s relative over*

$$\bar{M}_\Gamma = \prod_{j=1, \dots, d} \bar{M}_{0, \Gamma_j}.$$

The map v of (1.8.1) induces a contracting birational map $v : \bar{M}_{0,n} \dashrightarrow X_\Gamma$ and D_Γ is the only component of the exceptional locus that intersects $M_{0,n}$.

Remarks 1.11. (a) A stable hypertree curve is a special case of a graph curve of Bayer and Eisenbud [BE].

(b) All irreducible hypertrees for small n were found by Scheidwasser [S] using computer search. Up to the action of S_n , there are 93 hypertrees for $n = 10$, 1027 hypertrees for $n = 11$, and so on. See Figure 1 for all hypertrees for $n < 10$.

(c) There are no irreducible hypertrees for $n = 5$. This reflects the fact that the effective cone of $\overline{M}_{0,5} \simeq \text{Bl}_4 \mathbb{P}^2$ is generated by boundary divisors alone, i.e., by the ten (-1) -curves.

(d) The first proofs that $\overline{\text{Eff}}(\overline{M}_{0,6})$ is not generated by boundary divisors were found by Keel and Vermeire [V]. (In particular, this shows that, for any $n \geq 6$, $\overline{\text{Eff}}(\overline{M}_{0,n})$ is not generated by boundary divisors.) Their description of an extremal divisor is very different from ours, which perhaps explains why it was not generalized to all n before. We will compare the two approaches in Section 9.

(e) Hassett and Tschinkel [HT] proved that $\overline{\text{Eff}}(\overline{M}_{0,6})$ is generated by boundary and Keel–Vermeire divisors. So Conjecture 1.1 is true for $n = 6$. It was proved by the first author [C] that in fact the Cox ring of $\overline{M}_{0,6}$ is generated by boundary and hypertree divisors. A pipe dream would be to prove an analogous statement for any n .

(f) The existence of the birational contractions X_Γ supports the conjecture of Hu and Keel [HK] that $\overline{M}_{0,n}$ is a Mori dream space. The map v of (1.8.1) is the first example of a birational contraction of $\overline{M}_{0,n}$ whose exceptional locus intersects the interior $M_{0,n}$. Birational contractions whose exceptional locus lies in the boundary have been previously constructed by Hassett [Has]. In particular, the map v gives a (hypothetical) new Mori chamber of $\overline{M}_{0,n}$. It would be interesting to factor $\overline{M}_{0,n} \dashrightarrow X_\Gamma$ through a small \mathbb{Q} -factorial modification, which perhaps has a functorial meaning.

(g) We take only irreducible hypertrees in Theorem 1.5 because if Γ is not irreducible, then if we define D_Γ as above, any component of D_Γ will be equal to $\pi^{-1}(D_{\Gamma'})$, where $\pi : \overline{M}_{0,n} \rightarrow \overline{M}_{0,k}$ is a forgetful map and Γ' is an irreducible hypertree on a subset $K \subset N$ (see Lemma 4.11).

(h) As Figure 1 suggests, the number of new extremal rays grows rapidly with n . One reason for this is the existence of spherical hypertrees, another reason is a “Fibonacci” inductive construction (Theorem 7.18) that multiplies irreducible non-spherical hypertrees.

(i) Keel and McKernan [KM] proved that the effective cone of the symmetrization $\overline{M}_{0,n}/S_n$ is generated by boundary divisors for any n . So in some sense, our hypertree divisors reflect S_n -monodromy.

Let us explain the layout of the paper. We start in Section 2 by introducing Brill–Noether loci of hypertree curves and use a trick to show that a hypertree divisor (if non-empty) generates an extremal ray of the effective cone of $\overline{M}_{0,n}$. In Section 3 we introduce *capacity*, which measures how far is a collection of subsets from being a hypertree. We relate capacity to the dimension of the image of a product of linear projections. In Section 4 we use calculations with discrepancies to show that a hypertree divisor is non-empty and irreducible. We also (partially) compute its class. In Section 5 we study the compactified Jacobian of a hypertree curve and show that $\overline{M}_{0,n}$ is birationally contracted to it. In

Section 6 we prove the characterization of D_Γ via projections of points given in the Introduction: in the previous sections we define D_Γ in a somewhat weaker fashion as a Brill–Noether locus. In Section 7 we study spherical and *generic* hypertrees. In particular, we show that if a hypertree is generic, then the hypertree divisor uniquely determines the hypertree, except in the case when the hypertree is spherical (in which case the divisor uniquely determines the triangulation). We also give an inductive construction of many non-spherical generic hypertrees. Section 8 is very elementary: we use basic linear algebra to find determinantal equations for hypertree divisors. As a corollary, we show that black and white hypertrees of a triangulated sphere give the same divisors on $\overline{M}_{0,n}$. In Section 9 we relate hypertree divisors to gonality divisors on \overline{M}_g via various gluing maps $\overline{M}_{0,n} \rightarrow \overline{M}_g$. Finally, in Section 10 we use the program Macaulay to give several examples of moving divisors on $\overline{M}_{0,n}$ which are pull-backs of extremal divisors on $\overline{M}_{g,k}$ via maps $\overline{M}_{0,n} \rightarrow \overline{M}_{g,k}$ ($n = 2g + k$) obtained by gluing pairs of markings. These divisors on $\overline{M}_{0,n}$ are linearly equivalent to sums of boundary (thus, at least in our examples, this construction does not lead to any new interesting divisors on $\overline{M}_{0,n}$).

Acknowledgment. We are grateful to Sean Keel for teaching us \overline{M}_g , to Valery Alexeev and Lucia Caporaso for answering our questions about compactified Jacobians, to Igor Dolgachev, Gabi Farkas, János Kollár, and Bernd Sturmfels for useful discussions.

Hypertrees for $n \leq 11$ were classified by Ilya Scheidwasser during an REU directed by the second author. He also performed the most difficult combinatorial calculations in Section 5. We are grateful to Ilya for the permission to reproduce his results and for the beautiful pictures he made. The “Fibonacci” construction of Theorem 7.18 was suggested to us by Anna Kazanova.

2. Brill–Noether loci of hypertree curves

We fix a hypertree $\Gamma = \{\Gamma_1, \dots, \Gamma_d\}$ and consider a hypertree curve Σ .

Definition 2.1. A linear system on Σ is called *admissible* if it is globally generated and the corresponding morphism $\Sigma \rightarrow \mathbb{P}^k$ sends singular points of Σ to distinct points. An invertible sheaf L is called admissible if the complete linear system $|L|$ is admissible.

We define the *Brill–Noether loci* W^r and G^r (cf. [ACGH]) as follows. First suppose that Γ consists of triples. Then Σ has genus $g = n - 3$ and the Picard scheme Pic^1 of line bundles of degree 1 on each irreducible component is isomorphic to \mathbb{G}_m^g (not canonically). The Brill–Noether locus W^r parametrizes admissible line bundles $L \in \text{Pic}^1$ such that

$$h^0(\Sigma, L) \geq r + 1.$$

The locus G^r parametrizes admissible pencils on Σ_Γ such that the corresponding line bundle is in W^r . So we have a natural forgetful map

$$G^r \xrightarrow{v} W^r.$$

If Γ contains not just triples, things get a little bit more complicated. Let us give a functorial definition that works in general. The space M_Γ defined in the Introduction

represents a functor

$$\mathcal{M}_\Gamma : \text{schemes} \rightarrow \text{sets}$$

that sends a scheme S to the set of isomorphism classes of flat families $\Sigma \rightarrow S$ with reduced geometric fibers isomorphic to hypertree curves. A hypertree curve is connected and it is easy to compute its genus

$$(2.1.1) \quad g = n - 3 - \dim M_\Gamma = d - 1.$$

Consider the relative Picard functor

$$\mathcal{Pic}^1 : \text{schemes} \rightarrow \text{sets}$$

that sends a scheme S to an object Σ of $\mathcal{M}_\Gamma(S)$ equipped with an invertible sheaf on Σ of multi-degree $(1, \dots, 1)$ modulo pull-backs of invertible sheaves on S . This functor is represented by a \mathbb{G}_m^g -torsor over M_Γ . This torsor is in fact trivial. Notice that the dimension of \mathcal{Pic}^1 is always equal to $n - 3$. Let

$$\mathcal{G}^1 : \text{schemes} \rightarrow \text{sets}$$

be a functor that sends a scheme S to the set of isomorphism classes of

(1) a family $\{p : \Sigma \rightarrow S\}$ in $\mathcal{M}_\Gamma(S)$,

(2) a morphism $f : \Sigma \rightarrow \mathbb{P}_S^1$ such that (a) images of irreducible components of Σ^{sing} are disjoint and (b) each irreducible component of Σ maps isomorphically onto \mathbb{P}_S^1 .

Here two morphisms are considered isomorphic if they differ by isomorphisms of S -schemes both on the source and the target. Let

$$v : \mathcal{G}^1 \rightarrow \mathcal{Pic}^1$$

be the natural transformation such that

$$(\Sigma \rightarrow S, f : \Sigma \rightarrow \mathbb{P}_S^1) \mapsto (\Sigma \rightarrow S, f^* \mathcal{O}_{\mathbb{P}_S^1}(1)).$$

We will see below that \mathcal{G}^1 is represented by $M_{0,n}$. For any $r \geq 2$, let $G^r \subset G^1$ be the closed subset (with the induced reduced scheme structure) of points where $p_*(f^* \mathcal{O}_{\mathbb{P}_S^1}(1))$ has rank at least $r + 1$ (where (p, f) is the universal family of \mathcal{G}^1). We define $W^r \subset \mathcal{Pic}^1$ as a scheme-theoretic image of G^r .

Definition 2.2. Let $f : X \rightarrow Y$ be a quasiprojective morphism of Noetherian schemes. The *exceptional locus* $\text{Exc}(f)$ is the complement to the union of points in X isolated in their fibers. $\text{Exc}(f)$ is closed ([G], Section 4.4.3).

Definition 2.3. An extremal ray R of a closed convex cone $\mathcal{C} \subset \mathbb{R}^s$ is called an *edge* if the vector space $R^\perp \subset (\mathbb{R}^s)^*$ (of linear forms that vanish on R) is generated by supporting hyperplanes for \mathcal{C} . This technical condition means that \mathcal{C} is “not rounded” at R .

Theorem 2.4. *The functor \mathcal{G}^1 is represented by $M_{0,n}$. The map*

$$v : M_{0,n} \simeq G^1 \rightarrow \text{Pic}^1$$

is birational. Its exceptional locus is G^2 . The map v induces an isomorphism

$$(2.4.1) \quad M_{0,n} \setminus G^2 \simeq v(M_{0,n} \setminus G^2) = W^1 \setminus W^2 \subset \text{Pic}^1.$$

Any irreducible component of G^2 is a divisor whose closure in $\bar{M}_{0,n}$ generates an edge of $\overline{\text{Eff}}(\bar{M}_{0,n})$. The closure of the pre-image of G^2 in $\bar{M}_{0,n+1}$ with respect to the forgetful map $M_{0,n+1} \rightarrow M_{0,n}$ is contracted by a birational morphism

$$(2.4.2) \quad \prod_{j=1}^d \pi_{\Gamma_j \cup \{n+1\}} : \bar{M}_{0,n+1} \rightarrow \prod_{j=1}^d \bar{M}_{0,\Gamma_j \cup \{n+1\}}.$$

All other exceptional divisors of this morphism belong to the boundary.

Remark 2.5. In the subsequent sections we will show that if a hypertree is irreducible, then G^2 is non-empty and irreducible. By definition, a point in G^2 can be obtained by mapping a hypertree curve to \mathbb{P}^2 and projecting its singular vertices from a point. The definition of the divisor D_Γ in the Introduction is stronger, but eventually we will show that $D_\Gamma = \bar{G}^2$.

Remark 2.6. If we consider collections Γ satisfying only the first two conditions in Definition 1.2 (i.e., the convexity and normality axioms may fail), one may similarly define hypertree curves and Brill–Noether loci. The map v may not be birational anymore, but parts of Theorem 2.10 still hold: the functor \mathcal{G}^1 is represented by $M_{0,n}$ and the exceptional locus of the map v is G^2 . In Section 3 we will give conditions under which the map v is birational onto its image (see Remark 3.3).

Proof of Theorem 2.4. We proceed in several steps.

2.7. Each datum $(\Sigma \rightarrow S, f : \Sigma \rightarrow \mathbb{P}_S^1) \in \mathcal{G}^1(S)$ gives rise to an isomorphism class of a flat family over S with reduced geometric fibers given by \mathbb{P}^1 and with n disjoint sections given by images of irreducible components of Σ^{sing} . This gives a natural transformation $\mathcal{G}^1 \rightarrow \mathcal{M}_{0,n}$ which is in fact a natural isomorphism: given a flat family of marked \mathbb{P}^1 's, we can just push-out d copies of \mathbb{P}_S^1 along sections in each Γ_i . This gives a flat family of hypertree curves over S with a map to \mathbb{P}_S^1 , i.e., a datum in $\mathcal{G}^1(S)$.

2.8. Next we define two auxiliary Brill–Noether loci, C^r and \tilde{G}^r . We call an effective Cartier divisor *admissible* if it does not contain singular points. On the level of geometric points,

$$C^r = \{\text{a curve } \Sigma, \text{ an admissible divisor } D \text{ on } \Sigma \text{ such that } \mathcal{O}(D) \in W^r\},$$

$$\tilde{G}^r = \{(L, V) \in G^r, \text{ an admissible } D \in |V|\}.$$

These loci fit in a natural commutative diagram of forgetful maps

$$\begin{array}{ccc} \tilde{\mathcal{G}}^r & \longrightarrow & \mathcal{C}^r \\ \downarrow & & \downarrow D \mapsto \mathcal{O}(D) \\ \mathcal{G}^r & \longrightarrow & \mathcal{W}^r. \end{array}$$

On a scheme-theoretic level, let Σ^{sm} be the smooth locus of the universal family $\Sigma \rightarrow \mathcal{M}_\Gamma$ with irreducible components $\Sigma_1^{\text{sm}}, \dots, \Sigma_d^{\text{sm}}$. Let

$$\mathcal{C}^0 = \Sigma_1^{\text{sm}} \times_{\mathcal{M}_\Gamma} \dots \times_{\mathcal{M}_\Gamma} \Sigma_d^{\text{sm}}$$

and let

$$u : \mathcal{C}^0 \rightarrow \mathcal{P}ic^1$$

be the Abel map that sends $(p_1, \dots, p_d) \in \mathcal{C}^0(S)$ to $\mathcal{O}_\Sigma(p_1 + \dots + p_d)$. The geometric fibers of u are open subsets of admissible divisors in complete linear systems on $\text{Pic}^1(\Sigma_k)$. Let

$$\mathcal{C}^r := u^{-1}(\mathcal{W}^r) \subset \mathcal{C}^0.$$

Finally, we define $\tilde{\mathcal{G}}^1$ as a functor schemes \rightarrow sets that sends S to the datum

$$(\Sigma \rightarrow S, f : \Sigma \rightarrow \mathbb{P}_S^1) \in \mathcal{G}^1(S)$$

and a section $s : S \rightarrow \mathbb{P}_S^1$ disjoint from the images of irreducible components of $\Sigma \setminus \Sigma^{\text{sm}}$. We define $\tilde{\mathcal{G}}^r$ as the preimage of \mathcal{G}^r for the forgetful map $\tilde{\mathcal{G}}^r \rightarrow \mathcal{G}^r$. We also have the natural transformation $\tilde{\mathcal{G}}^r \rightarrow \mathcal{C}^0$ that sends $(\Sigma \rightarrow S, f : \Sigma \rightarrow \mathbb{P}_S^1, s)$ to $f^{-1}(s(S))$. It factors through \mathcal{C}^r . The same argument as above shows that $\tilde{\mathcal{G}}^1$ is isomorphic to $\mathcal{M}_{0,n+1}$ and that \mathcal{C}^0 is isomorphic to $\prod_{j=1}^d \mathcal{M}_{0,\Gamma_j \cup \{n+1\}}$.

2.9. To summarize, we have the following commutative diagram,

$$\begin{array}{ccccc} \tilde{\mathcal{G}}^1 & \xrightarrow{V} & \mathcal{C}^1 & \longrightarrow & \mathcal{C}^0 \\ \parallel & \searrow & \searrow & & \parallel \xrightarrow{u} \\ \mathcal{M}_{0,n+1} & \xrightarrow{\prod_{j=1}^d \pi_{\Gamma_j \cup \{n+1\}}} & \mathcal{G}^1 & \xrightarrow{v} & \mathcal{W}^1 & \longrightarrow & \mathcal{P}ic^1 \\ \parallel & \parallel & \parallel & \parallel & \parallel & \parallel & \parallel \\ \mathcal{M}_{0,n+1} & \xrightarrow{\prod_{j=1}^d \pi_{\Gamma_j \cup \{n+1\}}} & \mathcal{M}_{0,n+1} & \xrightarrow{\prod_{j=1}^d \pi_{\Gamma_j}} & \mathcal{M}_{0,n+1} & \xrightarrow{\prod_{j=1}^d \pi_{\Gamma_j}} & \mathcal{P}ic^1 \\ \parallel & \parallel & \parallel & \parallel & \parallel & \parallel & \parallel \\ \mathcal{M}_{0,n} & \xrightarrow{\prod_{j=1}^d \pi_{\Gamma_j}} & \mathcal{M}_{0,n} & \xrightarrow{\prod_{j=1}^d \pi_{\Gamma_j}} & \mathcal{M}_{0,n} & \xrightarrow{\prod_{j=1}^d \pi_{\Gamma_j}} & \mathcal{M}_\Gamma \end{array}$$

where, for any subset $I \subset N$ with $|I| \geq 4$,

$$\pi_I : \overline{M}_{0,n} \rightarrow \overline{M}_{0,I}$$

is the morphism given by dropping the points of $N \setminus I$ (and stabilizing).

2.10. It is clear from the definition that the exceptional locus of v is exactly G^2 and that v is birational if and only if $G^1 \neq G^2$. This is equivalent to $\tilde{G}^1 \neq \tilde{G}^2$, which is equivalent to V being birational. This is proved in Theorem 3.2.

2.11. Finally, we note that \tilde{G}^2 is the preimage of G^2 . Since the closure of \tilde{G}^2 is in the exceptional locus of the regular morphism (2.4.2), Lemma 2.12 below shows that the closure of any irreducible component of G^2 in $\overline{M}_{0,n}$ is a divisor that generates an edge of $\overline{\text{Eff}}(\overline{M}_{0,n})$.

This finishes the proof of the theorem. \square

Lemma 2.12. *Consider the diagram of morphisms*

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ p \downarrow & & \\ Z & & \end{array}$$

of projective \mathbb{Q} -factorial varieties. Suppose that f is birational and that p is faithfully flat. Let D be an irreducible component of $\text{Exc}(f)$. If $p(D) \neq Z$ and a generic fiber of p along $p(D)$ is irreducible, then $p(D)$ is a divisor that generates an extremal ray (in fact an edge) of $\overline{\text{Eff}}(Z)$.

Proof. By van der Warden's purity theorem (see [GD], Section 21.12.12), D is a divisor. It is well known that it generates an edge of $\overline{\text{Eff}}(X)$. Since p is flat and $p(D) \neq Z$, $p(D)$ is an irreducible divisor. Since $p^{-1}(p(D))$ is irreducible (e.g. by [T], Lemma 2.6), $p^{-1}(p(D)) = D$. It follows that $p(D)$ generates an edge of $\overline{\text{Eff}}(Z)$ because $\overline{\text{Eff}}(Z)$ injects in $\overline{\text{Eff}}(X)$ by the pull-back p^* . \square

Remark 2.13. An interesting feature of this argument is that we study divisors $\overline{G}^2 \subset \overline{M}_{0,n}$ by pulling them to $\overline{M}_{0,n+1}$ and then contracting the preimage by a birational morphism. This gives a method of proving extremality of divisors by a flat base change. In Section 5 we will contract \overline{G}^2 by a contracting birational map (but not a morphism) from $\overline{M}_{0,n}$ to the compactified Jacobian of the stable hypertree curve Σ^s .

3. Capacity and products of linear projections

Definition 3.1. Let $\Gamma = \{\Gamma_\alpha\}$ be an arbitrary collection of subsets of the set $N = \{1, \dots, n\}$ such that each subset has at least three elements. We define its *capacity* as

$$\text{cap}(\Gamma) = \max_{\Gamma'} \left\{ \sum_{\beta} (|\Gamma'_\beta| - 2) \right\},$$

where Γ' runs through all sub-collections of Γ that satisfy the convexity axiom (\ddagger) . Here $\Gamma' = \{\Gamma'_\beta\}$ is a sub-collection of Γ if each Γ'_β is a subset of some Γ'_α . For example, if Γ is a hypertree, then

$$\text{cap}(\Gamma) = n - 2$$

by the convexity and normalization axioms.

