

# Modular compactifications of $\mathcal{M}_{2,n}$ with Gorenstein curves

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## ABSTRACT

We study the geometry of Gorenstein curve singularities of genus two, and of their stable limits. These singularities come in two families, corresponding to either Weierstrass or conjugate points on a semistable tail. For every  $1 \leq m < n$ , a stability condition - using one of the markings as a reference point, and thus not  $\mathfrak{S}_n$ -symmetric - defines proper Deligne-Mumford stacks  $\overline{\mathcal{M}}_{2,n}^{(m)}$  with a dense open substack representing smooth curves.

## 1. Introduction

We construct alternative compactifications of the moduli stack of smooth  $n$ -pointed curves of genus two. The boundary of the Deligne-Mumford compactification, consisting of stable nodal curves, is gradually replaced by ever more singular curves, complying with more restrictive combinatorial requirements on the dual graph. For  $1 \leq m < n$ , we introduce a notion of  $m$ -stability, that allows Gorenstein singularities of genus one and two while at the same time demanding that higher genus subcurves contain a minimum number of special points. Our main result concerning the stack of  $m$ -stable curves is the following:

**THEOREM.**  $\overline{\mathcal{M}}_{2,n}^{(m)}$  is a proper irreducible Deligne-Mumford stack over  $\mathrm{Spec}(\mathbb{Z}[\frac{1}{30}])$ .

This paper fits into the framework of alternative compactifications and birational geometry of the moduli space of curves, extending work of D.I. Smyth in genus one, but we expect it to find applications to enumerative geometry as well.

We classify Gorenstein singularities of genus two with any number of branches, and their (semi)stable models, highlighting the relation with Brill-Noether theory. The key insight in defining the new stability conditions is that we can avoid non-Gorenstein singularities by modifying the curve at the conjugate point of the special branch; we use one of the markings to identify the latter, and, more generally, to pick the limit in symmetric situations where multiple choices are a priori possible - as a result, our stability conditions are not  $\mathfrak{S}_n$ -symmetric.

We interpret crimping spaces (moduli of curves with a prescribed singularity type) as parameter spaces for the differential geometric data needed in order to construct a higher genus

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singularity from an ordinary  $m$ -fold point, and verify their impact on the existence of automorphisms, a phenomenon which had not fully emerged in lower genus.

Though a conspicuous amount of related research has been carried out on the birational geometry of  $\overline{\mathcal{M}}_{2,n}$  for low values of  $n$  [Has05, HL07, Rul01, HL14, FG18, JP18], this appears to be the first proposal of a sequence of modular compactifications for every  $n$ .

### 1.1 From the Deligne-Mumford space to the Hassett-Keel program

One of the most influential results of modern algebraic geometry is the construction of a modular compactification of the stack of smooth pointed curves  $\mathcal{M}_{g,n}$ , due to P. Deligne, D. Mumford, and F. Knudsen, with the introduction of *stable* pointed curves.

**DEFINITION 1.1.** [DM69] A connected, reduced, complete curve  $C$  over an algebraically closed field  $\mathbf{k}$ , with distinct markings  $(p_1, \dots, p_n)$  lying in the smooth locus of  $C$ , is *stable* if:

- (i)  $C$  admits only nodes (ordinary double points) as singularities;
- (ii) every rational component of  $C$  has at least three special points (markings or nodes), and every elliptic component has at least one.

**THEOREM 1.2.** [DM69, Knu83] Assume  $2g - 2 + n > 0$ . The moduli stack of stable pointed curves  $\overline{\mathcal{M}}_{g,n}$  is a smooth and proper connected Deligne-Mumford stack over  $\mathrm{Spec}(\mathbb{Z})$ , with projective coarse moduli space  $\overline{\mathbf{M}}_{g,n}$ , and normal crossing boundary representing nodal curves.

On one hand, the Deligne-Mumford compactification has nearly every desirable property one could hope for; on the other, it is certainly not the unique modular compactification of  $\mathcal{M}_{g,n}$ . Classifying all of them is a challenging task, which was set out and partially performed in the inspiring work of Smyth [Smy13]. The motivation comes mostly from birational geometry.

Even though the existence of  $\overline{\mathbf{M}}_{g,n}$  can be deduced from nowadays standard theorems on stacks [KM97], this moduli space was first constructed as a quotient, prompting the development of a powerful technique known as Geometric Invariant Theory [Gie82, MFK94, BS08]. Studying alternative compactifications of  $\mathcal{M}_{g,n}$  sheds some light on the Mori chamber decomposition of  $\overline{\mathbf{M}}_{g,n}$ , and it is not by chance that the first steps in this direction were moved from a GIT perspective - by changing the invariant theory problem or the stability condition under consideration, and analysing the modular properties of the resulting quotients [Sch91, Has05, HH13]. This program, initiated by B. Hassett and S. Keel, aims to describe all the quotients arising in this way, and to determine whether every step of a log minimal model program for  $\overline{\mathbf{M}}_{g,n}$  enjoys a modular interpretation in terms of curves with worse than nodal singularities [CTV18, CTV19]. Since the early stages of this program, it has developed into a fascinating playground for implementing ideas that originated from (v)GIT into a general structure theory of Artin stacks [AK16, AFSvdW17, AFS17a, AFS17b]. See for instance [Mor11, FS13] for more detailed and comprehensive accounts.

Only few steps of the Hassett-Keel program have been carried out in full generality. Yet, the program has been completed to a larger extent in low genus: with the introduction of Boggi-stable [Bog99] and weighted pointed curves [Has03] in genus zero, and with Smyth's pioneering work in genus one [Smy11a, Smy11b, Smy18], extending earlier work of D. Schubert. In a nutshell, an alternative compactification is defined by allowing a reasonably larger class of curve singularities (*local condition*) while identifying their (semi)stable models, and disallowing the latter by imposing a stronger stability condition (*global condition*, typically combinatorial); the valuative criterion ensures that the resulting moduli problem remains separated and universally closed.

A useful notion in this respect is that of the *genus* of an isolated curve singularity: let  $(C, q)$  be (the germ of) a reduced curve over an algebraically closed field  $\mathbf{k}$  at its unique singular point  $q$ , with normalisation  $\nu: \tilde{C} \rightarrow C$  and  $\mathcal{F} = \nu_* \mathcal{O}_{\tilde{C}} / \mathcal{O}_C$ , a skyscraper sheaf supported at  $q$ .

DEFINITION 1.3. [Smy11a] If  $C$  has  $m$  branches (irreducible components of the normalisation) at  $q$ , and  $\delta$  is the  $\mathbf{k}$ -dimension of  $\mathcal{F}$ , the genus of  $(C, q)$  is defined as:

$$g = \delta - m + 1.$$

The genus can be thought of as the number of conditions that a function must satisfy in order to descend from the seminormalisation (the initial object in the category of universal homeomorphisms  $C' \rightarrow C$ , see [Sta20, Tag 0EUS], or a curve with the same topological space as  $C$  and an ordinary  $m$ -fold point at  $q$ ) to  $C$ . The node, for example, has genus zero (it coincides with its own seminormalisation). The genus of a singular point represents its non-topological contribution to the arithmetic genus of the curve containing it.

Smyth found that, for every fixed number  $m$  of branches, there is a unique germ of Gorenstein singularity of genus one up to isomorphism, namely:

- $m = 1$  the cusp,  $V(y^2 - x^3) \subseteq \mathbb{A}_{x,y}^2$ ;
- $m = 2$  the tacnode,  $V(y^2 - yx^2) \subseteq \mathbb{A}_{x,y}^2$ ;
- $m \geq 3$  the union of  $m$  general lines through the origin of  $\mathbb{A}^{m-1}$ .

Singularities of this kind, with up to  $m$  branches, together with nodes, form a deformation-open class of singularities. Moreover, the elliptic  $m$ -fold point can be obtained by contracting a smooth elliptic curve with  $m$  rational tails in a one-parameter smoothing, and, roughly speaking, all stable models have a shape similar to this.

DEFINITION 1.4. [Smy11a] A connected, reduced, complete curve  $C$  of arithmetic genus one with smooth distinct markings  $(p_1, \dots, p_n)$  is  *$m$ -stable*,  $1 \leq m < n$ , if:

- (i) it admits only nodes and elliptic  $l$ -fold points,  $l \leq m$ , as singularities;
- (ii) for every connected subcurve  $E \subseteq C$  of arithmetic genus one, its *level*:  
 $|E \cap \overline{C \setminus E}| + |\{i: p_i \in E\}|$  is strictly larger than  $m$ ;
- (iii)  $H^0(C, \Omega_C^\vee(-\sum_i p_i)) = 0$  (finiteness of automorphism groups).

The latter can be taken for a decency condition on the moduli stack. The first two, instead, are essential in guaranteeing the uniqueness of  $m$ -stable limits, as per the discussion above. Smyth's main result is the following.

THEOREM 1.5. [Smy11a, Smy11b] *The moduli stack of  $m$ -stable curves  $\overline{\mathcal{M}}_{1,n}(m)$  is a proper irreducible Deligne-Mumford stack over  $\text{Spec } \mathbb{Z}[1/6]$ . It is not smooth for  $m \geq 6$ . The coarse moduli spaces  $\overline{\mathbf{M}}_{1,n}(m)$  arise as birational models of  $\overline{\mathbf{M}}_{1,n}$  for the big line bundles  $D(s) = s\lambda + \psi - \Delta$ , where  $\lambda$  is the Hodge class,  $\psi$  is the sum of the  $\psi$ -classes,  $\Delta$  is a boundary class, and there is an explicit relation between  $s$  and  $m$ .*

Some further information on the geometry and singularities of these spaces (with the restriction  $m = n - 1$ ) has been discovered by Y. Lekili and A. Polishchuk in their study of *strongly non-special* curves [LP17].

## 1.2 Experimenting on a genus two tale

In this subsection, we walk through the motivations and methods at the heart of our construction, exemplifying them in the simplest possible case, that of  $\overline{\mathcal{M}}_{2,2}^{(1)}$ . The facts we mention are either proved or explained in greater detail and generality in the paper. Here is a classical

**FACT.** *There are two unibranch singularities of genus two, the ramphoid cusp or  $A_4$ -singularity  $V(y^2 - x^5) \subseteq \mathbb{A}_{x,y}^2$ , and the ordinary genus two cusp  $\mathrm{Spec}(\mathbf{k}[t^3, t^4, t^5])$ . The former is Gorenstein, with stable model a Weierstrass tail (a genus two curve attached to a rational one at a Weierstrass point), while the latter is not Gorenstein, with stable model a non-Weierstrass tail of genus two.*

See Lemma 2.1 and Proposition 4.6 below. Recall that every smooth curve of genus two is hyperelliptic, i.e. it can be realised as a two-fold cover of  $\mathbb{P}^1$ , in a unique way up to projectivities. The cover automorphism is called the hyperelliptic involution  $\sigma$ ; ramification points (fixed points of  $\sigma$ ) are called Weierstrass, and in general  $\{p, \sigma(p)\}$  are called conjugate points. See Section 4.1.

Let us try Smyth's approach out on genus two curves, starting with  $\overline{\mathcal{M}}_{2,2}^{(1)}$ . If we are going to require the level of a genus two subcurve to be at least two, it seems that we will need non-Gorenstein singularities in order to keep our moduli space proper. This might lead us into trouble; for example, the (log) dualising line bundle is classically exploited to construct canonical polarisations on stable curves, which in turn are essential in the proof that  $\overline{\mathcal{M}}_{g,n}$  is an algebraic stack (or in the GIT construction of  $\overline{\mathbf{M}}_{g,n}$ ). Yet, there is a way around the singularity  $\mathbf{k}[[t^3, t^4, t^5]]$ .

**FACT.** *The  $A_5$ -singularity  $V(y^2 - yx^3) \subseteq \mathbb{A}_{x,y}^2$  is a Gorenstein singularity of genus two with two branches. Its stable model is a genus two bridge, with conjugate attaching points. A marked union of two copies of  $\mathbb{P}^1$  along an  $A_5$ -singularity has no non-trivial automorphisms as soon as one of the two branches contains at least two markings.*

See Proposition 2.2 and Corollary 3.7. Going back to  $\overline{\mathcal{M}}_{2,2}$ , suppose  $C$  is the nodal union of a genus two curve  $Z$  with a rational tail  $R$  supporting the two markings, so that  $\mathrm{lev}(Z) = 1$ . If  $R$  is attached to a Weierstrass point of  $Z$ , we may simply contract the latter (in a one-parameter smoothing), thus producing an irreducible ramphoid cusp with two markings. If instead  $R$  is attached to a non-Weierstrass point  $q_1$  of  $Z$ , we may blow-up the one-parameter family at the conjugate point  $\sigma(q_1)$  in the central fibre, and then contract  $Z$  to get a *dangling*  $A_5$ -singularity (meaning that one of the branches is unmarked), which nonetheless has trivial automorphism group. We pursue this strategy, which makes our compactifications not semistable (see [Smy13, Definition 1.2] for the terminology). The necessity to include such curves was prefigured in [AFS16].

To complete the picture, note that, in order to fix a deformation-open class of singularities, we need to allow cusps and tacnodes as well, due to the following

**FACT.** *The singularities appearing in the miniversal family of an  $A_m$ -singularity are all and only the  $A_l$ -singularities with  $l \leq m$ .*

See Theorem 5.5 for a more general statement - valid for all ADE singularities - due to A. Grothendieck. Since the semistable tail of a cusp (resp. tacnode) is an elliptic tail (resp. bridge), if we want our moduli space to remain separated, we should require that the level of a genus one subcurve be at least three at the same time as we introduce cusps and tacnodes. Hybrid situations may occur, such as an elliptic curve with a cusp, or an irreducible tacnode; since we need to allow a tacnode and a cusp sharing a branch, we should impose the level condition on genus one subcurves only when they are *nodally attached*. Besides, in the latter example, we need

to break the  $\mathfrak{S}_2$ -symmetry (relabelling the markings) in order to have a unique limit: we declare that  $p_1$  must lie on the cuspidal branch. See Figure 1.

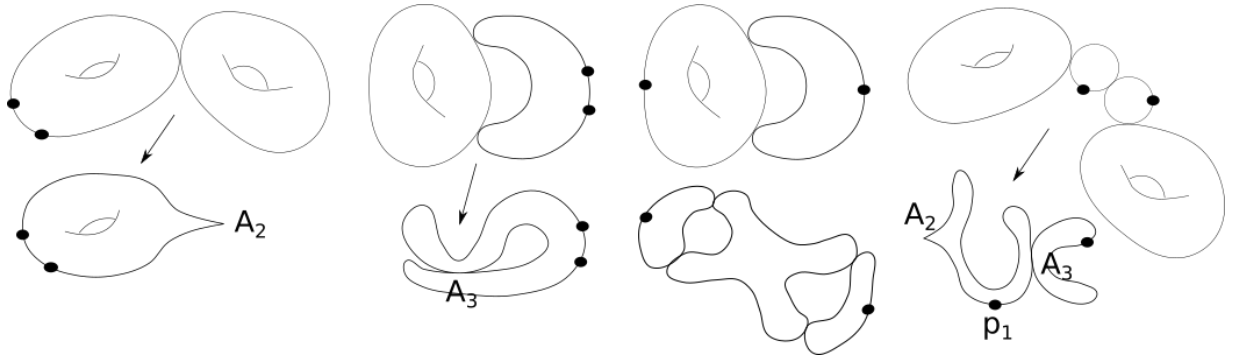


FIGURE 1. Examples of 2-pointed stable curves and their 1-stable counterparts.

We are now in a position to cast a plausible definition of  $\overline{\mathcal{M}}_{2,2}^{(1)}$ .

**DEFINITION 1.6.** A connected, reduced, complete curve of arithmetic genus two  $C$  over an algebraically closed field  $\mathbf{k}$ , with smooth and disjoint markings  $(p_1, p_2)$ , is 1-stable if:

- (i)  $C$  has only  $A_1$ –, ...,  $A_4$ – and dangling  $A_5$ – singularities.
- (ii)  $C$  coincides with its minimal subcurve of arithmetic genus two.
- (iii) A subcurve of arithmetic genus one is either nodally attached and of level three, or it is not nodally attached and it contains  $p_1$ .

The main result of the paper is that  $\overline{\mathcal{M}}_{2,2}^{(1)}$  is a proper Deligne-Mumford stack, and the generalisation of this statement to an arbitrary number of markings and a range of stability conditions that we are going to discuss in the next sections.

Let us note in passing that the birational map  $\overline{\mathcal{M}}_{2,2} \dashrightarrow \overline{\mathcal{M}}_{2,2}^{(1)}$  is not defined everywhere. The reason boils down to the following

**FACT.** *There is only one isomorphism class of 2-pointed curves whose normalisation is  $(\mathbb{P}^1, q_1) \sqcup (\mathbb{P}^1, q_2, p_1, p_2)$  and having an  $A_5$ -singularity at  $q_1 = q_2$ . On the other hand, the moduli space of 2-pointed irreducible curves of geometric genus zero with an  $A_4$ -singularity is isomorphic to  $\mathbb{A}^1$ .*

The second statement can be motivated as follows: the pointed normalisation of such a curve is  $(\mathbb{P}^1, q, p_1, p_2)$ , which has neither automorphisms, nor deformations. To produce an  $A_4$ -singularity at  $q$  we may first collapse a non-zero tangent vector at  $q$  (no choice involved), producing a cusp, and then collapse a line in the tangent space at the cusp, avoiding the support of its tangent cone  $\ell$  (therefore, the moduli space is  $\mathbb{P}^1 \setminus \{\ell\} = \mathbb{A}^1$ ). See Lemma 3.2 and the discussion thereafter.

Let  $\Delta = \Delta_{2,0|0,\{1,2\}} \subseteq \overline{\mathcal{M}}_{2,2}$  be the divisor of rational tails, and  $\mathscr{W} \subseteq \overline{\mathcal{M}}_{2,2}$  the codimension two locus of Weierstrass tails. The 1-stable limit of any point in  $\Delta \setminus \mathscr{W}$  is the dangling  $A_5$ -singularity, while the 1-stable limit of a Weierstrass tail is ill-defined (it depends on the choice of a 1-parameter smoothing); we conjecture that the rational map (identity on the locus of smooth curves) admits a factorisation:

$$\begin{array}{ccc}
 & \text{Bl}_{\mathcal{W}}(\overline{\mathcal{M}}_{2,2}) & \\
 \swarrow & & \searrow \\
 \overline{\mathcal{M}}_{2,2} & \xrightarrow{\quad\quad\quad} & \overline{\mathcal{M}}_{2,2}^{(1)}
 \end{array}$$

The blow-up should also encode enough information to contract an unmarked elliptic bridge to a tacnode. We plan to address this point in forthcoming work.

### 1.3 Relation to other work

It would be interesting to compare  $\overline{\mathcal{M}}_{2,2}^{(1)}$  explicitly with Smyth's  $\overline{\mathcal{M}}_{2,2}(\mathcal{Z})$  [Smy13], for the extremal assignment  $\mathcal{Z}$  of unmarked subcurves; here we only note that, while the divisor  $\Delta_{1,\{1\}|1,\{2\}}$  is contracted in  $\overline{\mathcal{M}}_{2,2}^{(1)}$ , the latter contains a copy of  $\overline{\mathcal{M}}_{0,4}$  (see the third column, second row of Figure 1) that is replaced by the class of the rational 4-fold point in  $\overline{\mathcal{M}}_{2,2}(\mathcal{Z})$ .  $\overline{\mathcal{M}}_{2,2}^{(1)}$  seems closely related to the space  $\mathcal{U}_{2,2}^{ns}(ii)$  constructed in [JP18]. More generally, it would be interesting to relate  $\overline{\mathcal{M}}_{2,n}^{(m)}$  (for high values of  $m$ ) to Polishchuk's moduli of curves with nonspecial divisors [Pol15]. Finally, it seems plausible that  $\overline{\mathcal{M}}_{2,n}^{(m)}$  (for low values of  $m$ ) corresponds to a pointed variant of the spaces of admissible hyperelliptic covers with AD singularities constructed in [Fed14].

