SEMISTABLE REDUCTION

1. Introduction

In this chapter we prove the semistable reduction theorem for curves. We will use the method of Artin and Winters from their paper [AW71].

It turns out that one can prove the semistable reduction theorem for curves without any results on desingularization. Namely, there is a way to establish the existence and projectivity of moduli of semistable curves using Geometric Invariant Theory (GIT) as developed by Mumford, see [MFK94]. This method was championed by Gieseker who proved the full result in his lecture notes [Gie82]. This is quite an amazing feat: it seems somewhat counter intuitive that one can prove such a result without ever truly studying families of curves over a positive dimensional base.

Historically the first proof of the semistable reduction theorem for curves can be found in the paper [DM69] by Deligne and Mumford. It proves the theorem by

---

This is a chapter of the Stacks Project, version e7402353, compiled on Sep 02, 2019.

1Gieseker’s lecture notes are written over an algebraically closed field, but the same method works over $\mathbb{Z}$. 
reducing the problem to the case of Abelian varieties which was already known at the time thanks to Grothendieck and others, see [GRR72 and DK73]. The semistable reduction theorem for abelian varieties uses the theory of Néron models which in turn rests on a treatment of birational group laws over a base.

The method in the paper by Artin and Winters relies on desingularization of singularities of surfaces to obtain regular models. Given the existence of regular models, the proof consists in analyzing the possibilities for the special fibre and concluding using an inequality for torsion in the Picard group of a 1-dimensional scheme over a field. A similar argument can be found in a paper [Sai87] of Saito who uses étale cohomology directly and who obtains a stronger result in that he can characterize semistable reduction in terms of the action of the inertia on ℓ-adic étale cohomology.

A different approach one can use to prove the theorem is to use rigid analytic geometry techniques. Here we refer the reader to [VP84] and [AW12].

Another overview paper that the reader may wish to consult is [Abb00] written by Ahmed Abbes.

The paper [Tem10] by Temkin uses valuation theoretic techniques (and proves a lot more besides); also Appendix A of this paper gives a nice overview of the different proofs and the relationship with desingularizations of 2 dimensional schemes.

Another overview paper that the reader may wish to consult is [Abb00] written by Ahmed Abbes.

2. Linear algebra

A couple of lemmas we will use later on.

**Lemma 2.1.** Let $A = (a_{ij})$ be a complex $n \times n$ matrix.

1. If $|a_{ii}| > \sum_{j \neq i} |a_{ij}|$ for each $i$, then $\det(A)$ is nonzero.
2. If there exists a real vector $m = (m_1, \ldots, m_n)$ with $m_i > 0$ such that $|a_{ii}m_i| > \sum_{j \neq i} |a_{ij}m_j|$ for each $i$, then $\det(A)$ is nonzero.

**Proof.** If $A$ is as in (1) and $\det(A) = 0$, then there is a nonzero vector $z$ with $Az = 0$. Choose $r$ with $|z_r|$ maximal. Then

$$|a_{rr}z_r| = \left| \sum_{k \neq r} a_{rk}z_k \right| \leq \sum_{k \neq r} |a_{rk}||z_k| \leq |z_r| \sum_{k \neq r} |a_{rk}| < |a_{rr}| |z_r|$$

which is a contradiction. To prove (2) apply (1) to the matrix $(a_{ij}m_i)$ whose determinant is $m_1 \ldots m_n \det(A)$. \hfill $\square$

**Lemma 2.2.** Let $A = (a_{ij})$ be a real $n \times n$ matrix with $a_{ij} \geq 0$ for $i \neq j$. Let $m = (m_1, \ldots, m_n)$ be a real vector with $m_i > 0$. For $I \subset \{1, \ldots, n\}$ let $x_I \in \mathbb{R}^n$ be the vector whose $i$th coordinate is $m_i$ if $i \in I$ and 0 otherwise. If

$$-a_{ii}m_i \geq \sum_{j \neq i} a_{ij}m_j$$

for each $i$, then $\text{Ker}(A)$ is the vector space spanned by the vectors $x_I$ such that

1. $a_{ij} = 0$ for $i \in I$, $j \notin I$, and
2. equality holds in (2.2.1) for $i \in I$.

**Proof.** After replacing $a_{ij}$ by $a_{ij}m_i$ we may assume $m_i = 1$ for all $i$. If $I \subset \{1, \ldots, n\}$ such that (1) and (2) are true, then a simple computation shows that $x_I$ is in the kernel of $A$. Conversely, let $x = (x_1, \ldots, x_n) \in \mathbb{R}^n$ be a nonzero vector in the kernel of $A$. We will show by induction on the number of nonzero coordinates
Let $0C5X$ and equality holds in (2.2.1) for $x$ of $0C6V$. Thus equality holds everywhere. In particular, we see that $a_{rk} = 0$ if $r \in I$, $k \not\in I$ and equality holds in (2.2.1) for $r \in I$. Then we see that we can subtract a suitable multiple of $x_I$ from $x$ to decrease the number of nonzero coordinates.

**Lemma 2.3.** Let $A = (a_{ij})$ be a symmetric real $n \times n$ matrix with $a_{ij} \geq 0$ for $i \neq j$. Let $m = (m_1, \ldots, m_n)$ be a real vector with $m_i > 0$. Assume

1. $Am = 0$,
2. there is no proper nonempty subset $I \subset \{1, \ldots, n\}$ such that $a_{ij} = 0$ for $i \in I$ and $j \not\in I$.

Then $x^tAx \leq 0$ with equality if and only if $x = qm$ for some $q \in \mathbb{R}$.

**First proof.** After replacing $a_{ij}$ by $a_{ij}m_im_j$ we may assume $m_i = 1$ for all $i$. Condition (1) means $-a_{ii} = \sum_{j \not= i} a_{ij}$ for all $i$. Recall that $x^tAx = \sum_{i,j} x_i a_{ij} x_j$. Then

$$\sum_{i \neq j} -a_{ij}(x_j - x_i)^2 = \sum_{i \neq j} -a_{ij} x_j^2 + 2a_{ij} x_i x_j - a_{ij} x_i^2$$

$$= \sum_j a_{jj} x_j^2 + \sum_{i \neq j} 2a_{ij} x_i x_j + \sum_j a_{jj} x_i^2$$

$$= 2x^tAx$$

This is clearly $\leq 0$. If equality holds, then let $I$ be the set of indices $i$ with $x_i \neq x_1$. Then $a_{ij} = 0$ for $i \in I$ and $j \not\in I$. Thus $I = \{1, \ldots, n\}$ by condition (2) and $x$ is a multiple of $m = (1, \ldots, 1)$.

**Second proof.** The matrix $A$ has real eigenvalues by the spectral theorem. We claim all the eigenvalues are $\leq 0$. Namely, since property (1) means $-a_{ii}m_i = \sum_{j \neq i} a_{ij}m_j$ for all $i$, we find that the matrix $A' = A - \lambda I$ for $\lambda > 0$ satisfies $|a_{ii}|m_i > \sum a_{ij}m_j = \sum |a_{ij}m_j|$ for all $i$. Hence $A'$ is invertible by Lemma 2.1. This implies that the symmetric bilinear form $x^tAx$ is semi-negative definite, i.e., $x^tAx \leq 0$ for all $x$. It follows that the kernel of $A$ is equal to the set of vectors $x$ with $x^tAx = 0$. The description of the kernel in Lemma 2.2 gives the final statement of the lemma.

**Lemma 2.4.** Let $L$ be a finite free $\mathbb{Z}$-module endowed with an integral symmetric bilinear positive definite form $(\ ,\ ) : L \times L \to \mathbb{Z}$. Let $A \subset L$ be a submodule with $L/A$ torsion free. Set $B = \{b \in L \mid (a, b) = 0, \forall a \in A\}$. Then we have injective maps

$$A^# / A \leftarrow L/(A \oplus B) \to B^#/B$$

whose cokernels are quotients of $L^#/L$. Here $A^# = \{a' \in A \otimes \mathbb{Q} \mid (a, a') \in \mathbb{Z}, \forall a \in A\}$ and similarly for $B$ and $L$.

**Proof.** Observe that $L \otimes \mathbb{Q} = A \otimes \mathbb{Q} \oplus B \otimes \mathbb{Q}$ because the form is nondegenerate on $A$ (by positivity). We denote $\pi_B : L \otimes \mathbb{Q} \to B \otimes \mathbb{Q}$ the projection. Observe that $\pi_B(x) \in B^#$ for $x \in L$ because the form is integral. This gives an exact sequence

$$0 \to A \to L \xrightarrow{\pi_B} B^# \to Q \to 0$$
where $Q$ is the cokernel of $L \to B^#$. Observe that $Q$ is a quotient of $L^#/L$ as the map $L^# \to B^#$ is surjective since it is the $\mathbb{Z}$-linear dual to $B \to L$ which is split as a map of $\mathbb{Z}$-modules. Dividing by $A \oplus B$ we get a short exact sequence

$$0 \to L/(A \oplus B) \to B^#/B \to Q \to 0$$

This proves the lemma. □

**Lemma 2.5.** Let $L_0, L_1$ be a finite free $\mathbb{Z}$-modules endowed with integral symmetric bilinear positive definite forms $\langle , \rangle : L_i \times L_i \to \mathbb{Z}$. Let $d : L_0 \to L_1$ and $d^* : L_1 \to L_0$ be adjoint. If $\langle , \rangle$ on $L_0$ is unimodular, then there is an isomorphism

$$\Phi : \text{Coker}(d^*d)_{\text{torsion}} \to \text{Im}(d^#)/\text{Im}(d)$$

with notation as in Lemma 2.4.

**Proof.** Let $x \in L_0$ be an element representing a torsion class in $\text{Coker}(d^*d)$. Then for some $a > 0$ we can write $ax = d^*d(y)$. For any $z \in \text{Im}(d)$, say $z = d(y')$, we have

$$\langle (1/a)d(y), z \rangle = \langle (1/a)d(y), d(y') \rangle = \langle x, y' \rangle \in \mathbb{Z}$$

Hence $(1/a)d(y) \in \text{Im}(d^#)$. We define $\Phi(x) = (1/a)d(y) \mod \text{Im}(d)$. We omit the proof that $\Phi$ is well defined, additive, and injective.

To prove $\Phi$ is surjective, let $z \in \text{Im}(d^#)$. Then $z$ defines a linear map $L_0 \to \mathbb{Z}$ by the rule $x \mapsto \langle z, d(x) \rangle$. Since the pairing on $L_0$ is unimodular by assumption we can find an $x' \in L_0$ with $\langle x', x \rangle = \langle z, d(x) \rangle$ for all $x \in L_0$. In particular, we see that $x'$ pairs to zero with $\text{Ker}(d)$. Since $\text{Im}(d^*d) \otimes \mathbb{Q}$ is the orthogonal complement of $\text{Ker}(d) \otimes \mathbb{Q}$ this means that $x'$ defines a torsion class in $\text{Coker}(d^*d)$. We claim that $\Phi(x') = z$. Namely, write $ax' = d^*d(y)$ for some $y \in L_0$ and $a > 0$. For any $x \in L_0$ we get

$$\langle z, d(x) \rangle = \langle x', x \rangle = \langle (1/a)d^*d(y), x \rangle = \langle (1/a)d(y), d(x) \rangle$$

Hence $z = \Phi(x')$ and the proof is complete. □

**Lemma 2.6.** Let $A = (a_{ij})$ be a symmetric $n \times n$ integer matrix with $a_{ij} \geq 0$ for $i \neq j$. Let $m = (m_1, \ldots, m_n)$ be an integer vector with $m_i > 0$. Assume

1. $Am = 0$,
2. there is no proper nonempty subset $I \subset \{1, \ldots, n\}$ such that $a_{ij} = 0$ for $i \in I$ and $j \not\in I$.

Let $e$ be the number of pairs $(i, j)$ with $i < j$ and $a_{ij} > 0$. Then for $\ell$ a prime number coprime with all $a_{ij}$ and $m_i$ we have

$$\dim_{\mathbb{F}_\ell}(\text{Coker}(A)[\ell]) \leq 1 - n + e$$

**Proof.** By Lemma 2.3 the rank of $A$ is $n - 1$. The composition

$$\mathbb{Z}_n^{\oplus n} \xrightarrow{\text{diag}(m_1, \ldots, m_n)} \mathbb{Z}_n^{\oplus n} \xrightarrow{(a_{ij})} \mathbb{Z}_n^{\oplus n} \xrightarrow{\text{diag}(m_1, \ldots, m_n)} \mathbb{Z}_n^{\oplus n}$$

has matrix $a_{ij}m_im_j$. Since the cokernel of the first and last maps are torsion of order prime to $\ell$ by our restriction on $\ell$ we see that it suffices to prove the lemma for the matrix with entries $a_{ij}m_im_j$. Thus we may assume $m = (1, \ldots, 1)$.

Assume $m = (1, \ldots, 1)$. Set $V = \{1, \ldots, n\}$ and $E = \{(i, j) \mid i < j \text{ and } a_{ij} > 0\}$. For $e = (i, j) \in E$ set $a_e = a_{ij}$. Define maps $s, t : E \to V$ by setting $s(i, j) = i$
and \( t(i, j) = j \). Set \( Z(V) = \bigoplus_{i \in V} Z i \) and \( Z(E) = \bigoplus_{e \in E} Z e \). We define symmetric positive definite integer valued pairings on \( Z(V) \) and \( Z(E) \) by setting
\[
\langle i, i \rangle = 1 \text{ for } i \in V, \quad \langle e, e \rangle = a_e \text{ for } e \in E
\]
and all other pairings zero. Consider the maps
\[
d : Z(V) \to Z(E), \quad i \mapsto \sum_{e \in E, s(e) = i} e - \sum_{e \in E, t(e) = i} e
\]
and
\[
d^*(e) = a_e (s(e) - t(e))
\]
A computation shows that
\[
(d(x), y) = \langle x, d^*(y) \rangle
\]
in other words, \( d \) and \( d^* \) are adjoint. Next we compute
\[
d^* d(i) = d^*(\sum_{e \in E, s(e) = i} e - \sum_{e \in E, t(e) = i} e)
\]
\[
= \sum_{e \in E, s(e) = i} a_e (s(e) - t(e)) - \sum_{e \in E, t(e) = i} a_e (s(e) - t(e))
\]
The coefficient of \( i \) in \( d^* d(i) \) is
\[
\sum_{e \in E, s(e) = i} a_e + \sum_{e \in E, t(e) = i} a_e = -a_{i i}
\]
because \( \sum_j a_{ij} = 0 \) and the coefficient of \( j \neq i \) in \( d^* d(i) \) is \(-a_{ij}\). Hence \( \text{Coker}(A) = \text{Coker}(d^* d) \).

Consider the inclusion
\[
\text{Im}(d) \oplus \ker(d^*) \subset Z(E)
\]
The left hand side is an orthogonal direct sum. Clearly \( Z(E)/\ker(d^*) \) is torsion free. We claim \( Z(E)/\text{Im}(d) \) is torsion free as well. Namely, say \( x = \sum x_e e \in Z(E) \) and \( a > 1 \) are such that \( ax = dy \) for some \( y = \sum y_i i \in Z(V) \). Then \( ax_e = y_{s(e)} - y_{t(e)} \). By property (2) we conclude that all \( y_i \) have the same congruence class modulo \( a \). Hence we can write \( y = ay' + (y_1, y_1, \ldots, y_1) \). Since \( d(y_1, y_1, \ldots, y_1) = 0 \) we conclude that \( x = d(y') \) which is what we had to show.

Hence we may apply Lemma 2.4 to get injective maps
\[
\text{Im}(d)^\# / \text{Im}(d) \leftarrow Z(E) / (\text{Im}(d) \oplus \ker(d^*)) \to \ker(d^*)^\# / \ker(d^*)
\]
whose cokernels are annihilated by the product of the \( a_e \) (which is prime to \( \ell \)). Since \( \ker(d^*) \) is a lattice of rank \( 1 - n + e \) we see that the proof is complete if we prove that there exists an isomorphism
\[
\Phi : M_{\text{torsion}} \to \text{Im}(d)^\# / \text{Im}(d)
\]
This is proved in Lemma 2.5. \qed
3. Numerical types

Definition 3.1. A numerical type $T$ is given by

$$n, m_i, a_{ij}, w_i, g_i$$

where $n \geq 1$ is an integer and $m_i, a_{ij}, w_i, g_i$ are integers for $1 \leq i, j \leq n$ subject to the following conditions

1. $m_i > 0, w_i > 0, g_i \geq 0$,
2. the matrix $A = (a_{ij})$ is symmetric and $a_{ij} \geq 0$ for $i \neq j$,
3. there is no proper nonempty subset $I \subset \{1, \ldots, n\}$ such that $a_{ij} = 0$ for $i \in I, j \notin I$,
4. for each $i$ we have $\sum_j a_{ij}m_j = 0$, and
5. $w_i | a_{ij}$.

This is obviously a somewhat annoying type of structure to work with, but it is exactly what shows up in special fibres of proper regular models of smooth geometrically connected curves. Of course we only care about these types up to reordering the indices.

Definition 3.2. We say two numerical types $n, m_i, a_{ij}, w_i, g_i$ and $n', m_i', a_{ij}', w_i', g_i'$ are equivalent types if there exists a permutation $\sigma$ of $\{1, \ldots, n\}$ such that $m_i = m_{\sigma(i)}', a_{ij} = a_{\sigma(i)\sigma(j)}', w_i = w_{\sigma(i)}', g_i = g_{\sigma(i)}'$.

A numerical type has a genus.

Lemma 3.3. Let $n, m_i, a_{ij}, w_i, g_i$ be a numerical type. Then the expression

$$g = 1 + \sum m_i (w_i(g_i - 1) - \frac{1}{2} a_{ii})$$

is an integer.

Proof. To prove $g$ is an integer we have to show that $\sum a_{ii}m_i$ is even. This we can see by computing modulo 2 as follows

$$\sum_i a_{ii}m_i \equiv \sum_i \text{odd} \; a_{ii}m_i$$

$$\equiv \sum_i \text{odd} \sum_{j \neq i} a_{ij}m_j$$

$$\equiv \sum_i \text{odd} \sum_{j \neq i, m_j \text{ odd}} a_{ij}m_j$$

$$\equiv \sum_{i<j, m_i \text{ and } m_j \text{ odd}} a_{ij}(m_i + m_j)$$

$$\equiv 0$$

where we have used that $a_{ij} = a_{ji}$ and that $\sum_j a_{ij}m_j = 0$ for all $i$. □

Definition 3.4. We say $n, m_i, a_{ij}, w_i, g_i$ is a numerical type of genus $g$ if $g = 1 + \sum m_i (w_i(g_i - 1) - \frac{1}{2} a_{ii})$ is the integer from Lemma 3.3.

We will prove below (Lemma 3.14) that the genus is almost always $\geq 0$. But you can have numerical types with negative genus.

Lemma 3.5. Let $n, m_i, a_{ij}, w_i, g_i$ be a numerical type of genus $g$. If $n = 1$, then $a_{11} = 0$ and $g = 1 + m_1 w_1 (g_1 - 1)$. Moreover, we can classify all such numerical types as follows
(1) If \( g < 0 \), then \( g_1 = 0 \) and there are finitely many possible numerical types of genus \( g \) with \( n = 1 \) corresponding to factorizations \( m_1 w_1 = 1 - g \).