Theorem 3.2. *Let $\Gamma = \{\Gamma_\alpha\}$ be an arbitrary collection of subsets of the set $N = \{1, \dots, n\}$ such that each subset has at least three elements and $\Gamma_\alpha \not\subset \Gamma_\beta$ if $\alpha \neq \beta$. The capacity of Γ is equal to the dimension of the image of the map*

$$(3.2.1) \quad \pi_{\Gamma \cup \{n+1\}} := \prod_{j=1}^d \pi_{\Gamma_j \cup \{n+1\}} : \overline{M}_{0, n+1} \rightarrow \prod_{j=1}^d \overline{M}_{0, \Gamma_j \cup \{n+1\}}.$$

Moreover, $\pi_{\Gamma \cup \{n+1\}}$ is birational onto its image if and only if Γ has maximum capacity $n - 2$. In particular, $\pi_{\Gamma \cup \{n+1\}}$ is birational onto its image if and only if Γ satisfies (\ddagger) and (\dagger) .

Remark 3.3. Let Γ be an arbitrary collection of subsets of the set $N = \{1, \dots, n\}$, satisfying the first two conditions in Definition 1.2 (see Remark 2.6). If Γ has maximum capacity $n - 2$, by Theorem 3.2 the map $\pi_{\Gamma \cup \{n+1\}}$ is birational onto its image and it follows that G^2 is a proper subset of G^1 .

To prove Theorem 3.2, we need two lemmas on linear projections.

Definition 3.4. For a projective subspace $U \subset \mathbb{P}^r$, let

$$\pi_U : \mathbb{P}^r \dashrightarrow \mathbb{P}^{l(U)}$$

be a linear projection from U , where $l(U) = \text{codim } U - 1$.

Lemma 3.5. *Let $U_1, \dots, U_s \subset \mathbb{P}^r$ be subspaces such that $U_i \not\subset U_j$ when $i \neq j$. Then:*

(a) *the rational map*

$$\pi = \pi_{U_1} \times \dots \times \pi_{U_s} : \mathbb{P}^r \dashrightarrow \mathbb{P}^{l(U_1)} \times \dots \times \mathbb{P}^{l(U_s)}$$

is dominant if and only if

$$(3.5.1) \quad l\left(\bigcap_{i \in S} U_i\right) \geq \sum_{i \in S} l(U_i) \quad \text{for any } S \subset \{1, \dots, s\}.$$

(b) *If $r = l(U_1) + \dots + l(U_s)$ and π is dominant, then π is birational.*

Proof. Let $l_i := l(U_i)$. The scheme-theoretic fibers of the morphism

$$\mathbb{P}^r \setminus \bigcup_i U_i \rightarrow \mathbb{P}^{l_1} \times \dots \times \mathbb{P}^{l_s}$$

are open subsets of projective subspaces. This implies (b). Now assume that π is dominant but (3.5.1) is not satisfied, for example we may assume that $W = U_1 \cap \cdots \cap U_m$ has dimension

$$(3.5.2) \quad w \geq r - (l_1 + \cdots + l_m).$$

The projections π_{U_i} for $i = 1, \dots, m$ factor through the projection $\pi_W : \mathbb{P}^r \dashrightarrow \mathbb{P}^{r-w-1}$. It follows that the map

$$\pi' = \pi_{U_1} \times \cdots \times \pi_{U_m} : \mathbb{P}^r \dashrightarrow \mathbb{P}^{l_1} \times \cdots \times \mathbb{P}^{l_m}$$

factors through π_W . If π is dominant, then so is π' , and therefore the induced map

$$\mathbb{P}^{r-w-1} \dashrightarrow \mathbb{P}^{l_1} \times \cdots \times \mathbb{P}^{l_m}$$

is dominant, which contradicts (3.5.2).

Assume (3.5.1). We will show that π is dominant. We argue by induction on r . Let H be a general hyperplane containing U_s . It suffices to prove that the restriction of $\pi_{U_1} \times \cdots \times \pi_{U_{s-1}}$ to H is dominant. The subspaces $U'_i := U_i \cap H$ have codimension $l_i + 1$ in H and, therefore, by the induction assumption, it suffices to prove that

$$(3.5.3) \quad \dim \bigcap_{i \in S} U'_i < (r-1) - \sum_{i \in S} l_i \quad \text{for any } S \subset \{1, \dots, r-1\}.$$

Let $W := \bigcap_{i \in S} U_i$. Let $L := \sum_{i \in S} l_i$. By (3.5.1), $\dim W < r - L$ and, therefore,

$$\dim H \cap W < r - L - 1$$

(i.e., we have (3.5.3)) unless $W \subset U_s$. But in the latter case

$$\dim \bigcap_{i \in S} U'_i = \dim(U_s \cap W) < r - (l_s + L)$$

by (3.5.1). \square

We would like to work out the case when all subspaces U_1, \dots, U_s are intersections of subspaces spanned by subsets of points $p_1, \dots, p_n \in \mathbb{P}^{n-2}$ in linearly general position. Let $N = \{1, \dots, n\}$. For any non-empty subset $I \subset N$, let $H_I = \langle p_i \rangle_{i \notin I}$.

Lemma 3.6. *The rational map*

$$\pi = \pi_{H_{\Gamma_1}} \times \cdots \times \pi_{H_{\Gamma_l}} : \mathbb{P}^{n-2} \dashrightarrow \mathbb{P}^{|\Gamma_1|-2} \times \cdots \times \mathbb{P}^{|\Gamma_l|-2}$$

is dominant if and only if (\ddagger) holds. It is birational if and only if (\ddagger) and (\dagger) hold.

Proof. For any $S \subset \{1, \dots, l\}$, let e_S be the number of connected components of N (with respect to $\{\Gamma_i\}_{i \in S}$) that have at least two elements. Let

$$\mathcal{H}_S = \bigcap_{i \in S} H_{\Gamma_i}.$$

Let $W \subset \mathbb{A}_{x_1, \dots, x_n}^n$ be a hyperplane $\sum x_i = 0$. In appropriate coordinates, $\mathbb{P}(W)$ is a projective space dual to \mathbb{P}^{n-2} and subspaces $H_I \subset \mathbb{P}^{n-2}$ are projectively dual to projectivizations of linear subspaces $\langle x_i - x_j \rangle_{i, j \in I}$. It follows that \mathcal{H}_S is projectively dual to a subspace $\langle e_i - e_j \rangle_{\exists k \in S: i, j \in \Gamma_k}$, which implies that

$$l(\mathcal{H}_S) = \left| \bigcup_{i \in S} \Gamma_i \right| - e_S - 1.$$

By Lemma 3.5, it follows that π is dominant if and only if

$$(3.6.1) \quad \left| \bigcup_{i \in S} \Gamma_i \right| - e_S - 1 \geq \sum_{i \in S} (|\Gamma_i| - 2) \quad \text{for any } S \subset \{1, \dots, l\}.$$

It remains to check that (3.6.1) and (\ddagger) are equivalent. It is clear that (3.6.1) implies (\ddagger) . Now assume (\ddagger) . Let I_1, \dots, I_{e_S} be the connected components of N (with respect to $\{\Gamma_i\}_{i \in S}$) that have at least two elements. This gives a partition $S = S_1 \sqcup \dots \sqcup S_{e_S}$ such that $I_k = \bigcup_{j \in S_k} \Gamma_j$ for any k . Applying (\ddagger) for each S_k gives

$$\left| \bigcup_{i \in S} \Gamma_i \right| - e_S - 1 \geq \sum_k \left(\left| \bigcup_{i \in S_k} \Gamma_i \right| - 2 \right) \geq \sum_k \sum_{i \in S_k} (|\Gamma_i| - 2) = \sum_{i \in S} (|\Gamma_i| - 2)$$

and this is nothing but (3.6.1). \square

Proof of Theorem 3.2. Let $p_1, \dots, p_n \in \mathbb{P}^{n-2}$ be general points. We have a birational morphism

$$\Psi : \bar{M}_{0, n+1} \rightarrow \mathbb{P}^{n-2}$$

(the Kapranov blow-up model), which is an iterated blow-up of \mathbb{P}^{n-2} along the points p_1, \dots, p_n , the proper transforms of lines connecting these points, and so on. Moreover, we have a commutative diagram of rational maps

$$\begin{array}{ccc} \bar{M}_{0, n+1} & \xrightarrow{\Psi} & \mathbb{P}^{n-2} \\ \pi_{S \cup \{n+1\}} \downarrow & & \downarrow p_S \\ \bar{M}_{0, k+1} & \xrightarrow{\Psi} & \mathbb{P}^{k-2} \end{array}$$

for each subset $S \subset N$ with k elements, where p_S is a linear projection away from the linear span of points p_i for $i \notin S$, see [K]. It follows that the “moreover” part of the theorem is just a reformulation of Lemma 3.6.

Let

$$Z \subset \bar{M}_{\Gamma \cup \{n+1\}} := \prod_{j=1}^d \bar{M}_{0, \Gamma_j \cup \{n+1\}}$$

be the image of $\pi_{\Gamma \cup \{n+1\}}$. Notice that $\pi_{\Gamma' \cup \{n+1\}}$ factors through $\pi_{\Gamma \cup \{n+1\}}$ for any sub-collection Γ' . So it follows from Lemma 3.6 that

$$\dim Z \geq \text{cap}(\Gamma)$$

and that, to prove an opposite inequality, it suffices to show the following. Suppose that $Z \neq \bar{M}_{\Gamma \cup \{n+1\}}$. We claim that one can choose a proper sub-collection Γ' such that $\dim p(Z) = \dim Z$, where

$$p : \bar{M}_{\Gamma \cup \{n+1\}} \rightarrow \bar{M}_{\Gamma' \cup \{n+1\}}$$

is an obvious projection. Consider all possible maximal sub-collections, i.e., let J be an indexing set obtained by taking $|\Gamma_\alpha|$ for each Γ_α . For each $j \in J$, let Γ'_j be a sub-collection obtained by removing the corresponding index from the corresponding Γ_α . Let $z \in Z$ be a general smooth point. Notice that z projects into $M_{0, \Gamma_\alpha \cup \{n+1\}}$ for each α , and so for each $j \in J$, the fiber of $p_j : \bar{M}_{\Gamma \cup \{n+1\}} \rightarrow \bar{M}_{\Gamma'_j \cup \{n+1\}}$ passing through z is a smooth rational curve. Moreover, it is easy to see that tangent vectors to these rational curves at z generate the tangent space to $\bar{M}_{\Gamma \cup \{n+1\}}$ at z . Since Z is smooth at z , it follows that $p_j|_Z$ is generically finite for one of the projections. \square

We have to refine Theorem 3.2 to see how the map

$$(3.6.2) \quad \pi : \bar{M}_{0, n+1} \rightarrow \bar{M}_{\Gamma \cup \{n+1\}} := \prod_{\Gamma_\alpha} \bar{M}_{0, \Gamma_\alpha \cup \{n+1\}}$$

affects the divisors of $\bar{M}_{0, n+1}$. We borrow a definition from matroid theory.

Definition 3.7. Let $I \subset N$ be any subset. We define the *contracted collection* Γ_I to be the collection of subsets of $I \cup \{p\}$ obtained from Γ by replacing all the indices in I^c with p (and removing all subsets with less than three elements). We define the *restricted collection* Γ'_I to be the collection of subsets in I^c given by intersecting each Γ_α with I^c (and removing subsets with less than three elements).

Lemma 3.8. For any hypertree Γ we have

$$\text{codim } \pi(\delta_{I \cup \{n+1\}}) - 1 = n - 3 - \text{cap}(\Gamma_I) - \text{cap}(\Gamma'_I).$$

Proof. For $I \subset N$, consider the products of forgetful maps

$$\begin{aligned} \pi_I : \bar{M}_{0, I \cup \{p, n+1\}} &\rightarrow \prod_{\Gamma_\alpha \subset I} \bar{M}_{0, \Gamma_\alpha \cup \{n+1\}} \times \prod_{\Gamma_\alpha \cap I^c \neq \emptyset, |\Gamma_\alpha \cap I| \geq 2} \bar{M}_{0, (\Gamma_\alpha \cap I) \cup \{p, n+1\}}, \\ \pi'_I : \bar{M}_{0, I^c \cup \{p\}} &\rightarrow \prod_{|\Gamma_\alpha \cap I^c| \geq 3} \bar{M}_{0, (\Gamma_\alpha \cap I^c) \cup \{p\}}, \end{aligned}$$

By Theorem 3.2, we have

$$\dim \text{Im}(\pi_I) = \text{cap}(\Gamma_I) \quad \text{and} \quad \dim \text{Im}(\pi'_I) = \text{cap}(\Gamma'_I).$$

Note that

$$\delta_{I \cup \{n+1\}} \simeq \bar{M}_{0, I \cup \{p, n+1\}} \times \bar{M}_{0, I^c \cup \{p\}}$$

and the restriction of the map π to $\delta_{I \cup \{n+1\}}$ factors as the product $\pi_I \times \pi'_I$ followed by a closed embedding. \square

Lemma 3.9. *Let Γ be an irreducible hypertree and let $I \subset N$ be a subset such that $2 \leq |I| \leq n - 2$ and either $I^c \subseteq \Gamma_\beta$ for some β , or $|I^c| = 2$. Then*

$$\text{cap}(\Gamma_I) = |I \cup \{p\}| - 2.$$

Proof. We construct a sub-collection Γ' of Γ_I that satisfies the convexity axiom and $\sum_{\alpha} (|\Gamma'_{\alpha}| - 2) = |I| - 1$. Without loss of generality, we may assume $I^c = \{1, \dots, l\}$. We define Γ' as follows:

(i) If $I^c \subseteq \Gamma_\beta$, let $\Gamma' = \Gamma_I$.

(ii) If $I^c = \Gamma_\beta$ or if $|I^c| = l = 2$ and $I^c \not\subseteq \Gamma_\alpha$ for any α : we may assume that $1 \in \Gamma_1$ (note that $\Gamma_1 \cap I^c = \{1\}$). Let $\Gamma'_1 = \Gamma_1 \setminus \{1\}$ if $|\Gamma_1| \geq 4$ (omit Γ'_1 otherwise), $\Gamma'_\alpha = (\Gamma_I)_\alpha$ for all $\alpha \neq 1$.

Note that in all the cases $\sum_{\alpha} (|\Gamma'_{\alpha}| - 2) = |I| - 1$. Hence, the condition (\ddagger) holds for the set of all indices α that appear in Γ' . Assume that (\ddagger) fails for a proper subset T of indices α :

$$(3.9.1) \quad \left| \bigcup_{\alpha \in T} \Gamma'_{\alpha} \right| \leq \sum_{\alpha \in T} (|\Gamma'_{\alpha}| - 2) + 1 \leq \sum_{\alpha \in T} (|\Gamma_{\alpha}| - 2) + 1.$$

Let $k = \left| \left(\bigcup_{\alpha \in T} \Gamma_{\alpha} \right) \cap I^c \right| \leq l$. Then we have

$$(3.9.2) \quad \left| \bigcup_{\alpha \in T} \Gamma'_{\alpha} \right| \geq \left| \bigcup_{\alpha \in T} \Gamma_{\alpha} \right| - k + 1.$$

Since Γ is an irreducible hypertree, we have

$$(3.9.3) \quad \left| \bigcup_{\alpha \in T} \Gamma_{\alpha} \right| \geq \sum_{\alpha \in T} (|\Gamma_{\alpha}| - 2) + 3.$$

By (3.9.1), (3.9.2), (3.9.3) we have $k \geq 3$. This is a contradiction if $|I^c| = 2$.

Assume now that $I^c \subset \Gamma_\beta$. Let $k' = \left| \left(\bigcup_{\alpha \in T} \Gamma_{\alpha} \right) \cap \Gamma_\beta \right|$. Then $k \leq k'$. Consider the case when $\beta \notin T$. Since Γ is an irreducible hypertree, we have:

$$(3.9.4) \quad \left| \bigcup_{\alpha \in T} \Gamma_{\alpha} \right| + |\Gamma_\beta| - k' = \left| \bigcup_{\alpha \in T} \Gamma_{\alpha} \cup \Gamma_\beta \right| \geq \sum_{\alpha \in T} (|\Gamma_{\alpha}| - 2) + (|\Gamma_\beta| - 2) + 3.$$

By (3.9.1), (3.9.2), (3.9.4) it follows that

$$\sum_{\alpha \in T} (|\Gamma_{\alpha}| - 2) + 1 \geq \sum_{\alpha \in T} (|\Gamma_{\alpha}| - 2) + k' - k + 2,$$

which is a contradiction, since $k' - k \geq 0$.

Consider the case when $\beta \in T$ (only possible in case (i)). As (\ddagger) fails,

$$(3.9.5) \quad \left| \bigcup_{\alpha \in T} \Gamma'_\alpha \right| \leq \sum_{\alpha \in T} (|\Gamma_\alpha| - 2) + 1 \leq \sum_{\alpha \in T, \alpha \neq \beta} (|\Gamma_\alpha| - 2) + (|\Gamma_\beta| - l - 1) + 1.$$

It follows from (3.9.5), (3.9.2), (3.9.3) that

$$\sum_{\alpha \in T} (|\Gamma_\alpha| - 2) - l + 2 \geq \sum_{\alpha \in T} (|\Gamma_\alpha| - 2) - l + 4,$$

which is a contradiction. This finishes the proof. \square

Lemma 3.10. *For any hypertree Γ (not necessarily irreducible), the collection Γ'_l satisfies the convexity axiom (\ddagger) . In particular,*

$$(3.10.1) \quad \text{cap}(\Gamma'_l) = \sum_{|\Gamma_\alpha \cap I^c| \geq 3} (|\Gamma_\alpha \cap I^c| - 2).$$

If moreover, Γ is an irreducible hypertree and if $|I^c| = 2$ or if $I^c \subseteq \Gamma_\alpha$ for some α , then $\text{cap}(\Gamma'_l) = |I^c| - 2$. Otherwise,

$$\text{cap}(\Gamma'_l) < |I^c| - 2.$$

Proof. Arguing by contradiction, let $S \subset \Gamma'_l$ be a subset such that

$$\left| \bigcup_{j \in S} (\Gamma'_l)_j \right| - 2 < \sum_{j \in S} (|(\Gamma'_l)_j| - 2).$$

Let $I_l = \{1, \dots, l\}$. After renumbering, we can assume that $I = I_k$. Since $\Gamma'_{l_0} = \Gamma'_0 = \Gamma$, which satisfies (\ddagger) , there exists l such that

$$(3.10.2) \quad \left| \bigcup_{j \in S} (\Gamma'_{l_l})_j \right| - 2 \geq \sum_{j \in S} (|(\Gamma'_{l_l})_j| - 2)$$

but

$$(3.10.3) \quad \left| \bigcup_{j \in S} (\Gamma'_{l_{l+1}})_j \right| - 2 < \sum_{j \in S} (|(\Gamma'_{l_{l+1}})_j| - 2).$$

It follows that some subsets $(\Gamma'_{l_l})_j$ contain $l + 1$, and so the left-hand side in (3.10.3) is equal to the left-hand side in (3.10.2) minus 1. However, the right-hand side in (3.10.3) is equal to the right-hand side in (3.10.2) minus the number of subsets $(\Gamma'_{l_l})_j$ that contain $l + 1$. This is a contradiction. This proves that Γ'_l satisfies the convexity axiom (\ddagger) .

Clearly, if $|I^c| = 2$ or if $I^c \subseteq \Gamma_\alpha$ for some α , then $\text{cap}(\Gamma'_l) = |I^c| - 2$. Assume now that $|I^c| > 2$ and $I^c \not\subseteq \Gamma_\alpha$ for any α . We argue by contradiction: assume that $|I^c| - 2 = \text{cap}(\Gamma'_l)$. If $|\Gamma'_l| = 0$, then it follows that $|I^c| = 2$. Similarly, if $|\Gamma'_l| = 1$, it follows that $I^c \subset \Gamma_\alpha$, for the unique α giving Γ'_l . Hence, we can assume that $|\Gamma'_l| > 1$.

If $|\mathcal{S}| \neq 0, 1, d$, the same proof as above shows that we have

$$\left| \bigcup_{j \in \mathcal{S}} (\Gamma'_I)_j \right| - 2 > \sum_{j \in \mathcal{S}} (|(\Gamma'_I)_j| - 2).$$

Hence, if $|\Gamma'_I| \neq d$, then $\text{cap}(\Gamma'_I) < |I^c| - 2$.

Assume now that $|\Gamma'_I| = d$. We have

$$|I^c| - 2 = \text{cap}(\Gamma'_I) = \sum_{\alpha=1}^d (|\Gamma_\alpha \cap I^c| - 2).$$

It follows that

$$|I| = \sum_{\alpha=1}^d (|\Gamma_\alpha \cap I|).$$

It follows that the subsets $\Gamma_\alpha \cap I$, for all α , are disjoint. This is a contradiction since every $i \in I$ belongs to at least two subsets Γ_α . \square

Lemma 3.11. *The following conditions are equivalent:*

- *A boundary divisor $\delta_{I \cup \{n+1\}}$ is not contracted by π .*
- $n - 3 = \text{cap}(\Gamma_I) + \text{cap}(\Gamma'_I)$.
- $|I^c| = 2$ or $I^c \subset \Gamma_\alpha$ for some α .

Proof. The equivalence of the first two conditions follows from Lemma 3.8.

If $|I^c| = 2$ or $I^c \subset \Gamma_\alpha$ for some α , then $\text{cap}(\Gamma_I) = |I| - 1$ by Lemma 3.9 and $\text{cap}(\Gamma'_I) = |I^c| - 2$ by Lemma 3.10. It follows that $\text{codim } \pi(\delta_{I \cup \{n+1\}}) = 1$ by Lemma 3.8.