### 1.4 Outline of results and plan of the paper

In Section 2 we classify all the Gorenstein curve singularities of genus two. They come in two families: the first one (*I*) includes the ramphoid cusp, the  $D_5$ -singularity, and for  $m \geq 3$  the union of a *singular branch* (a cusp) and  $m - 1$  lines living in  $\mathbb{A}^m$ . The second one (*II*) includes the  $A_5$ - and  $D_6$ -singularities, and for  $m \geq 4$  the union of *two tangent branches* (forming a tacnode) with  $m - 2$  lines in  $\mathbb{A}^{m-1}$ . See Proposition 2.2.

In Section 3 we translate the condition that a complete pointed curve of genus two has no infinitesimal automorphisms into a *mostly* combinatorial criterion. For every fixed number of branches  $m$  and genus two singularity type  $\in \{I, II\}$ , there are two isomorphism classes of pointed curves whose normalisation is  $\bigsqcup_{i=1}^m (\mathbb{P}^1, q_i, p_i)$  and having a singularity of the prescribed type at  $q$ ; one of them has  $\text{Aut}(C, p) = \mathbb{G}_m$ , while the other one has trivial automorphism group. This phenomenon is a novelty to genus two. We take a detour into moduli spaces of singularities to justify the claim, and explain how to interpret the *crimping spaces* geometrically in terms of the information we need to construct a genus two singularity from a (non-Gorenstein) singularity of lower genus. This is not strictly necessary in what follows, since the singularity with one-pointed branches never satisfies the level condition we demand from our curves, yet this description is expected to be useful in analysing the indeterminacy of  $\overline{\mathcal{M}}_{2,n}^{(m_1)} \dashrightarrow \overline{\mathcal{M}}_{2,n}^{(m_2)}$ .

In Section 4 we study the (semi)stable limits; starting from a 1-parameter family of semistable curves with smooth generic fibre and regular total space, we show that the shape of a subcurve of the central fibre that can be contracted into a Gorenstein singularity is strongly constrained. Singularities of type *I* arise when the special branch (corresponding to the cusp in the contraction) is attached to a *Weierstrass point* of the minimal subcurve of genus two (the *core*), while singularities of type *II* occur when the special branches (corresponding to the tacnode in the contraction) are attached to *conjugate points*. Furthermore, the size of the curve to be contracted only depends on one number - roughly speaking, the distance of the special branches from the core. The first statement is a consequence of the following simple observation: if  $\phi: \tilde{\mathcal{C}} \rightarrow \mathcal{C}$  is a contraction

to a family of Gorenstein curves,  $\phi^*\omega_{\mathcal{C}}$  is trivial on a neighbourhood of the exceptional locus of  $\phi$ , and it coincides with  $\omega_{\widetilde{\mathcal{C}}}$  outside it. Now, whereas the dualising line bundle of a Gorenstein curve of genus one with no separating nodes is trivial (see [Smy11a, Lemma 3.3]) and all smooth points display the same behaviour (in the sense that they are non-special), the simplest instance of Brill-Noether theory manifests itself in genus two, with the distinction between Weierstrass and non-Weierstrass points, and the expression  $\omega_Z = \mathcal{O}_Z(q + \sigma(q))$ . The correct extension of these concepts to nodal curves was formulated in the '80s within the theory of admissible covers and limit linear series, and we spend some time to discuss the relevant combinatorics.

In Section 5 we define the notion of *m-stable n-pointed curve* of genus two, for every  $1 \leq m < n$ . The basic idea is to trade worse singularities - of both genus one and two, bounded by  $m$  in the sense of the embedding dimension - with more constraints on the combinatorics of the dual graph - the *level* condition, which bounds below in terms of  $m$  the number of special points (nodes and markings) that any subcurve of genus one or two has to contain. On the other hand, it is already clear from the discussion above that we need to break the  $\mathfrak{S}_n$ -symmetry, in order to write the dualising line bundle of the minimal subcurve of genus two as  $\mathcal{O}_Z(q_1 + \sigma(q_1))$ , in other words to choose which branches of a semistable model are to be dubbed special. We do so by using the first marking as a reference point, so that  $q_1$  comes to denote the point of  $Z$  closest to  $p_1$ . This shapes our algorithm to construct the *m-stable* limit of a given 1-parameter smoothing. Unavoidably, the formulation of the stability condition is slightly involved, including a prescription of the interplay between  $p_1$  and the singularity. We prove that the moduli stack of *m-stable* curves is algebraic, and it satisfies the valuative criterion of properness.

### 1.5 Future directions of work

Besides regarding this paper as a case-study of the birational geometry of moduli spaces of curves, we are looking forwards to explore its consequences in Gromov-Witten theory. We set up some questions we would like to come back to in future work.

- (i) The indeterminacy of the rational map  $\overline{\mathcal{M}}_{2,n}^{(m_1)} \dashrightarrow \overline{\mathcal{M}}_{2,n}^{(m_2)}$  can be resolved modularly: a space dominating all the  $\overline{\mathcal{M}}_{2,n}^{(m)}$  can be obtained as a logarithmic modification (as in [RSPW19a]) of the space of *admissible covers* (of degree two with six ramification points). We shall describe this construction in more details in a forthcoming paper. We wonder whether the models constructed here correspond to the trace of the minimal model program on a two-dimensional slice of the cone of pseudo-effective divisors, as in [Smy11b].  
More generally, a question outstanding to our knowledge is whether the whole program fits in the framework of stability developed in [Hal14].
- (ii) Applications to enumerative geometry: the link between reduced Gromov-Witten invariants in genus one (see for example [VZ08, Zin09, LZ09]) and maps from singular curves (see [Vis12]) was partially uncovered in [BCM18], and brought in plain view by [RSPW19a, RSPW19b]. In joint work with F. Carocci [BC20], we exploit similar techniques to desingularise the main component of the space of genus two maps to projective space. We enrich the logarithmic structure by including a compatible admissible cover. A universal morphism to a Gorenstein curve is constructed on a logarithmically étale model of the base, using tools from logarithmic geometry and after choosing a *tropical canonical divisor*. We stress the fact that non-reduced fibres (*singular ribbons*) arise naturally in that context. The main component is recovered as those maps that factor through the Gorenstein contraction. Our desingularisation is less efficient than [HLN18], but maps from singular curves provide a conceptual definition of

reduced invariants for projective complete intersections and beyond. We hope that they will make comparison results (standard vs. reduced) easier to prove. This would lead to a modular interpretation of Gopakumar-Vafa invariants [Pan99].

## 2. Gorenstein curve singularities of genus two and their dualising line bundle

We produce an algebraic classification of the (complete) local rings of Gorenstein curve singularities of genus two over an algebraically closed field  $\mathbf{k}$ . The proof involves a technical calculation with the conductor ideal. Alternatively, one can look for a local generator of the dualising line bundle at the singularity; we remark on this below.

Let  $(C, q)$  be the germ of a reduced curve singularity, and let  $(R, \mathfrak{m})$  denote  $(\hat{\mathcal{O}}_{C,q}, \mathfrak{m}_q)$ , with normalisation  $(\tilde{R}, \tilde{\mathfrak{m}}) \simeq (\mathbf{k}[[t_1]] \oplus \dots \oplus \mathbf{k}[[t_m]], \langle t_1, \dots, t_m \rangle)$ . Here  $m$  is the number of branches of  $C$  at  $q$ . Recall the Definition 1.3 of the genus:

$$g = \delta - m + 1;$$

so, for genus two,  $\delta = m + 1$ . Following [Smy11a, Appendix A], we consider  $\tilde{R}/R$  as a  $\mathbb{Z}$ -graded module with:

$$(\tilde{R}/R)_i := \tilde{\mathfrak{m}}^i / (\tilde{\mathfrak{m}}^i \cap R) + \tilde{\mathfrak{m}}^{i+1};$$

furthermore, adapting Smyth's remarks in *loc. cit.* to our situation:

- (i)  $m + 1 = \delta(p) = \sum_{i \geq 0} \dim_{\mathbf{k}}(\tilde{R}/R)_i$ ;
- (ii)  $2 = g = \sum_{i \geq 1} \dim_{\mathbf{k}}(\tilde{R}/R)_i$ ;
- (iii) if  $(\tilde{R}/R)_i = (\tilde{R}/R)_j = 0$  then  $(\tilde{R}/R)_{i+j} = 0$ .

We will also make use of the following observations:

- (iv)  $\sum_{i \geq j} (\tilde{R}/R)_i$  is a grading of  $\tilde{\mathfrak{m}}^j / (\tilde{\mathfrak{m}}^j \cap R)$ ;
- (v) there is an exact sequence of  $R/\mathfrak{m} = \mathbf{k}$ -modules:

$$0 \rightarrow A_i := \frac{\tilde{\mathfrak{m}}^i \cap R}{\tilde{\mathfrak{m}}^{i+1} \cap R} \rightarrow \frac{\tilde{\mathfrak{m}}^i}{\tilde{\mathfrak{m}}^{i+1}} \rightarrow (\tilde{R}/R)_i \rightarrow 0$$

LEMMA 2.1. *There are two unibranch curve singularities of genus two; only one of them is Gorenstein, namely the  $A_4$ -singularity or ramphoid cusp:  $V(y^2 - x^5) \subseteq \mathbb{A}_{x,y}^2$ .*

*Proof.* In the unibranch case  $\dim_{\mathbf{k}}(\tilde{R}/R)_1 \leq 1$ , hence equality holds (by observation (iii) above). We are left with two cases:

- Either  $\dim_{\mathbf{k}}(\tilde{R}/R)_2 = 1$  and  $\dim_{\mathbf{k}}(\tilde{R}/R)_i = 0$  for all  $i \geq 3$ : in this case  $\tilde{\mathfrak{m}}^3 \subseteq \mathfrak{m}$  by observation (iv). From (v) we see that  $\tilde{\mathfrak{m}}^3 = \mathfrak{m}$ , hence  $R \simeq \mathbf{k}[[t^3, t^4, t^5]]$ , a non-Gorenstein singularity sitting in 3-space, which is obtained by collapsing a second-order infinitesimal neighbourhood of the origin in  $\mathbb{A}^1$  (we shall call it an ordinary cusp of genus two).
- Or  $\dim_{\mathbf{k}}(\tilde{R}/R)_3 = 1$  and  $\dim_{\mathbf{k}}(\tilde{R}/R)_i = 0$  for  $i = 2$  and for all  $i \geq 4$ : in this case  $\tilde{\mathfrak{m}}^4 \subseteq \mathfrak{m}$  by observation (iv). On the other hand from  $\dim_{\mathbf{k}}(\tilde{\mathfrak{m}}^2 \cap R / \tilde{\mathfrak{m}}^3 \cap R) = 1$  we deduce that there is a generator of degree 2, and from  $\dim_{\mathbf{k}}(\tilde{\mathfrak{m}}^3 \cap R / \tilde{\mathfrak{m}}^4 \cap R) = 0$  there is none of degree 3. We may write the generator as  $x = t^2 + ct^3$ , and  $\mathfrak{m} = \langle x \rangle + \tilde{\mathfrak{m}}^4$ . Up to a coordinate change (i.e. automorphism of  $\mathbf{k}[[t]]$ ), we may take  $x = t^2$ , and

$$\mathfrak{m}/\mathfrak{m}^2 = \langle t^2, t^5 \rangle,$$

so  $R \simeq \mathbf{k}[[x, y]]/(x^5 - y^2)$ , as anticipated.



□

From now on, we only look for Gorenstein singularities. With notation as above, let  $I = (R : \tilde{R}) = \text{Ann}_R(\tilde{R}/R)$  be the *conductor ideal* of the singularity. Recall e.g. [AK70, Proposition VIII.1.16]:  $(C, q)$  is Gorenstein if and only if

$$\dim_{\mathbf{k}}(R/I) = \dim_{\mathbf{k}}(\tilde{R}/R)(= \delta).$$

Recall from [Ste96, Definition 2-1] that a curve singularity  $(C, q)$  is *decomposable* if  $C$  is the union of two curves  $C_1$  and  $C_2$  that lie in distinct smooth spaces intersecting each other transversely in  $q$ . Given a parametrisation  $x_i = x_i(t_1, \dots, t_m)$ ,  $i = 1, \dots, l$ , this means that there is a partition  $S \sqcup S' = \{1, \dots, m\}$  such that  $x_i$  only depends on  $t_s, s \in S$ , or  $s \in S'$ , for all  $i$ . Aside from the node, Gorenstein singularities are never decomposable [AFS16, Proposition 2.1].

**PROPOSITION 2.2.** *For every fixed integer  $m \geq 2$ , there are exactly two Gorenstein curve singularities of genus two with  $m$  branches.*

*Proof.* We only need to find a basis for  $\mathfrak{m}/\mathfrak{m}^2$ , because a map of complete local rings that is surjective on cotangent spaces is surjective. From observation (iii) again, we find three possibilities for the vector  $(d_1, d_2, d_3)$ ,  $d_i = \dim_{\mathbf{k}}(\tilde{R}/R)_i$ ;  $d_{\geq 4} = 0$  in any case.

**Case  $(2, 0, 0)$ .** We see that  $\tilde{\mathfrak{m}}^2 \subseteq I$ , so, if  $(C, q)$  were Gorenstein, (v) would imply:

$$m + 1 = \delta = \dim_{\mathbf{k}}(R/I) \leq \dim_{\mathbf{k}}(R/\tilde{\mathfrak{m}}^2) = \dim_{\mathbf{k}} A_0 + \dim_{\mathbf{k}} A_1 = 1 + (m - 2) = m - 1,$$

a contradiction. Note: the singularity turns out to be decomposable in this case.

**Case  $(1, 1, 0)$ .** We have  $\tilde{\mathfrak{m}}^3 \subseteq I$ . We are going to write down the  $m - 1$  generators of  $A_1 \pmod{\tilde{\mathfrak{m}}^3}$ <sup>1</sup>. The first generator, call it  $x_1$ , has a non-trivial linear term in at least one of the variables, say  $t_1$ . By scaling  $x_1$  and possibly adding a multiple of  $x_1^2$ , we can make it into the form:  $x_1 = t_1 \oplus p_{1,2}(t_2) \oplus \dots \oplus p_{1,m}(t_m) \pmod{\tilde{\mathfrak{m}}^3}$ . Now we can use  $x_1$  and  $x_1^2$  to make sure the second generator does not involve  $t_1$  at all. It will still have a linear term independent of  $t_1$ , say non-trivial in  $t_2$ . By scaling and adding a multiple of  $x_2^2$ , we can write  $x_2 = 0 \oplus t_2 \oplus \dots \oplus p_{2,m}(t_m) \pmod{\tilde{\mathfrak{m}}^3}$ . By taking a linear combination of  $x_1$  with  $x_2$  and  $x_2^2$ , we may now reduce  $x_1$  to the form  $t_1 \oplus 0 \oplus p_{1,3}(t_3) \oplus \dots \oplus p_{1,m}(t_m) \pmod{\tilde{\mathfrak{m}}^3}$ . Continuing this way, by Gaussian elimination with the generators and their squares, we may write them as:

$$\begin{aligned} x_1 &= t_1 \oplus 0 \oplus \dots \oplus \alpha_{1,m} t_m + \beta_{1,m} t_m^2 \\ x_2 &= 0 \oplus t_2 \oplus \dots \oplus \alpha_{2,m} t_m + \beta_{2,m} t_m^2 \\ &\dots \\ x_{m-1} &= 0 \oplus \dots \oplus t_{m-1} \oplus \alpha_{m-1,m} t_m + \beta_{m-1,m} t_m^2 \pmod{\tilde{\mathfrak{m}}^3}. \end{aligned}$$

If  $x_i \in I$  for some  $i$ , then  $t_i \in R$ , and the singularity would be decomposable. So, by the Gorenstein condition,  $R/I$  is generated by  $1, x_1, \dots, x_{m-1}$ , and an extra element  $y$ . Hence  $x_i^2 \in I$  for all but at most one  $i$ , say  $i = 1$ . Then  $t_i^2 \in R$  for  $i = 2, \dots, m - 1$ . If  $\alpha_{i,m} \neq 0$  for some  $i$  in this range, then  $t_m^2 \in R$  as well, so  $t_1^2 = x_1^2 - O(t_m^2) \in R$ , contradicting  $\dim_{\mathbf{k}}(\tilde{R}/R)_2 = 1$ . Therefore  $\alpha_{i,m} = 0$  for  $i \in \{2, \dots, m - 1\}$ . If  $\alpha_{1,m} = 0$ , there would be another generator of  $\mathfrak{m}/\mathfrak{m}^2$ , that could be taken

<sup>1</sup>To express them in the simplest possible form, we perform at first only polynomial manipulations of the generators, while changing coordinates on the normalisation only at the end - the benefit of this two-step process will become apparent in the next section.

to be  $z = 0 \oplus \dots \oplus t_m^3$ . In this case, though, both  $x_1^2$  and  $z$  would belong to  $I$ , so  $\dim_k(R/I) = m$ , and the singularity could not be Gorenstein. We are reduced to the following expression:

$$\begin{aligned} x_1 &= t_1 \oplus 0 \oplus \dots \oplus \alpha_{1,m} t_m + \beta_{1,m} t_m^2 \\ x_2 &= 0 \oplus t_2 \oplus \dots \oplus \beta_{2,m} t_m^2 \\ &\dots \\ x_{m-1} &= 0 \oplus \dots \oplus t_{m-1} \oplus \beta_{m-1,m} t_m^2 \pmod{\tilde{\mathfrak{m}}^3}, \end{aligned} \tag{1}$$

with  $\beta_{1,m} \in \mathbf{k}$  and  $\alpha_{1,m}, \beta_{i,m} \in \mathbf{k}^\times$ ,  $i = 2, \dots, m-1$  (by indecomposability). Finally, we change coordinates in  $t_m$  (abusing notation,  $t_m := \alpha_{1,m} t_m + \beta_{1,m} t_m^2$ ) and rescale the other  $t_i$  to obtain:

$$\begin{aligned} x_1 &= t_1 \oplus 0 \oplus \dots \oplus t_m \\ x_2 &= 0 \oplus t_2 \oplus \dots \oplus t_m^2 \\ &\dots \\ x_{m-1} &= 0 \oplus \dots \oplus t_{m-1} \oplus t_m^2 \pmod{\tilde{\mathfrak{m}}^3}. \end{aligned} \tag{2}$$

We check that  $R/I = \langle 1, x_1, \dots, x_{m-1}, x_1^2 \rangle$  and  $\tilde{R}/R$  is of type  $(1, 1, 0)$ . In case  $m = 2$ , we need an extra generator  $y = t_2^3$ . Equations are given by:

- $y(y - x_1^3)$  if  $m = 2$  ( $A_5$ -singularity or *oscnode*);
- $x_1 x_2 (x_2 - x_1^2)$  if  $m = 3$  ( $D_6$ -singularity);
- $\langle x_3 (x_1^2 - x_2), x_i (x_j - x_k) \rangle_{1 \leq i < j < k \leq m-1 \text{ or } 1 < j < k < i \leq m-1}$  if  $m \geq 4$ .