(2) If \( g = 0 \), then \( m_1 = 1, w_1 = 1, g_1 = 0 \) as in Lemma 6.4.

(3) If \( g = 1 \), then we conclude \( g_1 = 1 \) but \( m_1, w_1 \) can be arbitrary positive integers; this is case (1) of Lemma 6.2.

(4) If \( g > 1 \), then \( g_1 > 1 \) and there are finitely many possible numerical types of genus \( g \) with \( n = 1 \) corresponding to factorizations \( m_1 w_1 (g_1 - 1) = g - 1 \).

**Proof.** The lemma proves itself. \( \Box \)

**Lemma 3.6.** Let \( n, m, a_{ij}, w_i, g_i \) be a numerical type of genus \( g \). If \( n > 1 \), then \( a_{ii} < 0 \) for all \( i \).

**Proof.** Lemma 2.3 applies to the matrix \( A \).

**Lemma 3.7.** Let \( n, m, a_{ij}, w_i, g_i \) be a numerical type of genus \( g \). Assume \( n > 1 \).

If \( i \) is such that the contribution \( m_i (w_i (g_i - 1) - \frac{1}{2} a_{ii}) \) to the genus \( g \) is \( g \), then \( g_i = 0 \) and \( a_{ii} = -w_i \).

**Proof.** Follows immediately from Lemma 3.6 and \( w_i > 0, g_i \geq 0 \), and \( w_i | a_{ii} \).

**Definition 3.8.** Let \( n, m, a_{ij}, w_i, g_i \) be a numerical type. We say \( i \) is a \((-1)-index\) if \( g_i = 0 \) and \( a_{ii} = -w_i \).

We can “contract” \((-1)-indices.\)

**Lemma 3.9.** Let \( n, m, a_{ij}, w_i, g_i \) be a numerical type \( T \). Assume \( n \) is a \((-1)-index.\) Then there is a numerical type \( T' \) given by \( n', m_i', a_{ij}', w_i', g_i' \) with

(1) \( n' = n - 1 \),
(2) \( m_i' = m_i \),
(3) \( a_{ij}' = a_{ij} - a_{in} a_{jn}/a_{nn} \),
(4) \( w_i' = w_i/2 \) if \( a_{in}/w_i \) even and \( a_{in}/w_i \) odd and \( w_i' = w_i \) else,
(5) \( g_i' = \frac{1}{w_i'} (g_i - 1) + \frac{a_{ii}}{2 w_i' a_{nn}} \).

Moreover, we have \( g = g' \).

**Proof.** Observe that \( n > 1 \) for example by Lemma 3.5 and hence \( n' \geq 1 \). We check conditions (1) – (5) of Definition 3.1 for \( n', m_i', a_{ij}', w_i', g_i' \).

Condition (1) is immediate.

Condition (2). Symmetry of \( A' = (a_{ij}') \) is immediate and since \( a_{nn} < 0 \) by Lemma 3.6 we see that \( a_{ij}' \geq a_{ij} \geq 0 \) if \( i \neq j \).

Condition (3). Suppose that \( I \subset \{1, \ldots, n - 1\} \) such that \( a_{ii'} = 0 \) for \( i \in I \) and \( i' \in \{1, \ldots, n - 1\} \setminus I \). Then we see that for each \( i \in I \) and \( i' \in I' \) we have \( a_{in} a_{i'n} = 0 \).

Thus either \( a_{in} = 0 \) for all \( i \in I \) and \( I \subset \{1, \ldots, n\} \) is a contradiction for property (3) for \( T \), or \( a_{i'n} = 0 \) for all \( i' \in \{1, \ldots, n - 1\} \setminus I \) and \( I \cup \{n\} \subset \{1, \ldots, n\} \) is a contradiction for property (3) of \( T \). Hence (3) holds for \( T' \).

Condition (4). We compute

\[
\sum_{j=1}^{n-1} a_{ij}' m_j = \sum_{j=1}^{n-1} (a_{ij} m_j - \frac{a_{in} a_{jn} m_j}{a_{nn}}) = -a_{in} m_n - \frac{a_{in}}{a_{nn}} (-a_{nn} m_n) = 0
\]
as desired.
Condition (5). We have to show that $w'_i$ divides $a_{in}a_{jn}/a_{nn}$. This is clear because $a_{nn} = -w_n$ and $w_n|a_{jn}$ and $w_i|a_{in}$.

To show that $g = g'$ we first write
\[
g = 1 + \sum_{i=1}^{n} m_i(g_i - 1) - \frac{1}{2}a_{ii}
= 1 + \sum_{i=1}^{n-1} m_i(g_i - 1) - \frac{1}{2}a_{ii} - \frac{1}{2}m_n w_n
= 1 + \sum_{i=1}^{n-1} m_i(g_i - 1) - \frac{1}{2}a_{ii} - \frac{1}{2}a_{in}
\]
Comparing with the expression for $g'$ we see that it suffices if
\[
w'_i(g'_i - 1) - \frac{1}{2}a'_{ii} = w_i(g_i - 1) - \frac{1}{2}a_{in} - \frac{1}{2}a_{ii}
\]
for $i \leq n - 1$. In other words, we have
\[
g'_i = \frac{2w_i(g_i - 1) - a_{in} - a_{ii} + a'_{ji} + 2w'_i}{2w'_i} = \frac{w_i}{w'_i}(g_i - 1) + 1 + \frac{a_{in} - w_n a_{in}}{2w'_i w_n}
\]
It is elementary to check that this is an integer $\geq 0$ if we choose $w'_i$ as in (4). □

Lemma 3.10. Let $n, m_i, a_{ij}, w_i, g_i$ be a numerical type. Let $e$ be the number of pairs $(i, j)$ with $i < j$ and $a_{ij} > 0$. Then the expression $g_{top} = 1 - n + e$ is $\geq 0$.

Proof. If not, then $e < n - 1$ which means there exists an $i$ such that $a_{ij} = 0$ for all $j \neq i$. This contradicts assumption (3) of Definition 3.1. □

Definition 3.11. Let $n, m_i, a_{ij}, w_i, g_i$ be a numerical type $T$. The topological genus of $T$ is the nonnegative integer $g_{top} = 1 - n + e$ from Lemma 3.10.

We want to bound the genus by the topological genus. However, this will not always be the case, for example for numerical types with $n = 1$ as in Lemma 3.5. But it will be true for minimal numerical types which are defined as follows.

Definition 3.12. We say the numerical type $n, m_i, a_{ij}, w_i, g_i$ of genus $g$ is minimal if there does not exist an $i$ with $g_i = 0$ and $a_{ii} = -w_i$, in other words, if there does not exist a $(-1)$-index.

We will prove that the genus $g$ of a minimal type with $n > 1$ is greater than or equal to $\max(1, g_{top})$.

Lemma 3.13. If $n, m_i, a_{ij}, w_i, g_i$ is a minimal numerical type with $n > 1$, then $g \geq 1$.

Proof. This is true because $g = 1 + \sum \Phi_i$ with $\Phi_i = m_i(w_i(g_i - 1) - \frac{1}{2}a_{ii})$ non-negative by Lemma 3.7 and the definition of minimal types. □

Lemma 3.14. If $n, m_i, a_{ij}, w_i, g_i$ is a minimal numerical type with $n > 1$, then $g \geq g_{top}$.

Proof. The reader who is only interested in the case of numerical types associated to proper regular models can skip this proof as we will reprove this in the geometric situation later. We can write
\[
g_{top} = 1 - n + \frac{1}{2} \sum_{a_{ij} > 0} 1 = 1 + \sum_i (-1 + \frac{1}{2} \sum_{j \neq i, a_{ij} > 0} 1)
\]
On the other hand, we have
\[ g = 1 + \sum m_i (w_i (g_i - 1) - \frac{1}{2} a_{ii}) \]
\[ = 1 + \sum m_i w_i g_i - \sum m_i w_i + \frac{1}{2} \sum_{i \neq j} a_{ij} m_j \]
\[ = 1 + \sum m_i w_i (-1 + g_i + \frac{1}{2} \sum_{j \neq i} a_{ij} / w_i) \]
The first equality is the definition, the second equality uses that \( \sum a_{ij} m_j = 0 \),
and the last equality uses that uses \( a_{ij} = a_{ji} \) and switching order of summation.
Comparing with the formula for \( g_{top} \), we conclude that the lemma holds if
\[ \Psi_i = m_i w_i (-1 + g_i + \frac{1}{2} \sum_{j \neq i} a_{ij} / w_i) - (-1 + \frac{1}{2} \sum_{j \neq i, a_{ij} > 0} 1) \]
is \( \geq 0 \) for each \( i \). However, this may not be the case. Let us analyze for which
indices we can have \( \Psi_i < 0 \). First, observe that
\[ (-1 + g_i + \frac{1}{2} \sum_{j \neq i} a_{ij} / w_i) \geq (-1 + \frac{1}{2} \sum_{j \neq i, a_{ij} > 0} 1) \]
because \( a_{ij} / w_i \) is a nonnegative integer. Since \( m_i w_i \) is a positive integer we conclude that
\( \Psi_i \geq 0 \) as soon as either \( m_i w_i = 1 \) or the left hand side of the inequality is
\( \geq 0 \) which happens if \( g_i > 0 \), or \( a_{ij} > 0 \) for at least two indices \( j \), or if there is a \( j \)
with \( a_{ij} > w_i \). Thus
\[ P = \{ i : \Psi_i < 0 \} \]
is the set of indices \( i \) such that \( m_i w_i > 1, g_i = 0, a_{ij} > 0 \) for a unique \( j \), and
\( a_{ij} = w_i \) for this \( j \). Moreover
\[ i \in P \Rightarrow \Psi_i = \frac{1}{2} (-m_i w_i + 1) \]
The strategy of proof is to show that given \( i \in P \) we can borrow a bit from \( \Psi_j \)
where \( j \) is the neighbour of \( i \), i.e., \( a_{ij} > 0 \). However, this won’t quite work because \( j \)
may be an index with \( \Psi_j = 0 \).
Consider the set
\[ Z = \{ j : g_j = 0 \text{ and } j \text{ has exactly two neighbours } i, k \text{ with } a_{ij} = w_j = a_{jk} \} \]
For \( j \in Z \) we have \( \Psi_j = 0 \). We will consider sequences \( M = (i, j_1, \ldots, j_s) \) where
\( s \geq 0, i \in P, j_1, \ldots, j_s \in Z, \) and \( a_{ij_1} > 0, a_{j_1j_2} > 0, \ldots, a_{j_{s-1}j_s} > 0, \)\)
If our numerical type consists of two indices which are in \( P \) or more generally if our
numerical type consists of two indices which are in \( P \) and all other indices in \( Z \),
then \( g_{top} = 0 \) and we win by Lemma 3.13. We may and do discard these cases.
Let \( M = (i, j_1, \ldots, j_s) \) be a maximal sequence and let \( k \) be the second neighbour
of \( j_s \). (If \( s = 0 \), then \( k \) is the unique neighbour of \( i \).) By maximality \( k \not\in Z \) and by
what we just said \( k \not\in P \). Observe that \( w_i = a_{ij_1} = w_{j_1} = a_{j_1j_2} = \ldots = w_{j_s} = a_{j, k} \).
Looking at the definition of a numerical type we see that
\[ m_i a_{ii} + m_{j_1} w_i = 0, \]
\[ m_i w_i + m_{j_1} a_{j_1j_1} + m_{j_2} w_i = 0, \]
\[ \ldots \]
\[ m_{j_{s-1}} w_i + m_{j_s} a_{j,s, k} + m_k w_i = 0 \]
Let $k$ be an index such that we have a $t > 0$ and pairwise distinct maximal sequences $M_1, \ldots, M_t$ as above, with $M_b = (i_b, j_b, \ldots, j_{b,s_b})$ such that $k$ is a neighbour of $j_{b,s_b}$ for $b = 1, \ldots, t$. We will show that $\Phi_j + \sum_{k=1}^{t} \Phi_{i_k} \geq 0$. This will finish the proof of the lemma by what we said above. Let $M$ be the union of the indices occurring in $M_b$, $b = 1, \ldots, t$. We write

$$
\Psi_k = - \sum_{b=1}^{t} \Psi_{i_b} + \Psi'_k
$$

where

$$
\Psi'_k = m_k w_k \left( -1 + g_k + \frac{1}{2} \sum_{b=1}^{t} \left( \frac{a_{kj_b,s_b}}{w_k} - \frac{m_{i_b} w_{i_b}}{m_k w_k} \right) + \frac{1}{2} \sum_{l \neq k, i \notin M} \frac{a_{kl}}{w_k} \right) 
$$

Assume $\Psi'_k < 0$ to get a contradiction. If the set $\{l : l \neq k, i \notin M, a_{kl} > 0\}$ is empty, then $\{1, \ldots, n\} = M \cup \{k\}$ and $g_{top} = 0$ because $e = n - 1$ in this case and the result holds by Lemma 3.13. Thus we may assume there is at least one such $l$ which contributes $(1/2)a_{kl}/w_k \geq 1/2$ to the sum inside the first brackets. For each $b = 1, \ldots, t$ we have

$$
\frac{a_{kj_b,s_b}}{w_k} - \frac{m_{i_b} w_{i_b}}{m_k w_k} = \frac{w_{i_b}}{w_k} \left( 1 - \frac{m_{i_b}}{m_k} \right)
$$

This expression is $\geq 1/2$ because $m_k \geq 2m_{i_b}$ by the previous paragraph and is $\geq 1$ if $w_k < w_{i_b}$. It follows that $\Psi'_k < 0$ implies $g_k = 0$. If $t \geq 2$ or $t = 1$ and $w_k < w_{i_1}$, then $\Psi'_k \geq 0$ (here we use the existence of an $l$ as shown above) which is a contradiction too. Thus $t = 1$ and $w_k = w_{i_1}$. If there at least two nonzero terms in the sum over $l$ or if there is one such $k$ and $a_{kl} > w_k$, then $\Psi'_k \geq 0$ as well. The final possibility is that $t = 1$ and there is one $l$ with $a_{kl} = w_k$. This is disallowed as this would mean $k \in Z$ contradicting the maximality of $M_1$.

**Lemma 3.15.** Let $n, m_i, a_{ij}, w_i, g_i$ be a numerical type of genus $g$. Assume $n > 1$. If $i$ is such that the contribution $m_i(w_i(g_i - 1) - 1/2a_{ii})$ to the genus $g$ is 0, then $g_i = 0$ and $a_{ii} = -2w_i$.

**Proof.** Follows immediately from Lemma 3.6 and $w_i > 0$, $g_i \geq 0$, and $w_i|a_{ii}$. \qed

It turns out that the indices satisfying this relation play an important role in the structure of minimal numerical types. Hence we give them a name.

**Definition 3.16.** Let $n, m_i, a_{ij}, w_i, g_i$ be a numerical type of genus $g$. We say $i$ is a $(-2)$-index if $g_i = 0$ and $a_{ii} = -2w_i$.

Given a minimal numerical type of genus $g$ the $(-2)$-indices are exactly the indices which do not contribute a positive number to the genus in the formula

$$
g = 1 + \sum m_i(w_i(g_i - 1) - 1/2a_{ii})
$$

Thus it will be somewhat tricky to bound the quantities associated with $(-2)$-indices as we will see later.
Here is the definition.

Let \( n, m \) be a minimal numerical type with \( n > 1 \).

Equality \( g = g_{top} \) can hold in Lemma 3.14. For example, if \( m_i = w_i = 1 \) and \( g_i = 0 \) for all \( i \) and \( a_{ij} \in \{0, 1\} \) for \( i < j \).

### 4. The Picard group of a numerical type

**Definition 4.1.** Let \( n, m, a_{ij}, w_i, g_i \) be a numerical type \( T \). The Picard group of \( T \) is the cokernel of the matrix \( (a_{ij}/w_i) \), more precisely

\[
\text{Pic}(T) = \text{Coker} \left( \mathbb{Z}^\oplus n \rightarrow \mathbb{Z}^\oplus n, \quad e_i \mapsto \sum a_{ij} w_j e_j \right)
\]

where \( e_i \) denotes the \( i \)th standard basis vector for \( \mathbb{Z}^\oplus n \).

**Lemma 4.2.** Let \( n, m, a_{ij}, w_i, g_i \) be a numerical type \( T \). The Picard group of \( T \) is a finitely generated abelian group of rank 1.

**Proof.** If \( n = 1 \), then \( A = (a_{ij}) \) is the zero matrix and the result is clear. For \( n > 1 \) the matrix \( A \) has rank \( n - 1 \) by either Lemma 2.2 or Lemma 2.3. Of course the rank is not affected by scaling the rows by \( 1/w_i \). This proves the lemma. \( \square \)

**Lemma 4.3.** Let \( n, m, a_{ij}, w_i, g_i \) be a numerical type \( T \). Then \( \text{Pic}(T) \subset \text{Coker}(A) \) where \( A = (a_{ij}) \).

**Proof.** Since \( \text{Pic}(T) \) is the cokernel of \( (a_{ij}/w_i) \) we see that there is a commutative diagram

\[
\begin{array}{ccc}
0 & \rightarrow & \mathbb{Z}^\oplus n \\
\downarrow \text{id} & & \downarrow \text{diag}(w_1, \ldots, w_n) \\
0 & \rightarrow & \mathbb{Z}^\oplus n \\
\end{array}
\]

with exact rows. By the snake lemma we conclude that \( \text{Pic}(T) \subset \text{Coker}(A) \). \( \square \)

**Lemma 4.4.** Let \( n, m, a_{ij}, w_i, g_i \) be a numerical type \( T \). Assume \( n \) is a \((-1)\)-index. Let \( T' \) be the numerical type constructed in Lemma 3.9. There exists an injective map

\[
\text{Pic}(T) \rightarrow \text{Pic}(T')
\]

whose cokernel is an elementary abelian 2-group.

**Proof.** Recall that \( n' = n - 1 \). Let \( e_i \), resp., \( e_i' \) be the \( i \)th basis vector of \( \mathbb{Z}^\oplus n \), resp. \( \mathbb{Z}^\oplus n-1 \). First we denote

\[
q : \mathbb{Z}^\oplus n \rightarrow \mathbb{Z}^\oplus n-1, \quad e_n \mapsto 0 \text{ and } e_i \mapsto e_i' \text{ for } i \leq n - 1
\]

and we set

\[
p : \mathbb{Z}^\oplus n \rightarrow \mathbb{Z}^\oplus n-1, \quad e_n \mapsto \sum_{j=1}^{n-1} a_{nj} w_j e_j' \text{ and } e_i \mapsto \frac{w_i}{w_j} e_i' \text{ for } i \leq n - 1
\]

A computation (which we omit) shows there is a commutative diagram

\[
\begin{array}{ccc}
\mathbb{Z}^\oplus n & \xrightarrow{(a_{ij}/w_i)} & \mathbb{Z}^\oplus n \\
\downarrow q & & \downarrow p \\
\mathbb{Z}^\oplus n' & \xrightarrow{(a'_{ij}/w'_i)} & \mathbb{Z}^\oplus n'
\end{array}
\]
In this section we assume given a numerical type $\text{Pic}(T')$. Since the cokernel of the top arrow is $\text{Pic}(T)$ and the cokernel of the bottom arrow is $\text{Pic}(T')$, we obtain the desired homomorphism of Picard groups. Since $\frac{w_i}{w_i'} \in \{1, 2\}$ we see that the cokernel of $\text{Pic}(T) \to \text{Pic}(T')$ is annihilated by 2 (because $2e'_i$ is in the image of $p$ for all $i \leq n - 1$). Finally, we show $\text{Pic}(T) \to \text{Pic}(T')$ is injective. Let $L = (l_1, \ldots, l_n)$ be a representative of an element of $\text{Pic}(T)$ mapping to zero in $\text{Pic}(T')$. Since $q$ is surjective, a diagram chase shows that we can assume $L$ is in the kernel of $p$. This means that $l_ia_{ni}/w'_i + l_iw_i/w'_i = 0$, i.e., $l_i = -a_{ni}/w_il_n$. Thus $L$ is the image of $-l_ne_n$ under the map $(a_{ij}/w_j)$ and the lemma is proved.