Assume that $|I^c| > 2$ and $I^c \not\subseteq \Gamma_\alpha$ for any α . Then $\text{cap}(\Gamma'_I) < |I^c| - 2$ by Lemma 3.10. Since $\text{cap}(\Gamma_I) \leq |I| - 1$, it follows by Lemma 3.8 that $\text{codim } \pi(\delta_{I \cup \{n+1\}}) > 1$. \square

4. Irreducibility of D_Γ and its class

In this section we define D_Γ as the closure of $G^2 \subset M_{0,n}$ in $\overline{M}_{0,n}$. We will show in Section 6 that this coincides with a stronger definition of D_Γ given in the Introduction. Rather than computing the class of D_Γ directly, we (partially) compute the class of its pull-back $\pi_N^* D_\Gamma$, where $\pi_N : \overline{M}_{0,n+1} \rightarrow \overline{M}_{0,n}$ is the forgetful map. We will use the fact that $\pi_N^* D_\Gamma$ is one of the divisors in the exceptional locus of the map π of (3.6.2) with other possible exceptional divisors all listed in Lemma 3.11.

Notation 4.1. One advantage of $\overline{M}_{0,n+1}$ over $\overline{M}_{0,n}$ is that $\text{Pic } \overline{M}_{0,n+1}$ has an equivariant basis with respect to permutations of the first n indices. Let $\Psi : \overline{M}_{0,n+1} \rightarrow \mathbb{P}^{n-2}$ be the

Kapranov iterated blow-up of \mathbb{P}^{n-2} along points p_1, \dots, p_n and proper transforms of subspaces $\langle p_i \rangle_{i \in I}$ for $|I| \leq n-3$. Let E_I be the exceptional divisor over this subspace. Recall that $\text{Pic } \bar{M}_{0,n+1}$ is freely generated by $H := \Psi^* \mathcal{O}(1)$ and by the classes E_I .

We denote as usual by v_i the valence of $i \in N$.

Theorem 4.2. *Let $\Gamma = \{\Gamma_1, \dots, \Gamma_d\}$ be an irreducible hypertree on N . Then D_Γ is non-empty, irreducible, and $v(D_\Gamma) = W^2 \subset \text{Pic}^1$ has codimension 3. We have*

$$\pi_N^* D_\Gamma \sim (d-1)H - \sum_{\substack{I \subset N \\ 1 \leq |I| \leq n-3}} m_I E_I,$$

where

$$(4.2.1) \quad m_I \geq |I| - 1 + |\{\Gamma_\alpha \mid \Gamma_\alpha \subset I^c\}| - \text{cap}(\Gamma_I),$$

$$(4.2.2) \quad m_{\{i\}} = d - v_i,$$

$$(4.2.3) \quad m_{N \setminus \Gamma_\alpha} = 1,$$

$$(4.2.4) \quad m_{\Gamma_\alpha} = d + |\Gamma_\alpha| - \sum_{i \in \Gamma_\alpha} v_i.$$

If I is properly contained in Γ_α , then

$$(4.2.5) \quad m_{N \setminus I} = 0,$$

$$(4.2.6) \quad m_I = d + |I| - 1 - \sum_{i \in I} v_i.$$

Proof. By Theorem 3.2, the map π of (3.6.2) is a birational morphism. By Theorem 2.4, its exceptional locus consists of $\mathcal{E} := \pi_N^* D_\Gamma$ and the boundary divisors $\delta_{I \cup \{n+1\}}$ contracted by π (where $I \subset N$, $1 \leq |I| \leq n-2$).

Lemma 4.3. *D_Γ is non-empty and irreducible.*

Proof. It suffices to show that $\pi_N^* D_\Gamma$ is non-empty and irreducible. We compare ranks of the Neron–Severi groups and use the fact that

$$\rho(\bar{M}_{0,n+1}) - \rho\left(\prod_{\Gamma_\alpha} \bar{M}_{0,\Gamma_\alpha \cup \{n+1\}}\right)$$

is equal to the number of irreducible components in $\text{Exc}(\pi)$. We have

$$\rho(\bar{M}_{0,n+1}) = 2^n - 1 - \frac{n(n+1)}{2}$$

and

$$\rho\left(\prod_{\Gamma_\alpha} \bar{M}_{0,\Gamma_\alpha \cup \{n+1\}}\right) = \sum_{\alpha=1}^d \left(2^{|\Gamma_\alpha|} - 1 - \frac{|\Gamma_\alpha|(|\Gamma_\alpha| + 1)}{2}\right).$$

The total number of boundary divisors of $\bar{M}_{0,n+1}$ is $2^n - n - 2$. By Lemma 3.11, the number of boundary components *not* contracted by π is

$$\frac{n(n-1)}{2} + \sum_{\alpha=1}^d \left(2^{|\Gamma_\alpha|} - 1 - |\Gamma_\alpha| - \frac{|\Gamma_\alpha|(|\Gamma_\alpha| - 1)}{2} \right).$$

It follows after some simple manipulations that the number of irreducible components of \mathcal{E} is exactly one. \square

4.4. Next we compare the canonical classes. We have

$$(4.4.1) \quad K_{\bar{M}_{0,n+1}} - \pi^* K_{\bar{M}_{\Gamma \cup \{n+1\}}} = c\mathcal{E} + \sum_{\delta_{I \cup \{n+1\}} \in \text{Exc}(\pi)} a_I \delta_{I \cup \{n+1\}} = c\mathcal{E} + \sum_{\substack{I \subset N \\ 1 \leq |I| \leq n-3}} a_I E_I,$$

for some positive integers a_I and c , see [KoM], p. 53. Here we use the fact that if $|I| = n - 2$, then $\delta_{I \cup \{n+1\}}$ is not an exceptional divisor in the Kapranov model, but a proper transform of the hyperplane in \mathbb{P}^{n-2} that passes through all p_i , $i \in I$. These divisors are not in $\text{Exc}(\pi)$ by Lemma 3.11.

4.5. We use the following basic property of discrepancies:

$$c \geq \text{codim } \pi(\mathcal{E}) - 1 \quad \text{and} \quad a_I \geq \text{codim } \pi(\delta_{I \cup \{n+1\}}) - 1.$$

By Lemma 3.8, it follows that

$$(4.5.1) \quad a_I \geq n - 3 - \text{cap}(\Gamma_I) - \text{cap}(\Gamma'_I).$$

4.6. Next we compute the canonical classes. Standard calculations give

$$K_{\bar{M}_{0,n+1}} = -(n-1)H + \sum_I (n-2-|I|)E_I$$

and

$$\begin{aligned} \pi_{\Gamma_\alpha \cup \{n+1\}}^* K_{\bar{M}_{\Gamma_\alpha \cup \{n+1\}}} &= -(|\Gamma_\alpha| - 1) \left(H - \sum_{I \cap \Gamma_\alpha = \emptyset} E_I \right) \\ &+ \sum_{\substack{I' \subset \Gamma_\alpha \\ 1 \leq |I'| \leq |\Gamma_\alpha| - 3}} (|\Gamma_\alpha| - 2 - |I'|) \sum_{I'' \subset N \setminus \Gamma_\alpha} E_{I' \cup I''}. \end{aligned}$$

Combining these formulas together gives

$$m_I \geq |I| - 1 - \text{cap}(\Gamma_I) - \text{cap}(\Gamma'_I) + \sum_{I \cap \Gamma_\alpha = \emptyset} (|\Gamma_\alpha| - 1) + \sum_{1 \leq |\Gamma_\alpha \cap I| \leq |\Gamma_\alpha| - 3} (|\Gamma_\alpha| - 2 - |\Gamma_\alpha \cap I|).$$

This formula along with (3.10.1) imply formula (4.2.1).

Lemma 4.7. *Formulas (4.2.2)–(4.2.6) hold.*

Proof. Using (4.2.1) it is easy to see that the left-hand side of any of these formulas is greater than or equal to the right-hand side.

Since the boundary divisors $\delta_{N \cup \{n+1\} \setminus \Gamma_\alpha}$ and $\delta_{N \cup \{n+1\} \setminus I}$ are not in the exceptional locus of π , formulas (4.2.3) and (4.2.5) follow from (4.4.1) and from the calculations of the canonical classes above.

By the projection formula, $\pi_N^* D_\Gamma \cdot C = 0$ for any curve C in the fiber of π_N . Let C be a general fiber. Then $\Psi(C)$ is a rational normal curve in \mathbb{P}^{n-2} , and therefore $H \cdot C = n - 2$. We have $E_i \cdot C = \delta_{i,n+1} \cdot C = 1$ and any other boundary divisor E_I intersects C trivially. It follows that

$$\begin{aligned} 0 &= \pi_N^* D_\Gamma \cdot C = (n-2)(d-1) - \sum_{i=1}^n m_i \leq (n-2)(d-1) - \sum_{i=1}^n (d-v_i) \\ &= (n-2)(d-1) - nd + \sum_{i=1}^n v_i = (n-2)(d-1) - nd + (n-2) + 2d = 0. \end{aligned}$$

It follows that $m_i = d - v_i$ for any i .

Now let C be the curve in the fiber of π_N over a general point in δ_{Γ_α} such that the $(n+1)$ -st marked point moves along the component with points marked by $I \subset \Gamma_\alpha$. Then $H \cdot C = |I| - 1$, $\delta_{i,n+1} \cdot C = 1$ if $i \in I$ and 0 otherwise,

$$\delta_{I \cup \{n+1\}} \cdot C = -1, \quad \delta_{N \cup \{n+1\} \setminus I} \cdot C = 1,$$

and other boundary divisors intersect C trivially. Since we already know that $m_i = d - v_i$ by the above, and that $m_{N \setminus I} = 1$ (if $I = \Gamma_\alpha$) and 0 otherwise by (4.2.3) and (4.2.5), a simple calculation gives m_I . \square

Finally, we claim that

$$c = 1, \quad \text{codim } \pi(\mathcal{E}) = 2, \quad \text{and} \quad \text{codim } v(D_\Gamma) = 3.$$

Indeed, c obviously divides all coefficients m_I but some of them are equal to 1 by (4.2.3). So $c = 1$. Since \mathcal{E} is exceptional and $c \geq \text{codim } \pi(\mathcal{E}) - 1$, we have $\text{codim } \pi(\mathcal{E}) = 2$. It follows by Theorem 2.4 that the map $\mathcal{E} \rightarrow \pi(\mathcal{E})$ is generically a \mathbb{P}^1 -bundle, i.e., $W_2 \neq W_3$. Since $G^2 \rightarrow W^2$ has 2-dimensional fibers outside of W^3 , we have the formula $\text{codim } v(D_\Gamma) = 3$. \square

The reader is perhaps disappointed that we do not give a closed formula for the class of a hypertree divisor D_Γ . The difficulty in computing this class stems from the fact that π has (exponentially) many exceptional boundary divisors and the discrepancy of a boundary divisor $\delta_I \subset \overline{M}_{0,n+1}$ for the map π (3.6.2) is not always equal to $\text{codim } \pi(\delta_I) - 1$. However, there is one case when they are equal, namely when $\text{codim } \pi(\delta_I) = 2$. This happens quite often: see for example Lemma 7.12, which is used in Theorem 7.7 to recover the hypertree from its class.

Definition 4.8. A triple $\{i, j, k\} \subset N$ is called a *wheel* of an irreducible hypertree Γ if it is not contained in any hyperedge, but there are hyperedges $\Gamma_{\alpha_1}, \Gamma_{\alpha_2}, \Gamma_{\alpha_3}$ of Γ such that $\{i, j\} \subset \Gamma_{\alpha_1}, \{j, k\} \subset \Gamma_{\alpha_2}, \{i, k\} \subset \Gamma_{\alpha_3}$.

Lemma 4.9. *Suppose Γ contains only triples, with $\{i, j, k\}$ not one of them and not a wheel, with the property that*

$$\text{cap}(\Gamma_{N \setminus \{i, j, k\}}) = n - 4$$

(which is equivalent to $\text{codim } \pi(\delta_{ijk}) = 2$). Then we have equality in (4.2.1).

Proof. We know that $\text{codim } \pi(\delta_{ijk}) = 2$ and we are claiming that the discrepancy of π at δ_{ijk} is equal to 1. It will be enough to show that no other divisor of $\bar{M}_{0, n+1}$ has the same image as δ_{ijk} under π . Indeed, then we can cut by hypersurfaces in a very ample linear system on the target of π to reduce the discrepancy calculation to the case of a birational morphism of smooth surfaces with a unique exceptional divisor over a point, in which case the discrepancy is equal to 1 by standard factorization results for birational morphisms of smooth surfaces [Ha], Section 5.3.

We write $a \leftrightarrow b$ if vertices $a, b \in N$ belong to some Γ_α . Up to symmetries, there are three possible cases:

(X) $i \leftrightarrow j$ and $j \leftrightarrow k$.

(Y) $i \leftrightarrow j$ but $i \not\leftrightarrow k$ and $j \not\leftrightarrow k$.

(Z) $i \not\leftrightarrow j, j \not\leftrightarrow k$, and $i \not\leftrightarrow k$.

Notice that $\pi(\delta_{ijk})$ belongs to the boundary $\bar{M}_{\Gamma \cup \{n+1\}} \setminus M_{\Gamma \cup \{n+1\}}$ in cases (X) and (Y). So in these cases $\pi(\delta_{ijk})$ cannot be equal to $\pi(\mathcal{E})$, where $\mathcal{E} = \pi_N^*(D_\Gamma)$ is the only exceptional divisor of π intersecting the interior $M_{0, n+1}$. In case (Z), the image of δ_{ijk} intersects the interior M_Γ , but we claim that in this case $\pi(\delta_{ijk}) \neq \pi(\mathcal{E})$ as well. Arguing by contradiction, suppose $\pi(\delta_{ijk}) = \pi(\mathcal{E})$. Notice that the rational map $v : \bar{M}_{0, n} \dashrightarrow \mathbb{G}_m^{n-3}$ of Theorem 2.4 is defined at the generic point of $\delta_{ijk} \subset \bar{M}_{0, n}$ in case (Z): just take a map $\Sigma \rightarrow \mathbb{P}^1$ that collapses points i, j, k to the same point and pull-back $\mathcal{O}_{\mathbb{P}^1}(1)$ (a similar analysis will be given below, see Lemma 4.10). Since $W^2 \subset \mathbb{G}_m^{n-3}$ has codimension 3, a generic line bundle in W^2 has $h^0 = 3$ (see Theorem 4.2). Passing to an open subset in $\bar{M}_{0, n}$ containing the generic point of δ_{ijk} , we have that $v(\delta_{ijk}) = W^2$. But this implies that, in a planar realization that corresponds to a generic line bundle in W^2 , points i, j, k are collinear. We will show in Theorem 6.1 that this is not the case.

So it remains to check the statement for boundary divisors only, i.e., to show that if $\pi(\delta_{ijk}) = \pi(\delta_I)$ and $n + 1 \notin I$, then $I = \{i, j, k\}$. Let $\Gamma' \subset \Gamma$ be a subset of all triples other than the triple containing $\{i, j\}$ (in cases (X) and (Y)) and the triple containing $\{j, k\}$ (in case (X)). Consider the morphism

$$\pi' : \bar{M}_{0, n+1} \rightarrow \bar{M}_{\Gamma' \cup \{n+1\}} := \prod_{\Gamma_\alpha \in \Gamma'} \bar{M}_{\Gamma_\alpha \cup \{n+1\}}.$$

Then we have that $\pi'(\delta_{ijk}) = \pi'(\delta_I)$ has dimension $n - 4$ and intersects the interior $M_{\Gamma'}$. So I has the following properties:

- $i, j, k \in I$ in case (X); $i, j \in I$ in case (Y).

• I contains s whole triples from Γ' and q “separate” points in N not related by \leftrightarrow to any other point in I .

From $\delta_I \simeq \bar{M}_{0,|I|+1} \times \bar{M}_{0,(n+1)-|I|+1}$ we have the following easy estimate,

$$n - 4 = \dim \pi'(\delta_I) \leq s + \dim \bar{M}_{0,(n+1)-|I|+1} = n - |I| + s - 1,$$

and therefore

$$(4.9.1) \quad |I| \leq s + 3.$$

Consider the case (X). Since

$$n - 4 = \dim \pi(\delta_{ijk}) = \text{cap}((\Gamma')_{N \setminus \{i,j,k\}}),$$

it follows that for any subset T ($|T| \geq 2$) of triples from Γ' ,

$$\left| \bigcup_{\alpha \in T} \Gamma_\alpha \right| \geq |T| + 4,$$

if $i, j, k \in \bigcup_{\alpha \in T} \Gamma_\alpha$.

Assume $s \geq 2$. If $i, j, k \in \bigcup_{\Gamma_\alpha \subset I} \Gamma_\alpha$, then we have

$$|I| - q \geq \left| \bigcup_{\Gamma_\alpha \subset I} \Gamma_\alpha \right| \geq s + 4,$$

which contradicts (4.9.1).

If one of i, j, k , say i , is not in $\bigcup_{\Gamma_\alpha \subset I} \Gamma_\alpha$, then

$$|I \setminus \{i\}| - q \geq \left| \bigcup_{\Gamma_\alpha \subset I} \Gamma_\alpha \right| \geq s + 3,$$

which again contradicts (4.9.1).

Assume $s = 1$. Let Γ_1 be the unique triple in Γ' contained in I . We have $|I| = q + 3$ and by (4.9.1), $|I| \leq 4$. It follows that $q = 0$ or 1 . Since $i, j, k \in I$, it follows that at least two of the indices i, j, k are in Γ_1 , which is a contradiction.

Consider now the cases (Y), (Z). We have a usual diagram of morphisms,

$$\begin{array}{ccc} M_{0,n+1} & \xrightarrow{\pi'} & M_{\Gamma' \cup \{n+1\}} \\ \pi_N \downarrow & & \downarrow D \mapsto \mathcal{O}(D) \\ M_{0,n} & \xrightarrow{v} & \text{Pic}^1(\Sigma'). \end{array}$$

Lemma 4.10. *The morphism v can be extended to the generic points of δ_{ijk} and δ_I as follows: Let C be a fiber of the universal family over a general point of δ_{ijk} (resp., δ_I). On one component C_1 we have points i, j, k (resp., I) and the attaching point p , while on the other component C_2 we have points $N \setminus \{i, j, k\}$ (resp., $N \setminus I$) and the attaching point q . This gives a morphism $f : \Sigma' \rightarrow \mathbb{P}^1$ obtained by sending points in $N \setminus \{i, j, k\}$ (resp., $N \setminus I$) to the corresponding points of the second component of C and by sending points in i, j, k (resp., I) to the point q . Consider the line bundle $L = f^* \mathcal{O}_{\mathbb{P}^1}(1)$. The line bundle L has degree 0 on the components $\Gamma_\alpha \subset I$. Each such component Γ_α can be identified with C_1 , thus we can twist L by $\mathcal{O}_{\Sigma'}(p)$, which gives a line bundle in $\tilde{L} \in \text{Pic}^1(\Sigma)$.*

Proof. Take $|\Gamma'|$ copies of the universal family $\bar{M}_{0,n+1}$ over $\bar{M}_{0,n}$, indexed by triples in Γ' . Let \mathbf{X} be the push-out of these families, glued along sections, as prescribed by Γ' . (The fiber of \mathbf{X} over a point in $M_{0,n}$ is Σ .) Let U be the open in $\bar{M}_{0,n}$ which is the union of $M_{0,n}$ and δ_{ijk} (resp., δ_I), not containing any other boundary strata. Let \mathbf{X}^0 be the pre-image of U in \mathbf{X} .

There are maps $u : \mathbf{X}^0 \rightarrow U \times \Sigma$ (given by stabilization) and $f : \mathbf{X}^0 \rightarrow U \times \mathbb{P}^1$ (obtained by contracting the points in I). Let $M = f^* \mathcal{O}_{\mathbb{P}^1}(1)$ and $L = u_*(M)$. It follows from a local calculation in $[\mathbb{F}]$ that L is invertible and for $m \in U$ we have $L_m \in \text{Pic}^1(\Sigma)$ satisfying the lemma. \square

After shrinking $\bar{M}_{0,n}$ to an open subset containing the generic points of δ_{ijk} and δ_I , this gives

$$v(\delta_{ijk}) = v(\delta_I).$$

In case (Z), $v(\delta_{ijk}) \notin W^2$, i.e., a general line bundle L in $v(\delta_{ijk})$ has $h^0 = 2$ and it induces a map $f : \Sigma \rightarrow \mathbb{P}^1$ that collapses only the points i, j, k to the point q . Since $v(\delta_{ijk}) = v(\delta_I)$, the map f collapses the points in I to the point q . It follows that $I = \{i, j, k\}$. This finishes case (Z).

In case (Y), since $\pi'(\delta_{ijk})$ has codimension 1, the map $\pi'|_{\delta_{ijk}}$ generically has 1-dimensional fibers, this implies that $v(\delta_{ijk}) \notin W^3$, i.e., a general line bundle in $v(\delta_{ijk})$ has $h^0 = 3$ and gives an admissible map $f : \Sigma' \rightarrow \mathbb{P}^2$ such that points i, j, k belong to a line $H \subset \mathbb{P}^2$. The corresponding point of $\bar{M}_{0,n}$ is obtained by projecting Σ' from a general point of H . Note that the points in $N \setminus \{i, j, k\}$ will be mapped to distinct points via this projection, hence no points in $N \setminus \{i, j, k\}$ will lie on the line H .