**Case  $(1, 0, 1)$ .** We have  $\tilde{\mathfrak{m}}^4 \subseteq I$ . By an argument similar to the above one, we write generators for  $A_1$  as  $x_i = \dots \oplus t_i \oplus \dots \oplus \alpha_{i,m} t_m + \beta_{i,m} t_m^2 + \gamma_{i,m} t_m^3$ , for  $i = 1, \dots, m-1$ . Then  $R/I = \langle 1, x_1, \dots, x_{m-1}, y \rangle$ . For all but at most one  $i$ ,  $x_i^2 \in I$ , but definitely  $x_i^3 \in I$  for all  $i$ . On the other hand  $t_m^3 \notin R$ , because otherwise  $t_i^3 = x_i^3 - \alpha_{i,m}^3 t_m^3 + O(t_m^4)$  would belong to  $R$  as well, contradicting  $\dim_{\mathbf{k}}(\tilde{R}/R)_3 = 1$ . From this we deduce that  $\alpha_{i,m} = 0$  for all  $i = 1, \dots, m-1$ . Since  $\dim_{\mathbf{k}}(\tilde{R}/R)_2 = 0$ , there has to be another generator of  $\mathfrak{m}/\mathfrak{m}^2$  of degree two in  $t_m$ , which we may write as  $x_m = t_m^2 + \gamma_{m,m} t_m^3$ . We can use  $x_m$  to remove all the  $t_m^2$  pieces from  $x_1, \dots, x_{m-1}$ , so we are reduced to the following expression:

$$\begin{aligned} x_1 &= t_1 \oplus 0 \oplus \dots \oplus \gamma_{1,m} t_m^3 \\ x_2 &= 0 \oplus t_2 \oplus \dots \oplus \gamma_{2,m} t_m^3 \\ &\dots \\ x_{m-1} &= 0 \oplus \dots \oplus t_{m-1} \oplus \gamma_{m-1,m} t_m^3 \\ x_m &= 0 \oplus \dots \oplus t_m^2 + \gamma_{m,m} t_m^3 \pmod{\tilde{\mathfrak{m}}^4}, \end{aligned} \tag{3}$$

with  $\gamma_{m,m} \in \mathbf{k}$  and  $\gamma_{i,m} \in \mathbf{k}^\times$ ,  $i = 1, \dots, m-1$  (by indecomposability). Finally, we change

coordinates in  $t_m$  (abusing notation  $t_m := t_m \sqrt{1 + \gamma_{m,m} t_m}$ )<sup>2</sup> and rescale the other  $t_i$  to obtain:

$$\begin{aligned} x_1 &= t_1 \oplus 0 \oplus \dots \oplus t_m^3 \\ x_2 &= 0 \oplus t_2 \oplus \dots \oplus t_m^3 \\ &\dots \\ x_{m-1} &= 0 \oplus \dots \oplus t_{m-1} \oplus t_m^3 \\ x_m &= 0 \oplus \dots \oplus t_m^2 \pmod{\tilde{\mathfrak{m}}^4}. \end{aligned} \tag{4}$$

We check that  $R/I = \langle 1, x_1, \dots, x_{m-1}, x_m \rangle$  and  $\tilde{R}/R$  is of type  $(1, 0, 1)$ . Incidentally, when  $m = 1$ , we recover the unique Gorenstein singularity of Lemma 2.1. Equations are given by:

- $x^5 - y^2$  if  $m = 1$  ( $A_4$ -singularity or *ramploid cusp*, with  $x = t^2, y = t^5$ );
- $y(y^3 - x^2)$  if  $m = 2$  ( $D_5$ -singularity, with  $x = x_1, y = x_2$ );
- $\langle x_3(x_1 - x_2), x_3^3 - x_1 x_2 \rangle$  if  $m = 3$ ;
- $\langle x_i(x_j - x_k), x_m(x_i - x_j), x_m^3 - x_1 x_2 \rangle_{i,j,k \in \{1, \dots, m-1\}}$  all different if  $m \geq 4$ .

□

*Remark 2.3.* We sketch an alternative proof of the above proposition based on meromorphic differentials, see also Corollary 2.5 below. We address the case  $(1, 0, 1)$  and leave the (easier) case  $(1, 1, 0)$  to the interested reader. The setup is as in [RSPW19b, §2.1]: let  $C$  be a projective Gorenstein curve with a unique singularity of genus two at the point  $q$ . Let:

$$\tilde{C} \xrightarrow{\nu} \hat{C} \xrightarrow{\mu} C$$

be respectively the normalisation and semi-normalisation of  $C$ . We have inclusions:

$$\begin{array}{cccc} \mathcal{O}_C & \subseteq \mu_* \mathcal{O}_{\hat{C}} & \subseteq \mu_* \nu_* \mathcal{O}_{\tilde{C}} & \subseteq K \\ J \supseteq \omega_C & \supseteq \mu_* \omega_{\hat{C}} & \supseteq \mu_* \nu_* \omega_{\tilde{C}} & \end{array}$$

where  $K$  is the sheaf of rational functions, and  $J$  the sheaf of meromorphic differentials. The rows are dual to each other with respect to the residue pairing  $J \otimes K \rightarrow \mathbf{k}$  [AK70, Proposition 1.16(ii)]. The skyscraper sheaf  $\omega_{\hat{C}}/\nu_* \omega_{\tilde{C}}$  is generated by the logarithmic differentials:

$$\frac{dt_i}{t_i} - \frac{dt_j}{t_j}, \quad i, j \in \{1, \dots, m\}. \tag{5}$$

The skyscraper sheaves  $\mu_* \mathcal{O}_{\hat{C}}/\mathcal{O}_C$  and  $\omega_C/\mu_* \omega_{\hat{C}}$  have length two. Let  $\eta_1$  be a generator of the latter; since  $C$  is Gorenstein, we may assume that  $\eta_1$  is a local generator of  $\omega_C$ . Since  $\tilde{\mathfrak{m}}^4 \subseteq R$  and by Equation (5), we may assume that  $\eta_1$  takes the following form:

$$\eta_1 = \zeta \frac{dt_1}{t_1} + \sum_{i=1}^m \alpha_i \frac{dt_i}{t_i^2} + \sum_{i=1}^m \beta_i \frac{dt_i}{t_i^3} + \sum_{i=1}^m \gamma_i \frac{dt_i}{t_i^4}. \tag{6}$$

Since the constant functions descend to  $C$ , the residue condition implies that  $\zeta = 0$ . Now,  $\mu_* \omega_{\hat{C}}/\omega_C$  has a second generator  $\eta_2$  of the form  $\eta_2 = f \eta_1$  for some  $f \in R$ . Expanding  $f = f_0 + \sum_{i,j} f_{i,j} t_i^j$  we may write:

$$\eta_2 = \sum_{i=1}^m (\beta_i f_{i,1} + \gamma_i f_{i,2}) \frac{dt_i}{t_i^2} + \sum_{i=1}^m \gamma_i f_{i,1} \frac{dt_i}{t_i^3}. \tag{7}$$

---

<sup>2</sup>For this to be possible, we have to assume that  $\mathbf{k}$  has characteristic different from 2.

Not all the  $\gamma_i$  can be zero, otherwise we would have  $\tilde{\mathfrak{m}}^3 \subseteq R$ , so say  $\gamma_m \neq 0$ ; this implies that  $t_m^3 \notin R$  (and in particular  $t_m \notin R$ ). Up to scaling we have  $\gamma_m = 1$ . Since  $A_3$  has dimension one, for every  $i = 1, \dots, m-1$  there is a linear combination:

$$g_i = t_i^3 + x_i t_m^3 \in R.$$

Pairing with  $\eta_1$  we find  $x_i = -\gamma_i$ .

Since  $A_2 = 0$ , for every  $i = 1, \dots, m$  there is a linear combination:

$$h_i = t_i^2 + y_i t_m^3 \in R.$$

Pairing with  $\eta_1$  we find  $y_i = -\beta_i$ . Pairing with  $\eta_2$  we find  $\gamma_i f_{i,1} = 0$  (so  $f_{m,1} = 0$ ). Equation (7) becomes:

$$\eta_2 = \left( \sum_{i:\gamma_i=0, f_{i,1} \neq 0} \beta_i f_{i,1} + \sum_{i:\gamma_i \neq 0, f_{i,1}=0} \gamma_i f_{i,2} \right) \frac{dt_i}{t_i^2}.$$

Since  $A_1$  has dimension one and  $t_m \notin R$ , for every  $i = 1, \dots, m-1$  there is a linear combination:

$$l_i = t_i + z_i t_m^3 \in R.$$

Pairing with  $\eta_1$  we find  $z_i = -\alpha_i$ . So  $\alpha_i \neq 0$  for  $i = 1, \dots, m-1$ , otherwise  $C$  would be decomposable. Pairing with  $\eta_2$  we find

$$\beta_i f_{i,1} + \gamma_i f_{i,2} = 0, \quad i = 1, \dots, m-1. \quad (8)$$

Taking  $l_i^2$ , we have  $t_i^2 \in R, i = 1, \dots, m-1$ , as well. Pairing with  $\eta_1$ , we find  $\beta_i = 0$ .

Taking  $l_i^3$ , we have  $t_i^3 \in R, i = 1, \dots, m-1$ , as well. Pairing with  $\eta_1$ , we find  $\gamma_i = 0$ . So, ultimately, we find:

$$\eta_2 = \frac{dt_m}{t_m^2}.$$

By taking a linear combination with  $\eta_2$ , Equation (6) becomes:

$$\eta_1 = \sum_{i=1}^{m-1} \alpha_i \frac{dt_i}{t_i^2} + \beta_m \frac{dt_m}{t_m^3} + \frac{dt_m}{t_m^4}, \text{ with } \alpha_i \in \mathbf{k}^\times, \beta_m \in \mathbf{k}.$$

DEFINITION 2.4. In case  $(1, 0, 1)$ , we say the singularity is *of type I*, and the branch parameterised by  $t_m$  is called *singular*; in case  $(1, 1, 0)$ , we say the singularity is *of type II*, and the branches parameterised by  $t_1$  and  $t_m$  are called *twin*. We shall refer to the singular or twin branches as *special* or *distinguished*; all other branches are *axes*. *Branch* remains a generic name, indicating any of the previous ones.

We gather a description of the dualising line bundle in the following:

COROLLARY 2.5. Let  $\nu: C \rightarrow \bar{C}$  be the normalisation of a Gorenstein singularity of genus two, with  $\nu^{-1}(q) = \{q_1, \dots, q_m\}$ .

(I) With local parametrisation as in (4),  $\omega_{\bar{C}}$  is generated by:

$$\frac{dt_1}{t_1^2} + \dots + \frac{dt_{m-1}}{t_{m-1}^2} - \frac{dt_m}{t_m^4},$$

$$\text{and } \nu^* \omega_{\bar{C}} = \omega_C(2q_1 + \dots + 2q_{m-1} + 4q_m).$$

(II) With local parametrisation as in (2),  $\omega_{\tilde{C}}$  is generated by:

$$\frac{dt_1}{t_1^3} + \frac{dt_2}{t_2^2} + \dots + \frac{dt_{m-1}}{t_{m-1}^2} - \frac{dt_m}{t_m^3},$$

and  $\nu^*\omega_{\tilde{C}} = \omega_C(3q_1 + 2q_2 + \dots + 2q_{m-1} + 3q_m)$ .

### 3. Tangent sheaf, crimping space, and automorphisms

In this section we analyse the tangent sheaf of a genus two singularity. For a complete pointed Gorenstein curve of genus two, we translate the absence of infinitesimal automorphisms into a (mostly) combinatorial criterion. We will use this in Section 5, when we define stability conditions on the stack of pointed Gorenstein curves of genus two, to make sure that the resulting substacks are Deligne-Mumford. The crimping space naturally makes an appearance. Although we do not use it explicitly in this paper, it parametrises singularities of a given type and pointed normalisation. It helps understanding the birational map between two compactifications of  $\mathcal{M}_{2,n}$ .

In the next lemma, we find explicit conditions for a vector field on the normalisation, vanishing at the preimage of the singular point, to descend to the singular curve.

LEMMA 3.1. *Let  $(C, q)$  be a Gorenstein curve singularity of genus two, with pointed normalisation  $\nu: (\tilde{C}, \{q_i\}_{i=1,\dots,m}) \rightarrow (C, q)$ , and assume  $\text{char}(\mathbf{k}) \neq 2, 3$ . There are exact sequences of sheaves*

$$\begin{array}{ccccccc} 0 & \longrightarrow & \nu_*\Omega_{\tilde{C}}^\vee(-\sum_i 3q_i) & \longrightarrow & \nu_*\Omega_{\tilde{C}}^\vee(-\sum_i q_i) & \longrightarrow & \nu_*\bigoplus_i \Omega_{\tilde{C}}^\vee(-q_i)_{|2q_i} \longrightarrow 0 \\ & & \parallel & & \uparrow & & \square & \uparrow \phi \\ 0 & \longrightarrow & \nu_*\Omega_{\tilde{C}}^\vee(-\sum_i 3q_i) & \longrightarrow & \Omega_C^\vee & \longrightarrow & \mathbf{k}^{\oplus m} \longrightarrow 0 \end{array}$$

The image of the rightmost vertical map admits an explicit description in local coordinates.

*Proof.* Let  $K(\tilde{C})$  denote the locally constant sheaf of rational functions on  $\tilde{C}$ . A section of  $\Omega_{\tilde{C}}^\vee \otimes K(\tilde{C})$  is contained in  $\Omega_{\tilde{C}}^\vee$  if and only if its image under the push-forward map:

$$\nu_*: \nu_*\mathcal{H}om(\Omega_{\tilde{C}}, K(\tilde{C})) \rightarrow \mathcal{H}om(\Omega_C, K(\tilde{C}))$$

lies in the subspace  $\mathcal{H}om(\Omega_C, \mathcal{O}_C)$ . Since in any case  $\tilde{\mathbf{m}}^4 \subseteq \mathbf{m}$  (see the proof of Proposition 2.2), vector fields vanishing up to order three certainly descend. In order to find the remaining conditions, we may work locally around the singular point in the coordinates of Section 2.

(A<sub>4</sub>): In the coordinates  $x = t^2 + ct^3, y = t^4, z = t^5$  (they are redundant, but this will be irrelevant), the section  $f(t)\frac{d}{dt} \in \nu_*\Omega_{\tilde{C}}^\vee \otimes K(\tilde{C})$  pushes forward to

$$\nu_*\left(f(t)\frac{d}{dt}\right) = (2t + 3ct^2)f(t)\frac{d}{dx} + 4t^3f(t)\frac{d}{dy} + 5t^4f(t)\frac{d}{dz},$$

from which, writing  $f(t) = f_0 + f_1t + f_2t^2 + O(t^3)$ , we see that

$$(2t + 3ct^2)f(t), 4t^3f(t), 5t^4f(t) \in \hat{\mathcal{O}}_{C,p} \Leftrightarrow f_0 = 0, cf_1 + 2f_2 = 0.$$

(A<sub>5</sub>): In the coordinates  $x = t_1 \oplus at_2 + bt_2^2, y = t_1^3$  (we have  $a \neq 0$ ), the section  $f_1(t_1)\frac{d}{dt_1} \oplus f_2(t_2)\frac{d}{dt_2}$  pushes forward to

$$\nu_*\left(f_1(t_1)\frac{d}{dt_1} \oplus f_2(t_2)\frac{d}{dt_2}\right) = (f_1(t_1) \oplus (a + 2bt_2)f_2(t_2))\frac{d}{dx} + 3t_1^2f_1(t_1)\frac{d}{dy},$$

from which, writing  $f_i(t_i) = f_{i0} + f_{i1}t_i + f_{i2}t_i^2 + O(t_i^3)$ ,  $i = 1, 2$ , we see that

$$f_1(t_1) \oplus (a + 2bt_2)f_2(t_2), 3t_1^2f_1(t_1) \in \hat{\mathcal{O}}_{C,p} \Leftrightarrow \begin{cases} f_{10} = f_{20} = 0, \\ f_{11} = f_{21}, \\ 2bf_{21} + af_{22} = a^2f_{12}. \end{cases}$$

$(I_{m \geq 2})$  : In the coordinates of (3),

$$\nu_* \left( \sum_{i=1}^m f_i(t_i) \frac{d}{dt_i} \right) = \sum_{i=1}^{m-1} (f_i(t_i) \oplus 3\gamma_{i,m} t_m^2 f_m(t_m)) \frac{d}{dx_i} + (2t_m + 3\gamma_{m,m} t_m^2) f_m(t_m) \frac{d}{dx_m},$$

hence we deduce that

$$\nu_* \left( \sum_{i=1}^m f_i(t_i) \frac{d}{dt_i} \right) \in \Omega_C^\vee \otimes \hat{\mathcal{O}}_{C,p} \Leftrightarrow \begin{cases} f_{i0} = 0 & i = 1, \dots, m, \\ f_{i1} = 3f_{m1}, & i = 1, \dots, m-1, \\ 3\gamma_{m,m} f_{m1} + 2f_{m2} = 0. \end{cases}$$

$(II_{m \geq 3})$  : In the coordinates of (1),

$$\nu_* \left( \sum_{i=1}^m f_i(t_i) \frac{d}{dt_i} \right) = (f_1(t_1) \oplus (\alpha_{1,m} + 2\beta_{1,m} t_m) f_m(t_m)) \frac{d}{dx_1} + \sum_{i=2}^m (f_i(t_i) \oplus 2\beta_{i,m} t_m f_m(t_m)) \frac{d}{dx_i},$$

hence we deduce that

$$\nu_* \left( \sum_{i=1}^m f_i(t_i) \frac{d}{dt_i} \right) \in \Omega_C^\vee \otimes \hat{\mathcal{O}}_{C,p} \Leftrightarrow \begin{cases} f_{i0} = 0 & i = 1, \dots, m, \\ 2f_{11} = f_{i1} = 2f_{m1}, & i = 2, \dots, m-1, \\ \beta_{1,m} f_{m1} + \alpha_{1,m} f_{m2} = \alpha_{1,m}^2 f_{12}. \end{cases}$$

□

We anticipate that the letters  $\alpha, \beta$  and  $\gamma$  will play a role in determining the automorphism group of a complete curve with markings. We recall some key concepts from F. van der Wyck's thesis. Working over  $\mathbf{k}$ , he considers the stacks:

- $\mathcal{S}$  of reduced one-dimensional (1d)  $\mathbf{k}$ -algebras  $R$ ,
- $\mathcal{T}$  of reduced 1d algebras with resolution  $(R \hookrightarrow (S, J))$ , where  $S$  is a smooth one-dimensional  $\mathbf{k}$ -algebra, and  $J$  the radical of the conductor of  $R \subseteq S$ .

Basically,  $R$  represents the (local) ring of a reduced curve with one singular point,  $S$  is its normalisation, and  $J$  is the ideal of the reduced fibre over the singular point of  $\text{Spec}(R)$ .  $\mathcal{S}$  and  $\mathcal{T}$  are limit-preserving stacks over  $\text{Spec}(\mathbf{k})$  [vdW10, Proposition 1.21]. Furthermore, we may fix a reduced 1d algebra with resolution  $\tau_0 : (R_0 \hookrightarrow (S_0, J_0))$ , and consider the substack  $\mathcal{T}(\tau_0)$  of reduced 1d algebras with singularity type  $\tau_0$  (i.e. isomorphic to  $\tau_0$  locally on both the base and the curve, see [vdW10, Definition 1.64]; that various notions of “locally” coincide is proved in [vdW10, Proposition 1.50]). There is a forgetful morphism  $\mathcal{T} \rightarrow \mathcal{S}$ , and the *crimping space* of  $\tau_0$  is defined to be the fibre over  $R_0$  of the restriction of such morphism to  $\mathcal{T}(\tau_0)$ . The crimping space is a smooth  $\mathbf{k}$ -scheme [vdW10, Theorems 1.70 and 1.73]; indeed, it is isomorphic to the quotient of  $\text{Aut}_{(S_0, J_0)/\mathbf{k}}$  by  $\text{Aut}_{(S_0, J_0)/R_0}$ , the latter consisting of automorphisms of the normalisation that preserve the subalgebra of the singularity; moreover, by [vdW10, Theorem 1.53] the quotient can

be computed after modding out the lowest power of  $J$  contained in  $R$ , denoted by  $\text{Aut}_{(S,J)}^{\text{mod } J^k}$  respectively  $\text{Aut}_{(S,J)/R}^{\text{mod } J^k}$ . Crimping spaces can be thought of as moduli for the normalisation map.

**LEMMA 3.2.** *If  $\text{char}(\mathbf{k}) \neq 2, 3$ , the crimping space of a genus two singularity of type I (resp. II) with  $m$  branches is the disjoint union of  $m$  (resp.  $\binom{m}{2}$ ) copies of  $\mathbb{A}^1 \times (\mathbb{A}^1 \setminus \{0\})^{m-1}$ .*

*Proof.* We resume notation from the previous section. We are going to fix the subalgebra  $\tau_0$  given in coordinates by (4) and (2) respectively.