**Lemma 4.5.** Let $n, m_i, a_{ij}, w_i, g_i$ be a numerical type $T$. If the genus $g$ of $T$ is $\leq 0$, then $\text{Pic}(T) = \mathbb{Z}$.

**Proof.** By induction on $n$. If $n = 1$, then the assertion is clear. If $n > 1$, then $T$ is not minimal by Lemma 3.13. After replacing $T$ by an equivalent type we may assume $n$ is a $(−1)$-index. By Lemma 4.4 we find $\text{Pic}(T) \subset \text{Pic}(T')$. By Lemma 3.9 we see that the genus of $T'$ is equal to the genus of $T$ and we conclude by induction.

**5. Classification of proper subgraphs**

In this section we assume given a numerical type $n, m_i, a_{ij}, w_i, g_i$ of genus $g$. We will find a complete list of possible "subgraphs" consisting entirely of $(−2)$-indices (Definition 3.16) and at the same time we classify all possible minimal numerical types of genus 1. In other words, in this section we prove Proposition 6.17 and Lemma 6.2.

Our strategy will be as follows. Let $n, m_i, a_{ij}, w_i, g_i$ be a numerical type of genus $g$. Let $I \subset \{1, \ldots, n\}$ be a subset consisting of $(−2)$-indices such that there does not exist a nonempty proper subset $J \subset I$ with $a_{jj'} = 0$ for $j \in J$, $j' \in I \setminus J$. We work by induction on the cardinality $|I|$ of $I$. If $I = \{i\}$ consists of 1 index, then the only constraints on $m_i$, $a_{ii}$, and $w_i$ are $w_i|a_{ii}$ from Definition 3.1 and $a_{ii} < 0$ from Lemma 3.6 and this will serve as our base case. In the induction step we first apply the induction hypothesis to subsets $I' \subset I$ of size $|I'| < |I|$. This will put some constraints on the possible $m_i, a_{i j}, w_i, i, j \in I$. In particular, since $|I'| < |I| \leq n$ it will follow from $\sum a_{ij}m_j = 0$ and Lemma 2.3 that the sub matrices $\langle a_{ij} \rangle_{i, j \in I'}$ are negative definite and their determinant will have sign $(−1)^{m}$. For each possibility left over we compute the determinant of $\langle a_{ij} \rangle_{i, j \in I}$. If the determinant has sign $−(−1)^{|I|}$ then this case can be discarded because Sylvester’s theorem tells us the matrix $\langle a_{ij} \rangle_{i, j \in I}$ is not negative semi-definite. If the determinant has sign $(−1)^{|I|}$, then $|I| < n$ and we (tentatively) conclude this case can occur as a possible proper subgraph and we list it in one of the lemmas in this section. If the determinant is 0, then we must have $|I| = n$ (by Lemma 2.3 again) and $g = 0$. In these cases we actually find all possible $m_i, a_{ij}, w_i, i, j \in I$ and list them in Lemma 6.2. After completing the argument we obtain all possible minimal numerical types of genus 1 with $n > 1$ because each of these necessarily consists entirely of $(−2)$-indices (and hence will show up in the induction process) by the formula for the genus and the remarks in the previous section. At the very end of the day the reader can go through the list of possibilities given in Lemma 6.2 to see that all configurations of proper subgraphs listed in this section as possible do in fact occur already for numerical types of genus 1.
Suppose that \( i \) and \( j \) are \((-2)\)-indices with \( a_{ij} > 0 \). Since the matrix \( A = (a_{ij}) \) is semi-negative definite by Lemma 2.3 we see that the matrix
\[
\begin{pmatrix}
-2w_i & a_{ij} \\
a_{ij} & -2w_j
\end{pmatrix}
\]
is negative definite unless \( n = 2 \). The case \( n = 2 \) can happen: then the determinant \( 4w_1w_2 - a_{12}^2 \) is zero. Using that \( \text{lcm}(w_1, w_2) \) divides \( a_{12} \) the reader easily finds that the only possibilities are
\[
(w_1, w_2, a_{12}) = (w, w, 2w), (w, 4w, 4w), \text{ or } (4w, w, 4w)
\]
Observe that the case \((4w, w, 4w)\) is obtained from the case \((w, 4w, 4w)\) by switching the indices \( i, j \). In these cases \( g = 1 \). This leads to cases 6, 2, 3 of Lemma 6.2. Assuming \( n > 2 \) we see that the determinant \( 4w_1w_2 - a_{12}^2 \) of the displayed matrix is \( > 0 \) and we conclude that \( a_{ij}^2/w_1w_j < 4 \). On the other hand, we know that \( \text{lcm}(w_i, w_j)|a_{ij} \) and hence \( a_{ij}^2/w_1w_j \) is an integer. Thus \( a_{ij}^2/w_1w_j \in \{1, 2, 3\} \) and \( w_i/w_j \) or vice versa. This leads to the following possibilities
\[
(w_1, w_2, a_{12}) = (w, w, w), (w, 2w, 2w), (w, 3w, 3w), (2w, w, 2w), \text{ or } (3w, w, 3w)
\]
Observe that the case \((2w, w, 2w)\) is obtained from the case \((w, 2w, 2w)\) by switching the indices \( i, j \) and similarly for the cases \((3w, w, 3w)\) and \((w, 3w, 3w)\). The first three solutions lead to cases 6, 2, 3 of Lemma 5.1. In this lemma we wrote out the consequences for the integers \( m_i \) and \( m_j \) using that \( \sum a_{ik}m_i = 0 \) for each \( k \) in particular implies \( a_{ii}m_i + a_{ij}m_j \leq 0 \) for \( k = i \) and \( a_{ij}m_i + a_{jj}m_j \leq 0 \) for \( k = j \).

**Lemma 5.1.** Classification of proper subgraphs of the form

\[
\text{If } n > 2, \text{ then given a pair } i, j \text{ of } (-2)\text{-indices with } a_{ij} > 0, \text{ then up to ordering we have the } m\text{'s, } a\text{'s, } w\text{'s}
\]

\(0C7N\)  \(1\) are given by
\[
\begin{pmatrix} m_1 \\ m_2 \end{pmatrix}, \begin{pmatrix} -2w & w \\ w & -2w \end{pmatrix}, \begin{pmatrix} w \\ w \end{pmatrix}
\]
with \( w \) arbitrary and \( 2m_3 \geq m_2 \) and \( 2m_2 \geq m_1 \), or

\(0C7P\)  \(2\) are given by
\[
\begin{pmatrix} m_1 \\ m_2 \end{pmatrix}, \begin{pmatrix} -2w & 2w \\ 2w & -4w \end{pmatrix}, \begin{pmatrix} w \\ 2w \end{pmatrix}
\]
with \( w \) arbitrary and \( m_1 \geq m_2 \) and \( 2m_2 \geq m_1 \), or

\(0C7Q\)  \(3\) are given by
\[
\begin{pmatrix} m_1 \\ m_2 \end{pmatrix}, \begin{pmatrix} -2w & 3w \\ 3w & -6w \end{pmatrix}, \begin{pmatrix} w \\ 3w \end{pmatrix}
\]
with \( w \) arbitrary and \( 2m_1 \geq 3m_2 \) and \( 2m_2 \geq m_1 \).

**Proof.** See discussion above. \(\square\)

Suppose that \( i, j, \) and \( k \) are three \((-2)\)-indices with \( a_{ij} > 0 \) and \( a_{jk} > 0 \). In other words, the index \( i \) “meets” \( j \) and \( j \) “meets” \( k \). We will use without further mention
Classification of proper subgraphs of the form $0C7R$

A possibility is the set of integers. Using the restrictions on the numbers given above we see that the only possibilities are

$$\begin{pmatrix} -2w_i & a_{ij} & a_{ik} \\ a_{ij} & -2w_j & a_{jk} \\ a_{ik} & a_{jk} & -2w_k \end{pmatrix}$$

is negative definite unless $n = 3$. The case $n = 3$ can happen: then the determinant of the matrix is zero and we obtain the equation

$$4 = \frac{a_{ij}^2}{w_i w_j} + \frac{a_{jk}^2}{w_j w_k} + \frac{a_{ik}^2}{w_i w_k} + a_{ij} a_{ik} a_{jk}$$

of integers. The last term on the right in this equation is determined by the others because

$$\left( \frac{a_{ij} a_{ik} a_{jk}}{w_i w_j w_k} \right)^2 = \frac{a_{ij}^2}{w_i w_j} \frac{a_{jk}^2}{w_j w_k} \frac{a_{ik}^2}{w_i w_k}$$

Since we have seen above that $\frac{a_{ij}^2}{w_i w_j}, \frac{a_{jk}^2}{w_j w_k}, \frac{a_{ik}^2}{w_i w_k}$ are in $\{1, 2, 3\}$ and $\frac{a_{ij}^2}{w_i w_j}$ in $\{0, 1, 2, 3\}$, we conclude that the only possibilities are

$$\left( \frac{a_{ij}^2}{w_i w_j}, \frac{a_{jk}^2}{w_j w_k}, \frac{a_{ik}^2}{w_i w_k} \right) = (1, 1, 1), (1, 3, 0), (2, 2, 0), \text{ or } (3, 1, 0)$$

Observe that the case $(3, 1, 0)$ is obtained from the case $(1, 3, 0)$ by reversing the order of the indices $i, j, k$. In each of these cases $g = 1$; the reader can find these as cases $(4), (5), (6), (7), (8), (9)$ of Lemma 6.2 with one case corresponding to $(1, 1, 1)$, two cases corresponding to $(1, 3, 0)$, and three cases corresponding to $(2, 2, 0)$. Assuming $n > 3$ we obtain the inequality

$$4 > \frac{a_{ij}^2}{w_i w_j} + \frac{a_{jk}^2}{w_j w_k} + \frac{a_{ik}^2}{w_i w_k} + a_{ij} a_{ik} a_{jk}$$

of integers. Using the restrictions on the numbers given above we see that the only possibilities are

$$\left( \frac{a_{ij}^2}{w_i w_j}, \frac{a_{jk}^2}{w_j w_k}, \frac{a_{ik}^2}{w_i w_k} \right) = (1, 1, 0), (1, 2, 0), \text{ or } (2, 1, 0)$$

in particular $a_{ik} = 0$ (recall we are assuming $a_{ij} > 0$ and $a_{jk} > 0$). Observe that the case $(2, 1, 0)$ is obtained from the case $(1, 2, 0)$ by reversing the ordering of the indices $i, j, k$. The first two solutions lead to cases $(1), (2)$, and $(3)$ of Lemma 5.2 where we also wrote out the consequences for the integers $m_i, m_j, \text{ and } m_k$. 

**Lemma 5.2.** Classification of proper subgraphs of the form

If $n > 3$, then given a triple $i, j, k$ of $(-2)$-indices with at least two $a_{ij}, a_{ik}, a_{jk}$ nonzero, then up to ordering we have the $m$'s, $a$'s, $w$'s

**0C7S**

1. are given by

$$\begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}, \begin{pmatrix} -2w & w & 0 \\ w & -2w & w \\ 0 & w & -2w \end{pmatrix}, \begin{pmatrix} w \\ w \end{pmatrix}$$

2. It is $-8w_i w_j w_k + 2a_{ij}^2 w_k + 2a_{jk}^2 w_i + 2a_{ik}^2 w_j + 2a_{ij} a_{ik} a_{jk}$. 

---
we conclude that the only possible solutions are given by

\[
\begin{pmatrix}
1 & -2w & w & 0 \\
2 & w & -2w & 2w \\
3 & 0 & 2w & -4w \\
4 & w & 2w & -2w
\end{pmatrix}
\]

with \(2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2\), or

\[
\begin{pmatrix}
1 & -4w & 2w & 0 \\
2 & 2w & -4w & 2w \\
3 & 0 & 2w & -2w \\
4 & 2w & 2w & -2w
\end{pmatrix}
\]

with \(2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2\), or

\[
\begin{pmatrix}
1 & -4w & 2w & 0 \\
2 & 2w & -4w & 2w \\
3 & 0 & 2w & -2w \\
4 & 2w & 2w & -2w
\end{pmatrix}
\]

with \(2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, m_3 \geq m_2\).

**Proof.** See discussion above. \(\square\)

Suppose that \(i, j, k, l\) are four \((-2)\)-indices with \(a_{ij} > 0, a_{jk} > 0, a_{kl} > 0\).
In other words, the index \(i\) "meets" \(j\), \(j\) "meets" \(k\), and \(k\) "meets" \(l\). Then we see from Lemma 5.2 that \(a_{ik} = a_{jl} = 0\). Since the matrix \(A = (a_{ij})\) is semi-negative definite we see that the matrix

\[
\begin{pmatrix}
-2w_i & a_{ij} & 0 & a_{il} \\
a_{ij} & -2w_j & a_{jk} & 0 \\
0 & a_{jk} & -2w_k & a_{kl} \\
a_{il} & 0 & a_{kl} & -2w_l
\end{pmatrix}
\]

is negative definite unless \(n = 4\). The case \(n = 4\) can happen: then the determinant of the matrix is zero and we obtain the equation

\[
16 + \frac{a_{ij}^2}{w_i w_j w_k w_l} + \frac{a_{jk}^2}{w_j w_k w_l} + \frac{a_{kl}^2}{w_k w_l} = 4 \frac{a_{ij}^2}{w_i w_j} + 4 \frac{a_{jk}^2}{w_j w_k} + 4 \frac{a_{kl}^2}{w_k w_l} + 4 \frac{a_{il}^2}{w_i w_l} + 2 \frac{a_{ij} a_{il} a_{jk} a_{kl}}{w_i w_j w_k w_l}
\]

of nonnegative integers. The last term on the right in this equation is determined by the others because

\[
\left( \frac{a_{ij} a_{il} a_{jk} a_{kl}}{w_i w_j w_k w_l} \right)^2 = \frac{a_{ij}^2}{w_i w_j} \frac{a_{jk}^2}{w_j w_k} \frac{a_{kl}^2}{w_k w_l}
\]

Since we have seen above that \(\frac{a_{ij}^2}{w_i w_j}, \frac{a_{jk}^2}{w_j w_k}, \frac{a_{kl}^2}{w_k w_l}\) are in \(\{1, 2\}\) and \(\frac{a_{ij}^2}{w_i w_j}\) in \(\{0, 1, 2\}\), we conclude that the only possible solutions are

\[
\left( \frac{a_{ij}^2}{w_i w_j}, \frac{a_{jk}^2}{w_j w_k}, \frac{a_{kl}^2}{w_k w_l} \right) = (1, 1, 1, 1) \text{ or } (2, 1, 2, 0)
\]

and case \(g = 1\); the reader can find these as cases \(10, 11, 12,\) and \(13\) of Lemma 5.2. Assuming \(n > 4\) we obtain the inequality

\[
16 + \frac{a_{ij}^2}{w_i w_j w_k w_l} + \frac{a_{jk}^2}{w_j w_k w_l} + \frac{a_{kl}^2}{w_k w_l} > 4 \frac{a_{ij}^2}{w_i w_j} + 4 \frac{a_{jk}^2}{w_j w_k} + 4 \frac{a_{kl}^2}{w_k w_l} + 4 \frac{a_{il}^2}{w_i w_l} + 2 \frac{a_{ij} a_{il} a_{jk} a_{kl}}{w_i w_j w_k w_l}
\]

\[\text{It is } 16w_i w_j w_k w_l - 4a_{ij}^2 w_k w_l - 4a_{jk}^2 w_j w_l - 4a_{kl}^2 w_k w_l - 4a_{il}^2 w_i w_l + a_{ij}^2 a_{kl}^2 + a_{jk}^2 a_{il}^2 - 2a_{ij} a_{il} a_{jk} a_{kl}.\]
of nonnegative integers. Using the restrictions on the numbers given above we see that the only possibilities are

\[
\begin{pmatrix}
     a_{ij}^2 \\
     w_i w_j \\
     w_j w_k
\end{pmatrix},
\begin{pmatrix}
     a_{jk}^2 \\
     w_j w_k \\
     w_k w_l
\end{pmatrix},
\begin{pmatrix}
     a_{kl}^2 \\
     w_k w_l \\
     w_l w_i
\end{pmatrix},
\begin{pmatrix}
     a_{il}^2 \\
     w_l w_i \\
     w_i w_j
\end{pmatrix} = (1, 1, 1, 0), (1, 1, 2, 0), (1, 2, 1, 0), \text{ or } (2, 1, 1, 0)
\]

in particular \(a_{il} = 0\) (recall that we assumed the other three to be nonzero). Observe that the case \((2,1,1,0)\) is obtained from the case \((1,1,2,0)\) by reversing the ordering of the indices \(i, j, k, l\). The first three solutions lead to cases \([1], [2], [3]\), and \([4]\) of Lemma 5.3 where we also wrote out the consequences for the integers \(m_i, m_j, m_k,\) and \(m_l\).