The same analysis for δ_I combined with the fact that $v(\delta_{ijk}) = v(\delta_I)$ shows that via the map f the points in I are collinear. Since in case (Y) we have $i, j \in I$, it follows that the points in I lie on H . This implies $I = \{i, j, k\}$. \square

Finally, we analyze hypertrees that are not irreducible. Recall that we denote by D_Γ the closure of $G^2(\Gamma)$ in $\bar{M}_{0,n}$.

Lemma 4.11. *If Γ is not irreducible and $D_\Gamma \neq \emptyset$, then for every irreducible D component of D_Γ there exists an irreducible hypertree Γ' on a subset $N' \subset N$ such that*

$$D = \pi^{-1}(D_{\Gamma'}),$$

where $\pi : \bar{M}_{0,n} \rightarrow \bar{M}_{0,N'}$ is the forgetful map.

Proof. If Γ' is an irreducible hypertree, then $D_{\Gamma'}$ is an irreducible divisor in $\overline{M}_{0,N'}$ intersecting the interior. Since π is flat with irreducible fibers along points in $M_{0,N'}$, $\pi^{-1}(D_{\Gamma'})$ is irreducible. Hence, it is enough to prove $D \subset \pi^{-1}(D_{\Gamma'})$. Note, since $D_{\Gamma} \neq \emptyset$, we have $G^2(\Gamma) \neq \emptyset$.

We argue by induction on d . Let $S \subset \{1, \dots, d\}$ be a subset such that (\ddagger) is an equality. We may assume that S is minimal with this property. Let $d' = |S|$, let Γ' be a collection of Γ_i for $i \in S$. Let $N' = \bigcup_{i \in S} \Gamma_i$. Then Γ' is almost a hypertree: all axioms are satisfied except possibly for the second axiom: it could happen that there exists an index $i \in N'$ that belongs to only one subset Γ'_j . In this case we can remove i from N' (and remove Γ'_j from Γ' if $|\Gamma'_j| = 3$). Continuing in this fashion, we get a subset $N' \subset N$ and a hypertree Γ' on it. By minimality of S , Γ' is irreducible.

Let D be a component of D_{Γ} (i.e., the closure of a component of $G^2(\Gamma)$). If D satisfies $D \subseteq \pi^{-1}(D_{\Gamma'})$, then we are done. Assume now that D is not contained in $\pi^{-1}(D_{\Gamma'})$. Then a dense open in D is disjoint from $\pi^{-1}(G^2(\Gamma'))$; hence, a general element in $D \cap G^2(\Gamma)$ is obtained via projection from a map $\Sigma \rightarrow \mathbb{P}^r$ ($r \geq 2$) that maps Σ' to a line. Let

$$\Gamma'' = (\Gamma \setminus \Gamma') \cup \{\Gamma_0\}, \quad \text{where } \Gamma_0 = \bigcup_{\Gamma_i \in \Gamma'} \Gamma_i.$$

If there exists an index $i \in N$ that belongs to only one subset Γ''_i , we remove it. Let N'' be the remaining set of indices. It is easy to check that Γ'' is a hypertree on N'' . Moreover, our assumptions imply that $D \subseteq \pi^{-1}(D_{\Gamma''})$. By our induction assumption, any component of $D''_{\Gamma''}$ is the preimage by a forgetful map of some $D_{\tilde{\Gamma}}$ for some irreducible hypertree $\tilde{\Gamma}$. \square

5. Compactified Jacobians of hypertree curves

Our goal in this section is to prove Theorem 1.10: if Γ is an irreducible hypertree, then the hypertree divisor $D_{\Gamma} \subset \overline{M}_{0,n}$ is contracted by a contracting birational map to the compactified Jacobian.

We start by considering any hypertree, not necessarily irreducible. We extend the universal stable hypertree curve Σ^s/M_{Γ} to a curve over \overline{M}_{Γ} in an obvious way. Let Σ_{Ω}^s be one of the geometric fibers.

Definition 5.1. A coherent sheaf on Σ_{Ω}^s is called *Gieseker semi-stable* (resp., *Gieseker stable*) if it is torsion-free, has rank 1 at generic points of Σ_{Ω}^s , and is semi-stable (resp., stable) with respect to the canonical polarization $\omega_{\Sigma_{\Omega}^s}$.

The *compactified Jacobian* ([OS], [C]) $\overline{\text{Pic}}/\overline{M}_{\Gamma}$ parametrizes gr-equivalence classes of Gieseker semi-stable sheaves. By [Si], it is functorial: consider the functor

$$\overline{\mathcal{P}ic} : \text{schemes} \rightarrow \text{sets}$$

that assigns to a scheme S the set of coherent sheaves on Σ_S^s flat over S and such that the restriction to any geometric fiber Σ_{Ω}^s is Gieseker semi-stable. Then there exists a natural

transformation $\overline{\mathcal{P}ic} \rightarrow h_{\overline{\mathcal{P}ic}}$ which has the universal property: for any scheme T , any natural transformation $\overline{\mathcal{P}ic} \rightarrow h_T$ factors through a unique morphism $\overline{\mathcal{P}ic} \rightarrow T$.

Over each geometric point of \overline{M}_Γ , $\overline{\mathcal{P}ic}$ is a stable toric variety of $\text{Pic}^0(\Sigma_\Omega)$ and its normalization is a disjoint union of toric varieties.

Proposition 5.2. *The pull-back of an invertible sheaf in $\text{Pic}^1(\Sigma_\Omega)$ is Gieseker stable on Σ_Ω^s .*

Proof. Let $X = \Sigma^s$ be a stable hypertree curve. We call an irreducible component of X black if it is the proper transform of a component of Σ . Otherwise we call it white. It is well known that slope stability on reducible curves reduces to the following *Gieseker's basic inequality*. For any proper subcurve $Y \subset X$, we have

$$(5.2.1) \quad \left| b(Y) - b(X) \frac{m(Y)}{m(X)} \right| < \frac{1}{2} \# Y.$$

Here,

$$b(S) = \deg L|_S, \quad m(S) = \deg \omega_{\Sigma^s}|_S, \quad \text{and} \quad \# Y := |Y \cap \overline{X \setminus Y}|.$$

In our case, $b(S)$ is just the number of black components in S , and we have

$$m(X) = 2g - 2 = 2d - 4.$$

We denote $m := m(Y)$, $b = b(Y)$, and have to show that

$$(5.2.2) \quad |(2d - 4)b - dm| < (d - 2)\# Y.$$

5.3. It is easy to see that the complementary subcurve $Y^c := \overline{X \setminus Y}$ satisfies (5.2.1) if and only if Y does. Hence, by interchanging Y with Y^c , we can assume that

$$(5.3.1) \quad dm - (2d - 4)b \geq 0$$

and try to show that

$$(5.3.2) \quad dm - (2d - 4)b - (d - 2)\# Y < 0.$$

5.4. Consider a white component w_1 of Σ^s which is not in Y but such that at least one adjacent black component is in Y . Enumerate the black components in Y intersecting w_1 as b_1, b_2, \dots, b_i , and the rest as b_{i+1}, \dots, b_k , with $1 \leq i \leq k$ (and $k \geq 3$). We claim that adding w_1 to Y does not decrease the left-hand side in (5.3.2) and increases the left-hand side in (5.3.1). We only need to show that $dm - (d - 2)\# Y$ increases. Adding w_1 to Y increases m by $k - 2$. If the original value of $\# Y$ is $x + i$, where i is the contribution from w_1 intersecting b_1 through b_i , then the value after adding w_1 to Y is $x + k - i$. Hence, $\# Y$ increases by $k - 2i$. Then the difference of values of the left-hand side is

$$d(k - 2) - (d - 2)(k - 2i) = (d - 2)i + k - d \geq (d - 2) + 3 - d > 0.$$

Hence we can assume that all white lines hit by a black component in Y are also in Y : by showing (5.3.2) in this situation, we show (5.3.2) in general.

5.5. Let P_i be the number of singular points of Σ of valence i . Then

$$\sum P_i = n \quad \text{and} \quad \sum iP_i = 2d + n - 2.$$

This is because $\sum iP_i$ is the total number of times a singular point is hit by a component in Σ . This is equal to $\sum |\Gamma_\alpha|$, which by the normalization axiom equals $2d + n - 2$. So we have

$$(5.5.1) \quad \sum (i-1)P_i = 2d + n - 2 - n = 2d - 2.$$

Let p_i be the number of singular points of Σ of valence i hit by the image of Y . Then (5.5.1) implies that

$$(5.5.2) \quad \sum_i (i-1)p_i \leq 2d - 2$$

with strict inequality if Y does not cover all the points in N .

Let b_i be the number of black components in Y with i singular points. By the convexity axiom, we have $\sum_i p_i \geq \sum_i (i-2)b_i + 2$. If Y covers all the points in N , then we claim that this inequality is strict: otherwise, as Y is a proper subcurve of X , the convexity axiom would be violated when we consider the components of Y and one extra component that is not in Y . This inequality together with (5.5.2) (at least one being strict) implies that

$$(5.5.3) \quad \sum_i (i-d)p_i + (d-1)\sum_i (i-2)b_i < 0.$$

Let l'_i be the number of isolated white components with i singularities (i.e., those not hit by any black components in Y). Since we obviously have $\sum (i-d)l'_i \leq 0$, (5.5.3) implies that

$$(5.5.4) \quad \sum_i (i-d)p_i + \sum_i (i-d)l'_i + (d-1)\sum_i (i-2)b_i < 0.$$

We claim that this inequality is equivalent to (5.3.2). Let l_i be the number of white components in Y with i singular points. Then

$$m = \sum (i-2)b_i + \sum (i-2)l_i = \sum (i-2)b_i + \sum (i-2)l'_i + \sum (i-2)p_i,$$

since $\sum (i-2)l'_i$ is the contribution to $\sum (i-2)l_i$ by isolated white components in Y and $\sum (i-2)p_i$ is the contribution by white components hit by black components in Y , which we can assume are all in Y . We also have

$$(5.5.5) \quad \#Y = \sum il'_i + \sum ip_i - \sum ib_i,$$

where $\sum il'_i$ is the contribution to $\#Y$ by isolated white components in Y , $\sum ip_i$ is the total number of times a point in the image of Y in Σ is hit by a black component (not necessarily in Y) and $\sum ib_i$ is the total number of times a black component in Y hits one of these

points, so their difference is the contribution to $\#Y$ by everything except isolated white components.

So we have

$$dm - (2d - 4)b - (d - 2)\#Y = 2 \sum (i - d)p_i + 2 \sum (i - d)l'_i + 2(d - 1) \sum (i - 2)b_i < 0$$

by (5.5.4). \square

Corollary 5.6. $\text{Pic}^1 \subset \overline{\text{Pic}}$.

5.7. Let $\overline{\text{Pic}}^1$ be the normalization of the closure of Pic^1 in $\overline{\text{Pic}}$. It compactifies the \mathbb{G}_m^g -torsor Pic^1 over M_Γ by adding boundary divisors of two sorts, *vertical* and *horizontal*. Vertical boundary divisors are divisors over the boundary of \overline{M}_Γ . The boundary divisors of \overline{M}_Γ are parametrized by subsets $I \subset \Gamma_\alpha$ with $|I|, |\Gamma_\alpha \setminus I| > 1$. The corresponding hypertree curve Σ' generically has $d + 1$ irreducible components, with the α 's component broken into a nodal curve with two components, C_α^1 (with singular points indexed by I) and C_α^2 (with singular points indexed by $\Gamma_\alpha \setminus I$). There could be two corresponding vertical boundary divisors. Generically they parametrize line bundles on Σ' that have degree 1 on C_α^1 and degree 0 on C_α^2 (resp., degree 0 on C_α^1 and degree 1 on C_α^2) and degree 1 on the remaining components. Notice that a priori it is not clear that these loci are non-empty divisors: one has to check that these line bundles are Gieseker semi-stable.

Horizontal boundary divisors are toric (over a geometric point of M_Γ) and can be described as follows. Choose a node in Σ^s and let $\hat{\Sigma}$ be a curve obtained from Σ^s by inserting a strictly semistable \mathbb{P}^1 at the node. Start with the multidegree $\underline{1}$ and choose a multidegree \hat{d} on $\hat{\Sigma}$ such that the degree on the extra \mathbb{P}^1 is 1 and the degree on one of the neighboring black components is lowered from 1 to 0 (lowering the degree on a white component would lead to an unstable sheaf). The corresponding Gieseker semi-stable sheaves on Σ^s are push-forwards of invertible sheaves \hat{F} on $\hat{\Sigma}$ of a given Gieseker semi-stable multidegree with respect to the stabilization morphism $\hat{\Sigma} \rightarrow \Sigma^s$. Note that this creates a sheaf which is not invertible at the node. An easy count shows that potentially this gives as many as $2d - 2 + n$ horizontal divisors.

Lemma 5.8. *If Γ is an irreducible hypertree, then $\overline{\text{Pic}}^1$ has a maximal possible number of horizontal $(2d - 2 + n)$ and vertical boundary divisors.*

Proof. This is a numerical question: one has to check that the corresponding multidegrees are Gieseker-stable. The proof is parallel to the proof of Proposition 5.2: a stronger (by 1) inequality satisfied by an irreducible hypertree compensates for the difference (by 1) in the multidegree. We omit this calculation. \square

Example 5.9. The papers [OS] and [A] contain a recipe for presenting the polytope of $\overline{\text{Pic}}^1$ as a slice of the hypercube. We will not go into the details here, but let us give our favorite example. Let Σ be the Keel–Vermeire curve with 4 components indexed by $\{1, 2, 3, 4\}$. Then the polytope is the rhombic dodecahedron of Figure 3. The normals to its faces are given by roots $\alpha_{ij} = \{e_i - e_j\}$ of the root system A_3 , where $i, j \in \{1, 2, 3, 4\}$, $i \neq j$. To describe a pure sheaf from the corresponding toric codimension 1 stratum, consider a quasi-stable curve Σ_{ij} obtained by inserting a \mathbb{P}^1 at the node of Σ where i -th and j -th

components intersect. Now just pushforward to Σ an invertible sheaf that has degree 1 on this \mathbb{P}^1 and at any component of Σ_{ij} other than the proper transform of the i -th component of Σ (where the degree is 0).



Figure 3. Compactified Jacobian of the Keel–Vermeire curve.

Now we can prove Theorem 1.10.

Proof. Our proof is parallel to the proof of irreducibility of D_Γ in Lemma 4.3. Consider the birational map $v : \overline{M}_{0,n} \dashrightarrow \overline{\text{Pic}}^1$. Note that $\overline{\text{Pic}}^1$ is in general not \mathbb{Q} -factorial. The map v contracts only one divisor intersecting $M_{0,n}$, namely D_Γ . The map v is necessarily contracting if

$$\rho(\overline{M}_{0,n}) - \rho'(\overline{\text{Pic}}^1) = 1 + |\{\text{boundary divisors contracted by } v\}|.$$

(Here $\rho'(X)$ denotes the rank of the class group $\text{Cl}(X)$). Computation of this number shows that it suffices to check that the following boundary divisors are *not* contracted by v :

- δ_{ij} for $\{i, j\} \not\subset \Gamma_\alpha$,
- δ_I for $I \subset \Gamma_\beta$.

We use the commutative diagram of rational maps (with v and the Abel map not everywhere defined)

$$\begin{array}{ccc} \overline{M}_{0,n+1} & \xrightarrow{\pi} & \prod_{\alpha} \overline{M}_{0,\Gamma_\alpha \cup \{n+1\}} \\ \pi_N \downarrow & & \downarrow u \\ \overline{M}_{0,n} & \xrightarrow{v} & \overline{\text{Pic}}^1. \end{array}$$

We lift the boundary divisors of $\overline{M}_{0,n}$ defined above to the boundary divisors δ_{ij} and δ_I of $\overline{M}_{0,n+1}$, respectively. By Lemma 3.11, these divisors are not contracted by π . Notice that $\pi(\delta_{ij})$ and $\pi(\delta_{\Gamma_\beta})$ are not boundary divisors of $\overline{M}_{\Gamma_\alpha \cup \{n+1\}}$ and are therefore mapped to

Pic^1 . We will prove in Lemma 5.10 that $v(\delta_{ij})$ and $v(\delta_{\Gamma_\beta})$ are divisors in $\overline{\text{Pic}}^1$ (but not boundary divisors).

Next we consider δ_I such that $1 < |I| < |\Gamma_\alpha| - 1$. This divisor is mapped to the divisor

$$\{\delta_I \subset \overline{M}_{0, \Gamma_\alpha \cup \{n+1\}}\} \times \prod_{\beta \neq \alpha} \overline{M}_{0, \Gamma_\beta \cup \{n+1\}} \subset \overline{M}_{\Gamma_\cup \{n+1\}}.$$

Note that the Abel map can be extended to the interior of this divisor and maps it to the corresponding vertical boundary divisor of $\overline{\text{Pic}}^1$. By Lemma 5.10 (iii), this map is dominant.

Finally, consider $\delta_{\Gamma_\alpha \setminus \{i\}}$. This divisor is mapped to the divisor

$$\{\delta_{i, n+1} \subset \overline{M}_{0, \Gamma_\alpha \cup \{n+1\}}\} \times \prod_{\beta \neq \alpha} \overline{M}_{0, \Gamma_\beta \cup \{n+1\}} \subset \overline{M}_{\Gamma_\cup \{n+1\}}.$$

This divisor maps onto the horizontal boundary divisor that corresponds to the i -th node of the α -th irreducible component (use Lemma 5.10 (iv)).

Lemma 5.10. *The Abel map restricted to $\pi(\delta_I)$ generically has one-dimensional fibers if I is one of the following:*

- (i) $I = \{i, j\}$ for $\{i, j\} \not\subset \Gamma_\alpha$ for any α ,
- (ii) $I = \Gamma_\beta$,
- (iii) $I \subset \Gamma_\beta$, $2 \leq |I| < |\Gamma_\beta| - 1$,
- (iv) $I = \Gamma_\beta \setminus \{i\}$, for $i \in \Gamma_\beta$.

Proof. Let $\overline{N} = (N \setminus I) \cup \{p\}$. Denote by δ_I° the interior of the boundary δ_I :

$$\delta_I^\circ \cong M_{0, I \cup \{p\}} \times M_{0, \overline{N} \cup \{p\}}.$$

Let $\overline{\Gamma}$ be the collection of subsets of \overline{N} obtained by identifying the points in I with p (and throwing away any subsets with fewer than three elements). Note that $\overline{\Gamma}$ has maximum capacity (moreover, in the cases (ii), (iii), (iv) $\overline{\Gamma}$ is a hypertree on \overline{N}) and therefore, Remark 3.3 applies.

We denote by $\overline{\Sigma}$ the corresponding hypertree curve and by $\text{Pic}_{\overline{\Gamma}}^1$ the relative Picard scheme of line bundles of multi-degree $(1, \dots, 1)$. Similarly, we let $G_{\overline{\Gamma}}^1, \tilde{G}_{\overline{\Gamma}}^1$, etc., be the corresponding Brill–Noether loci. We will use the usual commutative diagram of morphisms (with $\bar{\pi}$ the product of forgetful maps and \bar{u} the Abel map corresponding to $\overline{\Gamma}$):

$$\begin{array}{ccc} M_{0, \overline{N} \cup \{p\}} & \xrightarrow{\bar{\pi}} & \prod_{\alpha} M_{0, \overline{\Gamma}_\alpha \cup \{p\}} \\ \bar{\pi}_N \downarrow & & \downarrow \bar{u} \\ \overline{M}_{0, \overline{N}} & \longrightarrow & \text{Pic}_{\overline{\Gamma}}^1. \end{array}$$

The main observation that we will use is that generically along the image of $\bar{\pi}$, the Abel map \bar{u} has one-dimensional fibers.

Consider first the case (i). We have

$$\delta_I^o \cong M_{\bar{N} \cup \{p, n+1\}} \cong \tilde{G}_{\Gamma}^1.$$

A point $[m]$ in $M_{0, \bar{N} \cup \{p, n+1\}}$ corresponds via the above isomorphism to a morphism $\bar{f} : \bar{\Sigma} \rightarrow \mathbb{P}^1$ and an admissible section \bar{s} of $\bar{f}^* \mathcal{O}(1)$. By abuse of notation we consider $[m]$ as a point of δ_I^o . Then $\pi([m]) \in M_{\Gamma \cup \{n+1\}}$ corresponds to a pair (Σ, s) , where s is an admissible section such that $s = \rho^* \bar{s}$, where $\rho : \Sigma \rightarrow \bar{\Sigma}$ is the map that collapses i, j to p . Case (i) now follows from the commutative diagram

$$\begin{array}{ccccc} M_{0, \bar{N} \cup \{p\}} & \xrightarrow{\bar{\pi}} & \bar{\pi}(M_{0, \bar{N} \cup \{p\}}) & \xrightarrow{\bar{u}} & \bar{u}(\bar{\pi}(M_{0, \bar{N} \cup \{p\}})) \\ \cong \downarrow & & \cong \downarrow \rho^* & & \downarrow \rho^* \\ \delta_I^o & \xrightarrow{\pi} & \pi(\delta_I^o) & \xrightarrow{u} & u(\pi(\delta_I^o)) \end{array}$$

as the vertical maps (which are given by pull-back by ρ) are bijective.