**Type I:** recall that in this case  $\tilde{\mathfrak{m}}^4 \subseteq R$ . For a  $\mathbf{k}$ -algebra  $A$ , let

$$G_i(A) = \{t_i \mapsto g_{i1}t_i + g_{i2}t_i^2 + g_{i3}t_i^3, t_j \mapsto t_j \mid g_{i1} \in A^\times, g_{i2}, g_{i3} \in A\},$$

and notice that

$$\text{Aut}_{(\tilde{R}, \tilde{\mathfrak{m}})}^{\text{mod } \tilde{\mathfrak{m}}^4}(A) = (G_1 \times \dots \times G_m) \rtimes \mathfrak{S}_m(A).$$

Consider now the action of a group element of the form  $(g_1, \dots, g_m; \text{id}_{\mathfrak{S}_m})$  on the given generators of  $R$ :

$$\begin{aligned} x_i &\mapsto \dots \oplus g_{i1}t_i + g_{i2}t_i^2 + g_{i3}t_i^3 \oplus \dots \oplus g_{m1}^3t_m^3, \quad \text{for } i = 1, \dots, m-1; \\ x_m &\mapsto \dots \oplus g_{m1}^2t_m^2 + 2g_{m1}g_{m2}t_m^3 \pmod{\tilde{\mathfrak{m}}^4}. \end{aligned}$$

The former belongs to  $R$  iff  $g_{i1} = g_{m1}^3$ ; the latter does iff  $g_{m2} = 0$ . Thus such elements span a subgroup isomorphic to  $\mathbb{G}_m \times \mathbb{G}_a^{m-1} \times \mathbb{G}_a^m(A)$ . On the other hand, there is a special (singular) branch, parametrised by  $t_m$ . We conclude that

$$\text{Aut}_{\tau_0}^{\text{mod } \tilde{\mathfrak{m}}^4}(A) = (\mathbb{G}_m \times \mathbb{G}_a^{m-1} \times \mathbb{G}_a^m) \rtimes (\mathfrak{S}_{m-1})(A).$$

The quotient is therefore isomorphic to  $m$  copies of  $\mathbb{A}^1 \times (\mathbb{A}^1 \setminus \{0\})^{m-1}$ .

**Type II:** recall that in this case  $\tilde{\mathfrak{m}}^3 \subseteq R$ . For a  $\mathbf{k}$ -algebra  $A$ , let

$$G_i(A) = \{t_i \mapsto g_{i1}t_i + g_{i2}t_i^2, t_j \mapsto t_j \mid g_{i1} \in A^\times, g_{i2} \in A\},$$

and notice that

$$\text{Aut}_{(\tilde{R}, \tilde{\mathfrak{m}})}^{\text{mod } \tilde{\mathfrak{m}}^3}(A) = (G_1 \times \dots \times G_m) \rtimes \mathfrak{S}_m(A).$$

Consider now the action of a group element of the form  $(g_1, \dots, g_m; \text{id}_{\mathfrak{S}_m})$  on the given generators of  $R$ :

$$\begin{aligned} x_i &\mapsto \dots \oplus g_{i1}t_i + g_{i2}t_i^2 \oplus \dots \oplus g_{m1}^2t_m^2, \quad \text{for } i = 2, \dots, m-1; \\ x_1 &\mapsto g_{11}t_1 + g_{12}t_1^2 \oplus \dots \oplus g_{m1}t_m + g_{m2}t_m^2 \pmod{\tilde{\mathfrak{m}}^3}. \end{aligned}$$

The former belongs to  $R$  iff  $g_{i1} = g_{m1}$  and  $g_{i2} = g_{m2}$ ; the latter does iff  $g_{i1} = g_{m1}^2$ . Thus, such elements span a subgroup isomorphic to  $\mathbb{G}_m \times \mathbb{G}_a^{m-1}(A)$ . On the other hand, all branches are smooth (therefore, isomorphic to each other), but two of them (parametrised by  $t_1$  and  $t_m$  respectively) are tangent, thus forming a distinguished pair. We conclude that

$$\text{Aut}_{\tau_0}^{\text{mod } \tilde{\mathfrak{m}}^3}(A) = (\mathbb{G}_m \times \mathbb{G}_a^{m-1}) \rtimes (\mathfrak{S}_2 \times \mathfrak{S}_{m-2})(A).$$

The quotient is then isomorphic to  $\binom{m}{2}$  copies of  $\mathbb{A}^1 \times (\mathbb{A}^1 \setminus \{0\})^{m-1}$ .  $\square$

**Remark 3.3.** The restrictions on the characteristic of the base field in Lemmas 3.1 and 3.2 rule out the sporadic occurrence of infinite families of automorphisms, and its effect on the crimping spaces. For example, when  $\text{char}(\mathbf{k}) = 2$ , the singularities  $\mathbf{k}[[t^2, t^5]]$  and  $\mathbf{k}[[t^2 + t^3, t^4, t^5]]$  are not isomorphic, the group of infinitesimal automorphisms has positive dimension, and the crimping space consists of an isolated point [vdW10, Examples 1.79-80].

The benefit of a two-step classification should now be clear: if we do not allow ourselves to change coordinates (i.e. act by automorphisms of the normalisation) until the end, the crimping space appears in the expressions (1) and (3) for the generators of the singularity subalgebra.

There is a more geometric way to realise the crimping spaces. It is well-known that an ordinary cusp of genus one can be obtained by collapsing (*push-out*) any non-zero tangent vector at  $p \in \mathbb{A}^1$ . More generally, a Gorenstein singularity of genus one and  $m$  branches can be obtained by collapsing a generic (not contained in any coordinate linear subspace) tangent line at an ordinary  $m$ -fold point (a non-Gorenstein singularity of genus zero) [Smy11a, Lemma 2.2]. Therefore, the crimping space of the elliptic  $m$ -fold point, which is isomorphic to  $(\mathbb{A}^1 \setminus \{0\})^{m-1}$ , can be realised as the complement of the coordinate hyperplanes inside  $\mathbb{P}(T_p R_m) \simeq \mathbb{P}^{m-1}$ , where  $(R_m, p)$  is the rational  $m$ -fold point. Besides, this gives rise to a natural compactification of the crimping space supporting a universal family of curves - in fact, two: either we collapse non-generic tangent vectors, obtaining non-Gorenstein singularities along the boundary (this family  $\mathcal{C}$  admits a common (semi)normalisation by the trivial family  $\tilde{\mathcal{C}} = R_m \times \mathbb{P}(T_p R_m)$ ); or we blow  $\tilde{\mathcal{C}}$  up along the boundary (*sprouting*), so that the non-Gorenstein singularities are replaced by elliptic  $m$ -fold points having strictly semistable branches [Smy11b, §2.2-3].

Similarly, a Gorenstein singularity of genus two can be obtained by collapsing a generic line in the tangent space of a non-Gorenstein singularity of genus one. Indeed,  $\tau_0^I$  admits a partial normalisation by  $\sigma_0^I$ , which is the decomposable union of a cusp (parametrised by  $t_m$ ) together with  $m-1$  axes; the local ring of  $\sigma_0^I$  is obtained from that of  $\tau_0^I$  by adjoining the generator  $t_m^3$ .  $\tau_0^{II}$  admits a partial normalisation by  $\sigma_0^{II}$ , which is the decomposable union of a tacnode in the  $(t_1, t_m)$ -plane together with  $m-2$  axes, adjoining the generator  $t_m^2$ .

These fit together nicely in a unifying picture: if we restrict  $\mathcal{C}$  from the previous paragraph to the union of the coordinate lines in  $\mathbb{P}(T_p R_m)$ , we obtain  $m$  copies of  $\sigma_0^I$  over the coordinate points, together with  $\binom{m}{2}$  copies of the universal curve of type  $\sigma_0^{II}$  over its crimping space - which is isomorphic to  $\mathbb{A}^1 \setminus \{0\}$  - identified with the line minus two points. Let  $P = \mathbb{P}(T_{\mathcal{C}/\mathbb{P}, p} \cup \text{lines})$  be the projectivised tangent space of the fibre at the singular point. For each of the  $\binom{m}{2}$  coordinate lines,  $P$  has one component  $P_i^{II}$  that is a  $\mathbb{P}^{m-1}$ -bundle over the line; besides,  $P$  has  $m$  components  $P_j^I$  isomorphic to  $\mathbb{P}^m$  and supported over the points. The crimping space of the genus two singularities with  $m$  branches (of type  $I$  and  $II$  together) can be realised as an open subscheme of  $P$ , obtained by removing from the  $\mathbb{P}^{m-1}$ -fibres of  $P^{II}$  the  $m-1$  hyperplanes generated by (a) the tangent line to the tacnode and the  $m-2$  axes, and (b) the plane containing the tacnode and all but one of the  $m-2$  axes; and from each  $P_j^I$  the  $m$  planes generated by (a) the tangent cone of the cusp and the  $m-1$  axes, and (b) the plane containing the cusp and all but one of the  $m-1$  axes.

*Remark 3.4.* Crimping spaces are related to the space of arrows  $\phi$  in the diagram of Lemma 3.1.

We interpret  $H^0(\Omega_{\mathbb{P}^1}^\vee(-p)_{|2p})$  as the tangent space to the subgroup of  $PGL_2$  fixing the point  $p \in \mathbb{P}^1$ , thus it inherits a natural Lie algebra structure, isomorphic to the unique non-abelian Lie algebra of dimension two  $V$ . It has a basis:

$$e_1 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad e_2 = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \quad \text{with } [e_1, e_2] = -2e_2.$$

The vector  $(\varphi, \psi)$  is seen to correspond to the infinitesimal automorphism:

$$t \mapsto \frac{1 + \epsilon \varphi t}{1 - \epsilon(\varphi t + \psi)} = t + \epsilon(2\varphi t - \psi t^2).$$

We are interested in arrows  $\phi$  that are embeddings (i.e.  $\in \text{Gr}(m, V^{\oplus m})$ ) of Lie subalgebras, such



that the corresponding groups of infinitesimal automorphisms fix the subalgebra of a singularity of genus two inside  $\mathbf{k}[[t_1]] \oplus \dots \oplus \mathbf{k}[[t_m]]$ .

We start with some heuristics. Here is the unibranch case: the subalgebra of  $\mathbf{k}[[t]]$  generated by  $x = t^2 + ct^3$  is preserved by  $(\varphi, \psi)$  if and only if

$$(1 + 2\varphi)^2 t^2 - 2\psi(1 + 2\varphi)t^3 + c(1 + 2\varphi)^3 t^3 \text{ is a multiple of } t^2 + ct^3,$$

which reduces to  $\varphi(1 + 2\varphi)c = \psi$ . This further determines  $c$  if and only if  $\varphi \neq 0$ . Note that in this case (dimension one) the Lie subalgebra condition is automatically satisfied. We have found  $(\varphi, \psi) \in \mathbf{k}^\times \times \mathbf{k}$ .

The case of type  $II_2$ -algebras is more interesting. Let  $x = (t_1, \alpha t_2 + \beta t_2^2)$  be the generator of such an algebra. The image of  $x$  under  $(\varphi_1, \psi_1, \varphi_2, \psi_2)$  is:

$$((1 + 2\varphi_1)t_1 - \psi_1 t_1^2, \alpha(1 + 2\varphi_2)t_2 + (\beta(1 + 4\varphi_2) - \alpha\psi_2)t_2^2),$$

from which we deduce:

$$\varphi_1 = \varphi_2 \quad \text{and} \quad 2\beta\varphi_2 - \alpha\psi_2 = -\alpha^2\psi_1. \quad (9)$$

Now let  $\phi: \mathbf{k}^2 \rightarrow V^{\oplus 2}$  be given by  $\begin{pmatrix} \varphi_{11} & \psi_{11} & \varphi_{12} & \psi_{12} \\ \varphi_{21} & \psi_{21} & \varphi_{22} & \psi_{22} \end{pmatrix}$ , with Plücker coordinates  $w_{ij}$  for the minor of the  $i$ -th and  $j$ -th columns. The first condition in (9) immediately implies

$$w_{13} = 0 \quad \text{and} \quad w_{12} = -w_{23}, w_{14} = w_{34}. \quad (10)$$

The second condition in (9) implies

$$\alpha w_{12} = w_{14} \quad \text{and} \quad 2\beta w_{12} = \alpha w_{24} \quad (11)$$

so that  $(\alpha, \beta) \in \mathbf{k}^\times \times \mathbf{k}$  is determined as soon as  $w_{12}, w_{14} \neq 0$ . Notice that (10) implies in particular the Plücker equation

$$w_{12}w_{34} - w_{13}w_{24} + w_{14}w_{23}.$$

It is easy to see that the condition for  $\phi$  to be a sub-Lie algebra is

$$\text{rk} \begin{pmatrix} \varphi_{11} & \psi_{11} & \varphi_{12} & \psi_{12} \\ \varphi_{21} & \psi_{21} & \varphi_{22} & \psi_{22} \\ 0 & w_{12} & 0 & w_{34} \end{pmatrix} = 2,$$

translating into

$$\begin{aligned} w_{12}w_{13} &= 0 & w_{12}(w_{34} - w_{14}) &= 0 \\ w_{13}w_{34} &= 0 & (w_{12} + w_{23})w_{34} &= 0 \end{aligned}$$

automatically satisfied after (10) too. These equations cut inside  $\mathbb{P}_{[w_{ij}]}^5$  the locus

$$(\mathbb{A}_{w_{14}/w_{12}}^1 \setminus \{0\}) \times \mathbb{A}_{w_{24}/w_{12}}^1.$$

More generally, given a type  $II$  subalgebra  $R_{\alpha, \beta}$  of  $W = \bigoplus_{i=1}^m \mathbf{k}[[t_i]]/(t_i^2)$ , with generators of the form described in (1), the subalgebra of  $V_{(\varphi_i, \psi_i)_{i=1, \dots, m}}^{\oplus m}$  preserving  $R_{\alpha, \beta}$  is isomorphic to  $\mathbf{k}^{\oplus m}$  with equations (see Lemma 3.1):

$$\begin{cases} 2\varphi_1 = \varphi_i = 2\varphi_m, & \text{for } i = 2, \dots, m-1, \\ 2\beta_{1,m}\varphi_m - \alpha_{1,m}\psi_m = -\alpha_{1,m}^2\psi_1; \end{cases}$$

it is easily seen that such a subalgebra of  $V^{\oplus m}$  does not determine  $R_{\alpha, \beta}$ , but it does determine  $(\alpha_{1,m}, \beta_{1,m})$ . The case of type  $I$  is analogous.

We apply the preceding discussion to the study of automorphism groups of complete marked curves with a genus two singularity. The relevant category has been formalised in van der Wyck's thesis, see [vdW10, Proposition 1.102, Theorem 1.105 and Corollary 1.106], where he introduces the concept of type  $T$  reduced complete pointed curves with resolution, and the algebraic stack  $\mathcal{N}_T$  of such objects. The type encodes the number and isomorphism class of the singularities, the distribution of genus and markings among the components of the normalisation, and the adjacency data between components and singular points.

In the case that  $T$  has a unique singularity of genus two, with  $m$  one-marked rational branches, the stack  $\mathcal{N}_T$  is isomorphic to  $[\mathbb{A}^1/\mathbb{G}_m]$  (see [vdW10, Examples 1.111-112]), so it has two points: one with  $\mathbb{G}_m$ , and the other with trivial stabiliser.

DEFINITION 3.5. The *atom* of type  $I_m$  (the name is borrowed from [AFSvdW17]) is obtained by gluing the subalgebra of  $\mathbf{k}[t_1] \oplus \dots \oplus \mathbf{k}[t_m]$  generated by  $x_1, \dots, x_m$  as in (4) with  $m$  copies of  $(\mathbf{k}[s], (s))$  under the identification  $s_i = t_i^{-1}$ . The multiplicative group  $\mathbb{G}_m$  acts on the atom by  $\lambda.t_i = \lambda^3 t_i$  for  $i = 1, \dots, m-1$  and  $\lambda.t_i = \lambda t_i$  for  $i = m$ .

Similarly, the atom of type  $II_m$  is obtained by gluing the subalgebra of  $\mathbf{k}[t_1] \oplus \dots \oplus \mathbf{k}[t_m]$  generated by  $x_1, \dots, x_{m-1}$  (and  $y$ ) as in (2) (and following lines) with  $m$  copies of  $(\mathbf{k}[s], (s))$  under the identification  $s_i = t_i^{-1}$ . There is a  $\mathbb{G}_m$ -action on the type  $II$  atom by  $\lambda.t_i = \lambda t_i$  for  $i = 1, m$  and  $\lambda.t_i = \lambda^2 t_i$  for  $i = 2, \dots, m-1$ .

The curve with a genus two singularity and one-marked rational branches that has trivial automorphism group will be called the *non-atom*.

Again, here is a more geometric way to realise the dichotomy. The non-Gorenstein genus one singularity of type  $\sigma_0^{II}$  (resp.  $\sigma_0^I$ ), with one-marked rational branches, has automorphism group  $\mathbb{G}_m^{m-1}$  (resp.  $\mathbb{G}_m^m$ ). This acts on the tangent space at the singular point: of the lines fixed by this action, only one (call it  $\ell'$ ) sits inside the open subset corresponding to the crimping space; all other lines in the crimping space are identified under the group action (call  $\ell$  their equivalence class). Collapsing  $\ell$  yields the non-atom, while collapsing  $\ell'$  yields the atom.

As a third viewpoint, automorphisms can be studied by twisting the exact sequences of Lemma 3.1 by the ideal of the markings, and then taking global sections. The dicotomy arises then from the map  $\phi$ : if the last condition imposed on infinitesimal automorphisms interweaves first and second order non-trivially (i.e. when  $\beta_{1,m}$ , resp.  $\gamma_{m,m}$ , are non-zero) then it is enough that automorphisms are trivial to second order on every branch for them to be trivial for good.

Finally, we shall rephrase the finiteness of automorphism groups explicitly in terms of types. Recall Smyth's description of genus one curves with no infinitesimal automorphisms [Smy11a, Proposition 2.3, Corollary 2.4].

DEFINITION 3.6. Let  $(C, p_1, \dots, p_n)$  be a reduced pointed curve. A connected subcurve  $D \subseteq C$  is said to be *nodally attached* if  $D \cap \overline{C \setminus D}$  consists of nodes only. We say that  $C$  is *residually DM* (rDM) if every nodal and nodally attached subcurve  $D$  of  $C$ , marked by  $\{p_i \in D\} \cup (D \cap \overline{C \setminus D})$ , is Deligne-Mumford stable. As usual, by *special points* we mean markings and nodes.

COROLLARY 3.7. Let  $(C, p_1, \dots, p_n)$  be a Gorenstein pointed curve of arithmetic genus two over a field of characteristic  $\neq 2, 3$ .  $H^0(C, \Omega_C^\vee(-\sum_{i=1}^n p_i)) = 0$  is equivalent to either of the following:

- (i)  $C$  has a singularity of type  $I_{m \geq 1}$ : either all branches contain exactly one special point and  $C$  is the non-atom; or each of its axes contains at least one special point, and at least one branch has at least two. Furthermore  $C$  is rDM.

- (ii)  $C$  has a singularity of type  $II_{m \geq 2}$ : either all branches contain exactly one special point and  $C$  is the non-atom; or at least one of its twin branches contains a special point, each of its axes contains at least one, and at least one branch has at least two. Furthermore  $C$  is rDM.
- (iii)  $C$  has two elliptic  $m$ -fold points: each of their branches contains at least one special point or is shared, and at least one branch for each singular point contains at least one extra special point. Furthermore  $C$  is rDM.
- (iv)  $C$  has one elliptic  $m$ -fold point: one of its branches is a genus one curve, and every other branch contains at least one special point; otherwise, all branches contain at least one, and either two of its branches coincide, or at least one branch has at least two special points. Furthermore  $C$  is rDM.
- (v)  $C$  contains only nodes and is Deligne-Mumford stable.

#### 4. Admissible covers and semistable tails

Given a family of prestable (pointed) curves of genus two over the spectrum of a discrete valuation ring  $\mathcal{C} \rightarrow \Delta$ , with smooth generic fibre  $\mathcal{C}_\eta$  and regular total space, we classify the subcurves of the central fibre  $\mathcal{C}_0$  that can be contracted to yield a Gorenstein singularity of genus two.

In the genus one case, Smyth answered the analogous question by identifying the class of *balanced* subcurves [Smy11a, Definition 2.11]: subcurves of arithmetic genus one, such that, when breaking them into a *core* (minimal subcurve of genus one, not containing any separating node) and a number of rational trees (with root corresponding to the component adjacent to the core, and leaves corresponding to the components adjacent to the portion of  $\mathcal{C}_0$  that is not contracted), the distance between any leaf and the root of any such tree is constant, not depending on the tree either.

In the case at hand, the answer turns out to be slightly more complicated: first, the special branch(es) of a type  $I$  (resp.  $II$ ) singularity are connected through rational chains to a Weierstrass (resp. two conjugate) point(s) of the core. Second, the lengths of the rational trees may vary according to where their attaching points lie, but the special chains are always the shortest, and, together with the configuration of the attaching points on the core, they determine the length of any other chain.