**Lemma 5.3.** Classification of proper subgraphs of the form

\[
\begin{array}{c}
\mathbf{\bullet} \\
\mathbf{\bullet} \\
\mathbf{\bullet} \\
\mathbf{\bullet}
\end{array}
\]

If \(n > 4\), then given four \((-2)\)-indices \(i, j, k, l\) with \(a_{ij}, a_{jk}, a_{kl}\) nonzero, then up to ordering we have the \(m\)'s, \(a\)'s, \(w\)'s

<table>
<thead>
<tr>
<th>Case</th>
<th>Constraints</th>
<th>Matrix Form</th>
</tr>
</thead>
</table>
| 1    | \(2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4, \text{ and } 2m_4 \geq m_3\) | \[
\begin{pmatrix}
     m_1 \\
     m_2 \\
     m_3 \\
     m_4
\end{pmatrix},
\begin{pmatrix}
     -2w & w & 0 & 0 \\
     w & -2w & w & 0 \\
     0 & w & -2w & w \\
     0 & 0 & w & -2w
\end{pmatrix},
\begin{pmatrix}
     w \\
     w \\
     w \\
     w
\end{pmatrix}
\] |
| 2    | \(2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4, \text{ and } 2m_4 \geq m_3\) | \[
\begin{pmatrix}
     m_1 \\
     m_2 \\
     m_3 \\
     m_4
\end{pmatrix},
\begin{pmatrix}
     -2w & w & 0 & 0 \\
     w & -2w & w & 0 \\
     0 & w & -2w & 2w \\
     0 & 0 & 2w & -4w
\end{pmatrix},
\begin{pmatrix}
     w \\
     w \\
     w \\
     2w
\end{pmatrix}
\] |
| 3    | \(2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4, \text{ and } 2m_4 \geq m_3\) | \[
\begin{pmatrix}
     m_1 \\
     m_2 \\
     m_3 \\
     m_4
\end{pmatrix},
\begin{pmatrix}
     -4w & 2w & 0 & 0 \\
     2w & -4w & 2w & 0 \\
     0 & 2w & -4w & 2w \\
     0 & 0 & 2w & -2w
\end{pmatrix},
\begin{pmatrix}
     2w \\
     2w \\
     2w \\
     w
\end{pmatrix}
\] |
| 4    | \(2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4, \text{ and } m_4 \geq m_3\) | \[
\begin{pmatrix}
     m_1 \\
     m_2 \\
     m_3 \\
     m_4
\end{pmatrix},
\begin{pmatrix}
     -2w & w & 0 & 0 \\
     w & -2w & 2w & 0 \\
     0 & 2w & -4w & 2w \\
     0 & 0 & 2w & -4w
\end{pmatrix},
\begin{pmatrix}
     w \\
     w \\
     2w \\
     2w
\end{pmatrix}
\] |

**Proof.** See discussion above.

Suppose that \(i, j, k,\) and \(l\) are four \((-2)\)-indices with \(a_{ij} > 0, a_{ij} > 0,\) and \(a_{ij} > 0\). In other words, the index \(i\) “meets” the indices \(j, k, l\). Then we see from Lemma
Lemma 5.2. Assuming $a_{jl} = a_{kl} = 0$. Since the matrix $A = (a_{ij})$ is semi-negative definite we see that the matrix

$$
egin{pmatrix}
-2w_i & a_{ij} & a_{ik} & a_{il} \\
a_{ij} & -2w_j & 0 & 0 \\
a_{ik} & 0 & -2w_k & 0 \\
a_{il} & 0 & 0 & -2w_l
\end{pmatrix}
$$

is negative definite unless $n = 4$. The case $n = 4$ can happen: then the determinant of the matrix is zero and we obtain the equation

$$4 = \frac{a_{ij}^2}{w_iw_j} + \frac{a_{ik}^2}{w_iw_k} + \frac{a_{il}^2}{w_jw_l}
$$

of nonnegative integers. Since we have seen above that $\frac{a_{ij}^2}{w_iw_j}, \frac{a_{ik}^2}{w_iw_k}, \frac{a_{il}^2}{w_jw_l}$ are in \{1, 2\}, we conclude that the only possibilities are up to reordering: $4 = 1 + 1 + 2$. In each of these cases $g = 1$; the reader can find these as cases (14) and (15) of Lemma 5.4. Assuming $n > 4$ we obtain the inequality

$$4 > \frac{a_{ij}^2}{w_iw_j} + \frac{a_{ik}^2}{w_iw_k} + \frac{a_{il}^2}{w_jw_l}
$$

of nonnegative integers. This implies that $\frac{a_{ij}^2}{w_iw_j} = \frac{a_{ik}^2}{w_iw_k} = \frac{a_{il}^2}{w_jw_l} = 1$ and that $w_i = w_j = w_k = w_l$. This leads to case (1) of Lemma 5.4 where we also wrote out the consequences for the integers $m_i, m_j, m_k, m_l$.

**Lemma 5.4.** Classification of proper subgraphs of the form

$$
\bullet \quad \bullet \quad \bullet \quad \bullet
$$

If $n > 4$, then given four $(-2)$-indices $i, j, k, l$ with $a_{ij}, a_{ik}, a_{il}$ nonzero, then up to ordering we have the $m$'s, $a$'s, $w$'s

(1) are given by

$$
(\begin{array}{c}
m_1 \\
m_2 \\
m_3 \\
m_4
\end{array}) =
(\begin{array}{cccc}
-2w & w & w & w \\
w & -2w & 0 & 0 \\
w & 0 & -2w & 0 \\
w & 0 & 0 & -2w
\end{array})
\begin{pmatrix}
w \\
w
\end{pmatrix}
$$

with $2m_1 \geq m_2 + m_3 + m_4, 2m_2 \geq m_1, 2m_3 \geq m_1, 2m_4 \geq m_1$. Observe that this implies $m_1 \geq \max(m_2, m_3, m_4)$.

**Proof.** See discussion above.

Suppose that $h, i, j, k, l$ are five $(-2)$-indices with $a_{hi} > 0, a_{ij} > 0, a_{jk} > 0,$ and $a_{kl} > 0.$ In other words, the index $h$ “meets” $i$, $i$ “meets” $j$, $j$ “meets” $k$, and $k$ “meets” $l$. Then we can apply Lemmas 5.2 and 5.3 to see that $a_{hj} = a_{hk} = a_{ik} = a_{il} = a_{jl} = 0$ and that the fractions $\frac{a_{ij}}{w_iw_j}, \frac{a_{ik}}{w_iw_k}, \frac{a_{ij}}{w_jw_k}, \frac{a_{il}}{w_jw_l}$ are in \{1, 2\} and the

$\text{It is } 16w_iw_jw_kw_l - 4a_{ij}^2w_kw_j - 4a_{ik}^2w_jw_k - 4a_{il}^2w_jw_l - 4a_{jl}^2w_jw_l.$
fraction \( \frac{a^2_{hi}}{w_kw_l} \in \{0, 1, 2\} \). Since the matrix \( A = (a_{ij}) \) is semi-negative definite we see that the matrix

\[
\begin{pmatrix}
-2w_h & a_{hi} & 0 & 0 & a_{hl} \\
a_{hi} & -2w_i & a_{ij} & 0 & 0 \\
0 & a_{ij} & -2w_j & a_{jk} & 0 \\
0 & 0 & a_{jk} & -2w_k & a_{kl} \\
a_{hl} & 0 & 0 & a_{kl} & -2w_l
\end{pmatrix}
\]

is negative definite unless \( n = 5 \). The case \( n = 5 \) can happen: then the determinant of the matrix is zero and we obtain the equation

\[
16 + \frac{a^2_{hi}}{w_hw_i w_j w_k} + \frac{a^2_{ij}}{w_i w_j w_k w_l} + \frac{a^2_{ij}}{w_i w_j w_k w_l} + \frac{a^2_{hl}}{w_h w_i w_j w_l} + \frac{a^2_{jk}}{w_h w_i w_j w_k} = 4 \frac{a^2_{hi}}{w_hw_i} + 4 \frac{a^2_{ij}}{w_i w_j} + 4 \frac{a^2_{jk}}{w_h w_i} + 4 \frac{a^2_{hl}}{w_h w_i} + \frac{a_{hi}a_{ij}a_{jk}a_{kl}a_{hl}}{w_h w_i w_j w_k w_l}
\]

of nonnegative integers. The last term on the right in this equation is determined by the others because

\[
\left( \frac{a_{hi}a_{ij}a_{jk}a_{kl}a_{hl}}{w_h w_i w_j w_k w_l} \right)^2 = \frac{a^2_{hi}}{w_hw_i} \frac{a^2_{ij}}{w_i w_j} \frac{a^2_{jk}}{w_h w_i} \frac{a^2_{hl}}{w_h w_i}
\]

We conclude the only possible solutions are

\[
(\frac{a^2_{hi}}{w_kw_l}, \frac{a^2_{ij}}{w_j w_l}, \frac{a^2_{hk}}{w_j w_l}, \frac{a^2_{kl}}{w_h w_i}) = (1, 1, 1, 1, 1), (1, 1, 2, 1, 0), (1, 1, 2, 1, 0), \text{ or } (2, 1, 1, 2, 0)
\]

Observe that the case \( (1, 2, 1, 1, 0) \) is obtained from the case \( (1, 1, 2, 1, 0) \) by reversing the order of the indices \( h, i, j, k, l \). In these cases \( g = 1 \); the reader can find these as cases \( (16), (17), (18), (19), \text{ and } (21) \) of Lemma 6.2 with one case corresponding to \( (1, 1, 1, 1, 1) \), two cases corresponding to \( (1, 1, 2, 1, 0) \), and three cases corresponding to \( (2, 1, 1, 2, 0) \). Assuming \( n > 5 \) we obtain the inequality

\[
16 + \frac{a^2_{hi}}{w_hw_i w_j w_k} + \frac{a^2_{ij}}{w_i w_j w_k w_l} + \frac{a^2_{ij}}{w_i w_j w_k w_l} + \frac{a^2_{hl}}{w_h w_i w_j w_l} + \frac{a^2_{jk}}{w_h w_i w_j w_k} > 4 \frac{a^2_{hi}}{w_hw_i} + 4 \frac{a^2_{ij}}{w_i w_j} + 4 \frac{a^2_{ij}}{w_i w_j} + 4 \frac{a^2_{hl}}{w_h w_i} + \frac{a_{hi}a_{ij}a_{jk}a_{kl}a_{hl}}{w_h w_i w_j w_k w_l}
\]

of nonnegative integers. Using the restrictions on the numbers given above we see that the only possibilities are

\[
(\frac{a^2_{hi}}{w_h w_i}, \frac{a^2_{ij}}{w_i w_j}, \frac{a^2_{jk}}{w_j w_k}, \frac{a^2_{kl}}{w_h w_i}) = (1, 1, 1, 1, 0), (1, 1, 1, 2, 0), \text{ or } (2, 1, 1, 1, 0)
\]

in particular \( a_{hl} = 0 \) (recall that we assumed the other four to be nonzero). Observe that the case \( (1, 1, 1, 2, 0) \) is obtained from the case \( (2, 1, 1, 1, 0) \) by reversing the order of the indices \( h, i, j, k, l \). The first two solutions lead to cases \( (1), (2) \text{, and } (3) \) of Lemma 5.3 where we also wrote out the consequences for the integers \( m_h, m_i, m_j, m_k, \text{ and } m_l. \)

\[\text{It is } -32a_{hi}a_{ij}a_{jk}a_{kl}a_{hl} + 8a_{hi}^2w_jw_kw_l + 8a_{ij}^2w_iw_kw_l + 8a_{jk}^2w_hw_iw_l + 8a_{kl}^2w_hw_kw_l + 8a_{hi}^2w_jw_kw_l - 2a_{hi}a_{ij}a_{jk}a_{kl}w_h - 2a_{hi}a_{ij}a_{jk}a_{kl}w_k - 2a_{hi}a_{ij}a_{jk}a_{kl}w_l.
\]
Lemma 5.5. Classification of proper subgraphs of the form

If \( n > 5 \), then given five \((-2\)-indices \( h, i, j, k, l \) with \( a_{hi}, a_{ij}, a_{jk}, a_{kl} \) nonzero, then up to ordering we have the \( m \)'s, \( a \)'s, \( w \)'s

(1) are given by

\[
\begin{pmatrix}
  m_1 \\
  m_2 \\
  m_3 \\
  m_4 \\
  m_5
\end{pmatrix}, \quad
\begin{pmatrix}
  -2w & w & 0 & 0 & 0 \\
  w & -2w & w & 0 & 0 \\
  0 & w & -2w & w & 0 \\
  0 & 0 & w & -2w & w \\
  0 & 0 & 0 & w & -2w
\end{pmatrix}, \quad
\begin{pmatrix}
  w \\
  w \\
  w \\
  w \\
  w
\end{pmatrix}
\]

with \( 2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4, 2m_4 \geq m_3 + m_5, \) and \( 2m_5 \geq m_4 \), or

(2) are given by

\[
\begin{pmatrix}
  m_1 \\
  m_2 \\
  m_3 \\
  m_4 \\
  m_5
\end{pmatrix}, \quad
\begin{pmatrix}
  -2w & w & 0 & 0 & 0 \\
  w & -2w & w & 0 & 0 \\
  0 & w & -2w & w & 0 \\
  0 & 0 & w & -2w & 2w \\
  0 & 0 & 0 & 2w & -4w
\end{pmatrix}, \quad
\begin{pmatrix}
  w \\
  w \\
  w \\
  w \\
  2w
\end{pmatrix}
\]

with \( 2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4, 2m_4 \geq m_3 + m_5, \) and \( 2m_5 \geq m_4 \), or

(3) are given by

\[
\begin{pmatrix}
  m_1 \\
  m_2 \\
  m_3 \\
  m_4 \\
  m_5
\end{pmatrix}, \quad
\begin{pmatrix}
  -4w & 2w & 0 & 0 & 0 \\
  2w & -4w & 2w & 0 & 0 \\
  0 & 2w & -4w & 2w & 0 \\
  0 & 0 & 2w & -4w & 2w \\
  0 & 0 & 0 & 2w & -2w
\end{pmatrix}, \quad
\begin{pmatrix}
  2w \\
  2w \\
  2w \\
  2w \\
  w
\end{pmatrix}
\]

with \( 2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4, 2m_4 \geq m_3 + m_5, \) and \( m_4 \geq m_3 \).

Proof. See discussion above.

Suppose that \( h, i, j, k, \) and \( l \) are five \((-2\)-indices with \( a_{hi} > 0, a_{ij} > 0, a_{hk} > 0, \) and \( a_{hl} > 0 \). In other words, the index \( h \) "meets" the indices \( i, j, k, l \). Then we see from Lemma 5.2 that \( a_{ij} = a_{ik} = a_{il} = a_{jk} = a_{jl} = a_{kl} = 0 \) and by Lemma 6.4 that \( w_h = w_i = w_j = w_k = w_l = w \) for some integer \( w > 0 \) and \( a_{hi} = a_{hk} = a_{hl} = -2w \). The corresponding matrix

\[
\begin{pmatrix}
  -2w & w & w & w \\
  w & -2w & 0 & 0 \\
  w & 0 & -2w & 0 \\
  w & 0 & 0 & -2w \\
  w & 0 & 0 & 0 & -2w
\end{pmatrix}
\]

is singular. Hence this can only happen if \( n = 5 \) and \( g = 1 \). The reader can find this as case (22) Lemma 6.2.
\textbf{Lemma 5.6.} Nonexistence of proper subgraphs of the form

\includegraphics[width=0.2\textwidth]{graph.png}

If \( n > 5 \), there do not exist five \((-2)\)-indices \( h, i, j, k \) with \( a_{hi} > 0 \), \( a_{hj} > 0 \), \( a_{hk} > 0 \), and \( a_{hi} > 0 \).

\textbf{Proof.} See discussion above. \( \square \)

Suppose that \( h, i, j, k, \) and \( l \) are five \((-2)\)-indices with \( a_{hi} > 0 \), \( a_{ij} > 0 \), \( a_{jk} > 0 \), and \( a_{jl} > 0 \). In other words, the index \( h \) “meets” \( i \) and the index \( j \) “meets” the indices \( i, k, l \). Then we see from Lemma 5.3 that \( a_{ik} = a_{il} = a_{kl} = 0 \), \( w_i = w_j = w_k = w_i = w \), and \( a_{ij} = a_{jk} = a_{jl} = w \) for some integer \( w \). Applying Lemma 5.3 to the four tuples \( h, i, j, k \) and \( h, i, j, l \) we see that \( a_{hi} = a_{hk} = a_{hl} = 0 \), that \( w_h = w_i = w \), \( w_j = 2w \), and that correspondingly \( a_{hi} = w, w, \) or \( 2w \). Since \( A \) is semi-negative definite we see that the matrix

\[
\begin{pmatrix}
-2w_h & a_{hi} & 0 & 0 & 0 \\
a_{hi} & -2w & w & 0 & 0 \\
0 & w & -2w & w & w \\
0 & 0 & w & -2w & 0 \\
0 & 0 & w & 0 & -2w
\end{pmatrix}
\]

is negative definite unless \( n = 5 \). The reader computes that the determinant of the matrix is \( 0 \) when \( w_h = \frac{1}{2}w \) or \( 2w \). This leads to cases \([23]\) and \([24]\) of Lemma 6.2. For \( w_h = w \) we obtain case \([1]\) of Lemma 5.7.

\textbf{Lemma 5.7.} Classification of proper subgraphs of the form

\includegraphics[width=0.2\textwidth]{graph.png}

If \( n > 5 \), then given five \((-2)\)-indices \( h, i, j, k, l \) with \( a_{hi}, a_{ij}, a_{jk}, a_{jl} \) nonzero, then up to ordering we have the \( m \)'s, \( a \)'s, \( w \)'s

\begin{align*}
(1) & \text{ are given by} \\
\begin{pmatrix}
m_1 \\
m_2 \\
m_3 \\
m_4 \\
m_5
\end{pmatrix}, & \begin{pmatrix}
-2w & w & 0 & 0 & 0 \\
w & -2w & w & 0 & 0 \\
0 & w & -2w & w & w \\
0 & 0 & w & -2w & 0 \\
0 & 0 & w & 0 & -2w
\end{pmatrix}, & \begin{pmatrix}
w \\
w \\
w \\
w \\
w
\end{pmatrix}
\end{align*}

with \( 2m_1 \geq m_2 \), \( 2m_2 \geq m_1 + m_3 \), \( 2m_3 \geq m_2 + m_4 + m_5 \), \( 2m_4 \geq m_3 \), and \( 2m_5 \geq m_3 \).

\textbf{Proof.} See discussion above. \( \square \)

Suppose that \( t > 5 \) and \( i_1, \ldots, i_t \) are \( t \) distinct \((-2)\)-indices such that \( a_{i_ji_{j+1}} \) is nonzero for \( j = 1, \ldots, t - 1 \). We will prove by induction on \( t \) that if \( n = t \) this leads to possibilities \([25]\), \([26]\), \([27]\), \([28]\) of Lemma \(6.2\), and if \( n > t \) to cases \([1]\), \([2]\), and \([3]\) of Lemma \(5.8\). First, if \( a_{i_1i_t} \) is nonzero, then it is clear from the result of Lemma \(5.3\) that \( w_{i_1} = \ldots = w_{i_t} = w \) and that \( a_{i_ji_{j+1}} = w \) for \( j = 1, \ldots, t - 1 \).
and $a_{i_1i_2} = w$. Then the vector $(1, \ldots, 1)$ is in the kernel of the corresponding $t \times t$ matrix. Thus we must have $n = t$ and we see that the genus is 1 and that we are in case \[25\] of Lemma \[6.2\]. Thus we may assume $a_{i_1i_2} = 0$. By induction hypothesis (or Lemma \[5.5\] if $t = 6$) we see that $a_{i_ji_k} = 0$ if $k > j + 1$. Moreover, we have $w_{i_1} = \ldots = w_{i_{t-1}} = w$ for some integer $w$ and $w_{i_1}, w_{i_r} \in \{\frac{1}{2}w, w, 2w\}$. Moreover, the value of $w_{i_1}$, resp. $w_{i_r}$, being $\frac{1}{2}w$, $w$, or $2w$ implies that the value of $a_{i_1i_2}$, resp. $a_{i_{t-1}i_t}$, is $w$, $w$, or $2w$. This gives 9 possibilities. In each case it is easy to decide what happens:

1. If $(w_{i_1}, w_{i_1}) = (\frac{1}{2}w, \frac{1}{2}w)$, then we are in case \[27\] of Lemma \[6.2\].
2. If $(w_{i_1}, w_{i_1}) = (\frac{1}{2}w, w)$ or $(w_{i_1}, \frac{1}{2}w)$ then we are in case \[28\] of Lemma \[5.8\].
3. If $(w_{i_1}, w_{i_1}) = (\frac{1}{2}w, 2w)$ or $(2w, \frac{1}{2}w)$ then we are in case \[26\] of Lemma \[6.2\].
4. If $(w_{i_1}, w_{i_1}) = (w, w)$ then we are in case \[1\] of Lemma \[5.8\].
5. If $(w_{i_1}, w_{i_1}) = (w, 2w)$ or $(2w, w)$ then we are in case \[2\] of Lemma \[5.8\].
6. If $(w_{i_1}, w_{i_1}) = (2w, 2w)$ then we are in case \[28\] of Lemma \[6.2\].