Consider now case (ii). A point $[m]$ in $M_{0, \bar{N} \cup \{p\}} \cong \tilde{G}_{\Gamma}^1$ corresponds to a morphism $\bar{f} : \bar{\Sigma} \rightarrow \mathbb{P}^1$ and an admissible section \bar{s} of $\bar{f}^* \mathcal{O}(1)$. We have

$$\delta_I^o \cong M_{\bar{N} \cup \{p, n+1\}} \times M_{\Gamma_{\beta} \cup \{p\}} \cong \tilde{G}_{\Gamma}^1 \times M_{\Gamma_{\beta} \cup \{p\}}.$$

If $([m], [m']) \in \delta_I^o$, then the point $\pi([m], [m'])$ in $M_{\Gamma \cup \{n+1\}}$ corresponds to a pair (Σ, s) with the following properties: there is a morphism

$$\rho : \Sigma \rightarrow \bar{\Sigma}$$

that collapses the component Σ_{β} to p , and if $q \in \Sigma_{\beta}$ is determined by $[m'] \in M_{\Gamma_{\beta} \cup \{p\}}$, then $s = \rho^* \bar{s} + q$ is the corresponding admissible section. Note, if we fix a point in the image of $\pi(\delta_I^o)$ via the Abel map, this fixes the element $[m']$, and thus q . Case (ii) now follows from a similar commutative diagram (in the diagram above, take products with $M_{\Gamma_{\beta} \cup \{p\}}$ in the first row).

Cases (iii) and (iv) are similar. \square

This concludes the proof of Theorem 1.10. \square

6. Planar realizations of hypertrees

To distinguish between the various Brill–Noether loci of different collections of subsets, we denote by $G^2(\Gamma)$ the Brill–Noether locus G^2 corresponding to a collection of subsets $\Gamma = \{\Gamma_1, \dots, \Gamma_d\}$. Recall that an element of $G^2(\Gamma)$ can be obtained by composing a morphism $\Sigma \rightarrow \mathbb{P}^2$ with a linear projection $\mathbb{P}^2 \dashrightarrow \mathbb{P}^1$ such that the morphism

- has degree 1 on each component of Σ ,
- separates points in N .

So basically we choose N different points in \mathbb{P}^2 such that for each α , the points in Γ_α are collinear. By Theorem 4.2, if Γ is an irreducible hypertree, $G^2(\Gamma)$ is an irreducible subvariety of codimension 1 in $\overline{M}_{0,n}$. Recall that a hypertree Γ has a *planar realization* if there exists a map $\Sigma \rightarrow \mathbb{P}^2$ such that all points in N are distinct and the points in a subset $S \subset N$ with $|S| \geq 3$ are collinear *if and only if* $S \subset \Gamma_\alpha$ for some α . Clearly, this is an open condition on $G^2(\Gamma)$. We prove that this open set is non-empty:

Theorem 6.1. *Any irreducible hypertree has a planar realization.*

Proof. Let $\Gamma = \{\Gamma_1, \dots, \Gamma_d\}$ be an irreducible hypertree. Assume Γ does not have a planar realization. It follows that there is a triple

$$\Gamma_0 = \{a, b, c\} \subset N,$$

not contained in any Γ_α , such that the points in Γ_0 are collinear for any $\Sigma \rightarrow \mathbb{P}^2$ that gives a point of $G^2(\Gamma)$.

Let $\tilde{\Gamma} = \Gamma \cup \{\Gamma_0\}$. By our assumption, $G^2(\Gamma) = G^2(\tilde{\Gamma})$. We may assume $a \in \Gamma_1$. Since Γ_1 does not contain Γ_0 , we may assume $b \notin \Gamma_1$. Let $\Gamma'_1 = \Gamma_1 \setminus \{a\}$. Construct a new collection of subsets Γ' :

- (A) If $|\Gamma_1| = 3$, let $\Gamma' = \{\Gamma_2, \dots, \Gamma_d, \Gamma_0\}$.
- (B) If $|\Gamma_1| \geq 4$, let $\Gamma' = \{\Gamma'_1, \Gamma_2, \dots, \Gamma_d, \Gamma_0\}$.

Claim 6.2. *The collection of subsets Γ' is a hypertree.*

Proof of Claim 6.2. We prove that Γ' satisfies the convexity axiom (\ddagger). As Γ is an irreducible hypertree, for any $S \subset \{2, \dots, d\}$ we have

$$\left| \Gamma_0 \cup \bigcup_{j \in S} \Gamma_j \right| \geq \left| \bigcup_{j \in S} \Gamma_j \right| \geq \sum_{j \in S} (|\Gamma_j| - 2) + 3 = \sum_{j \in S} (|\Gamma_j| - 2) + (|\Gamma_0| - 2) + 2.$$

Similarly, if $S \subseteq \{2, \dots, d\}$, we have

$$\begin{aligned} \left| \Gamma'_1 \cup \Gamma_0 \cup \bigcup_{j \in S} \Gamma_j \right| &\geq \left| \Gamma'_1 \cup \bigcup_{j \in S} \Gamma_j \right| \geq \left| \Gamma_1 \cup \bigcup_{j \in S} \Gamma_j \right| - 1 \\ &\geq \sum_{j \in S} (|\Gamma_j| - 2) + (|\Gamma_1| - 2) + 3 - 1 \\ &= \sum_{j \in S} (|\Gamma_j| - 2) + (|\Gamma'_1| - 2) + (|\Gamma_0| - 2) + 2. \end{aligned}$$

It is easy to see that Γ' satisfies the normalization axiom (\dagger). It follows that Γ' is a hypertree (possibly not irreducible). \square

We use our working definition of D_Γ , namely $D_\Gamma = \overline{G^2(\Gamma)}$. Similarly, $D_{\Gamma'} = \overline{G^2(\Gamma')}$. By Theorem 2.4 and Theorem 3.2, $D_{\Gamma'}$ is a divisor in $\overline{M}_{0,n}$ (possibly reducible) and the map

$$\pi' : \overline{M}_{0,n+1} \rightarrow \overline{M}_{\Gamma' \cup \{n+1\}} := \prod_{\Gamma'_\alpha} \overline{M}_{0,\Gamma'_\alpha \cup \{n+1\}}$$

is a birational morphism whose exceptional locus consists of $\pi_N^{-1}(D_{\Gamma'})$ and boundary divisors in $\overline{M}_{0,n+1}$ contracted by π' .

By Theorem 4.2, $D_\Gamma = \overline{G^2(\Gamma)}$ is an irreducible divisor in $\overline{M}_{0,n}$. In addition, we have $G^2(\tilde{\Gamma}) \subseteq G^2(\Gamma')$ and by assumption $G^2(\tilde{\Gamma}) = G^2(\Gamma)$. It follows that D_Γ is an irreducible component of $D_{\Gamma'} = \overline{G^2(\Gamma')}$.

Let $\mathcal{E}_1, \dots, \mathcal{E}_s$ be the irreducible components of $\pi_N^{-1}D_{\Gamma'}$. We may assume $\mathcal{E}_1 = \pi_N^{-1}D_\Gamma$. By Theorem 4.2, we have

$$\mathcal{E}_1 = \pi_N^{-1}D_\Gamma = (d-1)H - \sum_{\substack{I \subset N \\ 1 \leq |I| \leq n-3}} m_I E_I,$$

where m_I satisfies inequality (4.2.1). By (4.2.2), we have $m_{\{i\}} = d - v_i$.

Notation 6.3. Let d' be the number of hyperedges in Γ' . (Hence, $d' = d$ in case (A) and $d' = d + 1$ in case (B).) Denote by v'_i the valence of $i \in N$ in Γ' .

Lemma 6.4. *The classes of the divisors \mathcal{E}_i are subject to the following relation:*

$$(6.4.1) \quad \sum_{i=1}^s c_i \mathcal{E}_i = (d' - 1)H - \sum_{\substack{I \subset N \\ 1 \leq |I| \leq n-3}} m'_I E_I - \sum_{\substack{|I|=n-2 \\ \delta_{I \cup \{n+1\}} \in \text{Exc}(\pi')}} a'_I \delta_{I \cup \{n+1\}},$$

where c_1, \dots, c_s are positive integers, a'_I is the discrepancy of the divisor $\delta_{I \cup \{n+1\}}$ with respect to the map π' and the integers $m'_I \geq 0$ satisfy the following inequality:

$$(6.4.2) \quad m'_I \geq |I| - 1 - \text{cap}((\Gamma')_I) + |\{\Gamma'_\alpha \mid \Gamma'_\alpha \subset I^c\}|.$$

In particular, we have

$$m'_i \geq d' - v'_i.$$

Proof. Note that formula (4.4.1) still holds (the map π' is birational):

$$(6.4.3) \quad \sum_{i=1}^s c_i \mathcal{E}_i = K_{\overline{M}_{0,n+1}} - \pi'^* K_{\overline{M}_{\Gamma' \cup \{n+1\}}} - \sum_{\delta_{I \cup \{n+1\}} \in \text{Exc}(\pi')} a'_I \delta_{I \cup \{n+1\}}.$$

For the purpose of the lemma, we ignore the terms $a'_I \delta_{I \cup \{n+1\}}$ for $|I| = n - 2$ in the above formula. Then the lemma follows from (4.4.1), combined with the inequality

$$a'_I \geq \text{codim } \pi'(\delta_{I \cup \{n+1\}}) - 1$$

and Lemma 3.10. \square

We compare the coefficient of H in both sides of the equation (6.4.1). Recall that the coefficient of H in \mathcal{E}_1 is $d - 1$.

Consider first case (A). Since the degree of H is at least $d - 1$ in the left-hand side, and at most $d - 1$ on the right, it follows that $a'_I = 0$ for all $|I| = n - 2$ and moreover, $s = 1$, $c_1 = 1$, i.e., we have

$$\mathcal{E}_1 = \pi_N^{-1} D_\Gamma = (d - 1)H - \sum_{\substack{I \subset N \\ 1 \leq |I| \leq n-3}} m'_I E_I.$$

It follows that $m_i = m'_i$ for all i . By Lemma 6.4, $m'_i \geq d - v'_i$. By (4.2.2), $m_i = d - v_i$. This leads to a contradiction, since $v'_i < v_i$ for all $i \in \Gamma_1 \setminus \{a, b, c\}$ (we use here the assumption that $\Gamma_1 \setminus \{a, b, c\} \neq \emptyset$).

Consider now case (B). The coefficient of H on the right-hand side of (6.4.1) is at most d , while the coefficient of H in \mathcal{E}'_1 is $d - 1$. If $s > 1$, it follows that $s = 2$ and \mathcal{E}_2 is an irreducible divisor that has H -degree 1. From the Kapranov blow-up model of $\overline{M}_{0,n+1}$ one can see that either \mathcal{E}_2 is a boundary divisor or $h^0(\mathcal{E}_2) > 1$. This is a contradiction, since \mathcal{E}_2 is a divisor that intersects the interior of $\overline{M}_{0,n+1}$ and moreover, it is an exceptional divisor for the birational map π' . The same argument shows that $c_1 = 1$.

Moreover, we must have $a'_{I_0} = 1$, for some $|I_0| = n - 2$ (with $a'_I = 0$ for all $I \neq I_0$). Let $\{u, v\} = I_0^c$. We have

$$\mathcal{E}_1 = \pi_N^{-1} D_\Gamma = dH - \sum_{\substack{I \subset N \\ 1 \leq |I| \leq n-3}} m'_I E_I - \delta_{u,v}.$$

In particular, $m_i = m'_i - 1$ for all $i \neq u, v$ and $m_i = m'_i$ if $i \in \{u, v\}$. Note that $v'_b = v_b + 1$, $v'_c = v_c + 1$, while $v'_i = v_i$ for all $i \neq b, c$. By Lemma 6.4,

$$m'_i \geq d' - v'_i = d + 1 - v'_i \quad \text{for all } i.$$

Since $m_i = d - v_i$ for all i , it follows that if $i \neq \{b, c\}$, then $i \neq \{u, v\}$, i.e., $\{u, v\} = \{b, c\}$. We have

$$(6.4.4) \quad \mathcal{E}_1 = \pi_N^{-1} D_\Gamma = dH - \sum_{\substack{I \subset N \\ 1 \leq |I| \leq n-3}} m'_I E_I - \delta_{b,c}.$$

We consider the coefficients m_I and m'_I for $I = \Gamma'_1$. By (4.2.6), we have

$$(6.4.5) \quad m_I = d + |I| - 1 - \sum_{i \in I} v_i.$$

By Lemma 6.4, we get

$$(6.4.6) \quad m'_I \geq |I| - 1 - \text{cap}((\Gamma')_I) + |\{\Gamma'_\alpha \mid \Gamma'_\alpha \subset I^c\}|.$$

Recall that we assume $b \notin \Gamma_1$. Note that

$$(6.4.7) \quad |\{\Gamma_\alpha \mid \Gamma_\alpha \subset I^c\}| = d - \sum_{i \in I} v_i + |I| - 1.$$

We will compare $|\{\Gamma_\alpha \mid \Gamma_\alpha \subset I^c\}|$ with $|\{\Gamma'_\alpha \mid \Gamma'_\alpha \subset I^c\}|$.

We consider two cases. First, assume $c \notin \Gamma_1$. Then $(\Gamma')_I = \{I\}$. Hence,

$$\text{cap}((\Gamma')_I) = |I| - 2.$$

Since $\Gamma_0 = \{a, b, c\} \subset I^c$, it follows that

$$m'_I \geq 1 + |\{\Gamma'_\alpha \mid \Gamma'_\alpha \subset I^c\}| = 2 + |\{\Gamma_\alpha \mid \Gamma_\alpha \subset I^c\}| = d + |I| + 1 - \sum_{i \in I} v_i,$$

which contradicts (6.4.5) since by (6.4.4) $m_I = m'_I - 1$.

Now assume $c \in \Gamma_1$. By (6.4.7) and from $\Gamma_0 \not\subseteq I^c$ it follows that

$$m'_I \geq 1 + |\{\Gamma'_\alpha \mid \Gamma'_\alpha \subset I^c\}| = 1 + |\{\Gamma_\alpha \mid \Gamma_\alpha \subset I^c\}| = d + |I| - \sum_{i \in I} v_i.$$

This contradicts (6.4.5), since by (6.4.4), $m_I = m'_I$. \square

7. Spherical and not so spherical hypertrees

Theorem 7.1. *Let \mathcal{K} be an even (i.e., bicolored) triangulation of a sphere with n vertices. Then its collection of black (resp., white) triangles Γ (resp., Γ') is a hypertree. It is irreducible if and only if \mathcal{K} is not a connected sum of two triangulations.*

Proof. Let d (resp., d') be the number of triangles in Γ (resp., Γ'). Since \mathcal{K} has $3d = 3d'$ edges, we have $d = d'$. By Euler's formula,

$$n - 3d + 2d = 2,$$

and therefore $d = n - 2$.

7.2. Take any k black triangles $\Gamma_1, \dots, \Gamma_k$ and let $\Delta \subset S^2$ be their union. As a simplicial complex, Δ has k faces, $3k$ edges, and $|\Gamma_1 \cup \dots \cup \Gamma_k|$ vertices. Since $h_2(\Delta) = 0$, we have

$$\chi(\Delta) = h_0(\Delta) - h_1(\Delta) = \left| \bigcup_{i=1}^k \Gamma_i \right| - 2k.$$

Abusing notation, let $S^2 \setminus \Delta$ denote the simplicial complex obtained by removing interiors of triangles in Δ . Let D be the closure of a connected component of the set $S^2 \setminus \Delta$ with vertices removed. Note that D is not necessarily a polygon (it is not necessarily simply connected), but its boundary edges are well-defined. Their number $e(D)$ is equal to three times

the number of white triangles inside D minus three times the number of black triangles inside D . It follows that $3 \mid e(D)$. Then the number of edges in $\partial(S^2 \setminus \Delta) = \partial\Delta$ equals

$$(7.2.1) \quad 3k = \sum e(D_i) \geq 3h_0(S^2 \setminus \Delta).$$

This implies that

$$(7.2.2) \quad h_0(S^2 \setminus \Delta) \leq k \quad \text{for any union } \Delta \text{ of } k \text{ black (resp., white) faces.}$$

7.3 (Γ satisfies the convexity axiom (\dagger)). By Alexander duality,

$$h_1(\Delta) = h_0(S^2 \setminus \Delta) - 1 \leq k - 1,$$

and we have

$$\left| \bigcup_{i=1}^k \Gamma_i \right| - 2 = 2k + h_0(\Delta) - h_1(\Delta) - 2 \geq 2k + h_0(\Delta) + 1 - k - 2 \geq k.$$

It follows that Γ is a hypertree.

7.4. Suppose that Γ is not irreducible. Then one can find a subset of k black triangles $\Gamma_1, \dots, \Gamma_k$ as above with $1 < k < n - 2$ such that all inequalities above are equalities, i.e.,

$$h_0(S^2 \setminus \Delta) = k, \quad h_0(\Delta) = 1.$$

Hence, $S^2 \setminus \Delta$ has k connected components D_1, \dots, D_k . Moreover, using (7.2.1) we have $e(D_i) = 3$ for all i . Some (but not all) of the D_i are just white triangles \mathcal{K} , others are unions of black and white triangles. But all of them are simply-connected polygons, since $h_1(S^2 \setminus \Delta) = 0$ by Alexander duality (hence, $S^2 \setminus \Delta$ is simply connected).

Now it is clear that we are done: Let D be one of the connected components of $S^2 \setminus \Delta$ which is not a white triangle. But the boundary of D is a triangle, and it is clear that \mathcal{K} is a connected sum of two triangulations \mathcal{K}_1 and \mathcal{K}_2 glued along the boundary of D . Namely, \mathcal{K}_1 is formed by removing all triangles inside D and gluing a white triangle along the boundary of D instead, and \mathcal{K}_2 is formed by removing all triangles not in D and gluing a black triangle along the boundary of D instead.

The other way around, if \mathcal{K} is a connected sum of triangulations \mathcal{K}_1 and \mathcal{K}_2 , then Γ is not irreducible: just take the set S to be the set of all black triangles of \mathcal{K}_1 . \square

The proof of Theorem 7.1 shows the following:

Lemma 7.5. *If \mathcal{K} is an even triangulation of a sphere and D is a polygon such that any triangle inside D adjacent to a boundary edge of D is white (equivalently, D is one of the connected components of the complement to a union of black triangles in \mathcal{K}), then the number of edges of D is divisible by 3. Moreover, \mathcal{K} is irreducible if and only if whenever the number of edges of D is three, then D is a white triangle or the complement of a black triangle.*

We will prove in Corollary 8.4 that white and black hypertrees of any irreducible even triangulation give the same divisor on $\overline{M}_{0,n}$. We will now show that under a mild genericity assumption there are no other hypertrees that give the same divisor.

Definition 7.6. Let Γ be an irreducible hypertree composed of triples. We call Γ *generic* if for any triple $\{i, j, k\} \subset N$ that is not a hyperedge or a wheel (see Definition 4.8), we have

$$(7.6.1) \quad \text{cap}(\Gamma_{N \setminus \{i,j,k\}}) = n - 4,$$

where $\Gamma_{N \setminus \{i,j,k\}}$ is the collection of triples obtained from Γ by identifying vertices i, j , and k (and removing triples which contain two of the points i, j, k).

Theorem 7.7. *Let Γ, Γ' be generic hypertrees. If $D_\Gamma = D_{\Gamma'}$, then Γ' is irreducible and there exists a bicolored triangulation \mathcal{K} of S^2 such that Γ is its collection of black faces and Γ' is its collection of white faces. In this case, Γ uniquely determines the triangulation.*

Theorem 7.7 and Lemmas 7.8, 7.9 give a lower bound on the number of extremal rays of the effective cone of $\overline{M}_{0,n}$, namely, the number of generic non-spherical irreducible hypertrees plus half of the number of generic spherical irreducible hypertrees (on all subsets of N).

Lemma 7.8. *Let Γ be an irreducible hypertree on a subset K of N and consider the forgetful map $\pi_K : \overline{M}_{0,n} \rightarrow \overline{M}_{0,K}$. Then $\pi_K^{-1}D_\Gamma$ generates an extremal ray of $\overline{\text{Eff}}(\overline{M}_{0,n})$.*

Proof. We may assume without loss of generality that $K = \{1, \dots, k\}$ for $k \leq n$. By Theorem 4.3, the divisor D_Γ is irreducible. Therefore, the divisor $\pi_K^{-1}D_\Gamma$ is irreducible. Moreover, $\pi_{\Gamma \cup \{n+1\}}(D_\Gamma)$ has codimension at least two in $\overline{M}_{\Gamma \cup \{n+1\}}$. It is enough to construct a hypertree $\tilde{\Gamma}$ on the set N such that $\pi_K^{-1}D_\Gamma$ is in the exceptional locus of $\pi_{\tilde{\Gamma} \cup \{n+1\}}$. This will be the case if for example $\Gamma \subseteq \tilde{\Gamma}$. Let $\tilde{\Gamma} = \Gamma \cup \{\Gamma'_1, \dots, \Gamma'_{n-k}\}$ where

$$\Gamma'_1 = \{k + 1, 1, 2\}, \Gamma'_2 = \{k + 2, 1, 3\}, \dots, \Gamma'_{n-k} = \{n, 1, n - k\}. \quad \square$$

Lemma 7.9. *Let Γ be an irreducible hypertree on the set N . If for some forgetful maps $\pi : \overline{M}_{0,\tilde{N}} \rightarrow \overline{M}_{0,N}$ and $\pi' : \overline{M}_{0,\tilde{N}} \rightarrow \overline{M}_{0,N'}$ for subsets N and N' of \tilde{N} , we have*

$$\pi^{-1}(D_\Gamma) = \pi'^{-1}(D_{\Gamma'}),$$

for some irreducible hypertree Γ' on $N' \subseteq \tilde{N}$, then $N = N'$, $D_\Gamma = D_{\Gamma'}$.