##### 4.1 A quick recap on admissible covers

While there are no special points on a smooth curve of genus zero or one, the simplest instance of Brill-Noether theory involves smooth curves of genus two. Every such  $C$  is *hyperelliptic*: it admits a unique (up to reparametrisation) two-fold cover  $\phi: C \rightarrow \mathbb{P}^1$ , induced by the complete canonical linear system, i.e.  $|K_C|$  is the unique  $\mathfrak{g}_2^1$  on  $C$ ; said otherwise, there is a unique element  $\sigma \in \text{Aut}(C)$ , called the *hyperelliptic involution*, such that  $C/\langle \sigma \rangle \simeq \mathbb{P}^1$ . A point  $x \in C$  is called *Weierstrass* if it is a ramification point for  $\phi$  (or, equivalently, a fixed point for  $\sigma$ ); from the Riemann-Hurwitz formula it follows that there are six Weierstrass points on every smooth curve of genus two. Two points  $x_1, x_2$  are said to be conjugate (write  $x_2 = \bar{x}_1$ ) if there exists a point  $z \in \mathbb{P}^1$  such that  $\phi^{-1}(z) = \{x_1, x_2\}$  (or, equivalently,  $\sigma(x_1) = x_2$ ). These notions may be extended to nodal curves by declaring  $(C, x)$  to be Weierstrass if its stabilisation lies in the closure of

$$\mathcal{W} = \{(C, x) \mid C \text{ smooth and } x \text{ Weierstrass}\} \subseteq \overline{\mathcal{M}}_{2,1},$$

and similarly for conjugate points. We then need to study the limiting behaviour of Weierstrass points when a smooth curve degenerates to a nodal one. This is a difficult problem when it

comes to higher genus curves; it has received considerable attention since the '70s, in work of E. Arbarello, D. Eisenbud, J. Harris, and many others. In our case it boils down to understanding admissible covers [HM82] of degree two with a branch locus of degree six; said otherwise, up to the involution action, the Weierstrass locus is isomorphic to  $\overline{\mathcal{M}}_{0,6}/\mathfrak{S}_5$ , and the conjugate locus is isomorphic to  $\overline{\mathcal{M}}_{0,7}/\mathfrak{S}_6$ . We remark that  $(C, x)$  being Weierstrass is an intrinsic notion if  $C$  is of compact type (or, more generally, tree-like), but it may depend on the smoothing otherwise (i.e. the fibre of  $\overline{\mathcal{W}} \rightarrow \overline{\mathcal{M}}_2$  may have positive dimension); we have benefited from the exposition in [Dia85, Appendix 2], [Cuk89, Proposition (3.0.6)], and [HM98, Theorem 5.45].

- If  $x$  belongs to a component of genus one  $E$ , which is attached to another component of genus one at a node  $y$ , then  $x$  is Weierstrass iff  $2x \sim 2y \in \text{Pic}(E)$ ; if instead  $E$  has a self-node that glues  $y_1$  with  $y_2$ , then  $x$  is Weierstrass iff  $2x \sim y_1 + y_2 \in \text{Pic}(E)$ .

If  $x$  is on a rational component  $R$ ,  $x$  is Weierstrass if either  $R$  is attached to a genus one curve at two distinct points; or  $R$  has a self-node gluing  $y_1$  and  $y_2$  and is attached to a genus one tail at  $y_3$ , in which case we require  $\phi(y_1) = \phi(y_2)$  for a double cover  $\phi: R \rightarrow \mathbb{P}^1$  ramified at  $x$  and  $y_3$ ; or  $R$  has two self-nodes gluing  $y_1$  with  $y_2$ , and  $y_3$  with  $y_4$ , in which case we require  $x$  to be a ramification point for a double cover  $\phi: R \rightarrow \mathbb{P}^1$  such that  $\phi(y_1) = \phi(y_2)$  and  $\phi(y_3) = \phi(y_4)$  - geometrically, if we embed  $\mathbb{P}^1$  as a conic  $C \subseteq \mathbb{P}^2$ , the line through  $x$  and  $\overline{y_1 y_2} \cap \overline{y_3 y_4}$  should be tangent to  $C$  at  $x$ . See Figure 2.

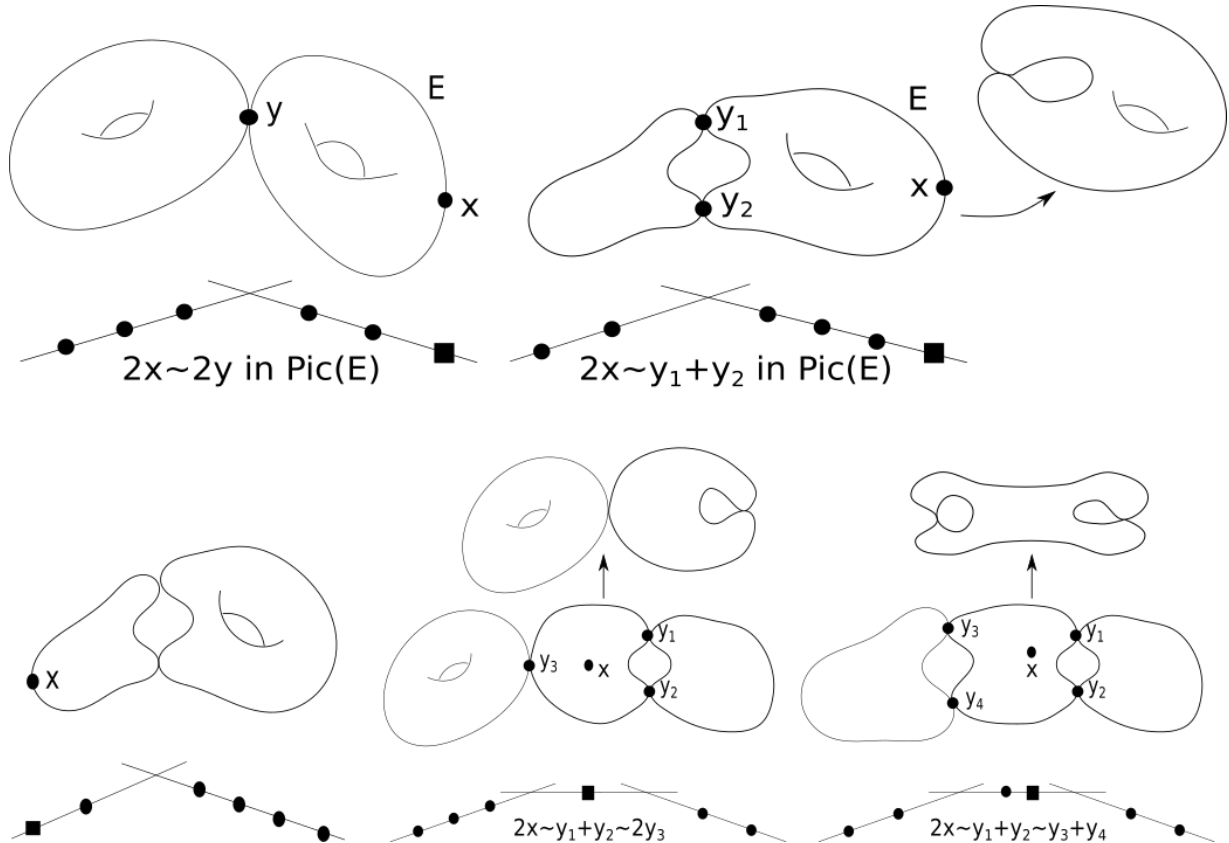


FIGURE 2. Admissible covers and Weierstrass points.

- If  $x_1$  and  $x_2$  are conjugate, they have to map to the same component of the target of the admissible cover. We may adapt the description of the previous point by replacing every condition on  $2x$  by its analogue for  $x_1 + x_2$ . There are a few more situations to take into account:  $x_1$  and  $x_2$  could belong to a rational component  $R$  bubbling off from a Weierstrass point of a genus two curve; or bridging between two distinct curves of genus one; or  $x_1$  and  $x_2$  could lie on two distinct rational components  $R_1$  and  $R_2$  intersecting each other at one node and meeting a curve of genus one in two distinct points ( $\dagger$ ); or  $R_1$  and  $R_2$  intersecting each other in three points. See Figure 3.

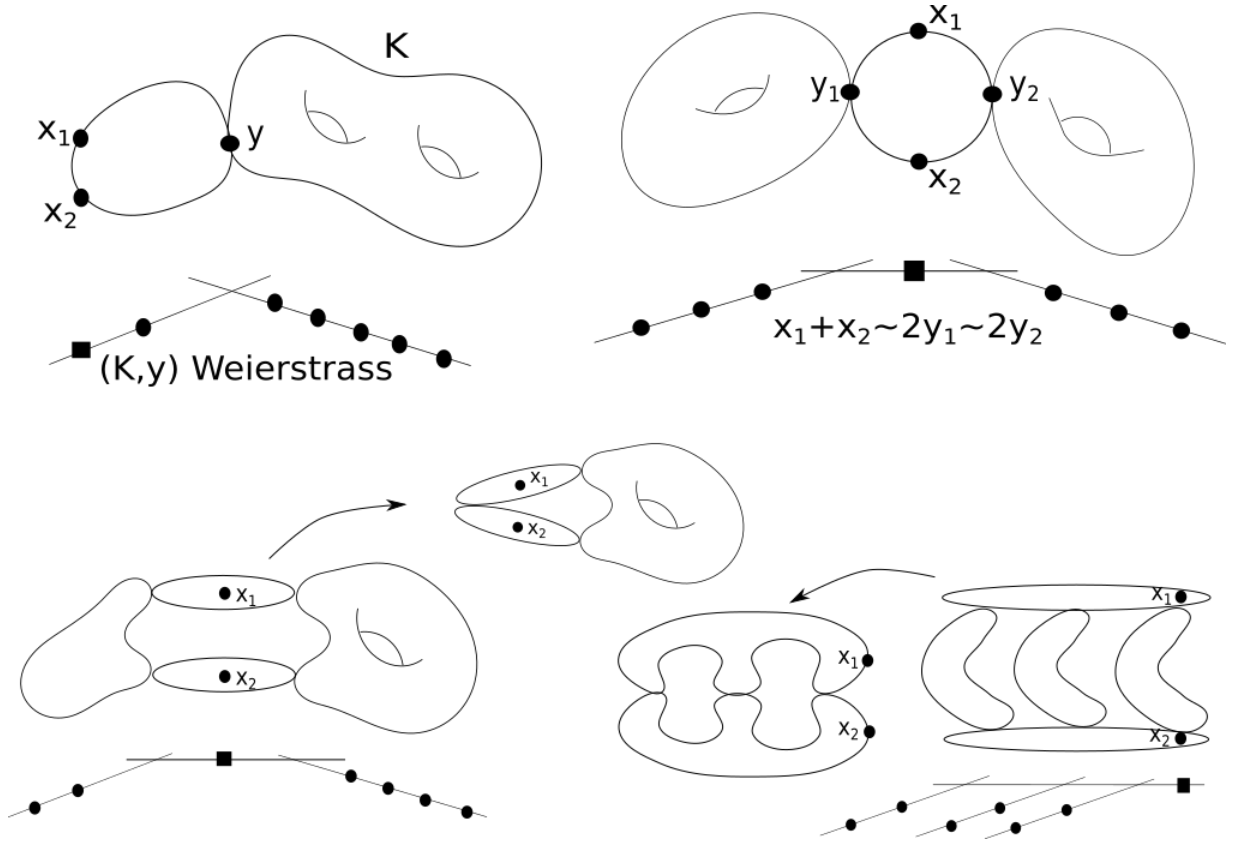


FIGURE 3. Admissible covers and conjugate points.

*Remark 4.1.* In case ( $\dagger$ ), the singularity of the total space of a smoothing  $\mathcal{C} \rightarrow \Delta$  at the two distinguished nodes (separating the elliptic component from the rational chain) are both  $A_k$  for the same  $k$ , because they map to the same node of the target in the admissible cover. This consideration is stable under base change, and it therefore entails a symmetry of the rational chain in the model with regular total space.

## 4.2 Minimal curves

**DEFINITION 4.2.** A projective Gorenstein curve  $C$  is *minimal* if it contains no node  $x$  such that the normalisation of  $C$  at  $x$  consists of two connected components, one of which has genus zero.

When  $C$  is nodal, minimal is equivalent to semistable (no rational tails). Compare with [Cat82, Definition 3.2] for an even stronger notion. When  $C$  has arithmetic genus one, this is the same

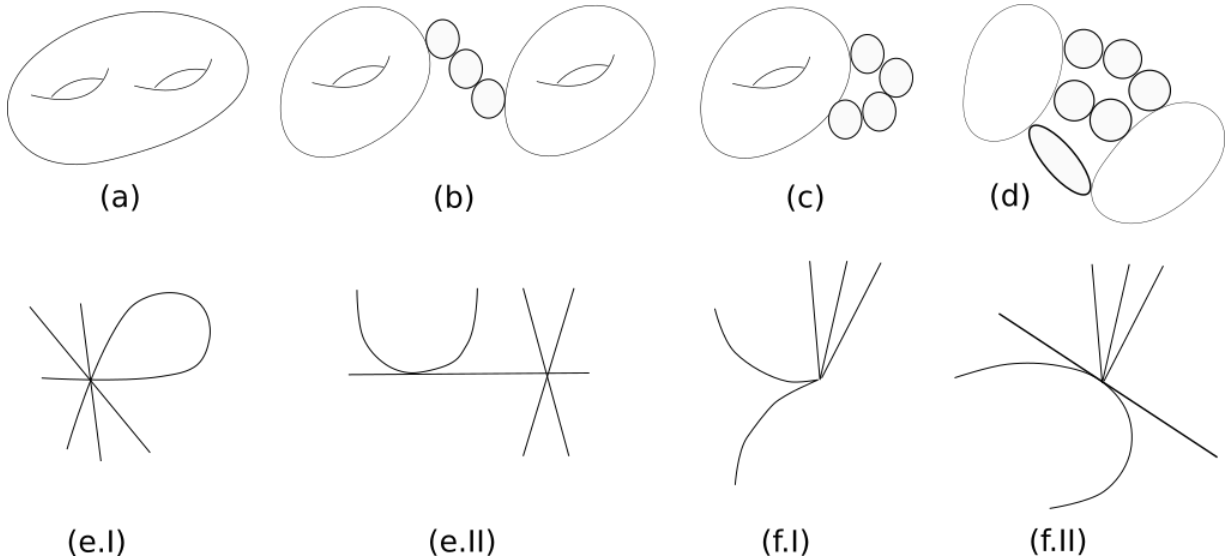


FIGURE 4. Minimal curves of genus two.

as saying that  $C$  contains no separating nodes. Recall [Smy11a, Lemma 3.3].

LEMMA 4.3. *A minimal Gorenstein curve  $Z$  of arithmetic genus one can be: a smooth elliptic curve; a ring of  $r \geq 1$  copies of  $\mathbb{P}^1$ ; or an elliptic  $m$ -fold point whose normalisation is the disjoint union of  $m$  copies of  $\mathbb{P}^1$ . In any case  $\omega_Z \simeq \mathcal{O}_Z$ .*

We provide a similar description of minimal curves of genus two; the proof is left to the reader.

LEMMA 4.4. *A minimal Gorenstein curve of genus two can be either of the following (Figure 4):*

- (a) *a smooth curve of genus two;*
- (b) *the union of two minimal Gorenstein curves of genus one,  $E_1$  and  $E_2$ , nodally separated by a (possibly empty) rational chain  $R$ ;*
- (c) *the union of a minimal Gorenstein curve of genus one  $E$ , and a (possibly empty) rational chain  $R$ , along two distinct nodes;*
- (d) *the union of two copies of  $(\mathbb{P}^1, 0, 1, \infty)$  with three (possibly empty) rational chains  $R_0, R_1, R_\infty$  joining the homonymous points;*
- (e) *an elliptic  $m$ -fold point whose pointed normalisation is the disjoint union of either  $m - 2$  copies of  $(\mathbb{P}^1, 0)$  and a semistable rational chain  $(R, 0, \infty)$ , or  $m - 1$  copies of  $(\mathbb{P}^1, 0)$  and a 1-pointed minimal Gorenstein curve of genus one (if the latter is not irreducible and  $m \neq 1$ , there are two genus one subcurves sharing a rational branch);*
- (f) *or a singularity of genus two with  $m$ -branches, whose normalisation is the disjoint union of  $m$  copies of  $\mathbb{P}^1$ .*

Remark 4.5. In both cases ((e)) and ((f)) there are *special* branches supporting the degree of  $\omega_Z$  (compare with Definition 2.4 and Corollary ??; recall that the restriction of the dualising sheaf to a component introduces a twist by the conductor ideal, see Noether's formula [Cat82, Proposition 1.2]). Notice that the notion of conjugate points is not always intrinsic to the curve.

### 4.3 Semistable tails

Let  $\overline{\mathcal{C}}_0$  be a minimal curve with a genus two singularity of type *I* (resp. *II*), and let  $\overline{\mathcal{C}}$  be a one-parameter smoothing over a trait  $\Delta$ . Let  $\mathcal{P}$  denote  $\mathbb{P}(\pi_*\omega_{\overline{\mathcal{C}}/\Delta})$ , which is a  $\mathbb{P}^1$ -bundle over  $\Delta$ . It follows from an easy calculation (or from [Cat82, Theorem D]) that the canonical series is basepoint-free, and so there is a morphism:

$$\begin{array}{ccc} \overline{\mathcal{C}} & \xrightarrow{\quad} & \mathcal{P} \\ & \searrow \quad \swarrow & \\ & \Delta & \end{array}$$

such that, in the central fibre, it restricts to a double cover on the special branch (resp. an isomorphism on each of the special branches) and it contracts the axes. The general fibre is the hyperelliptic cover  $\overline{\mathcal{C}}_{\bar{\eta}} \rightarrow \mathbb{P}_{\bar{\eta}}^1$ , endowing  $\mathbb{P}_{\bar{\eta}}^1$  with a length 6 branch divisor  $B_{\bar{\eta}}$ . Possibly after passing to a finite cover of  $\Delta$ ,  $B_{\bar{\eta}}$  is actually defined over  $\eta$ , and we can take the stable model  $(\mathcal{T}, B)$  of  $(\mathbb{P}_{\eta}^1, B_{\eta})$ , together with its associated double cover  $\mathcal{C}$ . We thus have a diagram:

$$\begin{array}{ccc} \mathcal{C} & \xrightarrow{\psi} & \mathcal{T} \\ \downarrow \phi & & \downarrow \\ \overline{\mathcal{C}} & \longrightarrow & \mathcal{P} \end{array}$$

over  $\Delta$  (by a slight abuse of notation), where the upper row is a family of admissible covers.

The line bundle  $\mathcal{O}_{\mathcal{P}}(1)$  pulls back to  $\omega_{\overline{\mathcal{C}}}$  on  $\overline{\mathcal{C}}$ . Its pullback  $\mathcal{O}_{\mathcal{T}}(1)$  on  $\mathcal{T}$  has degree 1 on exactly one component of the tree. Pulling back further to  $\mathcal{C}$ , we gather the following information:

- (a)  $\phi^*\omega_{\overline{\mathcal{C}}} = \omega_{\mathcal{C}}(\mathcal{Z})$  for a vertical divisor  $\mathcal{Z}$  supported on the exceptional locus  $\text{Exc}(\phi) =: \mathcal{Z}$ .
- (b)  $\psi^*\mathcal{O}_{\mathcal{T}}(1) = \mathcal{O}_{\mathcal{C}}(q + \bar{q})$  for a choice of two conjugate points of  $\mathcal{C}$  lying over the same point of  $\mathcal{T}$ , belonging to the component on which  $\mathcal{O}_{\mathcal{T}}(1)$  is ample.
- (c)  $\mathcal{Z}$  is the pullback of a vertical divisor on  $\mathcal{T}$ .

This description leads to the following simple observations:

- (I) If  $\overline{\mathcal{C}}_0$  has a type *I* singularity, the branch of  $\mathcal{C}_0$  corresponding to the singular branch of  $\overline{\mathcal{C}}_0$  is attached to a Weierstrass point of  $\mathcal{Z}$  with respect to  $\psi$ .
- (II) If  $\overline{\mathcal{C}}_0$  has a type *II* singularity, the branches of  $\mathcal{C}_0$  corresponding to the twin branches of  $\overline{\mathcal{C}}_0$  are attached to two conjugate points of  $\mathcal{Z}$  with respect to  $\psi$ .