---

**Lemma 5.8.** Classification of proper subgraphs of the form $0C^8D$ and $w$ is nonzero for $t > 1$.

**Proof.** Let $t > 5$ and $n > t$. Then given $t$ distinct $(-2)$-indices $i_1, \ldots, i_t$ such that $a_{i_ji_{j+1}}$ is nonzero for $j = 1, \ldots, t - 1$, then up to reversing the order of these indices we have the $a$'s and $w$'s

0CSA (1) are given by $w_{i_1} = w_{i_2} = \ldots = w_{i_t} = w$, $a_{i_ji_{j+1}} = w$, and $a_{i_ji_k} = 0$ if $k > j + 1$, or

0CSB (2) are given by $w_{i_1} = w_{i_2} = \ldots = w_{i_{t-1}} = w$, $w_{i_t} = 2w$, $a_{i_ji_{j+1}} = w$ for $j < t - 1$, $a_{i_{t-1}i_t} = 2w$, and $a_{i_ji_k} = 0$ if $k > j + 1$, or

0CSC (3) are given by $w_{i_1} = w_{i_2} = \ldots = w_{i_{t-1}} = 2w$, $w_{i_t} = w$, $a_{i_ji_{j+1}} = 2w$, and $a_{i_ji_k} = 0$ if $k > j + 1$.

**Proof.** See discussion above.

Suppose that $t > 4$ and $i_1, \ldots, i_{t+1}$ are $t+1$ distinct $(-2)$-indices such that $a_{i_ji_{j+1}} > 0$ for $j = 1, \ldots, t - 1$ and such that $a_{i_{t-1}i_t} > 0$. See picture in Lemma \[5.9\]. We will prove by induction on $t$ that if $n = t + 1$ this leads to possibilities \[29\] and \[30\] of Lemma \[6.2\] and if $n > t + 1$ to case \[1\] of Lemma \[5.9\]. By induction hypothesis (or Lemma \[5.7\] in case $t = 5$) we see that $a_{i_ji_k}$ is zero outside of the required nonvanishing ones for $j, k \geq 2$. Moreover, we see that $w_2 = \ldots = w_{t+1} = w$ for some integer $w$ and that the nonvanishing $a_{i_ji_k}$ for $j, k \geq 2$ are equal to $w$. Applying Lemma \[5.8\] (or Lemma \[5.5\] if $t = 5$) to the sequence $i_1, \ldots, i_t$ and to the sequence $i_1, \ldots, i_{t-1}, i_{t+1}$ we conclude that $a_{i_ji_k} = 0$ for $j \geq 3$ and that $w_1$ is equal to $\frac{1}{2}w$, $w$, or $2w$ and that correspondingly $a_{i_1i_2}$ is $w$, $w$, $2w$. This gives 3 possibilities. In each case it is easy to decide what happens:

1. If $w_1 = \frac{1}{2}w$, then we are in case \[30\] of Lemma \[6.2\].
2. If $w_1 = w$, then we are in case \[1\] of Lemma \[5.9\].
3. If $w_1 = 2w$, then we are in case \[29\] of Lemma \[6.2\].

---

**Lemma 5.9.** Classification of proper subgraphs of the form $0C^8D$ and $w$ is nonzero for $t > 1$. 

**Proof.** See discussion above.
Let $t > 4$ and $n > t + 1$. Then given $t + 1$ distinct $(-2)$-indices $i_1, \ldots, i_{t+1}$ such that $a_{i_ji_{j+1}}$ is nonzero for $j = 1, \ldots, t-1$ and $a_{i_{t-1}i_{t+1}}$ is nonzero, then we have the a’s and w’s

\[ a_{i_{t-1}i_{t+1}} = w \text{ and } a_{i_ik} = 0 \text{ for other pairs } (j,k) \text{ with } j > k. \]

**Proof.** See discussion above.

Suppose we are given 6 distinct $(-2)$-indices $g, h, i, j, k, l$ such that $a_{gh}, a_{hi}, a_{ij}, a_{jk}, a_{kl}$ are nonzero. See picture in Lemma 5.10. Then we can apply Lemma 5.7 to see that we must be in the situation of Lemma 5.10. Since the determinant is $3w^6 > 0$ we conclude that in this case it never happens that $n = 6$!

\[ \square \]

**Lemma 5.10.** Classification of proper subgraphs of the form

\[ \bullet \bullet \bullet \bullet \bullet \bullet \]

Let $n > 6$. Then given 6 distinct $(-2)$-indices $i_1, \ldots, i_6$ such that $a_{i_1i_2}, a_{i_3i_4}, a_{i_5i_6}$ are nonzero, then we have the m’s, a’s, and w’s

\[ (1) \text{ are given by} \]

\[
\begin{pmatrix}
  m_1 \\
m_2 \\
m_3 \\
m_4 \\
m_5 \\
m_6 \\
\end{pmatrix} =
\begin{pmatrix}
  -2w & w & 0 & 0 & 0 & 0 \\
w & -2w & w & 0 & 0 & 0 \\
0 & w & -2w & w & 0 & w \\
0 & 0 & w & -2w & w & 0 \\
0 & 0 & 0 & w & -2w & 0 \\
0 & 0 & 0 & w & 0 & -2w \\
\end{pmatrix} =
\begin{pmatrix}
w \\
w \\
w \\
w \\
w \\
w \\
\end{pmatrix}
\]

with $2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4 + m_6, 2m_4 \geq m_3 + m_5, 2m_5 \geq m_3, \text{ and } 2m_6 \geq m_3$.

**Proof.** See discussion above.

Suppose that $t \geq 4$ and $i_0, \ldots, i_{t+1}$ are $t+2$ distinct $(-2)$-indices such that $a_{i_0i_{t+1}} > 0$ for $j = 1, \ldots, t-1$ and $a_{i_{t-1}i_{t+1}} > 0$. See picture in Lemma 5.11. Then we can apply Lemmas 5.7 and 5.9 to see that all other $a_{i_{ij}}$ for $j < k$ are zero and that $w_{i_0i_{t+1}} = \ldots = w_{i_{t-1}i_{t+1}} = w$ for some integer $w$ and that the required nonzero off diagonal entries of $A$ are equal to $w$. A computation shows that the determinant of the corresponding matrix is zero. Hence $n = t + 2$ and we are in case (3) of Lemma 6.2.

\[ \square \]

**Lemma 5.11.** Nonexistence of proper subgraphs of the form

\[ \bullet \bullet \bullet \bullet \bullet \bullet \]

Assume $t \geq 4$ and $n > t + 2$. There do not exist $t + 2$ distinct $(-2)$-indices $i_0, \ldots, i_{t+1}$ such that $a_{i_ji_{j+1}} > 0$ for $j = 1, \ldots, t - 1$ and $a_{i_0i_2} > 0$ and $a_{i_{t-1}i_{t+1}} > 0$.

**Proof.** See discussion above.

\[ \square \]
Suppose we are given 7 distinct \((-2)\)-indices \(f, g, h, i, j, k, l\) such that the numbers \(a_{fg}, a_{gh}, a_{ij}, a_{jh}, a_{kl}, a_{lh}\) are nonzero. See picture in Lemma 5.12. Then we can apply Lemma 5.7 to see that the corresponding matrix is

\[
\begin{pmatrix}
-2w & w & 0 & 0 & 0 & 0 & 0 \\
w & -2w & w & 0 & 0 & 0 & 0 \\
0 & w & -2w & w & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -2w & w & 0 \\
0 & 0 & w & 0 & 0 & -2w & w \\
0 & 0 & 0 & 0 & 0 & 0 & -2w \\
0 & 0 & 0 & w & 0 & 0 & 0 \\
0 & 0 & 0 & w & 0 & 0 & -2w \\
0 & 0 & 0 & w & 0 & 0 & 0
\end{pmatrix}
\]

Since the determinant is 0 we conclude that we must have \(n = 7\) and \(g = 1\) and we get case (32) of Lemma 6.2.

\[\textbf{0CSI Lemma 5.12. Nonexistence of proper subgraphs of the form}
\begin{center}
\begin{tikzpicture}
\node (A) at (0,0) {$\cdot$};
\node (B) at (1,0) {$\cdot$};
\node (C) at (2,0) {$\cdot$};
\node (D) at (3,0) {$\cdot$};
\node (E) at (4,0) {$\cdot$};
\node (F) at (5,0) {$\cdot$};
\node (G) at (6,0) {$\cdot$};
\node (H) at (0,-1) {$\cdot$};
\end{tikzpicture}
\end{center}
Assume \(n > 7\). There do not exist 7 distinct \((-2)\)-indices \(f, g, h, i, j, k, l\) such that \(a_{fg}, a_{gh}, a_{ij}, a_{jh}, a_{kl}, a_{lh}\) are nonzero.

**Proof.** See discussion above. \(\Box\)

Suppose we are given 7 distinct \((-2)\)-indices \(f, g, h, i, j, k, l\) such that the numbers \(a_{fg}, a_{gh}, a_{hi}, a_{ij}, a_{jk}, a_{il}\) are nonzero. See picture in Lemma 5.13. Then we can apply Lemmas 5.7 and 5.9 to see that we must be in the situation of Lemma 5.13. Since the determinant is \(-8w^7 \neq 0\) we conclude that in this case it never happens that \(n = 7!\).

\[\textbf{0CSJ Lemma 5.13. Classification of proper subgraphs of the form}
\begin{center}
\begin{tikzpicture}
\node (A) at (0,0) {$\cdot$};
\node (B) at (1,0) {$\cdot$};
\node (C) at (2,0) {$\cdot$};
\node (D) at (3,0) {$\cdot$};
\node (E) at (4,0) {$\cdot$};
\node (F) at (5,0) {$\cdot$};
\node (G) at (0,-1) {$\cdot$};
\end{tikzpicture}
\end{center}
Let \(n > 7\). Then given 7 distinct \((-2)\)-indices \(i_1, \ldots, i_7\) such that \(a_{i_2}, a_{i_3}, a_{i_4}, a_{i_5}, a_{i_6}\) are nonzero, then we have the \(m\)'s, \(a\)'s, and \(w\)'s

\[\begin{align*}
(m_1) &= \begin{pmatrix}
-2w & w & 0 & 0 & 0 & 0 & 0 \\
w & -2w & w & 0 & 0 & 0 & 0 \\
0 & w & -2w & w & 0 & 0 & 0 \\
0 & 0 & w & -2w & w & 0 & 0 \\
0 & 0 & 0 & w & -2w & w & 0 \\
0 & 0 & 0 & 0 & w & -2w & 0 \\
0 & 0 & 0 & 0 & 0 & w & -2w \\
0 & 0 & 0 & 0 & 0 & w & 0
\end{pmatrix}, \\
(m_2) &= \begin{pmatrix}
-2w & w & 0 & 0 & 0 & 0 & 0 \\
w & -2w & w & 0 & 0 & 0 & 0 \\
0 & w & -2w & w & 0 & 0 & 0 \\
0 & 0 & w & -2w & w & 0 & 0 \\
0 & 0 & 0 & w & -2w & w & 0 \\
0 & 0 & 0 & 0 & w & -2w & 0 \\
0 & 0 & 0 & 0 & 0 & w & -2w \\
0 & 0 & 0 & 0 & 0 & w & 0
\end{pmatrix}, \\
m_3 &= \begin{pmatrix}
w \\
w \\
w \\
w \\
w \\
w \\
w \\
w
\end{pmatrix}, \\
m_4 &= \begin{pmatrix}
-2w & w & 0 & 0 & 0 & 0 & 0 \\
w & -2w & w & 0 & 0 & 0 & 0 \\
0 & w & -2w & w & 0 & 0 & 0 \\
0 & 0 & w & -2w & w & 0 & 0 \\
0 & 0 & 0 & w & -2w & w & 0 \\
0 & 0 & 0 & 0 & w & -2w & 0 \\
0 & 0 & 0 & 0 & 0 & w & -2w \\
0 & 0 & 0 & 0 & 0 & w & 0
\end{pmatrix}
\end{align*}\]
with \(2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4, 2m_4 \geq m_3 + m_5 + m_7,\)
\(2m_5 \geq m_4 + m_6, 2m_6 \geq m_5 + m_7,\) and \(2m_7 \geq m_4.

**Proof.** See discussion above. \(\square\)

Suppose we are given 8 distinct \((-2)\)-indices whose pattern of nonzero entries \(a_{ij}\) of the matrix \(A\) looks like

\[
\bullet \cdots \bullet \bullet \cdot \bullet \cdots \bullet \bullet \cdot \bullet
\]

or like

\[
\bullet \cdots \bullet \bullet \cdot \bullet \cdots \bullet \bullet \cdot \bullet
\]

Arguing exactly as in the proof of Lemma [5.13] we see that the first pattern leads to case 1 in Lemma 5.14 and does not lead to a new case in Lemma 6.2. Arguing exactly as in the proof of Lemma [5.12] we see that the second pattern does not occur if \(n > 8\), but leads to case \((33)\) in Lemma 6.2 when \(n = 8\).

**Lemma 5.14.** Classification of proper subgraphs of the form

\[
\bullet \cdots \bullet \bullet \cdot \bullet \cdots \bullet \bullet \cdot \bullet \cdot \bullet
\]

Let \(n > 8\). Then given 8 distinct \((-2)\)-indices \(i_1, \ldots, i_8\) such that \(a_{i_1 2}, a_{i_2 3}, a_{i_3 4}, a_{i_4 5}, a_{i_5 6}, a_{i_6 7}\) are nonzero, then we have the \(m\)’s, \(a\)’s, and \(w\)’s

\[
\begin{pmatrix}
m_1 \\
m_2 \\
m_3 \\
m_4 \\
m_5 \\
m_6 \\
m_7 \\
m_8
\end{pmatrix}
= \begin{pmatrix}
-2w & w & 0 & 0 & 0 & 0 & 0 & 0 \\
w & -2w & w & 0 & 0 & 0 & 0 & 0 \\
0 & w & -2w & w & 0 & 0 & 0 & 0 \\
0 & 0 & w & -2w & w & 0 & 0 & 0 \\
0 & 0 & 0 & w & -2w & w & 0 & 0 \\
0 & 0 & 0 & 0 & w & -2w & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & w & -2w & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & w & -2w
\end{pmatrix}
\begin{pmatrix}
w \\
w \\
w \\
w \\
w \\
w \\
w \\
w
\end{pmatrix}
\]

with \(2m_1 \geq m_2, 2m_2 \geq m_1 + m_3, 2m_3 \geq m_2 + m_4, 2m_4 \geq m_3 + m_5,\)
\(2m_5 \geq m_4 + m_6 + m_8, 2m_6 \geq m_5 + m_7, 2m_7 \geq m_6,\) and \(2m_8 \geq m_5.\)

**Proof.** See discussion above. \(\square\)

**Lemma 5.15.** Nonexistence of proper subgraphs of the form

\[
\bullet \cdots \bullet \bullet \cdot \bullet \cdots \bullet \bullet \cdot \bullet \cdot \bullet
\]

Assume \(n > 8\). There do not exist 8 distinct \((-2)\)-indices \(e, f, g, h, i, j, k, l\) such that \(a_{ef}, a_{fg}, a_{gh}, a_{hi}, a_{ij}, a_{jk}, a_{kl}\) are nonzero.
Proof. See discussion above.

Suppose we are given 9 distinct \((-2)\)-indices whose pattern of nonzero entries \(a_{ij}\) of the matrix \(A\) looks like

\[
\begin{array}{cccccccc}
\bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\
\end{array}
\]

Arguing exactly as in the proof of Lemma 5.12 we see that this pattern does not occur if \(n > 9\), but leads to case (34) in Lemma 6.2 when \(n = 9\).

**Lemma 5.16.** Nonexistence of proper subgraphs of the form

\[
\begin{array}{cccccccc}
\bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\
\end{array}
\]

Assume \(n > 9\). There do not exist 9 distinct \((-2)\)-indices \(d,e,f,g,h,i,j,k,l\) such that \(a_{de}, a_{ef}, a_{fg}, a_{gh}, a_{hi}, a_{ij}, a_{jk}, a_{lh}\) are nonzero.

Proof. See discussion above.

Collecting all the information together we find the following.

**Proposition 5.17.** Let \(n, m_i, a_{ij}, w_i, g_i\) be a numerical type of genus \(g\). Let \(I \subset \{1, \ldots, n\}\) be a proper subset of cardinality \(\geq 2\) consisting of \((-2)\)-indices such that there does not exist a nonempty proper subset \(I' \subset I\) with \(a_{i'i} = 0\) for \(i' \in I, i \in I \setminus I'\). Then up to reordering the \(m_i\)'s, \(a_{ij}\)'s, \(w_i\)'s for \(i, j \in I\) are as listed in Lemmas 5.1, 5.2, 5.3, 5.4, 5.5, 5.7, 5.8, 5.9, 5.10, 5.13, or 5.14.

Proof. This follows from the discussion above; see discussion at the start of Section 5.

6. Classification of minimal type for genus zero and one

**Lemma 6.1** (Genus zero). The only minimal numerical type of genus zero is \(n = 1, m_1 = 1, a_{11} = 0, w_1 = 1, g_1 = 0\).

Proof. Follows from Lemmas 3.13 and 5.5.