Proof. Consider the divisor class of the pull-back D of $\pi^{-1}(D_\Gamma)$ to $\overline{M}_{0,|\tilde{N}|+1}$ in the Kapranov model with respect to the $|\tilde{N}| + 1$ marking. Using Theorem 4.2, we have

$$D = (d - 1)H - \sum_{i \in \tilde{N} \setminus N} (d - 1)E_i - \sum_{i \in N} (d - v_i)E_i - \dots,$$

where $v_i \geq 2$ is the valence of i in Γ . If

$$\pi^{-1}(D_\Gamma) = \pi'^{-1}(D_{\Gamma'}),$$

then $d = d'$ and by reading off the coefficients of E_i that are equal to $d - 1$, it follows that $N = N'$ and $D_\Gamma = D_{\Gamma'}$. \square

Proof of Theorem 7.7. Comparing the classes of D_Γ and $D_{\Gamma'}$ given in Theorem 4.2, we see that $d = d' = n - 2$, i.e., Γ' is also composed of triples, and for each $i \in N$, the hypertrees Γ and Γ' have the same valences v_i .

Let Ξ (resp., Ξ') be the collection of wheels of Γ (resp., Γ'). We claim that

$$\Gamma \cup \Xi = \Gamma' \cup \Xi'.$$

Let m (resp., m') be the coefficients in the class of D_Γ (resp., $D_{\Gamma'}$), as in Theorem 4.2. Then by (4.2.3) and (4.2.1), $m'_{N \setminus \{i,j,k\}} \geq 1$ for any triple $\{i, j, k\}$ that is a hyperedge or a wheel in Γ' . But since Γ is a generic hypertree, using Lemma 4.9, we have $m_{N \setminus \{i,j,k\}} = 0$ for any triple $\{i, j, k\}$ which is not a hyperedge or a wheel. This proves that $\Gamma' \cup \Xi' \subset \Gamma \cup \Xi$. Since both Γ, Γ' are generic hypertrees, this proves the claim.

Suppose $\Gamma \neq \Gamma'$. Without loss of generality, we can assume that

$$\Gamma_1 \in \Gamma \setminus \Gamma'.$$

We are going to construct a finite bi-colored 2-dimensional polyhedral complex \mathcal{K} inductively, as the union of complexes $\mathcal{K}_1 \subset \mathcal{K}_2 \subset \dots$. On each step, any black face of \mathcal{K}_i is going to be a hyperedge in Γ and a wheel in Γ' , and vice versa for the white faces.

Let us define \mathcal{K}_1 . Its vertices are indexed by Γ_1 . Since Γ_1 is a wheel in Γ' , it can be identified with a triangle in a unique way, where the edges of the triangle are precisely the intersections (with two elements) of Γ_1 with the hyperedges of Γ' . So we let \mathcal{K}_1 be this polygon, colored black.

Next we define an inductive step. Suppose \mathcal{K}_n is given. Take a face X . Then X is either black or white. The construction is absolutely symmetric, so let us suppose that X is black. Then the set of vertices of X is a hyperedge in Γ and a wheel in Γ' . Moreover, we will make sure that, in our inductive construction, the edges of X are exactly the intersections (with two elements) of X with the hyperedges of Γ' . Notice that this holds for \mathcal{K}_1 .

Let $\{a, b\} \subset X$ be an edge that is not an edge of some white face. If any edge of X is also an edge of some white face, then discard X , and try another face. If we cannot find a face with an edge that is not an edge of some face of an opposite color, then the algorithm stops.

Since X is a wheel of Γ' , $\{a, b\}$ is the intersection of X with a unique hyperedge Y of Γ' . This will be our next face. Since $a, b \in X$, X is a unique hyperedge in Γ containing a, b . So Y must be a wheel in Γ . Therefore, we can identify Y with the vertices of a triangle such that its edges are identified with the (2-pointed) intersections of Y with the hyperedges in Γ . For example, (a, b) will be one of these edges. We define \mathcal{K}_{n+1} as \mathcal{K}_n with Y added as a new white polygon.

We have to check that \mathcal{K}_{n+1} is a bi-colored polygonal complex, i.e., that any two faces of \mathcal{K}_{n+1} share at most two vertices, and if they share exactly two vertices, then in

fact they share an edge and are colored differently. So let Z be a face of \mathcal{K}_n such that $|Z \cap Y| > 1$ but $Z \neq Y$. Then Z cannot be a hyperedge of Γ' , so Z is a black face. Since Z is a wheel of Γ' , $Z \cap Y$ is an edge of Z , and since Y is a wheel in Γ , $Z \cap Y$ is an edge of Y .

At some point this algorithm stops. Let \mathcal{K} be the resulting polygonal complex. Let $\{\Gamma_i | i \in S\}$ (resp., $\{\Gamma'_i | i \in S'\}$) be the collection of its black faces (resp., white faces) for some $S \subset \{1, \dots, n-2\}$ (resp., $S' \subset \{1, \dots, n-2\}$). Let

$$e = \sum_{i \in S} |\Gamma_i| = \sum_{i \in S'} |\Gamma'_i|$$

be the number of edges of \mathcal{K} and let

$$v = \left| \bigcup_{i \in S} \Gamma_i \right| = \left| \bigcup_{i \in S'} \Gamma'_i \right|$$

be the number of its vertices. Finally, let $f = f_b + f_w$ be the number of its faces, where $f_b = |S|$ (resp., $f_w = |S'|$) is the number of black faces (resp., white faces).

Notice that a priori \mathcal{K} is not necessarily homeomorphic to a closed surface, because at some vertices of \mathcal{K} several sheets can come together. At these points, the link of \mathcal{K} is homeomorphic to the disjoint union of several circles. Let $\overline{\mathcal{K}} \rightarrow \mathcal{K}$ be the “normalization” obtained by separating these sheets. Then $\overline{\mathcal{K}}$ is homeomorphic to a closed surface. Let $\bar{v} \geq v$ be the number of vertices in $\overline{\mathcal{K}}$. We have

$$\begin{aligned} 2(\bar{v} - e + f) &\geq 2v - 2e + 2f_b + 2f_w \\ &= \left| \bigcup_{i \in S} \Gamma_i \right| + \left| \bigcup_{i \in S'} \Gamma'_i \right| - \sum_{i \in S} |\Gamma_i| - \sum_{i \in S'} |\Gamma'_i| + 2|S| + 2|S'| \\ &= \left| \bigcup_{i \in S} \Gamma_i \right| - \sum_{i \in S} (|\Gamma_i| - 2) + \left| \bigcup_{i \in S'} \Gamma'_i \right| - \sum_{i \in S'} (|\Gamma'_i| - 2) \geq 4 \end{aligned}$$

since Γ and Γ' are hypertrees. Since they are irreducible hypertrees, the inequality is strict unless $S = S' = \{1, \dots, n-2\}$. It follows that

$$\chi(\overline{\mathcal{K}}) \geq 2,$$

and the inequality is strict unless $S = S' = \{1, \dots, n-2\}$. But the Euler characteristic cannot be bigger than 2, with equality if and only if $\overline{\mathcal{K}}$ is a sphere. It follows that $\overline{\mathcal{K}} = \mathcal{K}$ is a bi-colored triangulation of a 2-sphere which uses all hyperedges in Γ as black faces and all hyperedges in Γ' as white faces.

It remains to show that Γ uniquely determines the triangulation. It is enough to show that Γ' is the set of all wheels Ξ of Γ . Since $\Gamma' \subseteq \Xi$, it is enough to show that there are no wheels in Γ other than the set of white triangles in \mathcal{K} . Assume that there exists a wheel $\{i, j, k\}$ which is not a white triangle. Let D be one of the two polygons on the sphere bordered by this wheel. By switching between the two polygons, we may assume that at least two of the three edges of D are bordered by two black triangles which lie outside of D . If the remaining black triangle bordering D lies on the outside of D , this contradicts the

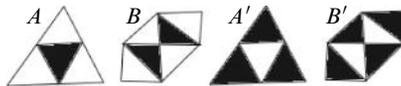
irreducibility of Γ . If the remaining black triangle lies on the inside of D , then we obtain a polygon bordered by white triangles and having four edges, which contradicts Lemma 7.5. \square

We now construct both spherical and non-spherical generic hypertrees.

Definition 7.10. Let \mathcal{H} be an even triangulation. Let D be a polygon such that any triangle inside D adjacent to a boundary edge of D is white.

We call \mathcal{H} a *generic triangulation* if:

- \mathcal{H} is irreducible, i.e., if D has three edges, then D is a white triangle or the complement of a black triangle (see Lemma 7.5).
- If D has six edges, then D is either a hexagon A or B or the complement of a hexagon A' or B' from the following picture:



Remark 7.11. Genericity means that vertices are sprinkled on the sphere sufficiently densely. We did not try to give a combinatorial classification of generic triangulations, although this is perhaps possible. But to give a flavor of what is going on, suppose \mathcal{H} is any even triangulation and let \mathcal{H}' be a “quadrupled” even triangulation obtained by the following procedure: take all vertices in \mathcal{H} and add a midpoint of any edge of \mathcal{H} as a new point of \mathcal{H}' . For any black (resp., white) triangle $T = \{a, b, c\}$ of \mathcal{H} , the triangulation \mathcal{H}' has black (resp., white) triangles $\{a, b', c'\}$, $\{a', b, c'\}$, and $\{a', b', c\}$ and a white (resp., black) triangle $\{a', b', c'\}$, where a', b', c' are new points in T opposite to vertices a, b, c , see Figure 4. It is not hard to see that after quadrupling \mathcal{H} several times the triangulation becomes generic. Indeed, any closed path with six edges will happen either in the region of the triangulation that looks like a standard A_2 -triangulated \mathbb{R}^2 , in which case D is a hexagon A or A' , or this path loops around a vertex of valence $\neq 6$. In this case the valence must be equal to 4, and we have a hexagon B or B' . In fact, quadrupling just once is enough ([H]).

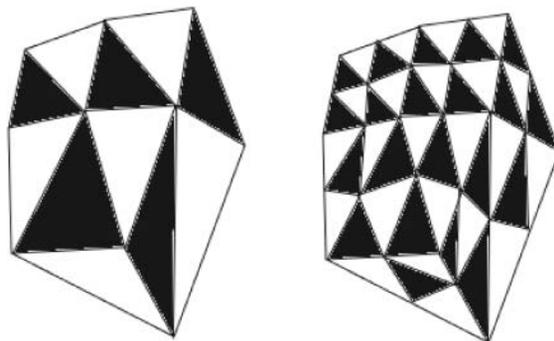


Figure 4. Quadrupling a triangulation.

Lemma 7.12. *Let \mathcal{K} be a generic triangulation and let Γ be its collection of black triangles. Then Γ is a generic hypertree, except when $n = 8$ and \mathcal{K} is the triangulation given by the bipyramid (see Section 9).*

Remark 7.13. The genericity assumption in Lemma 7.12 is necessary: the bipyramid is easily seen to not be a generic triangulation for $n > 8$ (for example there are many loops with six edges with black triangles on one side of it that pass once through the north pole and once through the south pole). We will show in Section 9 that the corresponding divisor is a pull-back of the “Brill–Noether divisor” for a certain map $\bar{M}_{0,n} \rightarrow \bar{M}_{n-3}$, and consequently its symmetry group is much larger than the dihedral group. This divisor can be realized by various hypertrees Γ' obtained from Γ by permuting equatorial points. By Lemma 7.12, the bipyramid for $n = 8$ is the only generic triangulation that does not correspond to a generic hypertree.

Proof of Lemma 7.12. We write $a \leftrightarrow b$ if the vertices a and b are connected by an edge. Up to symmetries, there are three possible cases.

Case X. ij and jk are both edges of black triangles. These triangles are removed in $\Gamma_{N \setminus \{i,j,k\}}$.

Case Y. ij is an edge of a black triangle, which will be removed in $\Gamma_{N \setminus \{i,j,k\}}$, but $i \not\leftrightarrow k$ and $j \not\leftrightarrow k$. We also remove a black triangle adjacent to k as follows: if i, j, k are vertices of the hexagon A' , then we remove the black triangle inside the hexagon adjacent to k ; in all other cases, we remove a random black triangle adjacent to k .

Case Z. $i \not\leftrightarrow j$, $j \not\leftrightarrow k$, and $i \not\leftrightarrow k$. In this case we remove two black triangles adjacent to the same point (it could be i, j , or k) according to the following rules. If one of the points i, j , or k has valence 2 (see Definition 1.8), then we remove both triangles adjacent to this point (any of i, j, k is going to work). If each of the points i, j, k has valence more than 2, but these points are vertices of the hexagon A' , then we remove the black triangle inside the hexagon adjacent to i and any other black triangle adjacent to i . In any other case we just remove two random black triangles adjacent to i .

We claim that the remaining $n - 4$ triangles $\tilde{\Gamma}$ form a hypertree if we identify $i = j = k$. Let $S \subset \tilde{\Gamma}$ be a proper subset of s black triangles, with $1 < s < n - 4$. It is enough to show that S covers at least $s + 2$ vertices (after we identify $i = j = k$). Let Δ be the union of the triangles in S before the identification. Since Γ is irreducible, Δ contains at least $s + 3$ vertices of N . So it suffices to prove the following:

Claim 7.14. *If $i, j, k \in \Delta$, then Δ contains at least $s + 4$ vertices of N .*

By 7.2, this claim is equivalent to the following more simple

Claim 7.15. *The complement $S^2 \setminus \Delta$ contains either a connected component with at least nine sides or at least two connected components with at least six sides each (by 7.2, the number of sides is always divisible by 3).*

We argue by contradiction. Note that we remove two triangles, and a connected component of $S^2 \setminus \Delta$ that contains any of them has at least six edges. Therefore both removed

triangles belong to the same connected component, call it D , with six edges (and all other connected components are white triangles). Recall that $i, j, k \in \Delta$ and $\Delta \subset S^2 \setminus D$.

We know how all hexagons look like: D must be either the “inside” of a hexagon A or B or the “outside” of a hexagon A' or B' . The hexagon A is excluded because it contains only one black triangle.

The hexagon B contains two black triangles inside, so they must be the removed triangles. Since $i, j, k \in \Delta$, it must be that i, j, k are on the boundary of the hexagon. In cases X and Y the removed triangles contain i, j, k ; hence, two opposite vertices of the hexagon B are excluded. In this case it follows that one of i, j, k is connected by an edge to the other two. This is only possible in case X. But in case X the removed triangles have in common only j ; hence, j must be strictly inside the hexagon, which is a contradiction. Finally, case Z is impossible because the removed triangles have in common i , therefore i must be the point strictly inside the hexagon, which is a contradiction.

Suppose that D is the outside of a hexagon A' or B' . Since the removed triangles are contained in D , it follows that no two of i, j, k can be connected by a black triangle inside the hexagon.

Assume D is the outside of a hexagon A' . Then i, j, k are the three vertices of A' with no two of them connected by an edge. In case Y and case Z, one of the removed triangles is inside A' , which is a contradiction.

Assume we are in case X. Let a (resp., b , resp., c) be the middle vertex (on the boundary of A') between i, j (resp., j, k , resp., i, k). We claim that i, j, a and j, k, b must form white triangles. (Assume $\{i, j, a\}$ is not a white triangle. Consider the polygon Q bordered by the white triangles that contain the edges $\{i, a\}, \{j, a\}, \{i, j\}$. Then Q has either three or four edges. This is a contradiction. The other case is identical.)

Consider the complement of the polygon P bordered by black triangles $\{i, a, c\}, \{k, b, c\}$ and the two black triangles adjacent to the edges $\{i, j\}$ and $\{j, k\}$. Since \mathcal{H} is a generic triangulation, it must be that P is either the complement of a hexagon A' or B' (in which case P contains two vertices strictly in its interior, while A', B' do not; hence, a contradiction) or P is the inside of a hexagon A or B . This completely determines the triangulation; in case A we must have $n = 8$, while in case B we have $n = 9$. It is easy to see that in case A this gives the bipyramid triangulation, and that case B cannot happen for an irreducible hypertree.

Assume now that D is the outside of a hexagon B' . Since no two of i, j, k can be connected by a black triangle inside the hexagon and since i, j, k are inside the hexagon, it follows that the point strictly in the interior of B' must be one of i, j, k . In cases X, Y since i, j, k belong to the removed triangles, which are in D , it follows that i, j, k are on the boundary of B' , which is a contradiction. In case Z, note that since the valence of the interior point is 2, the removed triangles must be the two black triangles inside B' , which is a contradiction. \square

7.16. W. Thurston [Th] suggests an approach for the classification of triangulations of the sphere based on hyperbolic geometry. Moreover, he gives a complete classification

for triangulations with $v_i = 2$ or 3 for all vertices i . It would be interesting to see how irreducible and generic triangulations fit in his classification.

We have not tried to classify all non-spherical hypertrees. It is easy to see that just choosing a random collection of triples is not going to work: one of the results in the theory of random hypergraphs is that they are almost surely disconnected. It is easy to see that disconnected hypertrees do not satisfy (\ddagger) . But perhaps one can enumerate all hypertrees inductively, using some simple “add a vertex” procedures. Here is an example of such a construction. The number of irreducible hypertrees produced this way grows very rapidly as n goes to infinity.

7.17. Construction. Suppose that Γ' is an irreducible hypertree on N with triples only. After renumbering, we can assume that n belongs to only two triples, namely to Γ'_{n-3} and Γ'_{n-2} . Suppose also that $n - 1 \in \Gamma'_{n-2}$. We define $n - 1$ triples for $k = n + 1$ as follows: $\Gamma_i := \Gamma'_i$ for $i = 1, \dots, n - 3$; if $\Gamma'_{n-2} = \{i, n - 1, n\}$, then we define $\Gamma_{n-2} := \{i, n - 1, n + 1\}$; and we define $\Gamma_{n-1} := \{a, n, n + 1\}$, where a is any index in $N \setminus (\Gamma_{n-2} \cup \Gamma_{n-3})$, see Figure 5.



Figure 5

Proposition 7.18. Γ is an irreducible hypertree.

Proof. Suppose $I \subset \{1, \dots, n - 1\}$, $1 < |I| < n - 1$. Consider several cases. If $I \subset \{1, \dots, n - 3\}$, then

$$\left| \bigcup_{i \in I} \Gamma_i \right| = \left| \bigcup_{i \in I} \Gamma'_i \right| \geq |I| + 3,$$

and we are done. If $I = I' \cup \{n - 2\}$ (resp., $I = I' \cup \{n - 1\}$), where $I' \subset \{1, \dots, n - 3\}$, then

$$\left| \bigcup_{i \in I} \Gamma_i \right| \geq \left| \bigcup_{i \in I'} \Gamma'_i \right| + 1,$$

because $n + 1$ belongs to the first union but does not belong to the second union. So again we are done unless $|I'| = 1$, in which case the claim is easy.

It remains to consider the case $I = I' \cup \{n - 2, n - 1\}$, where $I' \subset \{1, \dots, n - 3\}$ (and note that $|I'| < n - 3$). If I' is empty, then the claim is easy. Otherwise, let

$I'' = I' \cup \{n - 2\}$. Then $1 < |I''| < n - 2$ and so

$$\left| \bigcup_{i \in I''} \Gamma'_i \right| \geq |I''| + 3.$$

But

$$\bigcup_{i \in I} \Gamma_i \cong \bigcup_{i \in I''} \Gamma'_i \sqcup \{n + 1\}.$$

So Γ is an irreducible hypertree. \square

Lemma 7.19. *Let Γ' be an irreducible hypertree composed of triples and let Γ be the irreducible hypertree obtained from Γ' by the inductive Construction 7.17. If Γ' is generic, then Γ is generic.*

Proof. Let $\{i, j, k\}$ be a triple in $N \cup \{n + 1\}$ that is not a triple, nor a wheel in Γ . Denote by $\tilde{\Gamma}_\alpha$ the triple Γ_α obtained by identifying i, j, k with p , with the convention that we drop the $\tilde{\Gamma}_\alpha$'s that are not triples. We prove that we can find $n - 3$ triples $\tilde{\Gamma}_\alpha$ that satisfy (\ddagger) .