Moreover, the distance of the special branch(es) from the core is always less than that of the axes; the ratio is roughly 1 : 3 in case *I*, and 1 : 2 in case *II*, but, more precisely, this depends on the relative position of the attaching points of the chains in the dual graph of the core. An elegant treatment uses the language of tropical geometry.

We consider the tropicalization  $\square \rightarrow \top$  of  $\psi$  [CMR16]. After further base-change and normalised blow-ups, we can assume that  $\mathcal{C}$  has regular total space; this only affects  $\square$  by subdividing edges, not changing their lengths. Now  $\square$  is nothing but the dual graph of the special fiber  $\mathcal{C}_0$ , with edges of length 1.

The vertical divisor  $\mathcal{Z}$  can be represented by a piecewise-linear (PL) function on  $\square$  with integral slope along the edges (see for example [BN07]); moreover, observation (c) above shows that  $\lambda$  is pulled back from a PL function  $\lambda_{\top}$  on  $\top$  - for this to be true we have to allow half-integral

slopes along the edges. Finding  $\lambda$  becomes a simple matter of degree-matching on the tree  $\top$ ; this shows existence and uniqueness. Recall that the canonical divisor  $K_{\square}$  has degree:

$$2g(v) - 2 + \text{val}(v) \quad (12)$$

on a vertex  $v$  of  $\square$ , where  $g: V(\square) \rightarrow \mathbb{Z}$  is the genus assignment, and  $\text{val}(v)$  is the number of bounded edges adjacent to  $v$ ; (12) is also the degree of  $\omega_{\pi}$  when restricted to the component of  $\mathcal{C}_0$  corresponding to  $v$ .

Notice that  $\top$  is decorated with six unlabelled legs corresponding to the branch divisor  $B$ ; we call them *B-legs*. It follows from the Riemann-Hurwitz formula that the divisor  $\mathcal{O}_{\top}(1)$  on  $\top$  pulling back to  $K_{\square}$  has degree:

$$\text{val}(v') - 2 + \frac{1}{2} \# \{f \text{ B-leg} \mid f \rightarrow v'\}$$

on a vertex  $v'$  of  $\top$ . Therefore, the equation that we have to solve is:

$$\text{val}(v') - 2 + \frac{1}{2} \# \{f \text{ B-leg} \mid f \rightarrow v'\} + \sum_{e \rightarrow v'} s(\bar{\lambda}_T, e) = 1 \quad (13)$$

on the vertex of  $\top$  corresponding to the special branch, and 0 otherwise; where  $s(\bar{\lambda}_T, e)$  denotes the outgoing slope of  $\bar{\lambda}_T$  along the edge  $e$ .

For the reader's benefit, we include Figure 5 to illustrate the shape of  $\lambda$  in the simplest possible case, namely when the core is smooth. The blue numbers represent the slope of  $\lambda$  along the corresponding edges. Figure 6 exhibits how the distance of the axes from the core can vary when the latter becomes more degenerate.

Two important observations allow us to write down  $\lambda$  explicitly in all possible situations:

- (i) The balancing equation (13) is unaffected by *tropical modifications*, i.e. growing a tree on which  $\lambda$  has constant slope 1.
- (ii) The balancing equation (13) is stable under edge contraction.

It follows that it is enough to study the case that the core consists of a configuration of rational curves; there are only two stable such configurations, named *dumbbell* and *theta*. Figure 7 (from [BC20]) illustrates the situation: we draw both the source (above) and the target (below) of the tropical admissible cover; the blue numbers on the latter represent the slope of  $\lambda_T$  - that of  $\lambda$  can be recovered by multiplying with the expansion factor of  $\psi$ ; and the red vertices correspond to the special branches. The vertices corresponding to the axes of the genus two singularity do not appear in the picture: they lie at the same height as the red vertices, on an arbitrary configuration of trees emanating from the core, along which  $\lambda$  has slope 1.

Summing up, we have proven the following:

**PROPOSITION 4.6.** *Let  $\phi: \mathcal{C} \rightarrow \overline{\mathcal{C}}$  be a birational contraction over the spectrum of a discrete valuation ring  $\Delta$ , where:  $\mathcal{C} \rightarrow \Delta$  is a family of prestable (reduced, nodal) curves of arithmetic genus two with smooth generic fibre  $\mathcal{C}_{\eta}$ ;  $\overline{\mathcal{C}} \rightarrow \Delta$  is a family of Gorenstein curves with a genus two singularity of type  $I_m$  (resp.  $II_m$ ) at  $q \in \overline{\mathcal{C}}_0$ . Denote by  $(Z; q_1, \dots, q_m)$  the exceptional locus  $\text{Exc}(\phi) = \phi^{-1}(q)$ , marked with  $Z \cap \overline{\mathcal{C}}_0 \setminus Z$ , where  $q_m$  corresponds to the singular branch of  $\overline{\mathcal{C}}_0$  (resp.  $q_1, q_m$  correspond to the twin branches of  $\overline{\mathcal{C}}_0$ ). Then:*



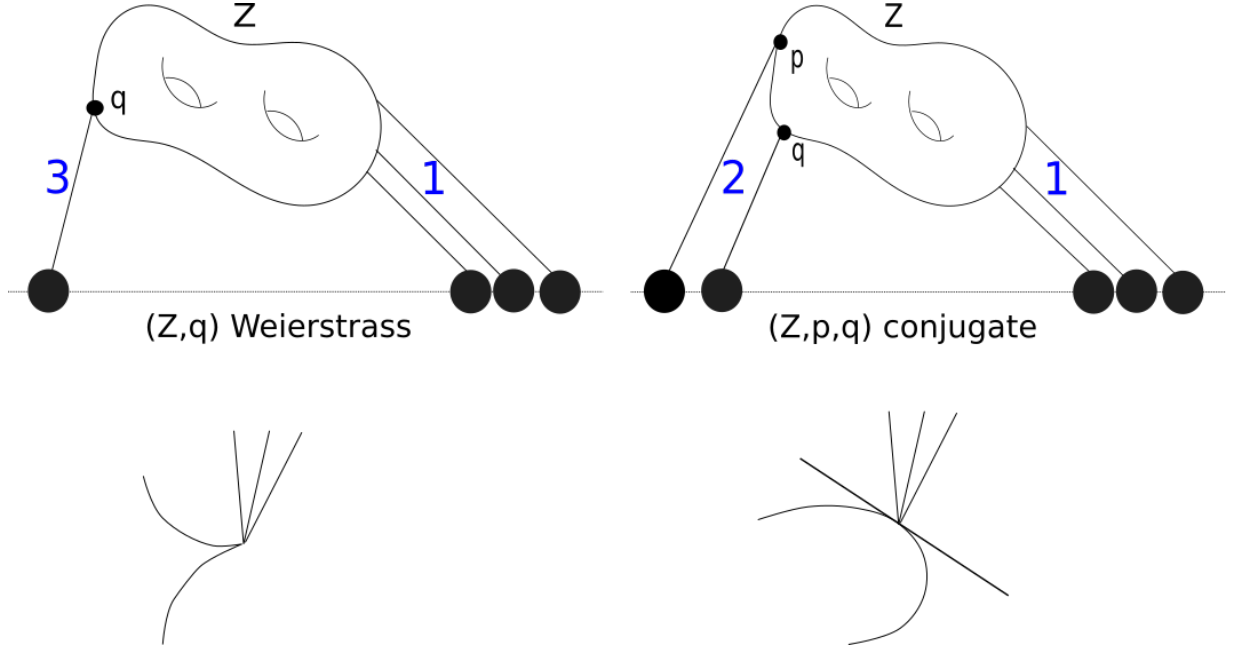


FIGURE 5. Semistable tail of a type  $I_4$  (left), resp. type  $II_5$  (right), singularity, generic case: the core is smooth, the singular branch is attached to a Weierstrass point (resp. the twin branches are attached to conjugate points), the other branches are attached to distinct points, and the corresponding edge-length is three (resp. two) times longer than the special one.

- (i)  $(Z, q_m)$  is Weierstrass (resp.  $(Z, q_1, q_m)$  is conjugate).
- (ii) On  $\text{trop}(\mathcal{C})$ , the distance of  $q_m$  (resp.  $q_1$  and  $q_m$  - they are equidistant) from the core is less than the distance of any other  $q_i$  from the core, and the former - together with the shape of  $\text{trop}(Z)$  - determines the latter.

Viceversa, every such genus two subcurve can be contracted to a Gorenstein singularity.

**PROPOSITION 4.7.** *Let  $(\mathcal{C}, p_1, \dots, p_n) \rightarrow \Delta$  be a family of pointed semistable curves of arithmetic genus two such that  $\mathcal{C}$  has regular total space and smooth generic fibre, and  $(\mathcal{C}, p_1) \rightarrow \Delta$  is Weierstrass (resp.  $(\mathcal{C}, p_1, \bar{p}_1) \rightarrow \Delta$  is conjugate). Let  $(Z, q_1, \dots, q_m)$  be a genus two subcurve of  $\mathcal{C}_0$  containing none of the  $p_i(0)$ , marked by  $Z \cap \overline{\mathcal{C}_0} \setminus Z$  so that the tail containing  $p_1$  is attached to  $Z$  at  $q_m$  (resp. the tails containing  $p_1$  and  $\bar{p}_1$  are attached to  $Z$  at  $q_1$  and  $q_m$ ), and satisfying all the shape prescriptions above. There exists a contraction  $\phi: \mathcal{C} \rightarrow \bar{\mathcal{C}}$  over  $\Delta$ , with exceptional locus  $Z$ , such that  $\bar{\mathcal{C}} \rightarrow \Delta$  is a family of Gorenstein curves containing a type  $I_m$  (resp. type  $II_m$ ) singularity in the central fibre.*

*Proof.* (of Proposition 4.7) By blowing down some rational tails outside  $Z$ , we can assume that  $\mathcal{C}_0 \setminus Z = \sqcup_{i=1}^m T_i$  with each  $T_i \simeq \mathbb{P}^1$ . The image of  $p_i(0)$  and  $p_j(0)$  might now coincide for  $i \neq j$ . The total space of the curve can still be assumed to be smooth by the Castelnuovo criterion. By abuse of notation, we denote the resulting family of pointed curves by  $(\mathcal{C}, p_1, \dots, p_n)$ . By assumption on the shape of  $Z$ , we can find an effective Cartier  $\mathcal{Z}$  supported on  $Z$  such that  $\mathcal{L} = \omega_{\mathcal{C}/\Delta}(\mathcal{Z} + \sum p_i)$  is trivial on  $Z$  and relatively ample elsewhere (both on  $T_i$  and on the generic fibre). Consider a second line bundle  $\mathcal{L}' = \mathcal{O}(2p_1 + \sum p_i)$  (resp.  $\mathcal{O}(p_1 + \bar{p}_1 + \sum p_i)$ ). Since we assumed  $p_1$  to be Weierstrass (resp.  $p_1$  and  $\bar{p}_1$  to be conjugate),  $\mathcal{L}_\eta \simeq \mathcal{L}'_\eta$ . On the other

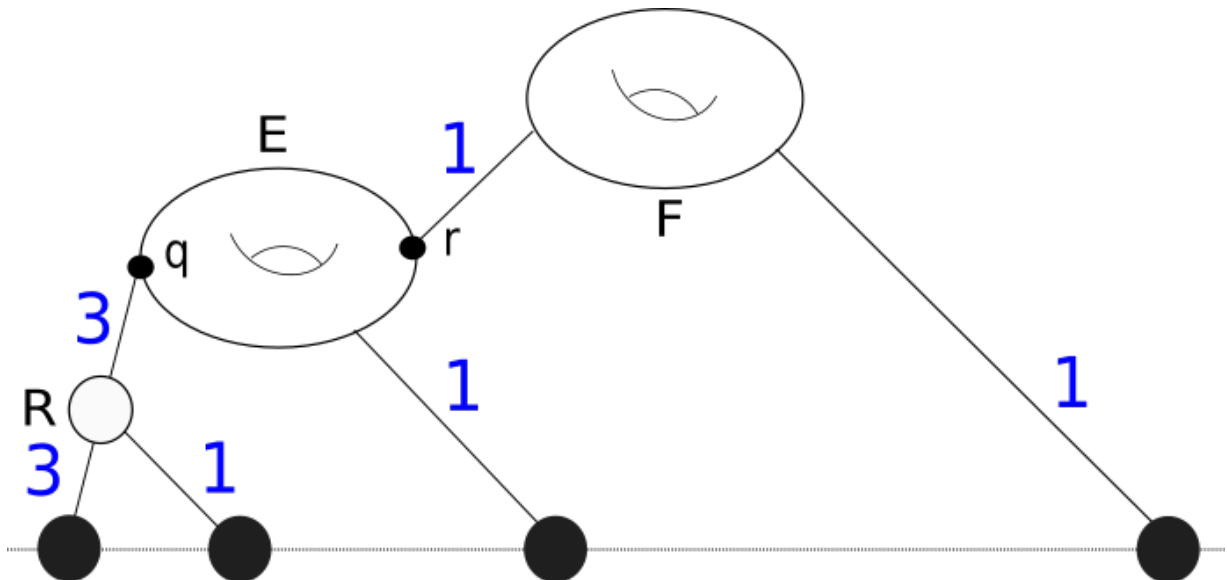


FIGURE 6. A more degenerate semistable tail of a type  $I_4$  singularity. Here  $Z$  consists of  $R$ ,  $E$ , and  $F$  together.  $(Z, q)$  is Weierstrass in the sense that  $2q \sim 2r \in \text{Pic}(E)$ .

hand it is easy to see that the multi-degrees of  $\mathcal{L}_0$  and  $\mathcal{L}'_0$  coincide, as  $Z$  is unmarked and each rational tail is isomorphic to  $\mathbb{P}^1$ ; it follows from the separatedness of  $\text{Pic}^0_{\mathcal{C}/\Delta} \rightarrow \Delta$  (see [Del85, p. 136] or [BLR90, §9.4]) that  $\mathcal{L}$  and  $\mathcal{L}'$  are isomorphic line bundles, so that, in particular,  $\mathcal{L}$  is trivial on a neighbourhood of  $Z$ . Observe now that

$$R^1\pi_*\mathcal{L}(-Z) = R^1\pi_*\omega_{\mathcal{C}/\Delta}(\sum p_i) = 0$$

by semistability, hence  $\pi_*\mathcal{L} \rightarrow \pi_*(\mathcal{L}|_Z) = \pi_*\mathcal{O}_Z$ , which contains the constants, showing that  $\mathcal{L}$  is semiample along  $Z$ ; that it is along the  $T_i$  is easier.

We therefore have a well-defined morphism:

$$\mathcal{C} \xrightarrow{\phi} \overline{\mathcal{C}} = \underline{\text{Proj}}_{\Delta} \left( \bigoplus_{n \geq 0} \pi_*\mathcal{L}^{\otimes n} \right) \rightarrow \Delta$$

associated to  $\mathcal{L}$ . The proof that  $\overline{\mathcal{C}} \rightarrow \Delta$  is a flat family of Gorenstein curves goes along the lines of [Smy11a, Lemma 2.13] or [RSPW19a, Proposition 3.7.3.1]. It is then clear from the classification that it contains a type  $I_m$  (resp.  $II_m$ ) singularity.

□

*Remark 4.8.* It follows that genus two Gorenstein singularities are smoothable.

*Caveat.* Given a family of semistable curves  $\pi: \mathcal{C} \rightarrow \Delta$  over a discrete valuation ring, and a line bundle  $\mathcal{L}$  on  $\mathcal{C}$  that is trivial on a higher genus subcurve  $Z$  of  $\mathcal{C}_0$  and  $\pi$ -ample elsewhere, is  $\mathcal{L}$   $\pi$ -semiample? is it relatively generated by global sections? In positive characteristic, a positive answer follows from results of S. Keel [Kee99]. If  $\text{char}(\mathbf{k}) = 0$ , the answer depends on the family; this should not come as a surprise, since we have seen how it relies on the tropicalization.

We construct a counterexample using the theory of limit linear series (l.l.s.): we produce a

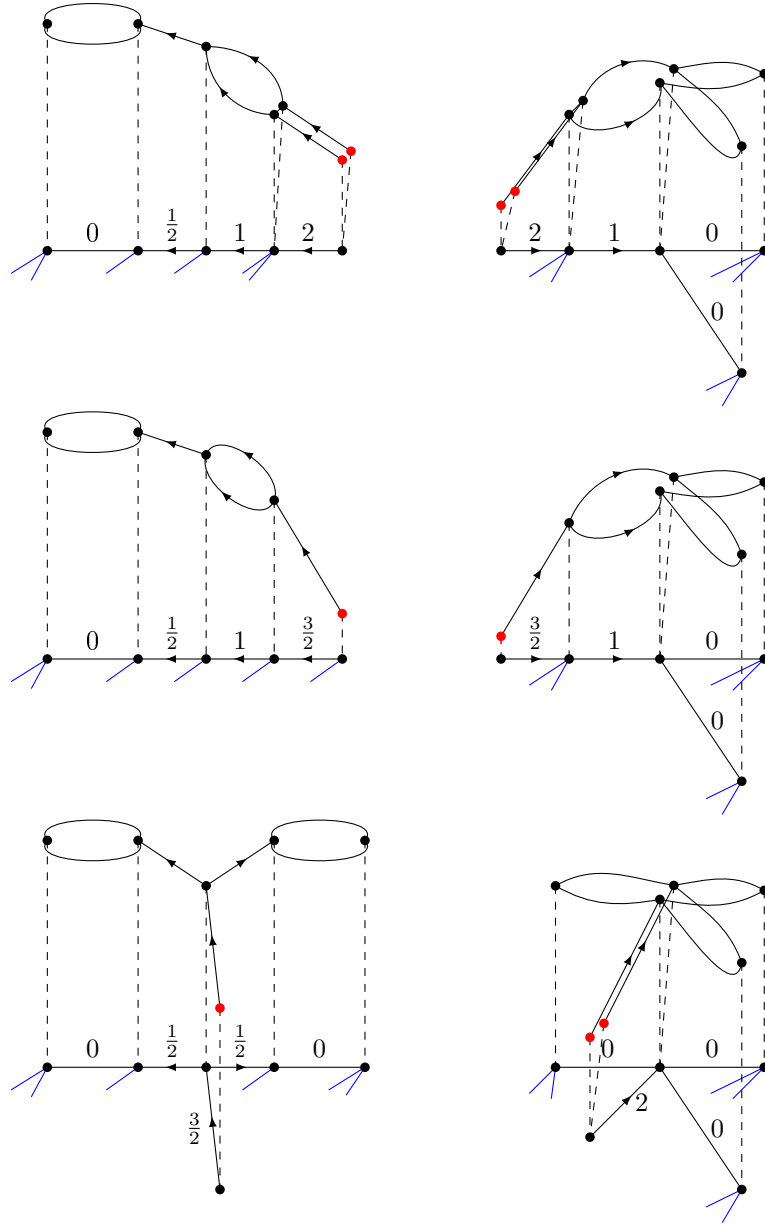


FIGURE 7. Tropicalization of semistable tails with maximally degenerated core: the dumbbell (l), and the theta graph (r). The red vertices correspond to the special branches.

linear series that can be smoothed while having basepoints along a Weierstrass tail.<sup>3</sup> For any such smoothing, the corresponding line bundle  $\mathcal{L}$  is not globally generated along  $Z$  - though we do not know how powers of  $\mathcal{L}$  behave, so we cannot conclude that  $\mathcal{L}$  is not semiample.