**Lemma 6.2** (Genus one). The minimal numerical types of genus one are up to equivalence

1. \(n = 1, a_{11} = 0, g_1 = 1, m_1, w_1 \geq 1\) arbitrary,
2. \(n = 2, m_i, a_{ij}, w_i, g_i\) given by

\[
\begin{pmatrix} m \\ m \end{pmatrix}, \quad \begin{pmatrix} -2w & 2w \\ 2w & -2w \end{pmatrix}, \quad \begin{pmatrix} w \\ w \end{pmatrix}, \quad \begin{pmatrix} 0 \\ 0 \end{pmatrix}
\]

with \(w\) and \(m\) arbitrary,
3. \(n = 2, m_i, a_{ij}, w_i, g_i\) given by

\[
\begin{pmatrix} 2m \\ m \end{pmatrix}, \quad \begin{pmatrix} -2w & 4w \\ 4w & -8w \end{pmatrix}, \quad \begin{pmatrix} w \\ 4w \end{pmatrix}, \quad \begin{pmatrix} 0 \\ 0 \end{pmatrix}
\]

with \(w\) and \(m\) arbitrary,
(4) \( n = 3, \) and \( m_i, a_{ij}, w_i, g_i \) given by
\[
\begin{pmatrix}
  m \\
  m \\
  m
\end{pmatrix}
\begin{pmatrix}
  -2w & w & w \\
  w & -2w & w \\
  w & w & -2w
\end{pmatrix}
\begin{pmatrix}
  w \\
  w \\
  w
\end{pmatrix}
\begin{pmatrix}
  0 \\
  0 \\
  0
\end{pmatrix}
\]
with \( w \) and \( m \) arbitrary,

(5) \( n = 3, \) and \( m_i, a_{ij}, w_i, g_i \) given by
\[
\begin{pmatrix}
  m \\
  2m \\
  3m
\end{pmatrix}
\begin{pmatrix}
  -2w & w & 0 \\
  w & -2w & 3w \\
  0 & 3w & -6w
\end{pmatrix}
\begin{pmatrix}
  w \\
  w \\
  w
\end{pmatrix}
\begin{pmatrix}
  0 \\
  0 \\
  0
\end{pmatrix}
\]
with \( w \) and \( m \) arbitrary,

(6) \( n = 3, \) and \( m_i, a_{ij}, w_i, g_i \) given by
\[
\begin{pmatrix}
  m \\
  2m \\
  3m
\end{pmatrix}
\begin{pmatrix}
  -6w & 3w & 0 \\
  3w & -6w & 3w \\
  0 & 3w & -2w
\end{pmatrix}
\begin{pmatrix}
  3w \\
  3w \\
  w
\end{pmatrix}
\begin{pmatrix}
  0 \\
  0 \\
  0
\end{pmatrix}
\]
with \( w \) and \( m \) arbitrary,

(7) \( n = 3, \) and \( m_i, a_{ij}, w_i, g_i \) given by
\[
\begin{pmatrix}
  2m \\
  2m \\
  m
\end{pmatrix}
\begin{pmatrix}
  -2w & 2w & 0 \\
  2w & -4w & 4w \\
  0 & 4w & -8w
\end{pmatrix}
\begin{pmatrix}
  w \\
  2w \\
  4w
\end{pmatrix}
\begin{pmatrix}
  0 \\
  0 \\
  0
\end{pmatrix}
\]
with \( w \) and \( m \) arbitrary,

(8) \( n = 3, \) and \( m_i, a_{ij}, w_i, g_i \) given by
\[
\begin{pmatrix}
  m \\
  m \\
  m
\end{pmatrix}
\begin{pmatrix}
  -2w & 2w & 0 \\
  2w & -4w & 2w \\
  0 & 2w & -2w
\end{pmatrix}
\begin{pmatrix}
  w \\
  2w \\
  w
\end{pmatrix}
\begin{pmatrix}
  0 \\
  0 \\
  0
\end{pmatrix}
\]
with \( w \) and \( m \) arbitrary,

(9) \( n = 3, \) and \( m_i, a_{ij}, w_i, g_i \) given by
\[
\begin{pmatrix}
  2m \\
  m \\
  m
\end{pmatrix}
\begin{pmatrix}
  -4w & 2w & 0 \\
  2w & -2w & 2w \\
  0 & 2w & -4w
\end{pmatrix}
\begin{pmatrix}
  2w \\
  2w \\
  2w
\end{pmatrix}
\begin{pmatrix}
  0 \\
  0 \\
  0
\end{pmatrix}
\]
with \( w \) and \( m \) arbitrary,

(10) \( n = 4, \) and \( m_i, a_{ij}, w_i, g_i \) given by
\[
\begin{pmatrix}
  m \\
  m \\
  m \\
  m
\end{pmatrix}
\begin{pmatrix}
  -2w & w & 0 & w \\
  w & -2w & w & 0 \\
  0 & w & -2w & w \\
  w & 0 & w & -2w
\end{pmatrix}
\begin{pmatrix}
  w \\
  w \\
  w \\
  w
\end{pmatrix}
\begin{pmatrix}
  0 \\
  0 \\
  0 \\
  0
\end{pmatrix}
\]
with \( w \) and \( m \) arbitrary,

(11) \( n = 4, \) and \( m_i, a_{ij}, w_i, g_i \) given by
\[
\begin{pmatrix}
  2m \\
  2m \\
  2m \\
  m
\end{pmatrix}
\begin{pmatrix}
  -2w & 2w & 0 & 0 \\
  2w & -4w & 2w & 0 \\
  0 & 2w & -4w & 4w \\
  0 & 0 & 4w & -8w
\end{pmatrix}
\begin{pmatrix}
  w \\
  2w \\
  2w \\
  4w
\end{pmatrix}
\begin{pmatrix}
  0 \\
  0 \\
  0 \\
  0
\end{pmatrix}
\]
with \( w \) and \( m \) arbitrary,
\[(\begin{array}{cccc}
-2w & 2w & 0 & 0 \\
2w & -4w & 2w & 0 \\
0 & 2w & -4w & 2w \\
0 & 0 & 2w & -2w
\end{array})\] and
\[(\begin{array}{c}
w \\
2w \\
w \\
w
\end{array})\]

with \(w\) and \(m\) arbitrary,

\[(\begin{array}{cccc}
-4w & 2w & 0 & 0 \\
2w & -2w & w & 0 \\
0 & w & -2w & 2w \\
0 & 0 & 2w & -4w
\end{array})\] and
\[(\begin{array}{c}
w \\
2w \\
w \\
w
\end{array})\]

with \(w\) and \(m\) arbitrary,

\[(\begin{array}{cccc}
-4w & w & w & 2w \\
w & -2w & w & 0 \\
w & 0 & -2w & 0 \\
2w & 0 & 0 & -4w
\end{array})\] and
\[(\begin{array}{c}
w \\
w \\
w \\
w
\end{array})\]

with \(w\) and \(m\) arbitrary,

\[(\begin{array}{cccc}
-4w & 2w & 2w & 2w \\
2w & -4w & 0 & 0 \\
2w & 0 & -4w & 0 \\
2w & 0 & 0 & -2w
\end{array})\] and
\[(\begin{array}{c}
w \\
w \\
w \\
w
\end{array})\]

with \(w\) and \(m\) arbitrary,

\[(\begin{array}{cccc}
-2w & w & 0 & 0 \\
w & -2w & w & 0 \\
0 & w & -2w & w \\
0 & 0 & w & -2w
\end{array})\] and
\[(\begin{array}{c}
w \\
w \\
w \\
w
\end{array})\]

with \(w\) and \(m\) arbitrary,
0C9B  (18) $n = 5$, and $m_i, a_{ij}, w_i, g_i$ given by

$$
\begin{pmatrix}
2m & 0 & 0 & 0 & 0 \\
2m & 0 & 0 & 0 & 0 \\
3m & 0 & 0 & 0 & 0 \\
4m & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
-4w & 2w & 0 & 0 & 0 \\
2w & -4w & 2w & 0 & 0 \\
0 & 2w & -4w & 2w & 0 \\
0 & 0 & 2w & -2w & w
\end{pmatrix}
\begin{pmatrix}
2w \\
w \\
w \\
w
\end{pmatrix}
\begin{pmatrix}
0 \\
0 \\
0 \\
0
\end{pmatrix}
$$

with $w$ and $m$ arbitrary,

0C9C  (19) $n = 5$, and $m_i, a_{ij}, w_i, g_i$ given by

$$
\begin{pmatrix}
2m & 0 & 0 & 0 & 0 \\
2m & 0 & 0 & 0 & 0 \\
2m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
-2w & 2w & 0 & 0 & 0 \\
2w & -4w & 2w & 0 & 0 \\
0 & 2w & -4w & 2w & 0 \\
0 & 0 & 2w & -4w & 4w
\end{pmatrix}
\begin{pmatrix}
w \\
w \\
w \\
w
\end{pmatrix}
\begin{pmatrix}
0 \\
0 \\
0 \\
0
\end{pmatrix}
$$

with $w$ and $m$ arbitrary,

0C9D  (20) $n = 5$, and $m_i, a_{ij}, w_i, g_i$ given by

$$
\begin{pmatrix}
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
-2w & 2w & 0 & 0 & 0 \\
2w & -4w & 2w & 0 & 0 \\
0 & 2w & -4w & 2w & 0 \\
0 & 0 & 2w & -4w & 2w
\end{pmatrix}
\begin{pmatrix}
w \\
w \\
w \\
w
\end{pmatrix}
\begin{pmatrix}
0 \\
0 \\
0 \\
0
\end{pmatrix}
$$

with $w$ and $m$ arbitrary,

0C9E  (21) $n = 5$, and $m_i, a_{ij}, w_i, g_i$ given by

$$
\begin{pmatrix}
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
-4w & 2w & 0 & 0 & 0 \\
2w & -2w & w & 0 & 0 \\
0 & w & -2w & w & 0 \\
0 & 0 & w & -2w & 2w
\end{pmatrix}
\begin{pmatrix}
w \\
w \\
w \\
w
\end{pmatrix}
\begin{pmatrix}
0 \\
0 \\
0 \\
0
\end{pmatrix}
$$

with $w$ and $m$ arbitrary,

0C9F  (22) $n = 5$, and $m_i, a_{ij}, w_i, g_i$ given by

$$
\begin{pmatrix}
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
-2w & w & w & w & w \\
w & -2w & 0 & 0 & 0 \\
w & 0 & -2w & 0 & 0 \\
w & 0 & 0 & -2w & 0
\end{pmatrix}
\begin{pmatrix}
w \\
w \\
w \\
w
\end{pmatrix}
\begin{pmatrix}
0 \\
0 \\
0 \\
0
\end{pmatrix}
$$

with $w$ and $m$ arbitrary,

0C9G  (23) $n = 5$, and $m_i, a_{ij}, w_i, g_i$ given by

$$
\begin{pmatrix}
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0 \\
m & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
-4w & 2w & 0 & 0 & 0 \\
2w & -2w & w & 0 & 0 \\
0 & w & -2w & w & 0 \\
0 & 0 & w & -2w & 0
\end{pmatrix}
\begin{pmatrix}
w \\
w \\
w \\
w
\end{pmatrix}
\begin{pmatrix}
0 \\
0 \\
0 \\
0
\end{pmatrix}
$$

with $w$ and $m$ arbitrary,
with $w$ and $m$ arbitrary,

(25) $n \geq 6$ and we have an $n$-cycle generalizing (16):

(a) $m_1 = \ldots = m_n = m$,
(b) $a_{12} = \ldots = a_{(n-1)n} = w$, $a_{1n} = w$, and for other $i < j$ we have $a_{ij} = 0$,
(c) $w_1 = \ldots = w_n = w$

with $w$ and $m$ arbitrary,

(26) $n \geq 6$ and we have a chain generalizing (19):

(a) $m_1 = \ldots = m_{n-1} = 2m$, $m_n = m$,
(b) $a_{12} = \ldots = a_{(n-2)(n-1)} = 2w$, $a_{(n-1)n} = 4w$, and for other $i < j$ we have $a_{ij} = 0$,
(c) $w_1 = w$, $w_2 = \ldots = w_{n-1} = 2w$, $w_n = 4w$

with $w$ and $m$ arbitrary,

(27) $n \geq 6$ and we have a chain generalizing (20):

(a) $m_1 = \ldots = m_n = m$,
(b) $a_{12} = \ldots = a_{(n-1)n} = w$, and for other $i < j$ we have $a_{ij} = 0$,
(c) $w_1 = w$, $w_2 = \ldots = w_{n-1} = 2w$, $w_n = w$

with $w$ and $m$ arbitrary,

(28) $n \geq 6$ and we have a chain generalizing (21):

(a) $m_1 = w$, $m_2 = \ldots = m_{n-1} = 2m$, $m_n = m$,
(b) $a_{12} = 2w$, $a_{23} = \ldots = a_{(n-2)(n-1)} = w$, $a_{(n-1)n} = 2w$, and for other $i < j$ we have $a_{ij} = 0$,
(c) $w_1 = 2w$, $w_2 = \ldots = w_{n-1} = w$, $w_n = 2w$

with $w$ and $m$ arbitrary,

(29) $n \geq 6$ and we have a type generalizing (22):

(a) $m_1 = m$, $m_2 = \ldots = m_{n-3} = 2m$, $m_{n-1} = m_n = m$,
(b) $a_{12} = 2w$, $a_{23} = \ldots = a_{(n-2)(n-1)} = w$, $a_{(n-2)n} = w$, and for other $i < j$ we have $a_{ij} = 0$,
(c) $w_1 = 2w$, $w_2 = \ldots = w_n = w$

with $w$ and $m$ arbitrary,
Let in our proof of semistable reduction for curves we’ll use a bound on Picard groups.

Lemma 7.2. □

Proof. This is proved in Section 5. See discussion at the start of Section 5. □

7. Bounding invariants of numerical types

In our proof of semistable reduction for curves we’ll use a bound on Picard groups of numerical types of genus $g$ which we will prove in this section.

Lemma 7.1. Let $n, m_i, a_{ij}, w_i, g_i$ be a numerical type of genus $g$. Given $i, j$ with $a_{ij} > 0$ we have $m_i a_{ij} \leq m_j |a_{jj}|$ and $m_i w_i \leq m_j |a_{jj}|$.

Proof. For every index $j$ we have $m_j a_{jj} + \sum_{i \neq j} m_i a_{ij} = 0$. Thus if we have an upper bound on $|a_{jj}|$ and $m_j$, then we also get an upper bound on the nonzero (and hence positive) $a_{ij}$ as well as $m_i$. Recalling that $w_i$ divides $a_{ij}$, the reader easily sees the lemma is correct. □

Lemma 7.2. Fix $g \geq 2$. For every minimal numerical type $n, m_i, a_{ij}, w_i, g_i$ of genus $g$ with $n > 1$ we have

1. the set $J \subset \{1, \ldots, n\}$ of non-$(-2)$-indices has at most $2g - 2$ elements,
(2) for $j \in J$ we have $g_j < g$,
(3) for $j \in J$ we have $m_j|a_{jj}| \leq 6g - 6$, and
(4) for $j \in J$ and $i \in \{1, \ldots, n\}$ we have $m_ia_{ij} \leq 6g - 6$.

**Proof.** Recall that $g = 1 + \sum m_i(w_j(g_j - 1) - \frac{1}{2}a_{jj})$. For $j \in J$ the contribution
$m_j(w_j(g_j - 1) - \frac{1}{2}a_{jj})$ to the genus $g$ is $> 0$ and hence $\geq 1/2$. This uses Lemma 3.7, Definition 3.8, Definition 3.12, Lemma 3.15, and Definition 3.16; we will use
these results without further mention in the following. Thus $J$ has at most $2(g - 1)$ elements. This proves (1).

Recall that $-a_{ii} > 0$ for all $i$ by Lemma 3.6. Hence for $j \in J$ the contribution
$m_j(w_j(g_j - 1) - \frac{1}{2}a_{jj})$ to the genus $g$ is $> m_jw_j(g_j - 1)$. Thus

$$g - 1 > m_jw_j(g_j - 1) \Rightarrow g_j < (g - 1)/m_jw_j + 1$$

This indeed implies $g_j < g$ which proves (2).

For $j \in J$ if $g_j > 0$, then the contribution $m_j(w_j(g_j - 1) - \frac{1}{2}a_{jj})$ to the genus $g$
is $\geq -\frac{1}{2}m_ja_{jj}$ and we immediately conclude that $m_j|a_{jj}| \leq 2(g - 1)$. Otherwise
$a_{jj} = -kw_j$ for some integer $k \geq 3$ (because $j \in J$) and we get

$$m_jw_j(-1 + \frac{k}{2}) \leq g - 1 \Rightarrow m_jw_j \leq \frac{2(g - 1)}{k - 2}$$

Plugging this back into $a_{jj} = -km_jw_j$ we obtain

$$m_j|a_{jj}| \leq 2(g - 1) - \frac{k}{k - 2} \leq 6(g - 1)$$

This proves (3).

Part (4) follows from Lemma 7.1 and (3).

---

**Lemma 7.3.** Fix $g \geq 2$. For every minimal numerical type $n, m_i, a_{ij}, w_i, g_i$ of
genus $g$ we have $m_i|a_{ii}| \leq 768g$.

**Proof.** By Lemma 7.1 it suffices to show $m_i|a_{ii}| \leq 768g$ for all $i$. Let $J \subset \{1, \ldots, n\}$ be the set of non-$(2)$-indices as in Lemma 7.2. Observe that $J$ is nonempty as $g \geq 2$. Also $m_j|a_{jj}| \leq 6g$ for $j \in J$ by the lemma.

Suppose we have $j \in J$ and a sequence $i_1, \ldots, i_7$ of $(2)$-indices such that $a_{ji}, a_{i_1i_2}, a_{i_2i_3}, a_{i_3i_4}, a_{i_4i_5}, a_{i_5i_6}$, and $a_{i_6i_7}$ are nonzero. Then we see from Lemma 7.1 that $m_{i_1}w_{i_1} \leq 6g$ and $m_{i_6}a_{i_6i_7} \leq 6g$. Because $i_1$ is a $(2)$-index, we have $a_{i_1i_2} = -2w_{i_1}$ and we conclude that $m_{i_1}|a_{i_1i_2}| \leq 12g$. Repeating the argument we conclude that $m_{i_2}w_{i_2} \leq 12g$ and $m_{i_7}a_{i_7i_8} \leq 12g$. Then $m_{i_2}|a_{i_2i_3}| \leq 24g$ and so on. Eventually we conclude that $m_{i_k}|a_{i_ki_k}| \leq 2^k(6g) \leq 768g$ for $k = 1, \ldots, 7$.

Let $I \subset \{1, \ldots, n\} \setminus J$ be a maximal connected subset. In other words, there does not exist a nonempty proper subset $I' \subset I$ such that $a_{ii'} = 0$ for $i' \in I'$ and $i \in I \setminus I'$ and $I$ is maximal with this property. In particular, since a numerical type is connected by definition, we see that there exists a $j \in J$ and $i \in I$ with $a_{ij} > 0$. Looking at the classification of such $I$ in Proposition 5.17, and using the result of the previous paragraph, we see that $w_i|a_{ii}| \leq 768g$ for all $i \in I$ unless $I$ is as described in Lemma 5.3 or Lemma 5.9. Thus we may assume the nonvanishing of $a_{ii'}$, $i, i' \in I$ has either the shape

* * * * * * * * * * * * * *
Let $0 < X$ other cases to reader (the argument is almost exactly the same in those cases).

We will prove the bound holds for the first subcase of Lemma 5.8 and leave the

other cases to reader (the argument is almost exactly the same in those cases).

After renumbering we may assume $I = \{1, \ldots, t\} \subset \{1, \ldots, n\}$ and there is an integer $w$ such that

$w = w_1 = \ldots = w_t = a_{12} = \ldots = a_{(t-1)t} = -\frac{1}{2}a_{11} = \ldots = -\frac{1}{2}a_{(t-1)t}$

The equalities $a_{ii} + \sum_{j \neq i} a_{ij}m_j = 0$ imply that we have

$2m_2 \geq m_1 + m_3, \ldots, 2m_{t-1} \geq m_{t-2} + m_t$

Equality holds in $2m_i \geq m_{i-1} + m_{i+1}$ if and only if $i$ does not “meet” any indices besides $i - 1$ and $i + 1$. And if $i$ does meet another index, then this index is in $J$ (by maximality of $I$). In particular, the map $\{1, \ldots, t\} \to \mathbb{Z}$, $i \mapsto m_i$ is concave.