Consider the case when $n + 1 \in \{i, j, k\}$, say $k = n + 1$: If $\{i, j\}$ is contained in some Γ_α for $\alpha \in \{1, \dots, n - 3\}$, say Γ_{n-3} , then we take as our $n - 3$ triples $\tilde{\Gamma}_1, \dots, \tilde{\Gamma}_{n-4}$ and one of $\tilde{\Gamma}_{n-2}, \tilde{\Gamma}_{n-1}$ (one that is a triple; for example, since $\Gamma_{n-2} \cap \Gamma_{n-1} = \{n + 1\}$ and $\{i, j, n + 1\}$ is not a wheel in Γ , one of $\Gamma_{n-2}, \Gamma_{n-1}$ does not contain i, j). If $\{i, j\}$ is not contained in any of $\Gamma_1, \dots, \Gamma_{n-3}$, we take $\tilde{\Gamma}_1, \dots, \tilde{\Gamma}_{n-3}$ as our triples. The result follows from the fact that for any $T \subset \{1, \dots, n - 3\}$, since $n + 1 \notin \bigcup_{\alpha=1}^{n-3} \Gamma_\alpha$, we have

$$\left| \bigcup_{\alpha \in T} \tilde{\Gamma}_\alpha \right| \geq \left| \bigcup_{\alpha \in T} \Gamma_\alpha \right| - 1 \geq |T| + 3 - 1 = |T| + 2.$$

Adding one of $\tilde{\Gamma}_{n-2}, \tilde{\Gamma}_{n-1}$ adds the index $n + 1$ to the union, and condition (\ddagger) is still satisfied. The case when $n \in \{i, j, k\}$, $n + 1 \notin \{i, j, k\}$ is similar: we take $\tilde{\Gamma}_1, \dots, \tilde{\Gamma}_{n-4}$ (note, $n \notin \bigcup_{\alpha=1}^{n-4} \Gamma_\alpha$) and $\tilde{\Gamma}_{n-1}$ as our triples.

Consider now the case when $n, n + 1 \notin \{i, j, k\}$. Then $\{i, j, k\}$ is not a triple, nor a wheel in Γ' . Since Γ' is a generic hypertree, there are $n - 4$ triples from Γ' which after identifying i, j, k with p , satisfy (\ddagger) .

If the $n - 4$ triples are also triples in Γ (i.e., Γ'_{n-2} is not among them), then adding one Γ_{n-1} to them will do. Assume the contrary. Since $|\tilde{\Gamma}'_{n-2}| = 3$, it follows that $|\tilde{\Gamma}_{n-2}| = 3$. We claim that the remaining $n - 5$ triples and $\tilde{\Gamma}_{n-2}, \tilde{\Gamma}_{n-1}$ will do the job. Let T be a subset of the $n - 5$ remaining triples. Clearly, $\{\tilde{\Gamma}_\alpha\}_{\alpha \in T}$ satisfy (\ddagger) . Adding one of $\tilde{\Gamma}_{n-2}, \tilde{\Gamma}_{n-1}$ to $\{\tilde{\Gamma}_\alpha\}_{\alpha \in T}$ will not violate (\ddagger) . But $\{\tilde{\Gamma}_\alpha\}_{\alpha \in T}, \tilde{\Gamma}_{n-2}, \tilde{\Gamma}_{n-1}$ also satisfy (\ddagger) :

$$\left| \bigcup_{\alpha \in T} \tilde{\Gamma}_\alpha \cup \tilde{\Gamma}_{n-2} \cup \tilde{\Gamma}_{n-1} \right| \geq \left| \bigcup_{\alpha \in T} \tilde{\Gamma}_\alpha \cup \tilde{\Gamma}'_{n-2} \cup \{n + 1\} \right| \geq (|T| + 1) + 2 + 1.$$

This finishes the proof. \square

8. Determinantal equations

In this section we give simple determinantal equations of hypertree divisors in $\overline{M}_{0,n}$ and then use them to show that black and white hypertrees of a spherical hypertree give the same divisor in $\overline{M}_{0,n}$.

We consider only the case when hyperedges are triples. Fix a hypertree

$$\Gamma = \{\Gamma_1, \dots, \Gamma_{n-2}\}$$

on the set $\{1, \dots, n\}$. We work in “homogeneous coordinates” on $M_{0,n}$, i.e., we represent a point of $M_{0,n}$ by n roots x_1, \dots, x_n of a binary n -form.

Proposition 8.1. *Let A be an $(n - 2) \times n$ matrix with the following rows (well-defined up to sign): if $\Gamma_\alpha = \{i, j, k\}$, then*

$$A_{\alpha i} = x_j - x_k, \quad A_{\alpha j} = x_k - x_i, \quad A_{\alpha k} = x_i - x_j.$$

Then D_Γ is given by the vanishing of any $(n - 3) \times (n - 3)$ minor of A obtained by deleting a row and three columns with non-zero entries in that row.

Example 8.2. Consider the unique (up to symmetry) hypertree for $n = 7$ with hyperedges

$$\Gamma = \{712, 734, 756, 135, 246\}.$$

Then we have

$$A = \begin{bmatrix} x_2 - x_7 & x_7 - x_1 & 0 & 0 & 0 & 0 & x_1 - x_2 \\ 0 & 0 & x_4 - x_7 & x_7 - x_3 & 0 & 0 & x_3 - x_4 \\ 0 & 0 & 0 & 0 & x_6 - x_7 & x_7 - x_5 & x_5 - x_6 \\ x_3 - x_5 & 0 & x_5 - x_1 & 0 & x_1 - x_3 & 0 & 0 \\ 0 & x_4 - x_6 & 0 & x_6 - x_2 & 0 & x_2 - x_4 & 0 \end{bmatrix}$$

and D_Γ is given by the equation

$$\begin{aligned} & -x_7^2 x_2 x_3 + x_7 x_1 x_2 x_3 + x_7^2 x_1 x_4 - x_7 x_1 x_2 x_4 - x_7 x_1 x_3 x_4 + x_7 x_2 x_3 x_4 \\ & + x_7^2 x_2 x_5 - x_7 x_1 x_2 x_5 - x_7^2 x_4 x_5 + x_1 x_2 x_4 x_5 + x_7 x_3 x_4 x_5 - x_2 x_3 x_4 x_5 - x_7^2 x_1 x_6 \\ & + x_7 x_1 x_2 x_6 + x_7^2 x_3 x_6 - x_1 x_2 x_3 x_6 - x_7 x_3 x_4 x_6 + x_1 x_3 x_4 x_6 + x_7 x_1 x_5 x_6 \\ & - x_7 x_2 x_5 x_6 - x_7 x_3 x_5 x_6 + x_2 x_3 x_5 x_6 + x_7 x_4 x_5 x_6 - x_1 x_4 x_5 x_6 = 0. \end{aligned}$$

Proof. This is very simple. Fix different points $x_1, \dots, x_n \in \mathbb{A}^1$. The condition that these points can be obtained by projecting a hypertree curve is as follows: there exist points $y_1, \dots, y_n \in \mathbb{A}^1$ such that a triple of points

$$(x_i, y_i), \quad (x_j, y_j), \quad (x_k, y_k)$$

lie on the line for any hyperedge $\Gamma_\alpha = \{i, j, k\}$. This can be expressed by the vanishing of the determinant

$$-\det \begin{bmatrix} 1 & x_i & y_i \\ 1 & x_j & y_j \\ 1 & x_k & y_k \end{bmatrix} = y_i(x_j - x_k) + y_j(x_k - x_i) + y_k(x_i - x_j) = 0.$$

This gives a homogeneous system of linear equations on y_i 's with the matrix of coefficients A . Notice that it has a 2-dimensional subspace of trivial solutions (obtained by placing all points p_i along some line on the plane). Thus the condition that there exists a planar realization of Γ with projections x_1, \dots, x_n is given by the vanishing of any non-trivial $(n - 3) \times (n - 3)$ minor. For example, fix a row that corresponds to $\Gamma_\alpha = \{i, j, k\}$. We can force $y_i = y_j = y_k = 0$, as these points have to lie on a line anyway. Then we get a system of linear equations in the remaining $n - 3$ variables and the condition is that this system has a non-trivial solution. This gives the minor as in the statement of the theorem. \square

These equations do not explain why black and white hypertrees of the spherical hypertree yield the same divisor: their matrices A_B and A_W will be vastly different. For example, one can check that $\text{rk } A_B \neq \text{rk } A_W$ for some values of variables x_1, \dots, x_n . Fortunately, D_Γ has another determinantal equation.

Proposition 8.3. *Let G be a 2-dimensional simplicial complex with simplices $\Gamma_1, \dots, \Gamma_{n-2}$ (oriented arbitrarily). Then $H_1(G, \mathbb{Z}) = \mathbb{Z}^{n-3}$. We choose a generating set of paths P_1, \dots, P_m (one can take $m = n - 3$), where*

$$P_i = (\alpha_i^1 \rightarrow \alpha_i^2 \rightarrow \dots \rightarrow \alpha_i^r \rightarrow \alpha_i^{r+1} = \alpha_i^1)$$

is a path in $\{1, \dots, n - 2\}$ such that $\Gamma_{\alpha_j^i} \cap \Gamma_{\alpha_{j+1}^i} \neq \emptyset$ for any j . Consider an $m \times (n - 2)$ -matrix B such that $B_{i\alpha} = 0$ if $\alpha \notin P_i$ and $B_{i\alpha} = x_k - x_l$ if $\alpha = \alpha_i^s \in P_i$, where $k = \Gamma_{\alpha_i^s} \cap \Gamma_{\alpha_i^{s+1}}$ and $l = \Gamma_{\alpha_i^s} \cap \Gamma_{\alpha_i^{s-1}}$. Then D_Γ is given by vanishing of any non-trivial $(n - 3) \times (n - 3)$ -minor of B .

Corollary 8.4. *Black and white hypertrees of a spherical hypertree give the same divisor on $\bar{M}_{0,n}$.*

Proof of the corollary. Notice that G is just the ‘‘black’’ part of the bi-colored triangulation of the sphere. We orient all black and white triangles according to an orientation of the sphere. We can choose a generating set of $H_1(G, \mathbb{Z})$ to be given by cycles around white triangles. Then B has the following very simple form. It has rows indexed by white triangles, columns indexed by black triangles. The entry B_{wb} is equal to zero if triangles w and b do not share an edge, and $B_{wb} = x_i - x_j$ if w and b intersect along the edge $[ij]$ (oriented according to the orientation of b). Now notice that the corresponding matrix for the white hypertree is just the minus transposed matrix $-B^t$. \square

Example 8.5. Consider the spherical hypertree from Example 1.6. The matrix B looks as follows (we skip zero entries):

Now let us explain the left-hand side of Figure 6. For any tri-partition, consider the map $\overline{M}_{0,6} \rightarrow \overline{M}_3$ obtained by gluing points in pairs



Keel defined a divisor $D_K \subset M_{0,6}$ as the pull-back of the hyperelliptic locus in \overline{M}_3 . This locus is divisorial. By the theory of admissible covers ([HM]), a hyperelliptic involution on the general genus 3 curve in the limit induces an involution of \mathbb{P}^1 that exchanges points in the pairs (12), (34), and (56). The quotient by this involution is a degree 2 map $\mathbb{P}^1 \rightarrow \mathbb{P}^1$, which can be realized by embedding \mathbb{P}^1 in \mathbb{P}^2 as a plane conic and projecting it from a point. It follows that $D_K \subset M_{0,6}$ is the locus of six points on a conic such that the chords connecting pairs of points (12), (34), and (56) are concurrent.

It is quite amazing that these two descriptions give the same divisor:

Proposition 9.1. $D_K = D_\Gamma$.

Proof. Passing to the projectively dual picture, let $A_1, A_2, A_3, A_4 \in \mathbb{P}^2$ be general points and let $L \subset \mathbb{P}^2$ be a general line. Let $\{L_{ij}\}$ be six lines connecting pairs of points A_i, A_j . The claim is that there exists an involution of L that permutes $L \cap L_{ij}$ and $L \cap L_{i'j'}$ if $\{i, j\} \cup \{i', j'\} = \{1, 2, 3, 4\}$. More precisely, we prove that $D_\Gamma \subset D_K$. Since D_K is an irreducible divisor (this is easy to see by the above description), the proposition follows.

The proof is illustrated in Figure 7. Let $T : \mathbb{P}^2 \dashrightarrow \mathbb{P}^2$ be the standard Cremona transformation with the base locus $\{A_1, A_2, A_3\}$. Then T contracts lines $L_{23}, L_{13},$ and L_{12} to points A'_1, A'_2, A'_3 . Let $A'_4 = T(A_4)$.

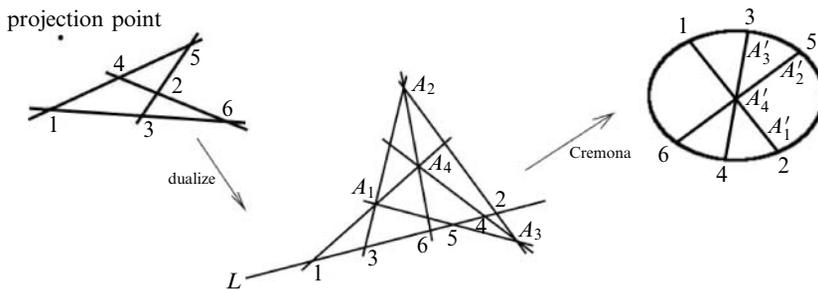


Figure 7. $D_K = D_\Gamma$.

Notice that $T(L) = C$ is a conic that passes through A'_1, A'_2, A'_3 . These points are the images of the points $L \cap L_{23}, L \cap L_{13},$ and $L \cap L_{12}$, respectively. For any $i = 1, 2, 3$, the map T sends the line L_{i4} to the line that passes through A'_i and A'_4 . So the diagonals connecting A'_i to $T(L_{i4} \cap L)$ are concurrent. \square

Remark 9.2. The equation of D_K was found by Joubert [Jo] in 1867. A point of $M_{0,6}$ is given by six roots x_1, \dots, x_6 of a binary sextic. Put them on the Veronese conic. This

gives six points $p_i = (1, x_i, x_i^2)$. The equation of the line $\langle p_i, p_j \rangle$ is

$$\frac{1}{x_j - x_i} \det \begin{bmatrix} X & Y & Z \\ 1 & x_i & x_i^2 \\ 1 & x_j & x_j^2 \end{bmatrix} = X(x_i x_j) - Y(x_i + x_j) + Z = 0.$$

The condition that the three lines are concurrent is

$$(9.2.1) \quad \det \begin{bmatrix} x_1 x_2 & x_1 + x_2 & 1 \\ x_3 x_4 & x_3 + x_4 & 1 \\ x_5 x_6 & x_5 + x_6 & 1 \end{bmatrix} = 0.$$

After some calculations, this gives

$$(9.2.2) \quad (14)(36)(25) + (16)(23)(45) = 0,$$

where we use the classical bracket notation $(ij) = x_i - x_j$. The equation for D_Γ is of course the same, see 8 and [St], p. 93.

Remark 9.3. In fact D_K was known earlier. Cayley [Ca] studied in 1856 Hilbert functions of graded algebras (using a different language) and computed the Hilbert function of the algebra of invariants of binary sextics:

$$h(k[\text{Sym}^6 k^2]^{\text{SL}_2}) = \frac{1 - x^{30}}{(1 - x^2)(1 - x^4)(1 - x^6)(1 - x^{10})(1 - x^{15})}.$$

This led him to the (correct) prediction that this algebra is generated by invariants A, B, C, D, E of degrees 2, 4, 6, 10, 15 with a single relation

$$E^2 = f(A, B, C, D)$$

for some polynomial f . Salmon [S] computed in 1866 these invariants and proved (page 210) that E has a very simple meaning: $E = 0$ if and only if roots of the sextic are in involution! We are not specifying a tri-partition here, so any of the 15 tri-partitions can occur. Salmon computes (page 275) an expression of E in terms of roots of the sextic: E is a product of 15 determinants (9.2.1), one determinant for each tri-partition $(ij)(kl)(mn)$.

One can ask if there are other hypertree divisors with similar “dual” meaning as pull-backs of Brill–Noether (or perhaps Koszul) divisors on \bar{M}_g . We will show that this is so for the easiest spherical hypertree one can draw: the bipyramid. We will leave it to the reader to find further examples.

Let $n = 2k + 2$. A hypertree curve is illustrated in Figure 8 (for $n = 12$). We label lines by $A_0 = B_0, A_i, B_i$ ($i = 1, \dots, k - 1$), and $A_k = B_k$. The labels are chosen so that the point 1 (resp., the point 2) belongs to the lines A_i, B_i for i even (resp., odd) and such that

the points $4, 5, \dots, 3 + (n - 2/2)$ are obtained by intersecting lines

$$A_0 = B_0 \rightarrow B_1 \rightarrow \dots \rightarrow B_k = A_k$$

while the points $4 + (n - 2/2), \dots, n, 3$ are obtained by intersecting

$$B_k = A_k \rightarrow A_{k-1} \rightarrow \dots \rightarrow A_0 = B_0.$$

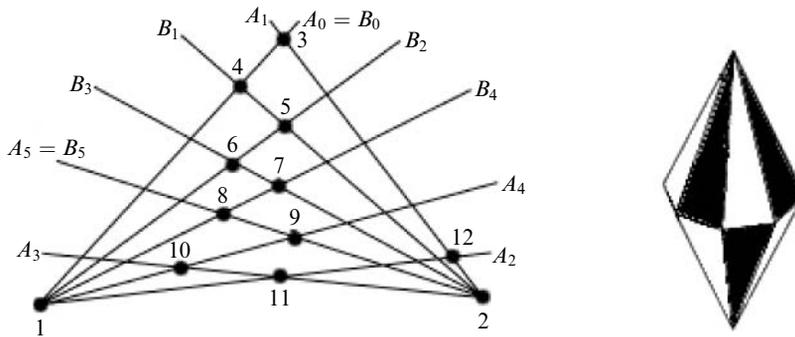


Figure 8. Bipyramid hypertree for $n = 12$.

The bipyramid determines a tri-partition

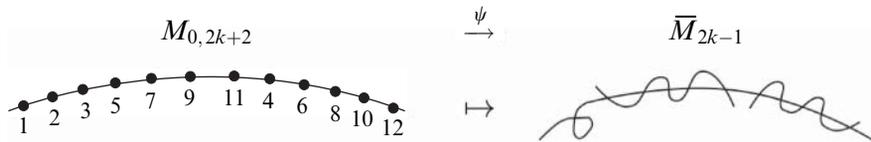
$$\{1, \dots, n\} = \{1, 2\} \cup X \cup Y$$

into two poles (in our example 1 and 2) and two “alternating” subsets X and Y of the equator with $|X| = |Y| = k$. In our example $k = 5$,

$$X = \{3, 5, 7, 9, 11\} \quad \text{and} \quad Y = \{4, 6, 8, 10, 12\}.$$

Let $D_\Gamma \subset \bar{M}_{0,n}$ be the corresponding hypertree divisor.

Definition 9.4. Consider the map



obtained by gluing the poles of \mathbb{P}^1 and then gluing to it two copies of \mathbb{P}^1 with k marked points on each one, along points of parts X and Y of the tri-partition. Let $D_K \subset M_{0,2k+2}$ be the pull-back of the Brill–Noether divisor in \bar{M}_{2k-1} that parametrizes k -gonal curves.²⁾

²⁾ If $k \geq 4$, then the attached \mathbb{P}^1 (and hence, the map ψ) are not uniquely defined. However, we will see that D_K does not depend on any choices.

Proposition 9.5. $D_K = D_\Gamma$.

Remark 9.6. It is well known that the Brill–Noether divisor on \overline{M}_{2k-1} is extremal for $k \leq 5$. However, for $k \geq 6$ the Brill–Noether divisor is not extremal ([Fa]). The proposition shows that nevertheless, the proper transform of the Brill–Noether divisor via the map ψ is an extremal divisor on $\overline{M}_{0,2k+2}$. See also Remark 10.1 and the examples in Section 10.

Proof. Using the theory of admissible covers, we can identify D_K with a locus in $M_{0,n}$ such that the corresponding \mathbb{P}^1 with n marked points admits a g_k^1 with members X, Y , and Z such that $1, 2 \in Z$. In other words, D_K parametrizes n -tuples $\{p_1, \dots, p_n\}$ of points on a rational normal curve

$$C \subset \mathbb{P}^k$$

such that

$$(9.6.1) \quad \langle p_1, p_2 \rangle \cap \langle p_i \rangle_{i \in X} \cap \langle p_i \rangle_{i \in Y} \neq \emptyset.$$

It is not hard to see that D_K is irreducible (D_K can be parametrized by an open in $(\mathbb{P}^1)^{n-1}$, as the markings p_i for $i = 1, \dots, n-1$ determine p_n). So it remains to show that $D_\Gamma \subset D_K$. Consider n points $p_1, \dots, p_n \in \mathbb{P}^1$ obtained by projecting vertices of a hypertree from Figure 8 (assume all lines A_i, B_i are distinct). We claim that if we put these points on a rational normal curve $C \subset \mathbb{P}^k$, the condition (9.6.1) is going to be satisfied.

In the projectively dual plane, we get a configuration of n lines in \mathbb{P}^2 depicted in Figure 9. Let us explain what is new in this picture. The line L is projectively dual to the focus of projection (we draw L as a curve because we are about to identify it with a rational normal curve in \mathbb{P}^k). The definition of points $Q_1, \dots, Q_{\frac{(k-1)(k-2)}{2}}$ is clear from the picture.