Let  $X_0$  be the nodal curve obtained by attaching  $R \simeq \mathbb{P}^1$  to a Weierstrass point  $q$  of a smooth genus two curve  $Z$ . Choose  $d \gg 0$  ( $d \geq 5$  is enough), and let us study the moduli space of complete linear systems of degree  $d$  on (smoothings of)  $X_0$ ; with  $r = d - 2$ , the Brill-Noether number is  $\rho = 2$  (the dimension of the Jacobian). On the other hand, assume that the  $R$ -aspect of the l.i.s. has  $\mathcal{L}_{Y|Z} \simeq \mathcal{O}_Z$ ; then the  $Z$ -aspect has  $\mathcal{L}_{Z|Z} \simeq \mathcal{O}_Z(dq)$ , whose vanishing sequence is  $\alpha_Z(q) = \{0, 1, \dots, d-5, d-4, d-2, d\}$ , from which we deduce for the complementary aspect  $\alpha_R(q) \geq \{0, 2, 4, 5, \dots, d-1, d\}$ . We want to show that all such aspects are smoothable, by appealing to the Regeneration Theorem [HM98, Theorem 5.41]. If  $t$  denotes a coordinate on  $R$  near the node, we have a choice of a two-dimensional subspace of  $\langle 1, t, t^2, t^3 \rangle_{\mathbf{k}} \subseteq H^0(\mathbb{P}^1, \mathcal{O}_{\mathbb{P}^1}(d))$  meeting the subspace  $\langle t^2, t^3 \rangle_{\mathbf{k}}$  non-trivially; this can be described as the locus of lines in  $\text{Gr}(1, \mathbb{P}^3)$  meeting a fixed line  $\ell$ : a Schubert cycle of dimension 3. The Regeneration Theorem needs:

$$\dim(\mathcal{G}_d^r(X/B)) = \dim(B) + \rho.$$

We therefore have to put  $X_0$  in a family over a base  $B$  of dimension 1 at least. We shall do so by considering the family  $X$  obtained by attaching  $R$  to a moving point of  $Z$ , so that  $X_0$  is the fibre of  $X$  over  $q \in Z$ .

Let us start by examining the other possibilities for  $\mathcal{G}_d^{d-2}(X_0)$ : the  $R$ -aspect can in fact restrict to any line bundle of degree 0 on  $Z$ , which we are going to write as  $\mathcal{O}_Z(p_1 + p_2 - 2q)$  for two moving points  $p_1, p_2$  on  $Z$  (think of them as coordinates on  $\text{Pic}(Z)$ ). Then  $\mathcal{L}_Z = \mathcal{O}_Z((d-2)q + p_1 + p_2)$ . In the table we collect: restrictions on  $p_1, p_2$  (together with the dimension of the locus they cut in  $\text{Pic}(Z)$ ) determining a fixed behaviour of  $\alpha_Z$  (of which we record only the two largest values), the restrictions on  $\alpha_R$  this imposes, and the corresponding locus of sections over  $R$  (in  $\text{Gr}(1, \mathbb{P}^3)$ , together with its dimension). We care about the sum of the two dimension terms.

$\subseteq \text{Pic}(Z)$	dim	$\alpha_{Z;d-3,d-2}$	$\alpha_{R;0,1}$	$\subseteq \mathbb{P}H^0(R, \mathcal{O}_R(d))$	dim
$p_1 + p_2 \sim 2q$	0	$\{d-2, d\}$	$\geq \{0, 2\}$	$\{\ell' \in \text{Gr}(1, \mathbb{P}^3)   \ell' \cap \ell \neq \emptyset\}$	3
$2q \approx p_1 + p_2 \geq q$	1	$\{d-3, d-1\}$	$\geq \{1, 3\}$	$\mathbb{P}^1$	1
$p_1 + p_2 \not\sim q$	2	$\{d-3, d-2\}$	$\{2, 3\}$	pt	0

Letting  $q$  vary in  $B = Z$ , we may generically assume that it is not Weierstrass. The first column labelled “dim” now also accounts for the varying attaching point. We find:

$\subseteq \text{Pic}(X)$	dim	$\alpha_{Z;d-3,d-2}$	$\alpha_{R;0,1}$	$\subseteq \mathbb{P}H^0(R, \mathcal{O}_R(d))$	dim
$p_1 + p_2 \sim \omega_Z$	$0 + 1$	$\{d-2, d-1\}$	$\geq \{1, 2\}$	$(\mathbb{P}^2)^*$	2
$p_1 + p_2 \sim 2q$	$0 + 1$	$\{d-3, d\}$	$\geq \{0, 3\}$	$\mathbb{P}^2$	2
$\omega_Z, 2q \approx p_1 + p_2 \geq q$	$1 + 1$	$\{d-3, d-1\}$	$\geq \{1, 3\}$	$\mathbb{P}^1$	1
$p_1 + p_2 \not\sim q$	$2 + 1$	$\{d-3, d-2\}$	$\{2, 3\}$	pt	0

We conclude that  $\mathcal{G}_d^{d-2}(X/B)$  has pure dimension 3. The Regeneration Theorem implies that all l.i.s. with  $\mathcal{L}_{R|Z} \simeq \mathcal{O}_Z$  - in particular those containing  $Z$  in the base-locus - are smoothable.

<sup>3</sup>It was pointed out by F. Carocci that a similar computation can be carried out for a genus one tail as well. This shows that the regularity assumption of [Smy11a, Lemma 2.13] is necessary.

## 5. The new moduli functors

The idea is to replace subcurves of positive genus with isolated singularities, the number of special points on the former bounding the number of branches of the latter. The following is a slight generalisation of [Smy11a, Definition 3.4].

DEFINITION 5.1. Let  $(C, p_1, \dots, p_n)$  be a reduced curve, marked by smooth points. For a nodally attached subcurve  $D \subseteq C$ , we define its *level* as

$$\text{lev}(D) = |D \cap \overline{C \setminus D}| + |\{p_1, \dots, p_n\} \cap D|.$$

In what follows, we impose a level condition only on nodally attached curves, hence we may remain agnostic as to how components attached along worse-than-nodal singularities should be counted towards the level.

We omit the proof of the following lemma; compare with [Smy11a, Corollary 3.2, Lemma 3.5].

LEMMA 5.2. *Let  $(C, p_1, \dots, p_n)$  be a pointed semistable curve of arithmetic genus two, with minimal genus two subcurve  $Z$ . For every subcurve  $Z' \subseteq C$  of genus two, we have an inclusion  $Z \subseteq Z'$  and  $\text{lev}(Z) \leq \text{lev}(Z')$ .*

DEFINITION 5.3. We say that a point *cleaves* to a component of a curve if it is connected to it by a possibly empty chain of rational curves.

Remark 5.4. Singularities of genus zero and one appear in the miniversal family of singularities of genus two. Also, singularities of type *I* do appear in the miniversal family of singularities of type *II*, and viceversa. For low values of  $m$ , this follows from a neat result of Grothendieck ([CML13, p. 2277], see also [Arn72, Dem75]):

THEOREM 5.5. *Let  $(C, q)$  be a curve singularity of ADE type. The singularities appearing in the miniversal deformation of  $(C, q)$  are all and only the ADE singularities whose Dynkin diagram can be obtained as a full subgraph of the Dynkin diagram of  $(C, q)$ .*

We finally come to the definition of  $m$ -stability for curves of genus two.

DEFINITION 5.6. Fix positive integers  $1 \leq m < n$ . Let  $(C, p_1, \dots, p_n)$  be a connected, reduced, complete curve of arithmetic genus two, marked by smooth distinct points. We say that  $C$  is  $m$ -stable if:

- (i)  $C$  is Gorenstein with only: nodes; elliptic  $l$ -fold points,  $l \leq m + 1$ ; type  $I_{\leq m}$ , type  $II_{\leq m}$ , and dangling  $II_{m+1}$  singularities of genus two, as singular points.
- (ii) If  $Z$  is a connected subcurve of arithmetic genus two, then  $\text{lev}(Z) > m$ .
- (iii) If  $E$  is a nodally attached subcurve of arithmetic genus one,  $\text{lev}(E) > m + 1$ .
- (iv)  $H^0(C, \Omega_C^\vee(-\sum_{i=1}^n p_i)) = 0$ .
- (v) If  $C$  contains a singularity of genus two, or an elliptic  $l$ -fold with a self-branch or a genus one branch,  $p_1$  cleaves to one of the special branches (see Remark 4.5). If  $C$  contains two genus one subcurves sharing a branch, and  $E_1$  has level less than  $m + 2$ , then  $p_1$  cleaves to  $E_1$ .

Remark 5.7. The definition is not  $\mathfrak{S}_n$ -symmetric. In the argument below, we exploit the asymmetry to write the dualising line bundle of a genus two (sub)curve  $Z$  as  $\omega_Z \simeq \mathcal{O}_Z(q_1 + \bar{q}_1)$ , where  $q_1$  is the point of  $Z$  closest to  $p_1$ , and  $\bar{q}_1$  its conjugate, sometimes depending on a one-parameter smoothing. Compare with the situation in genus one, where the dualising line bundle of a minimal Gorenstein curve is trivial (all smooth points are non-special). We also refer to  $p_1$  when deciding which genus one subcurve to contract first in case there are two of the same level.

*Remark 5.8.* If there is a nodally attached subcurve of genus one, condition (iii) and condition (iv) jointly imply condition (ii). Indeed, from Corollary 3.7 we have  $\text{lev}(Z) \geq \text{lev}(E) - 1$ . The only cases (up to relabelling) in which the level drops by one are: when  $Z = (E, p_1, \dots, p_{l-2}, q_1, q_2) \sqcup_{\{q_1, q_2\}} (\mathbb{P}^1, q_1, q_2, p_{l-1})$ ; and when  $Z = (E_1, p_1, \dots, p_{l-1}, q) \sqcup_q (E_2, q)$ , where all the  $E$  have genus one.

We are going to prove the following:

**THEOREM 5.9.** *For  $1 \leq m < n$ , the moduli stack of  $n$ -pointed  $m$ -stable curves of genus two  $\overline{\mathcal{M}}_{2,n}^{(m)}$  is a proper Deligne-Mumford stack of finite type over  $\text{Spec}(\mathbb{Z}[\frac{1}{6}])$  - containing  $\mathcal{M}_{2,n}$  as a dense open substack, and therefore irreducible.*

*Proof.* (i) *-Algebraicity (diagonal).* The diagonal  $\Delta: \overline{\mathcal{M}}_{2,n}^{(m)} \rightarrow \overline{\mathcal{M}}_{2,n}^{(m)} \times \overline{\mathcal{M}}_{2,n}^{(m)}$  is representable, quascompact, and of finite type. Since  $m$ -stable curves are canonically polarised, it follows from Grothendieck's theory of Hilbert schemes that the *Iso*-functor between two  $m$ -stable curves over  $S$  is representable by a quasiprojective scheme over  $S$ .

(ii) *-Algebraicity (atlas) & irreducibility.* There exists an irreducible scheme  $H$ , of finite type over  $\text{Spec}(\mathbb{Z}[\frac{1}{6}])$ , with a smooth and surjective morphism  $H \rightarrow \overline{\mathcal{M}}_{2,n}^{(m)}$ . Fix an integer  $N > 2 + 8(m + 1)$ ; let  $d = N(2 + n)$  and  $r = d - 2$ . By Lemma 5.10 below, every  $n$ -pointed  $m$ -stable curve over a field  $\mathbf{k}$  admits a pluri-log-canonical embedding of degree  $d$  in  $\mathbb{P}^r$ . Let  $H_0$  denote the Hilbert scheme of degree  $d$ , genus two curves in  $\mathbb{P}^r$ . Let  $H_1 \subseteq H_0 \times (\mathbb{P}^r)^{\times n}$  denote the locally closed subscheme consisting of  $([C], p_1, \dots, p_n)$  such that every  $p_i$  belongs to the smooth locus of  $C$ ; this is open in the incidence variety. By Lemma 5.11 below, there is an open subscheme  $H_2 \subseteq H_1$  parametrising  $m$ -stable curves (note that  $H_1$  is of finite type over  $\text{Spec}(\mathbb{Z}[\frac{1}{6}])$ , and in particular Noetherian). By the representability of the Picard scheme [MFK94, Proposition 5.1], there is a locally closed subscheme  $H \subseteq H_2$  representing  $([C], p_1, \dots, p_n)$  such that  $\mathcal{O}_C(1) = (\omega_C(\sum_{i=1}^n p_i))^N$ . Now there is a morphism  $H \rightarrow \overline{\mathcal{M}}_{2,n}^{(m)}$  that is surjective by construction, and smooth because two different embeddings of an  $m$ -stable curve differ by the choice of a basis of  $H^0(C, (\omega_C(\sum_{i=1}^n p_i))^N)$ . Since every  $m$ -stable curve is smoothable (Remark 4.8 and [Kol96, II.6.3]),  $H$  is irreducible.

(iii) *-DM.* The diagonal  $\Delta: \overline{\mathcal{M}}_{2,n}^{(m)} \rightarrow \overline{\mathcal{M}}_{2,n}^{(m)} \times \overline{\mathcal{M}}_{2,n}^{(m)}$  is unramified. It is enough to show that, for an  $m$ -stable curve  $(C, p_1, \dots, p_n)$  over a field  $\mathbf{k}$ , the *Iso*-group scheme  $\text{Aut}_{\mathbf{k}}(C, p_1, \dots, p_n)$  is unramified. Its tangent space at the identity can be identified with the vector space  $H^0(C, \Omega_C^\vee(-\sum_{i=1}^n p_i))$ , which vanishes by Definition 5.6iv. Note that we need the assumption on the base characteristic in order to translate this vanishing into a combinatorial criterion on the pointed normalisation and singularity type of the curves (Corollary 3.7).

(iv) *-Properness.* Follows from the valuative criterion (Proposition 5.12). □

**LEMMA 5.10** (boundedness). *If  $(C, p_1, \dots, p_n)$  is an  $m$ -stable curve of genus two, the  $N$ -th power of  $A = \omega_C(\sum_{i=1}^n p_i)$  is very ample for every  $N > 2 + 8(m + 1)$ .*

*Proof.* It is enough to show that, for every pair of points  $p, q \in C$  (possibly equal):

- (i) *basepoint-freeness:*  $H^1(C, A^{\otimes N} \otimes I_p) = 0$ ;
- (ii) *separating points and tangent vectors:*  $H^1(C, A^{\otimes N} \otimes I_p I_q) = 0$ .

By Serre duality we may equivalently show that  $H^0(C, \omega_C \otimes A^{-N} \otimes (I_p I_q)^\vee) = 0$ . Let  $\nu: \tilde{C} \rightarrow C$  be the normalisation, and let  $\nu^{-1}(p) = \{p_1, \dots, p_h\}$ ,  $\nu^{-1}(q) = \{q_1, \dots, q_k\}$ , with  $h, k \leq m + 1$ .

It follows from Proposition 2.2 (and [Smy11a, Proposition A.3]) that  $\nu_*\mathcal{O}_{\tilde{C}}(-D) \subseteq I_p I_q$  for  $D = 4(\sum_{i=1}^h p_i + \sum_{j=1}^k q_j)$  (note that  $\deg(D) \leq 8(m+1)$ ); furthermore, the quotient is torsion, therefore, by applying  $\mathcal{H}om(-, \mathcal{O}_C)$ , we find  $(I_p I_q)^\vee \subseteq \nu_*\mathcal{O}_{\tilde{C}}(D)$ . It is thus enough to show that  $H^0(\tilde{C}, \mathcal{O}_{\tilde{C}}(D) \otimes \nu^*(\omega_C \otimes A^{-N})) = 0$ . Finally,  $\nu^*\omega_C$  (resp.  $\nu^*A$ ) has degree at most two (resp. at least one) on each component of  $\tilde{C}$ , hence it is enough to take  $N > 2 + 8(m+1)$ .  $\square$

LEMMA 5.11 (deformation openness). *Let  $(\mathcal{C}, \sigma_1, \dots, \sigma_n) \rightarrow S$  be a family of curves over a Noetherian base scheme with  $n$  sections. The locus*

$$\{s \in S \mid (\mathcal{C}_{\bar{s}}, \sigma_1(\bar{s}), \dots, \sigma_n(\bar{s})) \text{ is } m\text{-stable}\}$$

*is Zariski-open in  $S$ .*

*Proof.* Having connected fibres which are Gorenstein curves of arithmetic genus two is an open condition (see for example [Sta20, Tag 0E1M]). Only singularities of genus zero (nodes), one (elliptic  $l$ -folds), and two may then occur.

The case  $m = 1$  deserves special attention. In this case, that condition (i) is open follows from acknowledging that  $I_1 = A_4$ ,  $I_2 = A_5$ , while tacnodes, cusps, and nodes are  $A_3$ ,  $A_2$ , and  $A_1$ -singularities respectively, and from Grothendieck's result on the deformation theory of ADE singularities (see Theorem 5.5 above).

The case  $m \geq 2$  simply follows from upper semicontinuity of embedded dimension and the fact that we have exhausted all possible Gorenstein singularities of genus  $\leq 2$ , and embedding dimension  $\leq m+1$ .

Condition (iv) translates to: the locus where the automorphism group is unramified is open in the base. Homogeneity can be used to prove that being unramified, which is open in the source, is also open in the target, for the structural morphism of a group scheme; see the end of the proof of [Smy11a, Lemma 3.10].

The other conditions are topological, hence constructible. Under Noetherian assumptions, it is enough to check their openness over the spectrum of a discrete valuation ring. Assume that the geometric generic fibre  $C_{\bar{\eta}}$  contains two genus one subcurves  $E_{1,\bar{\eta}}$  and  $E_{2,\bar{\eta}}$ ; their closures  $E_1$  and  $E_2$  in  $\mathcal{C}$  are then flat families of genus one curves over  $\Delta$ . If  $E_{1,\bar{\eta}}$  and  $E_{2,\bar{\eta}}$  are disconnected, then so are  $E_1$  and  $E_2$ , by local constancy of the number of connected components (from the Zariski decomposition and [Sta20, Tag 0E0D]). If  $E_{1,\bar{\eta}}$  and  $E_{2,\bar{\eta}}$  are joined by a disconnecting node  $q_{\bar{\eta}}$ , then so are  $E_{1,0}$  and  $E_{2,0}$ ; indeed, the unique limit of  $q_{\bar{\eta}}$  must be a singular point of the projection, but cannot be any worse than a node (because we have already used up all of our genus allowance). Finally, if  $E_{1,\bar{\eta}}$  and  $E_{2,\bar{\eta}}$  share a branch, then so do  $E_{1,0}$  and  $E_{2,0}$ ; on the other hand, if  $E_{i,\bar{\eta}}$  has more than one branch, then so does  $E_i$ . Similarly, if  $C_{\bar{\eta}}$  contains only one subcurve of genus one, with two nodes joined by a rational chain, so does  $C_0$ . To summarise,

$$|E_{i,\bar{\eta}} \cap \overline{C_{\bar{\eta}} \setminus E_{i,\bar{\eta}}}| = |E_{i,0} \cap \overline{C_0 \setminus E_{i,0}}|.$$

The number of markings on  $E_i$  is also constant. Hence we can deduce condition (iii) for  $C_{\bar{\eta}}$  from the same condition on  $C_0$ . Condition (ii) follows in this case from Remark 5.8; it can be proven analogously when there is no subcurve of genus one.

Finally, suppose that  $C_{\bar{\eta}}$  has a genus two singularity, then so does  $C_0$ . The (union of the) distinguished branch(es)  $E_{\bar{\eta}}$  of  $C_{\bar{\eta}}$  is a genus one singularity, and so is its limit  $E_0$  in  $C_0$ . It has to contain the distinguished branch(es) of  $C_0$ , because any subcurve not containing them has genus zero; therefore, by assumption,  $E_0$  contains  $p_{1,0}$ . Then also  $E_{\bar{\eta}}$  contains  $p_{1,\bar{\eta}}$ , because the markings are contained in the non-singular locus of the curve. Similarly, if  $C_{\bar{\eta}}$  has a genus one

singularity with a self-branch, the limit of such a branch is a genus one subcurve  $E_0$  of  $C_0$ ; the latter may very well acquire a genus two singularity, but  $E_0$  will contain the special branches of it, so it will be connected to  $p_1$ . We conclude as above. The case that  $C_{\bar{\eta}}$  contains a genus one subcurve of low level is analogous. We have thus proved that condition (v) is open.  $\square$

**PROPOSITION 5.12** (Valuative criterion of properness for  $\overline{\mathcal{M}}_{2,n}^{(m)}$ ). *Given a smooth  $n$ -pointed curve of genus two  $C_{\eta}$  over a discrete valuation field  $\eta = \text{Spec}(K) \hookrightarrow \Delta$ , there exists a finite base-change  $\Delta' \rightarrow \Delta$  after which  $C_{\eta}$  can be completed to an  $m$ -stable curve over  $\Delta'$ . Two such models are always dominated by a third one.*

*Existence of limits.* By the semistable reduction theorem [DM69, Corollary 2.7], we may find a finite base-change  $\Delta' \rightarrow \Delta$  and a semistable curve  $\mathcal{C}' \rightarrow \Delta'$  with regular total space, such that its generic fibre is isomorphic to the pullback of  $C_{\eta}$ . By Castelnuovo's criterion, we may further assume that the central fibre contains no rational tails.