Let $m = \max(m_i, i \in \{1, \ldots, t\})$. Then $m_i |_{ai_i} \leq 2mw$ for $i \leq t$ and our goal is to show that $2mw \leq 768g$. Let $s$, resp. $s'$ in $\{1, \ldots, t\}$ be the smallest, resp. biggest index with $m_s = m = m_{s'}$. By concavity we see that $m_i = m$ for $s \leq i \leq s'$. If $s > 1$, then we do not have equality in $2m_s \geq m_{s-1} + m_{s+1}$ and we see that $s$ meets an index from $J$. In this case $2mw \leq 12g$ by the result of the second paragraph of the proof. Similarly, if $s' < t$, then $s'$ meets an index from $J$ and we get $2mw \leq 12g$ as well. But if $s = 1$ and $s' = t$, then we conclude that $a_{ij} = 0$

for all $j \in J$ and $i \in \{2, \ldots, t - 1\}$. But as we’ve seen that there must be a pair $(i, j) \in I \times J$ with $a_{ij} > 0$, we conclude that this happens either with $i = 1$ or with $i = t$ and we conclude $2mw \leq 12g$ in the same manner as before (as $m_1 = m = m_t$ in this case).

\[\square\]

0C9X \textbf{Proposition 7.4.} Let $g \geq 2$. For every numerical type $T$ of genus $g$ and prime

number $t > 768g$ we have

$\dim F \mathfrak{c} \text{Pic}(T)[\ell] \leq g$

where $\text{Pic}(T)$ is as in Definition 4.1. If $T$ is minimal, then we even have

$\dim F \mathfrak{c} \text{Pic}(T)[\ell] \leq g_{\text{top}} \leq g$

where $g_{\text{top}}$ as in Definition 3.11.

\textbf{Proof.} Say $T$ is given by $n, \mathfrak{m}, a_{ij}, w_i, g_i$. If $T$ is not minimal, then there exists a

$(-1)$-index. After replacing $T$ by an equivalent type we may assume $n$ is a $(-1)$-index. Applying Lemma 1.4, we find $\text{Pic}(T) \subset \text{Pic}(T')$ where $T'$ is a numerical type of genus $g$ (Lemma 3.9) with $n - 1$ indices. Thus we conclude by induction on $n$ provided we prove the lemma for minimal numerical types.

Assume that $T$ is a minimal numerical type of genus $\geq 2$. Observe that $g_{\text{top}} \leq g$

by Lemma 3.14. If $A = (a_{ij})$ then since $\text{Pic}(T) \subset \text{Coker}(A)$ by Lemma 1.3, Thus it suffices to prove the lemma for $\text{Coker}(A)$. By Lemma 7.3 we see that $m_i |_{ai_j} \leq 768g$

for all $i, j$. Hence the result by Lemma 2.6. \[\square\]
8. Models

0C2R  In this chapter $R$ will be a discrete valuation ring and $K$ will be its fraction field. If needed we will denote $\pi \in R$ a uniformizer and $k = R/(\pi)$ its residue field.

Let $V$ be an algebraic $K$-scheme (Varieties, Definition 20.1). A model for $V$ will mean a flat finite type morphism $X \to \text{Spec}(R)$ endowed with an isomorphism $V \to X_K = X \times_{\text{Spec}(R)} \text{Spec}(K)$. We often will identify $V$ and the generic fibre $X_K$ of $X$ and just write $V = X_K$. The special fibre is $X_k = X \times_{\text{Spec}(R)} \text{Spec}(k)$. A morphism of models $X \to X'$ for $V$ is a morphism $X \to X'$ of schemes over $R$ which induces the identity on $V$.

We will say $X$ is a proper model of $V$ if $X$ is a model of $V$ and the structure morphism $X \to \text{Spec}(R)$ is proper. Similarly for separated models, smooth models, and add more here. We will say $X$ is a regular model of $V$ if $X$ is a model of $V$ and $X$ is a regular scheme. Similarly for normal models, reduced models, and add more here.

Let $R \subset R'$ be an extension of discrete valuation rings (More on Algebra, Definition 99.1). This induces an extension $K \subset K'$ of fraction fields. Given an algebraic scheme $V$ over $K$, denote $V'$ the base change $V \times_{\text{Spec}(K)} \text{Spec}(K')$. Then there is a functor

$$\text{models for } V \text{ over } R \to \text{models for } V' \text{ over } R'$$

sending $X$ to $X \times_{\text{Spec}(R)} \text{Spec}(R')$.

0C2S  Lemma 8.1. Let $V_1 \to V_2$ be a closed immersion of algebraic schemes over $K$. If $X_2$ is a model for $V_2$, then the scheme theoretic image of $V_1 \to X_2$ is a model for $V_1$.

Proof. Using Morphisms, Lemma 6.3 and Example 6.4 this boils down to the following algebra statement. Let $A_1$ be a finite type $R$-algebra flat over $R$. Let $A_1 \otimes_R K \to B_2$ be a surjection. Then $A_2 = A_1 / \ker(A_1 \to B_2)$ is a finite type $R$-algebra flat over $R$ such that $B_2 = A_2 \otimes_R K$. We omit the detailed proof; use More on Algebra, Lemma 22.11 to prove that $A_2$ is flat. \hfill \square

0C2T  Lemma 8.2. Let $X$ be a model of a geometrically normal variety $V$ over $K$. Then the normalization $\nu : X' \to X$ is finite and the base change of $X'$ to the completion $R^\wedge$ is the normalization of the base change of $X$. Moreover, for each $x \in X'$ the completion of $\mathcal{O}_{X',x}$ is normal.

Proof. Observe that $R^\wedge$ is a discrete valuation ring (More on Algebra, Lemma 42.5). Set $Y = X \times_{\text{Spec}(R)} \text{Spec}(R^\wedge)$. Since $R^\wedge$ is a discrete valuation ring, we see that

$$Y \setminus Y_k = Y \times_{\text{Spec}(R^\wedge)} \text{Spec}(K^\wedge) = V \times_{\text{Spec}(K)} \text{Spec}(K^\wedge)$$

where $K^\wedge$ is the fraction field of $R^\wedge$. Since $V$ is geometrically normal, we find that this is a normal scheme. Hence the first part of the lemma follows from Resolution of Surfaces, Lemma 11.6.

To prove the second part we may assume $X$ and $Y$ are normal (by the first part). If $x$ is in the generic fibre, then $\mathcal{O}_{X,x} = \mathcal{O}_{V,x}$ is a normal local ring essentially of finite type over a field. Such a ring is excellent (More on Algebra, Proposition 51.3). If $x$ is

6Occasionally it is useful to allow models to be locally of finite type over $R$, but we’ll cross that bridge when we come to it.
is a point of the special fibre with image \( y \in Y \), then \( \mathcal{O}_{X,x} = \mathcal{O}_{Y,y} \) by Resolution of Surfaces, Lemma 11.1. In this case \( \mathcal{O}_{Y,y} \) is an excellent normal local domain by the same reference as before as \( R^\wedge \) is excellent. If \( B \) is an excellent local normal domain, then the completion \( B^\wedge \) is normal (as \( B \to B^\wedge \) is regular and More on Algebra, Lemma 41.2 applies). This finishes the proof. □

Lemma 8.3. Let \( X \) be a model of a smooth curve \( C \) over \( K \). Then there exists a resolution of singularities of \( X \) and any resolution is a model of \( C \).

Proof. We check condition (4) of Lipman’s theorem (Resolution of Surfaces, Theorem 14.5) hold. This is clear from Lemma 8.2 except for the statement that \( X^\nu \) has finitely many singular points. To see this we can use that \( R \) is J-2 by More on Algebra, Proposition 47.6 and hence the nonsingular locus is open in \( X^\nu \). Since \( X^\nu \) is normal of dimension \( \leq 2 \), the singular points are closed, hence closedness of the singular locus means there are finitely many of them (as \( X \) is quasi-compact). Observe that any resolution of \( X \) is a modification of \( X \) (Resolution of Surfaces, Definition 14.1). This will be an isomorphism over the normal locus of \( X \) by Varieties, Lemma 17.3. Since the set of normal points includes \( C = X \bigcap K \) we conclude any resolution is a model of \( C \). □

Definition 8.4. Let \( C \) be a smooth projective curve over \( K \) with \( H^0(C, \mathcal{O}_C) = K \). A minimal model will be a regular, proper model \( X \) for \( C \) such that \( X \) does not contain an exceptional curve of the first kind (Resolution of Surfaces, Section 16).

Really such a thing should be called a minimal regular proper model or even a relatively minimal regular projective model. But as long as we stick to models over discrete valuation rings (as we will in this chapter), no confusion should arise.

Minimal models always exist (Proposition 8.6) and are unique when the genus is \( > 0 \) (Lemma 10.1).

Lemma 8.5. Let \( C \) be a smooth projective curve over \( K \) with \( H^0(C, \mathcal{O}_C) = K \). If \( X \) is a regular proper model for \( C \), then there exists a sequence of morphisms

\[
X = X_m \to X_{m-1} \to \ldots \to X_1 \to X_0
\]

of proper regular models of \( C \), such that each morphism is a contraction of an exceptional curve of the first kind, and such that \( X_0 \) is a minimal model.

Proof. By Resolution of Surfaces, Lemma 16.11 we see that \( X \) is projective over \( R \). Hence \( X \) has an ample invertible sheaf by More on Morphisms, Lemma 45.1 (we will use this below). Let \( E \subset X \) be an exceptional curve of the first kind. See Resolution of Surfaces, Section 16 By Resolution of Surfaces, Lemma 16.8 we can contract \( E \) by a morphism \( X \to X' \) such that \( X' \) is regular and is projective over \( R \). Clearly, the number of irreducible components of \( X'_k \) is exactly one less than the number of irreducible components of \( X_k \). Thus we can only perform a finite number of these contractions until we obtain a minimal model. □

Proposition 8.6. Let \( C \) be a smooth projective curve over \( K \) with \( H^0(C, \mathcal{O}_C) = K \). A minimal model exists.

Proof. Choose a closed immersion \( C \to \mathbf{P}^2_K \). Let \( X \) be the scheme theoretic image of \( C \to \mathbf{P}^2_K \). Then \( X \to \text{Spec}(R) \) is a projective model of \( C \) by Lemma 8.4. By Lemma 8.3 there exists a resolution of singularities \( X' \to X \) and \( X' \) is a model for
In this section we describe the geometry of a proper regular model \( X \) of a smooth projective curve \( C \) over \( K \) with \( H^0(C, \mathcal{O}_C) = K \).

**Lemma 9.1.** Let \( X \) be a regular model of a smooth curve \( C \) over \( K \).

1. The special fibre \( X_k \) is an effective Cartier divisor on \( X \).
2. Each irreducible component \( C_i \) of \( X_k \) is an effective Cartier divisor on \( X \).
3. \( X_k = \sum m_i C_i \) (sum of effective Cartier divisors) where \( m_i \) is the multiplicity of \( C_i \) in \( X_k \).
4. \( \mathcal{O}_X(X_k) \cong \mathcal{O}_X \).

**Proof.** Recall that \( R \) is a discrete valuation ring with uniformizer \( \pi \) and residue field \( k = R/\langle \pi \rangle \). Because \( X \to \text{Spec}(R) \) is flat, the element \( \pi \) is a nonzerodivisor affine locally on \( X \) (see More on Algebra, Lemma [22.11]). Thus if \( U = \text{Spec}(A) \subset X \) is an affine open, then

\[
X_k \cap U = U_k = \text{Spec}(A \otimes_R k) = \text{Spec}(A/\pi A)
\]

and \( \pi \) is a nonzerodivisor in \( A \). Hence \( X_k = V(\pi) \) is an effective Cartier divisor by Divisors, Lemma [13.2]. Hence (1) is true.

The discussion above shows that the pair \( (\mathcal{O}_X(X_k), 1) \) is isomorphic to the pair \( (\mathcal{O}_X, \pi) \) which proves (4).

By Divisors, Lemma [15.11] there exist pairwise distinct integral effective Cartier divisors \( D_i \subset X \) and integers \( a_i \geq 0 \) such that \( X_k = \sum a_i D_i \). We can throw out those divisors \( D_i \) such that \( a_i = 0 \). Then it is clear (from the definition of addition of effective Cartier divisors) that \( X_k = \bigcup D_i \) set theoretically. Thus \( C_i = D_i \) are the irreducible components of \( X_k \) which proves (2). Let \( \xi_i \) be the generic point of \( C_i \). Then \( \mathcal{O}_{X, \xi_i} \) is a discrete valuation ring (Divisors, Lemma [15.4]). The uniformizer \( \pi_i \in \mathcal{O}_{X, \xi_i} \) is a local equation for \( C_i \) and the image of \( \pi \) is a local equation for \( X_k \). Since \( X_k = \sum a_i C_i \) we see that \( \pi \) and \( \pi_i^{a_i} \) generate the same ideal in \( \mathcal{O}_{X, \xi_i} \). On the other hand, the multiplicity of \( C_i \) in \( X_k \) is

\[
m_i = \text{length}_{\mathcal{O}_{C_i, \xi_i}} \mathcal{O}_{X, \xi_i} = \text{length}_{\mathcal{O}_{C_i, \xi_i}} \mathcal{O}_{X, \xi_i}/(\pi) = \text{length}_{\mathcal{O}_{C_i, \xi_i}} \mathcal{O}_{X, \xi_i}/(\pi_i^{a_i}) = a_i
\]

This shows (3) is proved.

**Lemma 9.2.** Let \( X \) be a regular model of a smooth curve \( C \) over \( K \). Then

1. \( X \to \text{Spec}(R) \) is a Gorenstein morphism of relative dimension 1,
2. Each of the irreducible components \( C_i \) of \( X_k \) is Gorenstein.

**Proof.** Since \( X \to \text{Spec}(R) \) is flat, to prove (1) it suffices to show that the fibres are Gorenstein (Duality for Schemes, Lemma [25.3]). The generic fibre is a smooth curve, which is regular and hence Gorenstein (Duality for Schemes, Lemma [24.3]). For the special fibre \( X_k \) we use that it is an effective Cartier divisor on a regular (hence Gorenstein) scheme and hence Gorenstein for example by Dualizing Complexes, Lemma [21.6]. The curves \( C_i \) are Gorenstein by the same argument.
In Situation 9.3 there is an exact sequence

\[
\begin{align*}
0 & \to \mathbb{Z} \to \mathbb{Z}^\oplus_n \to \text{Pic}(X) \to \text{Pic}(C) \to 0
\end{align*}
\]

where the first map sends 1 to \((m_1, \ldots, m_n)\) and the second maps sends the \(i\)th basis vector to \(\mathcal{O}_X(C_i)\).

**Proof.** Observe that \(C \subset X\) is an open subscheme. The restriction map \(\text{Pic}(X) \to \text{Pic}(C)\) is surjective by Divisors, Lemma 28.3. Let \(L\) be an invertible \(\mathcal{O}_X\)-module such that there is an isomorphism \(s : \mathcal{O}_C \to L|_C\). Then \(s\) is a regular meromorphic section of \(L\) and we see that \(\text{div}(L) = \sum a_i C_i\) for some \(a_i \in \mathbb{Z}\) (Divisors, Definition 27.4). By Divisors, Lemma 27.6 (and the fact that \(X\) is normal) we conclude that \(L = \mathcal{O}_X(\sum a_i C_i)\). Finally, suppose that \(\mathcal{O}_X(\sum a_i C_i) \cong \mathcal{O}_X\). Then there exists an element \(g\) of the function field of \(X\) with \(\text{div}(g) = \sum a_i C_i\). In particular the rational function \(g\) has no zeros or poles on the generic fibre \(C\) of \(X\). Since \(C\) is a normal scheme this implies \(g \in H^0(C, \mathcal{O}_C) = K\). Thus \(g = \pi^u a\) for some \(a \in \mathbb{Z}\) and \(u \in R^+\). We conclude that \(\text{div}(g) = a \sum m_i C_i\) and the proof is complete. □

In Situation 9.3 for every invertible \(\mathcal{O}_X\)-module \(L\) and every \(i\) we get an integer

\[
\deg(L|_{C_i}) = \chi(C_i, L|_{C_i}) - \chi(C_i, \mathcal{O}_{C_i})
\]

by taking the degree of the restriction of \(L\) to \(C_i\) relative to the ground field \(k\) as in Varieties, Section 43.

**Lemma 9.5.** In Situation 9.3 given \(L\) an invertible \(\mathcal{O}_X\)-module and \(a = (a_1, \ldots, a_n) \in \mathbb{Z}^\oplus_n\) we define

\[
\langle a, L \rangle = \sum a_i \deg(L|_{C_i})
\]

Then \(\langle \cdot, \cdot \rangle\) is bilinear and for \(b = (b_1, \ldots, b_n) \in \mathbb{Z}^\oplus_n\) we have

\[
\langle a, \mathcal{O}_X(\sum b_i C_i) \rangle = \langle b, \mathcal{O}_X(\sum a_i C_i) \rangle
\]

**Proof.** Bilinearity is immediate from the definition and Varieties, Lemma 43.7. To prove symmetry it suffices to assume \(a\) and \(b\) are standard basis vectors in \(\mathbb{Z}^\oplus_n\). Hence it suffices to prove that

\[
\deg(\mathcal{O}_X(C_i)|_{C_i}) = \deg(\mathcal{O}_X(C_i)|_{C_j})
\]

for all \(1 \leq i, j \leq n\). If \(i = j\) there is nothing to prove. If \(i \neq j\), then the canonical section 1 of \(\mathcal{O}_X(C_j)\) restricts to a nonzero (hence regular) section of \(\mathcal{O}_X(C_j)|_{C_i}\) whose zero scheme is exactly \(C_i \cap C_j\) (scheme theoretic intersection). In other words, \(C_i \cap C_j\) is an effective Cartier divisor on \(C_i\) and

\[
\deg(\mathcal{O}_X(C_j)|_{C_i}) = \deg(C_i \cap C_j)
\]

\(\text{Observe that it may happen that the field } \kappa_i = H^0(C_i, \mathcal{O}_{C_i}) \text{ is strictly bigger than } k. \text{ In this case every invertible module on } C_i \text{ has degree (as defined above) divisible by } [\kappa_i : k].\)
by Varieties, Lemma 43.9. By symmetry we obtain the same (!) formula for the other side and the proof is complete.

In Situation 9.3 it is often convenient to think of $\mathbb{Z}^n$ as the free abelian group on the set $\{C_1, \ldots, C_n\}$. We will indicate an element of this group as $\sum a_i C_i$; here we think of this as a formal sum although equivalently we may (and we sometimes do) think of such a sum as a Weil divisor on $X$ supported on the special fibre $X_k$. Now Lemma 9.6 allows us to define a symmetric bilinear form $(\cdot, \cdot)$ on this free abelian group by the rule

\[
(\sum a_i C_i, \sum b_j C_j) = \langle a, O_X(\sum b_j C_j) \rangle = \langle b, O_X(\sum a_i C_i) \rangle
\]

We will prove some properties of this bilinear form.