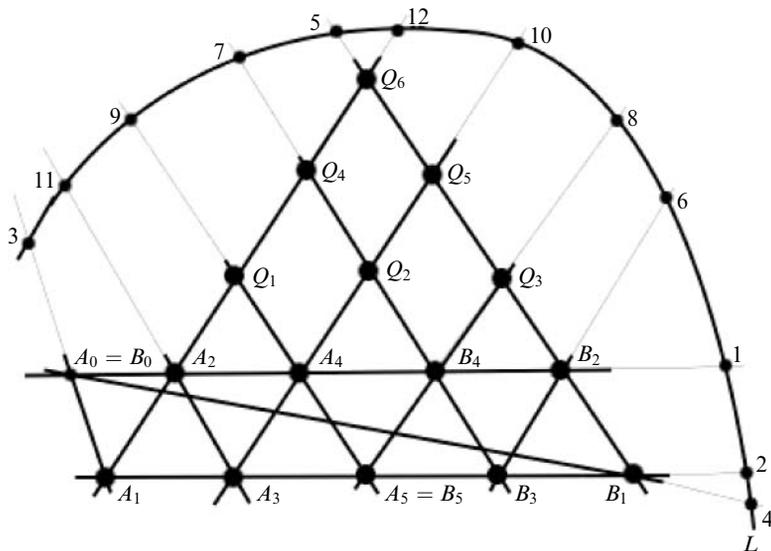


Figure 9. Dual configuration of a bipyramid ($n = 12$).

Let S be the blow-up of \mathbb{P}^2 in points A_i ($i > 0$), B_i ($i > 0$), and all Q_i . We do not blow-up $A_0 = B_0$, so basically we blow-up a “triangular number” of points arranged in the triangular grid. One has to be slightly careful though because this arrangement of lines has moduli, and in particular there are no “horizontal” lines containing points in the grid other than lines 1 and 2. For example, there is in general no line containing Q_1 , Q_2 , and Q_3 .

Consider a divisor

$$D = kH - A_1 - \cdots - A_k - B_1 - \cdots - B_{k-1} - Q_1 - \cdots - \frac{Q_{(k-1)(k-2)}}{2}$$

on S . The following effective divisors are linearly equivalent to D :

$$D_1 = L_3 \cup \cdots \cup L_{2k+1} \quad \text{and} \quad D_2 = L_4 \cup \cdots \cup L_{2k+2},$$

where L_i is a proper transform of a line number i . It follows that the linear system $|D|$ has no fixed components, and therefore it defines a rational map

$$\Psi : S \dashrightarrow \mathbb{P}^k$$

regular outside of points of intersection of D_1 and D_2 . In fact Ψ is regular at $A_0 = B_0$ because $|D|$ also contains

$$L_2 \cup L_6 \cup L_8 \cup \cdots \cup L_{2k+2}$$

which does not contain $A_0 = B_0$. The following argument proves that the dimension of the linear system $|D|$ is k and that the restriction of $|D|$ to L cuts a complete linear system: If $|D|$ contains a member \tilde{D} that contains L as a component, a simple analysis using Bézout’s theorem shows that $\tilde{D} \supset D_1 \cup D_2$, which is impossible (see a similar analysis below).

We see that $\Psi(L) = C \subset \mathbb{P}^k$ is a rational normal curve. Notice that hyperplanes $\langle p_i \rangle_{i \in X}$ and $\langle p_i \rangle_{i \in Y}$ are cut out by divisors D_1 and D_2 and that these divisors have another point in common on S , namely $A_0 = B_0$. Finally, let us consider the line $\langle p_1, p_2 \rangle$. Any hyperplane containing this line corresponds to a divisor \tilde{D} in $|D|$ that contains points 1 and 2. By Bézout’s theorem, \tilde{D} contains the line L_2 , and then the residual divisor $\tilde{D} - L_2$ contains the line L_1 (again by Bézout’s theorem). It follows that \tilde{D} also contains a point $A_0 = B_0$ and therefore

$$\Psi(A_0) \in \langle p_1, p_2 \rangle \cap \langle p_i \rangle_{i \in A} \cap \langle p_i \rangle_{i \in B}. \quad \square$$

The bipyramid divisor is very exceptional for its symmetries: the symmetry group of a bipyramid is the binary dihedral group \tilde{D}_k , but the corresponding divisor in $\bar{M}_{0,2k+2}$ is a pull-back from $\bar{M}_{0,2k+2}/S_2 \times S_k \times S_k$.

10. Pull-backs of divisors from \bar{M}_g

We will consider pull-backs of several “geometric” divisors on $\bar{M}_{g,k}$ (for special values of g and k) via maps

$$\rho : \bar{M}_{0,n} \rightarrow \bar{M}_{g,k}, \quad n = 2g + k,$$

obtained by identifying g pairs of markings on a rational stable curve. We give some evidence that in general this does not lead to any new interesting divisors on $\overline{M}_{0,n}$. This is in contrast with the case $n = 6$ (when we obtain the Keel–Vermeire divisors) and the cases in Section 9 (where we pull-back via different types of maps).

Remark 10.1. In our examples we will pull back divisors E on $\overline{M}_{g,k}$ which are extremal in $\overline{\text{Eff}}(\overline{M}_{g,k})$. Moreover, in the Examples 10.6 and 10.8, the divisor E is contracted to a point by a birational contraction $\overline{M}_{g,k} \dashrightarrow Y$ [J]. It is natural to ask whether the restriction to $\overline{M}_{0,n}$ is still a birational contraction onto the image, which would imply that the components of ρ^*E are extremal in $\overline{\text{Eff}}(\overline{M}_{0,n})$. This turns out not to be true in general, as in our examples we prove that the pull-back of E to $\overline{M}_{0,n}$ is not extremal.

10.2. We will consider proper transforms of divisors E in $\overline{M}_{0,n}$ via ρ :

$$(10.2.1) \quad D = \overline{\rho^{-1}(E)} \cap M_{0,n}.$$

The main reason for considering the proper transform is to avoid having boundary components contained in the pull-back ρ^*E . (This actually happens: see Example 10.8 for an instance of this.)

To compute the class of the divisor D we will consider its pull-back to the Fulton–MacPherson configuration space (see [FM]). Denote by $\mathbb{P}^1[n]$ (resp., $\mathbb{A}^1[n]$), the Fulton–MacPherson space of n points on \mathbb{P}^1 (resp., on \mathbb{A}^1). The space $\mathbb{P}^1[n]$ is isomorphic to the Kontsevich moduli space (see [FP]) of stable maps $\overline{M}_{0,n}(\mathbb{P}^1, 1)$. There are forgetful morphisms:

$$\tilde{\phi} : \mathbb{P}^1[n] \rightarrow \overline{M}_{0,n}, \quad \phi := \tilde{\phi}|_{\mathbb{A}^1[n]} : \mathbb{A}^1[n] \rightarrow \overline{M}_{0,n}.$$

Notation 10.3. Let D_I ($|I| \geq 2$) be the boundary divisor whose general point corresponds to a stable map $f : C \rightarrow \mathbb{P}^1$, with C a rational curve with two components C_1, C_2 , with markings from I on C_1 and markings from I^c on C_2 and such that f has degree 0 on C_1 and degree 1 on C_2 .

Lemma 10.4. *A divisor class D on $\overline{M}_{0,n}$ is determined by its pull-back ϕ^*D as follows: If in the Kapranov model of $\overline{M}_{0,n}$ with respect to the n -th marking we have $D = dH - \sum m_I E_I$, then*

$$\phi^*D = -dD_{\{1,\dots,n-1\}} - \sum_{3 \leq |I| < n-1, n \notin I} m_{\{1,\dots,n-1\} \setminus I} D_I + (\text{sum of } D_I \text{ with } n \in I).$$

Proof. This is an easy calculation using the relations between the boundary divisors D_I (see [FM]) and the fact that $\tilde{\phi}^* \delta_I = D_I + D_{I^c}$. Since the divisors

$$\{D_I\}_{|I| \geq 3, n \notin I}, \quad \{D_I\}_{|I| \geq 2, n \in I}$$

are linearly independent, it follows that D is determined by ϕ^*D . \square

10.5. Let x_1, \dots, x_n be coordinates on \mathbb{A}^n and let

$$U = \mathbb{A}^n \setminus \bigcup_{i \neq j} (x_i = x_j).$$

Clearly, we have $\phi(U) \subset M_{0,n}$. If D is an effective divisor on $\bar{M}_{0,n}$ such that all components of D intersect $M_{0,n}$, then all components of ϕ^*D intersect U . We will consider divisors D as in (10.2.1). Hence, any component of ϕ^*D is a component of the closure

$$E' = \overline{\phi^{-1}(\rho^{-1}(E))} \cap U.$$

In the cases that we study (Examples 10.6 and 10.8), the divisor E' is irreducible and linearly equivalent to a sum of boundary divisors.

The space $\mathbb{A}^1[n]$ can be described as the blow-up of \mathbb{A}^n along diagonals in increasing order of dimension. The divisor D_I is the exceptional divisor corresponding to the diagonal Δ_I where coordinates x_i for $i \in I$ are equal.

If F is an irreducible polynomial in x_1, \dots, x_n defining E' in U and having multiplicity n_I along the Δ_I , the class of E' in $\mathbb{A}^1[n]$ is given by

$$E' = - \sum n_I D_I.$$

Example 10.6. Let $\rho : \bar{M}_{0,7} \rightarrow \bar{M}_{3,1}$ be the map that identifies pairs of markings (12), (34), (56). Let E be the closure in $\bar{M}_{3,1}$ of the locus corresponding to pairs (C, p) with C a smooth genus 3 curve and $p \in C$ a Weierstrass point. Every smooth curve C has a finite number of Weierstrass points; hence, E is a divisor in $\bar{M}_{3,1}$.

Consider now an integral nodal curve C . Let w_C be the dualizing sheaf and let w_1, \dots, w_g be a basis for $H^0(C, w_C)$. Locally at a smooth point p of C we have $w_i = f_i(t) dt$, where t is a local parameter at p , f_i is a regular function. Just as for smooth curves, the point p is called a Weierstrass point if and only if the Wronskian of the functions f_1, \dots, f_g vanishes at p . (See [LW] for the general definitions of Weierstrass points on singular curves.)

Let $(C, p) \in \rho(M_{0,7})$. As there can only be finitely many Weierstrass points on C , it follows that C has a Weierstrass point at p if and only if (C, p) belongs to E .

Let t, x_i, y_i ($1 \leq i \leq 3$) be coordinates on \mathbb{A}^7 , with the pairs (x_i, y_i) the markings that get identified. The locus $E' \cap U$ (see 10.5) parametrizes data

$$(\mathbb{A}^1, x_1, x_2, x_3, y_1, y_2, y_3, t)$$

for which the corresponding tri-nodal curve has a Weierstrass point at t .

Consider the basis of (local) differentials $f_1 dt, f_2 dt, f_3 dt$, where

$$f_i(t) = \frac{1}{(t - x_i)(t - y_i)} \quad (1 \leq i \leq 3).$$

The divisor E' is defined in U by the vanishing of the Wronskian

$$\begin{vmatrix} f_1(t) & f_2(t) & f_3(t) \\ f_1'(t) & f_2'(t) & f_3'(t) \\ f_1''(t) & f_2''(t) & f_3''(t) \end{vmatrix}.$$

Moreover, it is easy to see that the determinant does not change if we replace the rational functions f_i with the polynomials

$$(10.6.1) \quad g_i(t) = f_i(t) \prod_{i=1}^3 (t - x_i)(t - y_i).$$

Using the program Macaulay, we compute the multiplicities of this determinant along the diagonals $\Delta_l \subset \mathbb{A}^7$. Using Lemma 10.4, we compute the class of the divisor

$$D = \phi(E') \subset \overline{M}_{0,7}$$

in the Kapranov model with respect to the 7-th marking to be

$$D = 3H - \sum_{i=1}^6 E_i - E_{12} - E_{34} - E_{56}.$$

The divisor D is clearly big as H is big, and we have $D = H + Q$, where Q is the proper transform of any quadric in \mathbb{P}^4 that contains the lines determined by the pairs of points (12), (34), (56).

Example 10.7. Consider the map $\rho : \overline{M}_{0,7} \rightarrow \overline{M}_{3,1}$ as in Example 10.6. Let E be the closure in $\overline{M}_{3,1}$ of the locus corresponding to pairs (C, p) with C a smooth genus 3 curve and $p \in C$ a point on a bitangent, i.e., $w_C = \mathcal{O}_C(2p + 2q)$ for some $q \in C$.

Let t, x_i, y_i ($1 \leq i \leq 3$) be coordinates on \mathbb{A}^7 , with the pairs (x_i, y_i) the markings that get identified. The locus $E' \cap U$ (see 10.5) parametrizes data

$$(\mathbb{A}^1, x_1, x_2, x_3, y_1, y_2, y_3, t)$$

for which the corresponding tri-nodal curve has the tangent at t tangent at some other point. Consider the canonical map

$$g : \mathbb{A}^1 \rightarrow \mathbb{P}^2, \quad t \mapsto (g_1(t), g_2(t), g_3(t)),$$

where g_1, g_2, g_3 are as in (10.6.1). Consider the following function in $t, s \in \mathbb{A}^1$:

$$m(t, s) = \frac{1}{(s - z)^2} \begin{vmatrix} g_1(t) & g_2(t) & g_3(t) \\ g_1(s) & g_2(s) & g_3(s) \\ g'_1(t) & g'_2(t) & g'_3(t) \end{vmatrix}.$$

For a fixed $t \in \mathbb{A}^1$, the equation $m(t, s) = 0$ computes the points of intersection of the tangent line at t with the curve $g(\mathbb{A}^1)$. The function $m(t, s)$ is quadratic in s :

$$m(t, s) = As^2 + Bs + C, \quad A = \frac{\partial^2 m}{\partial s^2}(t, 0), \quad B = \frac{\partial m}{\partial s}(t, 0), \quad C = m(t, 0).$$

The divisor E' is defined in U by the vanishing of the discriminant

$$\Delta = B^2 - 4AC.$$

As in Example 10.6, using the program Macaulay and Lemma 10.4, we compute the class of the divisor $D = \phi(E') \subset \overline{M}_{0,7}$ (in the Kapranov model with respect to the 7-th marking) to be

$$D = 8H - 4 \sum_{i=1}^6 E_i - 2 \sum_{i \neq j \in \{1, \dots, 6\}} E_{ij} - 2E_{123} - 2E_{456}.$$

The divisor D is clearly big as H is big, and we have

$$D = 2(H + \delta_{ij} + \delta_{lm} + \delta_{kn}),$$

for any $\{i, j, k\} = \{1, 2, 3\}$, $\{l, m, n\} = \{4, 5, 6\}$.

Example 10.8. Let $\rho: \overline{M}_{0,10} \rightarrow \overline{M}_5$ be the map that identifies the pairs of points $(11')$, $(22')$, $(33')$, $(44')$, $(55')$. Let E be the Brill–Noether divisor of trigonal curves in \overline{M}_5 . By the calculations in [HM], [EH], the class of E is equal to

$$8\lambda - \delta_{irr} - 4\delta_1 - 6\delta_2.$$

Using standard formulas for pull-backs of tautological classes, it is easy to compute the class of its pull-back ρ^*E . To preserve all symmetries of this divisor in the notation, we give the formula for the pull-back $\pi_{11}^*\rho^*E$ to $\overline{M}_{0,11}$ in the Kapranov model with respect to the 11-th marking. The class is given by

$$\begin{aligned} \pi_{11}^*\rho^*E &= 20H - 16 \sum E_1 - 12 \sum E_{12} - 12 \sum E_{11'} - 9 \sum E_{123} \\ &\quad - 6 \sum E_{121'} - 7 \sum E_{1234} - 4 \sum E_{1231'} - 6 \sum E_{121'2'} \\ &\quad - 6 \sum E_{12345} - 3 \sum E_{12341'} - 3 \sum E_{123451'} \\ &\quad - 2 \sum E_{1231'2'3'} - \sum E_{123451'2'} + 2 \sum E_{12341'2'3'}. \end{aligned}$$

To explain the notation, the sums are taken over all permutations that preserve the number of pairs from $(11')$, $(22')$, $(33')$, $(44')$, $(55')$. For example:

$$\begin{aligned} \sum E_1 &= \sum_{i=1}^5 E_i + \sum_{i=1}^5 E_{i'}, \\ \sum E_{11'} &= \sum_{1 \leq i \leq 5} E_{ii'}, \\ \sum E_{12} &= \sum_{i \neq j, 1 \leq i, j \leq 5} E_{ij} + E_{i'j'} + E_{ij'}, \\ \sum E_{123} &= \sum_{1 \leq i, j, k \leq 5, i \neq j, k, j \neq k} E_{ijk} + E_{i'j'k'} + E_{ijk'} + E_{ij'k'}, \quad \text{etc.} \end{aligned}$$

It is clear from this formula that ρ^*E is reducible and contains the main component (that intersects $M_{0,10}$), as well as some boundary divisors. These boundary divisors can be easily determined using the method of admissible covers, but computing the corresponding multiplicities is a bit subtle.

As in the previous examples, we can nevertheless compute the class of the main component. Let

$$x_1, \dots, x_5, y_1, \dots, y_5$$

be the coordinates on \mathbb{A}^{10} , with the pairs (x_i, y_i) the markings that get identified. Using the theory of admissible covers, the locus $E' \cap U$ (see 10.5) parametrizes data $(\mathbb{A}^1, x_1, \dots, x_5, y_1, \dots, y_5)$ for which the corresponding nodal curve in \bar{M}_5 has a g_3^1 , i.e., the chords determined by the pairs (x_i, y_i) have a common transversal when considering $\mathbb{A}^1 \subset \mathbb{P}^3$ as a twisted cubic via the Veronese embedding. Consider the Grassmannian of lines in \mathbb{P}^3 :

$$\mathbb{G}(1, 3) \subset \mathbb{P}(\wedge^2 k^4)$$

together with its Plücker embedding. By [St], Example 3.4.6, five lines in \mathbb{P}^3 with Plücker coordinates L_1, \dots, L_5 have a common transversal if and only if the determinant

$$\begin{vmatrix} 0 & L_1.L_2 & L_1.L_3 & L_1.L_4 & L_1.L_5 \\ L_2.L_1 & 0 & L_2.L_3 & L_2.L_4 & L_2.L_5 \\ L_3.L_1 & L_3.L_2 & 0 & L_3.L_4 & L_3.L_5 \\ L_4.L_1 & L_4.L_2 & L_4.L_3 & 0 & L_4.L_5 \\ L_5.L_1 & L_5.L_2 & L_5.L_3 & L_5.L_4 & 0 \end{vmatrix}$$

vanishes. Here $L_i.L_j$ denotes the wedge product in $\wedge^2 k^4$. Let L_i be the chord determined by the pair (x_i, y_i) . The lines L_i connect points on the twisted cubic, which we can parametrize as $(1, t, t^2, t^3)$. It follows that the wedge product $L_i.L_j$ is the Vandermonde determinant

$$\begin{vmatrix} 1 & 1 & 1 & 1 \\ x_i & y_i & x_j & y_j \\ x_i^2 & y_i^2 & x_j^2 & y_j^2 \\ x_i^3 & y_i^3 & x_j^3 & y_j^3 \end{vmatrix}.$$

As the terms $(y_i - x_i), (y_j - x_j)$ can be factored out, we are left with a degree 20 polynomial F that defines E' in U . Using the program Macaulay it is easy to see that F is irreducible and we can compute the multiplicities of F along the diagonals $\Delta_I \subset \mathbb{A}^{10}$. Using Lemma 10.4 it follows that the class of the pull-back π_N^*D of the divisor $D = \phi(E') \subset \bar{M}_{0,10}$ to $\bar{M}_{0,11}$ (in the Kapranov model with respect to the 11-th marking) is given by

$$\begin{aligned} \pi_N^*D &= 20H - 16 \sum E_1 - 12 \sum E_{12} - 12 \sum E_{11'} - 9 \sum E_{123} \\ &\quad - 8 \sum E_{121'} - 7 \sum E_{1234} - 5 \sum E_{1231'} - 6 \sum E_{121'2'} \\ &\quad - 6 \sum E_{12345} - 3 \sum E_{12341'} - 3 \sum E_{1231'2'} \\ &\quad - 3 \sum E_{123451'} - \sum E_{12341'2'} - 2 \sum E_{1231'2'3'} - \sum E_{123451'2'}. \end{aligned}$$

The divisor π_N^*D is linearly equivalent to a sum of boundary divisors: consider the sum of the 20 hyperplanes determined by choosing a pair of points $\{x_i, x_j\}$, or $\{y_i, y_j\}$

and taking the hyperplane passing through the remaining points (these are the boundary divisors δ_{x_i, x_j} and δ_{y_i, y_j}). It is easy to see that all the multiplicities of this union of hyperplanes are larger than the multiplicities in the formula for π_N^*D .

It follows that π_N^*D is a moving divisor. Since any effective divisor linearly equivalent to π_N^*D is a pull-back by π_N from $\overline{M}_{0,10}$, it follows that D is a moving divisor.

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Eingegangen 4. August 2010, in revidierter Fassung 17. Mai 2011