We check whether  $p_1$  is Weierstrass or not: in the former case, change base with  $\pi'' \mapsto (\pi')^3$  and resolve; in the latter, mark  $\mathcal{C}'$  with an extra section  $\bar{p}_1$  given by the closure of the conjugate point  $\bar{p}_1(\eta)$  (it might coincide with one of  $p_1, \dots, p_n$ ; if it coincides with  $p_1$ , we have a Weierstrass point indeed), then change base with  $\pi'' \mapsto (\pi')^2$  and resolve. We drop the primes from notation.  $\mathcal{C}_0$  is now marked with a(n extra) smooth point  $\bar{p}_1$ . The base-change is a technical expedient we find useful in the forthcoming construction.

We claim there is a unique genus two subcurve  $Z$  of  $\mathcal{C}_0$  that satisfies the shape requirements of Proposition 4.6 (resp. ??) - or consists of two disjoint balanced subcurves of genus one - such that the curve we obtain by contracting  $Z$  has bounded-above singularities and bounded-below level as in (i),(ii), and (iii) of Definition 5.6.

We think of this process as drawing a family of expanding circles on the dual graph (except, they are not exactly circles), as we have learned from [RSPW19a]. Note that we may at any point blow the curve up at a marking on the central fibre, and consider the strict transform of the corresponding section; thus markings can effectively be considered as infinite legs in the dual graph - this is important for all the valence considerations below. We are going to contract the strict interior of the circle; note that the number of branches of the resulting singularity is determined by the inner valence of the circle, and the level by the outer valence.

For simplicity, we start by examining the case that the core of  $\mathcal{C}_0$  is irreducible, and  $p_1$  is Weierstrass. Step 0: if the core  $K$  has level  $\geq m+1$ , then the curve is already  $m$ -stable. Otherwise, draw a first circle comprising  $K$ , and reaching every second closest rational component along any rational tree attached to  $K$ , except for the tree containing  $p_1$ . Note that the inner valence is exactly  $\text{lev}(K)$ , thanks to the base-change we have performed earlier, and in particular it is no larger than  $m$ ; on the other hand, semistability implies that the outer valence is non-decreasing: if it is  $\geq m+1$  we stop, otherwise we repeat the process. Calling  $K_1$  the union of the components strictly inside the first circle,  $\mathcal{C}_0$  is the union of  $K_1$  and a number of rational trees; if the outer valence at the first step is still  $\leq m$ , we enlarge the circle by reaching one step further along the rational tree containing  $p_1$ , and three steps further along every other. Because a circle of very large radius has both inner and outer valence equal to  $n > m$ , by increasing the radius step by step we will eventually reach level  $m+1$  or higher. If we stop at the  $l$ -th step, the line bundle we



will use to perform the contraction is

$$\begin{aligned} \mathcal{L} = \omega_{\mathcal{C}/\Delta}(3lK + \sum_{R \in [p_1, K]} [3l - 3 \operatorname{dist}(R, K)]_+ R + \sum_{R \notin T_1} [3l - \operatorname{dist}(R, K)]_+ R + \\ \sum_{R \in T_1, R \notin [p_1, K]} [3l - 3 \operatorname{dist}(T_1 \wedge T_R, K) - \operatorname{dist}(R, T_1 \wedge T_R)]_+ R + \sum_{i=1}^n p_i) \end{aligned}$$

where  $T_1$  is the rational tree (connected component of  $\mathcal{C}_0 \setminus K$ ) containing  $p_1$ ,  $T_R$  the one containing  $R$ ,  $T_1 \wedge T_R$  their common component furthest from the core,  $\operatorname{dist}$  is the distance on the dual graph, and  $[k]_+ = \max\{0, k\}$  for any integer  $k$ . If we write  $\mathcal{L} = \omega_{\mathcal{C}/\Delta}^{\log}(D)$  for an effective vertical divisor  $D$  whose support is  $Z$ , the shape prescription being satisfied by construction, it follows from Proposition 4.7 that  $\mathcal{L}$  is  $\pi$ -semiample, and the associated contraction yields a singularity of type  $I$  with  $p_1$  cleaving to the special branch. Note that  $\mathcal{L}$  contracts as well the semistable rational components that are disjoint from  $Z$ , hence the resulting curve has no (infinitesimal) automorphisms. The level condition is satisfied by construction, therefore  $\mathcal{C}_0$  is  $m$ -stable.

The case that the core is irreducible and  $p_1$  is not Weierstrass is dealt with in a similar fashion. Remember that in this case we have constructed a conjugate section  $\bar{p}_1$ ; this is an auxiliary marking that will be forgotten in the end, *and should not be taken into account when computing the level*. At every step we draw a larger circle by including one more component along the trees containing  $p_1$  and  $\bar{p}_1$ , and two more along every other tree; the inner valence of the new circle is the same as the outer valence of the old one, thanks to the base-change we performed at the beginning. At the  $l$ -th step we are going to use the line bundle

$$\begin{aligned} \mathcal{L} = \omega_{\mathcal{C}/\Delta}(2lK + \sum_{\substack{R \in [p_1, K] \\ \text{or } [\bar{p}_1, K]}} [2l - 2 \operatorname{dist}(R, K)]_+ R + \sum_{R \notin T_1, \bar{T}_1} [2l - \operatorname{dist}(R, K)]_+ R + \\ \sum_{\substack{R \in T_1, R \notin [p_1, K] \text{ or} \\ R \in \bar{T}_1, R \notin [\bar{p}_1, K]}} [2l - 2 \operatorname{dist}(T_1 \wedge T_R, K) - \operatorname{dist}(R, T_1 \wedge T_R)]_+ R + \sum_{i=1}^n p_i + \bar{p}_1) \end{aligned}$$

to contract the strict interior of the circle. It follows from Proposition ?? that  $\mathcal{L}$  is  $\pi$ -semiample, and the associated contraction contains a singularity of type  $II$  with  $p_1$  cleaving to one of the twin branches. Note that a  $II_{m+1}$  singularity will occur only if the level is exactly  $m$  and  $\bar{p}_1$  does not coincide with any other special point, so that one of the twin branches remains dangling after forgetting  $\bar{p}_1$ . Again, the stability condition is satisfied by construction.

Suppose next that the minimal subcurve of genus two  $Z$  contains two subcurves of genus one; call  $E_1$  and  $E_2$  the minimal such, and assume that  $p_1$  cleaves to  $E_1$  in a point that is 2-torsion with respect to the node separating  $E_1$  from  $E_2$ . We start by drawing expanding circles around  $E_2$  until the level condition for it is satisfied, and then we do the same for  $E_1$ , so that (v) holds; observe, though, that as soon as the two circles touch, the contraction will not have two distinguished genus one subcurves anymore, therefore we need to check (ii) rather than (iii). Here is a more detailed description of the process.

- If  $\operatorname{lev}(E_2) \geq m + 2$  is attained before the circle around  $E_2$  gets to touch  $E_1$ , take the next  $l_2 \equiv 2 \pmod{3}$  (thus “undoing” the  $3 : 1$  base-change, which was unnecessary in this case),

then contract the inner disc by the line bundle

$$\mathcal{L}_2 = \omega_{\mathcal{C}/\Delta}((l_2 + 1)E_2 + \sum [l_2 + 1 - \text{dist}(E_2, R)]_+ R + \sum_{i=1}^n p_i).$$

Smyth’s contraction lemma [Smy11a, Lemma 2.13] applies;  $E_2$  is contracted to an elliptic  $l$ -fold point  $q_2$  ( $l \leq m + 1$ ). Consider now  $E_1$ . If  $\text{lev}(E_1) \leq m + 1$ , start drawing expanding circles around it. Either level  $\geq m + 2$  can be reached before touching the singularity at  $q_2$ , or contracting the maximal balanced subcurve of genus one containing  $E_1$  and not  $q_2$  yields a curve with two genus one singularities sharing a branch. Note that  $p_1$  cleaves to the only genus one subcurve that may have level  $\leq m + 1$ .

- Otherwise, one step before including  $E_1$ , we may contract the disc around  $E_2$  to yield a genus one singularity with a genus one branch. If  $\text{lev}_2 \leq m$  at this point, we need to contract a genus two subcurve. At this *critical step* the multiplicity of  $D$  along  $E_1$  grows from 0 to 3, hence  $D$  will be supported three steps further along each rational tail departing from  $E_2$ . Since the critical step occurs at  $\equiv 1 \pmod{3}$ , the length of the rational tails is and remains  $\equiv 2 \pmod{3}$ , hence we perform only one “meaningful” step forward, thanks to the preliminary base-change. See Figure 8. In particular, the inner valence of the disc will be  $\leq m$ . We proceed now as in the irreducible case, expanding the circle by 1 along  $T_1$  and by 3 along all other rational tails.

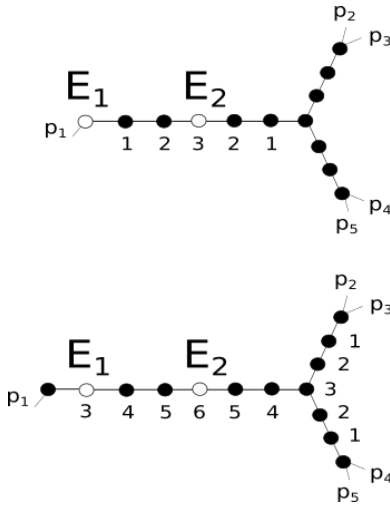


FIGURE 8. An instance of the critical step, from contracting the two genus one subcurves separately, to contracting the genus two subcurve as a whole. Above, the contraction yields a tacnode with a genus one branch, having  $\text{lev}_2 = 3$ . Below, the contraction yields a singularity of type  $I_3$ . Note that we had to blow-up at  $p_1$ .

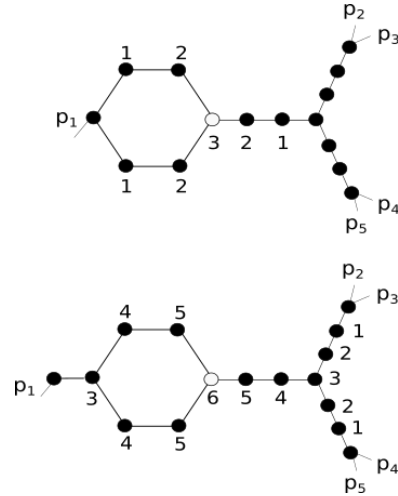


FIGURE 9. Another instance of the critical step, from contracting a genus one subcurve, to contracting a genus two subcurve. Above, the contraction yields an elliptic 3-fold point with two coinciding branches, having  $\text{lev}_2 = 3$ . Below, the contraction yields a singularity of type  $I_3$ . Note that in the meantime we have performed a blow-up at  $p_1$ .

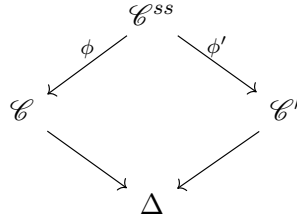
The case that the central fibre contains two subcurves of genus one, and  $p_1$  cleaves to a non-Weierstrass point, is analogous: it is enough to replace the number 3 by the number 2, and 2 by 1, in the previous argument. The only novelty is, it can happen that  $p_1$  is equidistant from  $E_1$  and  $E_2$ , cleaving to the rational chain joining them. In this case we start by expanding a circle

around the one with the lowest level; if they have the same level, expand them simultaneously. If at a later stage  $p_1$  becomes closer to one of the two circles, we proceed as above, namely by enlarging the circle furthest from  $p_1$ .

When the core consists of an elliptic curve  $E$  with a rational bridge  $R$ , and  $p_1$  cleaves to a Weierstrass point - either on  $E$  or on  $R$  -, we have noticed above (see the end of Section 4.1), that  $R$  comprises an odd number  $k = 2h + 1$  of rational components. We start as above by enlarging a balanced circle around  $E$  in order to establish the level condition (iii); there is a critical step (after which we contract a genus two subcurve, and have to satisfy (ii) instead) when the circle touches itself along  $R$ . This happens after the  $(3h + 2)$ -th step, therefore extending the circle by 1 along the tail containing  $p_1$ , and by 3 on all the other ones, only performs one meaningful step. See Figure 9. The case of a non-Weierstrass point on the elliptic bridge is analogous.

Finally, the case that the central fibre has geometric genus zero can be seen as a degeneration of the previous ones, since we only contract a genus zero subcurve when it is a semistable chain.  $\square$

*Uniqueness of limits.* Up to a further base-change, there is a diagram



extending the isomorphism between the generic fibres, where  $\mathcal{C}^{ss}$  has semistable central fibre and regular total space, by the semistable reduction theorem.

*Claim 1.* If  $\mathcal{C}'_0$  has only singularities of genus  $\leq i$  ( $i = 0, 1$ ), then so does  $\mathcal{C}_0$ .

First, assume that  $\mathcal{C}'_0$  has only nodes. If  $\mathcal{C}_0$  has a singular point  $x$  of genus one,  $E := \phi^{-1}(x)$  is an *unmarked* subcurve of arithmetic genus one and level  $\leq m + 1$  of  $\mathcal{C}^{ss}$ . Then so is  $\phi'(E)$ : indeed,  $\phi'$  being a contraction, it has connected fibres, which bars  $\phi'_E$  from being a finite cover of a  $\mathbb{P}^1$ . This contradicts the  $m$ -stability of  $\mathcal{C}'$ . We may argue similarly if  $x$  is a genus two singularity with  $\leq m$  branches. On the other hand, if  $x$  is dangling  $II_{m+1}$ , there is a  $-1$ -curve  $R$  adjacent to  $\phi^{-1}(x)$ ;  $\phi'$  must contract  $R$  by DM stability of  $\mathcal{C}'$ , hence  $\phi'(\phi^{-1}(x))$  is again a genus two curve of level  $\leq m$ .

Assume now that  $\mathcal{C}'_0$  has at worst singularities of genus one, while  $\mathcal{C}_0$  has a singularity  $x$  of genus two; the case of a dangling  $II_{m+1}$  can be excluded as above. Then  $\mathcal{C}_0^{ss} = Z \cup R_1 \cup \dots \cup R_l$ , with  $Z = \phi^{-1}(x)$  and  $l \leq m$ . If  $Z$  has geometric genus two, or is irreducible of geometric genus one,  $\phi'(Z)$  violates the  $m$ -stability of  $\mathcal{C}'$ . If  $Z$  contains a unique subcurve  $E$  of genus one, with a rational bridge  $R$ , then at least one of  $R_1, \dots, R_l$  must be connected to  $R$ , otherwise  $\mathcal{C}'_0$  - which is obtained by contracting a balanced subcurve around  $E$ , not including the entire  $R$  - would have a positive dimensional automorphism group (scaling a semistable component of  $R$ ). Therefore  $\text{lev}(E) \leq (l - 1) + 2 \leq m + 1$ . Similarly, if  $Z$  contains two subcurves of genus one  $E_1$  and  $E_2$ , then  $(\text{lev}(E_1) - 1) + (\text{lev}(E_2) - 1) \leq l$ , hence at least one of the two has level  $\leq m + 1$ . In any case,  $\phi'(E)$  contradicts the  $m$ -stability of  $\mathcal{C}'$ .

*Claim 2.* We may assume that  $\mathcal{C}^{ss}$  contains either no  $-1$ -curve, or only one, which is contracted by neither  $\phi$  nor  $\phi'$ .

If there is a  $-1$ -curve contracted by both,  $\phi$  and  $\phi'$  factor through a smaller regular model. Assume there is a  $-1$ -curve not contracted by  $\phi$ . Then, by condition (iv), its image has to be one of the special branches of a genus two singularity; on the other hand, by condition (v), the only special branch of a singularity of type  $I$  must contain some special points; therefore we conclude that the singular point  $x$  of  $\mathcal{C}_0$  is dangling of type  $II_{l+1}$ ,  $l \leq m$ . If we let  $Z = \phi^{-1}(x)$ , we may write  $\mathcal{C}_0 = Z \cup R_0 \cup \dots \cup R_l$ , with  $R_0 = R$ , and  $R_1$  the tail containing  $p_1$ . By Claim 1,  $\phi'$  has to contract a genus two subcurve  $Z'$  as well. If  $Z'$  is of the shape described in Proposition ?? and it contains  $R$ , then  $Z \subsetneq Z'$  is easily seen, which implies  $\mathcal{C}'_0$  has a singularity of type  $II$  with more than  $m+1$  branches, by the level condition (ii) on  $\mathcal{C}_0$ ; on the other hand, if  $Z' \subsetneq Z$  were disjoint from  $R$ , then  $\mathcal{C}'_0$  would not satisfy condition (ii). Similarly, if  $Z'$  were to be of the shape described in Proposition 4.7, then  $R_0$  and  $R_1$  would have to meet in a “trunk”  $T$  attached to a Weierstrass point of the core of  $\mathcal{C}_0^{ss}$ ; if  $Z'$  started down along the trunk closer to the core, then  $Z' \subsetneq Z$  (so  $\mathcal{C}'_0$  would not satisfy (ii)), while if  $Z'$  started at the top of the trunk or further away from the core, then  $Z \subsetneq Z'$  (so  $\mathcal{C}'_0$  would not satisfy (i)). We conclude that, if  $\mathcal{C}_0$  has a dangling  $II_{l+1}$  singularity, then so does  $\mathcal{C}'_0$ .

*Claim 3.* The exceptional loci of  $\phi$  and  $\phi'$  coincide.

If  $\mathcal{C}_0$  has only nodes, then so does  $\mathcal{C}'_0$  by Claim 1, and we can conclude by the uniqueness part of the stable reduction theorem.

If  $\mathcal{C}_0$  has a genus one singularity  $x$ , it cannot have a genus two singularity as well, so neither can  $\mathcal{C}'_0$  by Claim 1. If  $\mathcal{C}_0$  has a second genus one singularity  $y$ , let  $E_1 = \phi^{-1}(x)$  and  $E_2 = \phi^{-1}(y)$ ; they are disjoint balanced subcurves of genus one and level  $\leq m+1$  in  $\mathcal{C}_0^{ss}$ , therefore  $\phi'$  must contract them. Enlarging the contraction radius of any one of them would yield a singularity with at least  $m+2$  branches (by condition (iii) on  $\mathcal{C}_0$ ), unless by enlarging we make them touch, in which case we would contract to a genus two singularity; but this is not possible, by Claim 1. The case of a single genus one singularity with a genus one branch, or with a disjoint subcurve of genus one, or with two branches joined by a (possibly empty) rational chain, is similar.

Finally, the case that  $\mathcal{C}_0$  has a genus two singularity, has already been discussed at the end of Claim 2. To summarise, writing  $\mathcal{C}_0^{ss} = Z \cup R_1 \cup \dots \cup R_l$ , with  $Z = \phi^{-1}(x)$  and  $l \leq m$  - the case of a dangling  $II_{m+1}$  was dealt with before -,  $\phi'(Z)$  must be a point  $x'$ , by stability considerations. Call  $Z' = (\phi')^{-1}(x')$  and note that  $Z \subseteq Z'$ . If  $x$  and  $x'$  are singularities of the same type,  $Z = Z'$  is easily deduced by level/singularity (i.e. outer/inner valence) considerations, the key point being that the shape of the curve has only one parameter (the “radius” of the circle), which is determined by  $m$ -stability. On the other hand, if  $x$  were of type  $II$  and  $x'$  of type  $I$ , the two special trees determined by  $x$  would have to share a trunk attached to a Weierstrass point of the core, and  $Z \subseteq Z'$  would imply  $Z \subsetneq Z'$ , which together with condition (ii) for  $\mathcal{C}'$  would make  $x'$  into a singularity with too many branches.

The claim follows from observing that the exceptional locus of  $\phi$  (resp.  $\phi'$ ) is the union of the fibres  $F$  over higher genus singularities of  $\mathcal{C}_0$  (resp.  $\mathcal{C}'_0$ ), and the rational components with only two special points that are disjoint from  $F$ .

*Claim 4.* The generic isomorphism between  $\mathcal{C}$  and  $\mathcal{C}'$  extends over  $\Delta$ .

Follows from [Deb01, Lemma 1.15]. □

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