**Lemma 9.7.** In Situation 9.3 the symmetric bilinear form $(9.6.1)$ has the following properties

1. $(C_i \cdot C_j) \geq 0$ if $i \neq j$ with equality if and only if $C_i \cap C_j = \emptyset$,
2. $(\sum m_i C_i \cdot C_j) = 0$,
3. there is no nonempty proper subset $I \subset \{1, \ldots, n\}$ such that $(C_i \cdot C_j) = 0$ for $i \in I$, $j \notin I$,
4. $(\sum a_i C_i \cdot \sum a_i C_i) \leq 0$ with equality if and only if there exists a $q \in \mathbb{Q}$ such that $a_i = q m_i$ for $i = 1, \ldots, n$.

**Proof.** In the proof of Lemma 9.6 we saw that $(C_i \cdot C_j) = \deg(C_i \cap C_j)$ if $i \neq j$. This is $\geq 0$ and $> 0$ if and only if $C_i \cap C_j \neq \emptyset$. This proves (1).

Proof of (2). This is true because by Lemma 9.1 the invertible sheaf associated to $\sum m_i C_i$ is trivial and the trivial sheaf has degree zero.

Proof of (3). This is expressing the fact that $X_k$ is connected (Lemma 9.4) via the description of the intersection products given in the proof of (1).

Part (4) follows from (1), (2), and (3) by Lemma 2.3.

**Lemma 9.8.** In Situation 9.3 set $d = \gcd(m_1, \ldots, m_n)$ and let $D = \sum(m_i/d)C_i$ as an effective Cartier divisor. Then $O_X(D)$ has order dividing $d$ in $\text{Pic}(X)$ and $\mathcal{C}_{D/X}$ an invertible $O_D$-module of order dividing $d$ in $\text{Pic}(D)$.

**Proof.** We have

\[ O_X(D)^{\otimes d} = O_X(dD) = O_X(X_k) = O_X \]

by Lemma 9.4. We conclude as $\mathcal{C}_{D/X}$ is the pullback of $O_X(-D)$.

**Lemma 9.9.** In Situation 9.3 let $d = \gcd(m_1, \ldots, m_n)$. Let $D = \sum(m_i/d)C_i$ as an effective Cartier divisor. Then there exists a sequence of effective Cartier divisors

\[(X_k)_{\text{red}} = Z_0 \subset Z_1 \subset \ldots \subset Z_m = D \]

such that $Z_j = Z_{j-1} + C_{i_j}$ for some $i_j \in \{1, \ldots, n\}$ for $j = 1, \ldots, m$ and such that $H^0(Z_j, O_{Z_j})$ is a field finite over $k$ for $j = 0, \ldots m$.

**Proof.** The reduction $D_{\text{red}} = (X_k)_{\text{red}} = \sum C_i$ is connected (Lemma 9.4) and proper over $k$. Hence $H^0(D_{\text{red}}, O)$ is a field and a finite extension of $k$ by Varieties, Lemma 9.3. Thus the result for $Z_0 = D_{\text{red}} = (X_k)_{\text{red}}$ is true. Suppose that we have already constructed

\[(X_k)_{\text{red}} = Z_0 \subset Z_1 \subset \ldots \subset Z_t \subset D \]
with $Z_j = Z_{j-1} + C_i$, for some $i_j \in \{1, \ldots, n\}$ for $j = 1, \ldots, t$ and such that $H^0(Z_j, \mathcal{O}_{Z_j})$ is a field finite over $k$ for $j = 0, \ldots, t$. Write $Z_i = \sum a_i C_i$ with $1 \leq a_i \leq m_i/d$. If $a_i = m_i/d$ for all $i$, then $Z_t = D$ and the lemma is proved. If not, then $a_i < m_i/d$ for some $i$ and it follows that $(Z_t - Z_i) < 0$ by Lemma 9.7. This means that $(D - Z_t - Z_i) > 0$ because $(D - Z_t) = 0$ by the lemma. Thus we can find an $i$ with $a_i < m_i/d$ such that $(C_i \cdot Z_t) > 0$. Set $Z_{t+1} = Z_t + C_i$ and $i_{t+1} = i$. Consider the short exact sequence

$$0 \to \mathcal{O}_X(-Z_i)|_{C_i} \to \mathcal{O}_{Z_{t+1}} \to \mathcal{O}_{Z_t} \to 0$$

of Divisors, Lemma 14.3. By our choice of $i$ we see that $\mathcal{O}_X(-Z_i)|_{C_i}$ is an invertible sheaf of negative degree on the proper curve $C_i$, hence it has no nonzero global sections (Varieties, Lemma 43.12). We conclude that $H^0(\mathcal{O}_{Z_{t+1}}) \subset H^0(\mathcal{O}_{Z_t})$ is a field (this is clear but also follows from Algebra, Lemma 35.18) and a finite extension of $k$. Thus we have extended the sequence. Since the process must stop, for example because $t \leq \sum (m_i/d - 1)$, this finishes the proof. □

**Lemma 9.10.** In Situation 9.3 let $d = \gcd(m_1, \ldots, m_n)$. Let $D = \sum (m_i/d) C_i$ as an effective Cartier divisor on $X$. Then

$$\chi(C, \mathcal{O}_C) = \chi(X_k, \mathcal{O}_{X_k}) = \dim_k H^0(X_k, \mathcal{O}_{X_k}) - \dim_k H^1(X_k, \mathcal{O}_{X_k})$$

where $g_C$ is the genus of $C$, $g_D$ is the genus of $D$, and $\kappa = H^0(D, \mathcal{O}_D)$.

**Proof.** By Lemma 9.9 we see that $\kappa$ is a field and a finite extension of $k$. Since also $H^0(C, \mathcal{O}_C) = \kappa$ we see that the genus of $C$ and $D$ are defined (see Algebraic Curves, Definition 8.1) and we have $g_C = \dim_k H^1(C, \mathcal{O}_C)$ and $g_D = \dim_\kappa H^1(D, \mathcal{O}_D)$. By Derived Categories of Schemes, Lemma 28.2 we have

$$\chi(C, \mathcal{O}_C) = \chi(X_k, \mathcal{O}_{X_k}) = \dim_k H^0(X_k, \mathcal{O}_{X_k}) - \dim_k H^1(X_k, \mathcal{O}_{X_k})$$

We claim that

$$\chi(X_k, \mathcal{O}_{X_k}) = d\chi(D, \mathcal{O}_D)$$

This will prove the lemma because

$$\chi(D, \mathcal{O}_D) = \dim_k H^0(D, \mathcal{O}_D) - \dim_k H^1(D, \mathcal{O}_D) = |\kappa : k|(1 - g_D)$$

Observe that $X_k = dD$ as an effective Cartier divisor. To prove the claim we prove by induction on $1 \leq r \leq d$ that $\chi(rD, \mathcal{O}_{rD}) = r\chi(D, \mathcal{O}_D)$. The base case $r = 1$ is trivial. If $1 \leq r < d$, then we consider the short exact sequence

$$0 \to \mathcal{O}_X(rD)|_{D} \to \mathcal{O}_{(r+1)D} \to \mathcal{O}_{rD} \to 0$$

of Divisors, Lemma 14.3. By additivity of Euler characteristics (Varieties, Lemma 32.2) it suffices to prove that $\chi(D, \mathcal{O}_X(rD)|_D) = \chi(D, \mathcal{O}_D)$. This is true because $\mathcal{O}_X(rD)|_D$ is a torsion element of $\text{Pic}(D)$ (Lemma 9.8) and because the degree of a line bundle is additive (Varieties, Lemma 43.7) hence zero for torsion invertible sheaves. □

**Lemma 9.11.** In Situation 9.3 given a pair of indices $i, j$ such that $C_i$ and $C_j$ are exceptional curves of the first kind and $C_i \cap C_j \neq \emptyset$, then $n = 2$, $m_1 = m_2 = 1$, $C_1 \cong \mathbb{P}^1_k$, $C_2 \cong \mathbb{P}^1_k$, $C_1$ and $C_2$ meet in a $k$-rational point, and $C$ has genus 0.

**Proof.** Choose isomorphisms $C_i = \mathbb{P}^1_{k_i}$ and $C_j = \mathbb{P}^1_{k_j}$. The scheme $C_i \cap C_j$ is a nonempty effective Cartier divisor in both $C_i$ and $C_j$. Hence

$$(C_i \cdot C_j) = \deg(C_i \cap C_j) \geq \max(|\kappa_i : k|, |\kappa_j : k|)$$
The first equality was shown in the proof of Lemma 9.6. On the other hand, the self intersection \((C_i \cdot C_i)\) is equal to the degree of \(\mathcal{O}_X(C_i)\) on \(C_i\) which is \(-[\kappa_i : k]\) as \(C_i\) is an exceptional curve of the first kind. Similarly for \(C_j\). By Lemma 9.7

\[
0 \geq (C_i + C_j)^2 = -[\kappa_i : k] + 2(C_i \cdot C_j) - [\kappa_j : k]
\]

This implies that \([\kappa_i : k] = \deg(C_i \cap C_j) = [\kappa_j : k]\) and that we have \((C_i + C_j)^2 = 0\). Looking at the lemma again we conclude that \(n = 2, \{1, 2\} = \{i, j\}\), and \(m_1 = m_2\). Moreover, the scheme theoretic intersection \(C_i \cap C_j\) consists of a single point \(p\) with residue field \(\kappa\) and \(\kappa_i \to \kappa \leftarrow \kappa_j\) are isomorphisms. Let \(D = C_1 + C_2\) as effective Cartier divisor on \(X\). Observe that \(D\) is the scheme theoretic union of \(C_1\) and \(C_2\) (Divisors, Lemma 13.10) hence we have a short exact sequence

\[
0 \to \mathcal{O}_D \to \mathcal{O}_{C_1} \oplus \mathcal{O}_{C_2} \to \mathcal{O}_p \to 0
\]

by Morphisms, Lemma 4.6. Since we know the cohomology of \(C_i \cong \mathbb{P}_k^1\) (Cohomology of Schemes, Lemma 8.1), we conclude from the long exact cohomology sequence that \(H^0(D, \mathcal{O}_D) = \kappa\) and \(H^1(D, \mathcal{O}_D) = 0\). By Lemma 9.10 we conclude

\[
1 - g_C = d[\kappa : k](1 - 0)
\]

where \(d = m_1 = m_2\). It follows that \(g_C = 0\) and \(d = m_1 = m_2 = 1\) and \(\kappa = k\). □

10. Uniqueness of the minimal model

If the genus of the generic fibre is positive, then minimal models are unique (Lemma 10.1) and consequently have a suitable mapping property (Lemma 10.2).

Lemma 10.1. Let \(C\) be a smooth projective curve over \(K\) with \(H^0(C, \mathcal{O}_C) = K\) and genus \(g > 0\). There is a unique minimal model for \(C\).

Proof. We have already proven the hard part of the lemma which is the existence of a minimal model (whose proof relies on resolution of surface singularities), see Proposition 8.6. To prove uniqueness, suppose that \(X\) and \(Y\) are two minimal models. By Resolution of Surfaces, Lemma 17.2 there exists a diagram of \(S\)-morphisms

\[
X = X_0 \leftarrow X_1 \leftarrow \ldots \leftarrow X_n = Y_m \to \ldots \to Y_1 \to Y_0 = Y
\]

where each morphism is a blowup in a closed point. The exceptional fibre of the morphism \(X_n \to X_{n-1}\) is an exceptional curve of the first kind \(E\). We claim that \(E\) is contracted to a point under the morphism \(X_n = Y_m \to Y\). If this is true, then \(X_n \to Y\) factors through \(X_{n-1}\) by Resolution of Surfaces, Lemma 16.1. In this case the morphism \(X_{n-1} \to Y\) is still a sequence of contractions of exceptional curves by Resolution of Surfaces, Lemma 17.1. Hence by induction on \(n\) we conclude. (The base case \(n = 0\) means that there is a sequence of contractions \(X = Y_m \to \ldots \to Y_1 \to Y_0 = Y\) ending with \(Y\). However as \(X\) is a minimal model it contains no exceptional curves of the first kind, hence \(m = 0\) and \(X = Y\).)

Proof of the claim. We will show by induction on \(m\) that any exceptional curve of the first kind \(E \subset Y_m\) is mapped to a point by the morphism \(Y_m \to Y\). If \(m = 0\) this is clear because \(Y\) is a minimal model. If \(m > 0\), then either \(Y_m \to Y_{m-1}\) contracts \(E\) (and we’re done) or the exceptional fibre \(E' \subset Y_m\) of \(Y_m \to Y_{m-1}\) is a second exceptional curve of the first kind. Since both \(E\) and \(E'\) are irreducible components of the special fibre and since \(g_C > 0\) by assumption, we conclude that \(E \cap E' = \emptyset\) by Lemma 9.11. Then the image of \(E\) in \(Y_{m-1}\) is an exceptional curve of the first kind (this is clear because the morphism \(Y_m \to Y_{m-1}\) is an isomorphism in
a neighbourhood of $E$). By induction we see that $Y_{m-1} \to Y$ contracts this curve and the proof is complete. 

0C9Z \textbf{Lemma 10.2.} Let $C$ be a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$ and genus $> 0$. Let $X$ be the minimal model for $C$ (Lemma 10.1). Let $Y$ be a regular proper model for $C$. Then there is a unique morphism of models $Y \to X$ which is a sequence of contractions of exceptional curves of the first kind.

\textbf{Proof.} The existence and properties of the morphism $X \to Y$ follows immediately from Lemma 8.5 and the uniqueness of the minimal model. The morphism $Y \to X$ is unique because $C \subset Y$ is scheme theoretically dense and $X$ is separated (see Morphisms, Lemma 7.10).

0CA0 \textbf{Example 10.3.} If the genus of $C$ is 0, then minimal models are indeed nonunique. Namely, consider the closed subscheme

$$X \subset \mathbb{P}^2_R$$

defined by $T_1 T_2 - \pi T_0^2 = 0$. More precisely $X$ is defined as $\text{Proj}(R[T_0, T_1, T_2]/(T_1 T_2 - \pi T_0^2))$. Then the special fibre $X_k$ is a union of two exceptional curves $C_1$, $C_2$ both isomorphic to $\mathbb{P}^1_k$ (exactly as in Lemma 9.11). Projection from $(0 : 1 : 0)$ defines a morphism $X \to \mathbb{P}^1_R$ contracting $C_2$ and inducing an isomorphism of $C_1$ with the special fiber of $\mathbb{P}^1_R$. Projection from $(0 : 0 : 1)$ defines a morphism $X \to \mathbb{P}^1_R$ contracting $C_1$ and inducing an isomorphism of $C_2$ with the special fiber of $\mathbb{P}^1_R$. More precisely, these morphisms correspond to the graded $R$-algebra maps

$$R[T_0, T_1] \longrightarrow R[T_0, T_1, T_2]/(T_1 T_2 - \pi T_0^2) \longleftarrow R[T_0, T_2]$$

In Lemma 12.4 we will study this phenomenon.

11. A formula for the genus

0CA1 There is one more restriction on the combinatorial structure coming from a proper regular model.

0CA2 \textbf{Lemma 11.1.} In Situation 9.3 suppose we have an effective Cartier divisors $D, D' \subset X$ such that $D' = D + C_i$ for some $i \in \{1, \ldots, n\}$ and $D' \subset X_k$. Then

$$\chi(X_k, \mathcal{O}_{D'}) - \chi(X_k, \mathcal{O}_D) = \chi(X_k, \mathcal{O}_X(-D)|_{C_i}) = -(D \cdot C_i) + \chi(C_i, \mathcal{O}_{C_i})$$

\textbf{Proof.} The second equality follows from the definition of the bilinear form $(\cdot)$ in Lemma 9.11 and Lemma 9.6. To see the first equality we distinguish two cases. Namely, if $C_i \not\subset D$, then $D'$ is the scheme theoretic union of $D$ and $C_i$ (by Divisors, Lemma 13.10) and we get a short exact sequence

$$0 \to \mathcal{O}_{D'} \to \mathcal{O}_D \times \mathcal{O}_{C_i} \to \mathcal{O}_{D \cap C_i} \to 0$$

by Morphisms, Lemma 4.6. Since we also have an exact sequence

$$0 \to \mathcal{O}_X(-D)|_{C_i} \to \mathcal{O}_{C_i} \to \mathcal{O}_{D \cap C_i} \to 0$$

by Divisors, Remark 14.11, we conclude that the claim holds by additivity of euler characteristics (Variétés, Lemma 32.2). On the other hand, if $C_i \subset D$ then we get an exact sequence

$$0 \to \mathcal{O}_X(-D)|_{C_i} \to \mathcal{O}_{D'} \to \mathcal{O}_D \to 0$$

by Divisors, Lemma 14.3 and we immediately see the lemma holds.
In Situation 9.3 we have

\[ g_C = 1 + \sum_{i=1, \ldots, n} m_i \left( [\kappa_i : k](g_i - 1) - \frac{1}{2}(C_i \cdot C_i) \right) \]

where \( \kappa_i = H^0(C_i, \mathcal{O}_{C_i}) \), \( g_i \) is the genus of \( C_i \), and \( g_C \) is the genus of \( C \).

**Proof.** Our basic tool will be Derived Categories of Schemes, Lemma 28.2 which shows that

\[ 1 - g_C = \chi(C, \mathcal{O}_C) = \chi(X_k, \mathcal{O}_{X_k}) \]

Choose a sequence of effective Cartier divisors

\[ X_k = D_m \supset D_{m-1} \supset \ldots \supset D_1 \supset D_0 = \emptyset \]

such that \( D_j + 1 = D_j + C_{ij} \) for each \( j \). (It is clear that we can choose such a sequence by decreasing one nonzero multiplicity of \( D_j + 1 \) one step at a time.) Applying Lemma 11.1 starting with \( \chi(\mathcal{O}_{D_0}) = 0 \) we get

\[ 1 - g_C = \chi(X_k, \mathcal{O}_{X_k}) \]

\[ = \sum_j \left( -\left( D_j \cdot C_{ij} \right) + \chi(C_{ij}, \mathcal{O}_{C_{ij}}) \right) \]

\[ = -\sum_j (C_{i1} + C_{i2} + \ldots + C_{i,j-1} \cdot C_i) + \sum_j \chi(C_{ij}, \mathcal{O}_{C_{ij}}) \]

\[ = -\frac{1}{2} \sum_{j \neq j'} (C_{ij'} \cdot C_{ij}) + \sum m_i \chi(C_i, \mathcal{O}_{C_i}) \]

\[ = \frac{1}{2} \sum m_i (C_i \cdot C_i) + \sum m_i \chi(C_i, \mathcal{O}_{C_i}) \]

Perhaps the last equality deserves some explanation. Namely, since \( \sum_j C_{ij} = \sum m_i C_i \) we have \( \sum_j C_{ij} \cdot \sum_j C_{ij} = 0 \) by Lemma 9.7. Thus we see that

\[ 0 = \sum_{j \neq j'} (C_{ij'} \cdot C_{ij}) + \sum m_i (C_i \cdot C_i) \]

by splitting this product into “nondiagonal” and “diagonal” terms. Note that \( \kappa_i \) is a field finite over \( k \) by Varieties, Lemma 26.2. Hence the genus of \( C_i \) is defined and we have \( \chi(C_i, \mathcal{O}_{C_i}) = [\kappa_i : k](1 - g_i) \). Putting everything together and rearranging terms we get

\[ g_C = -\frac{1}{2} \sum m_i (C_i \cdot C_i) + \sum m_i [\kappa_i : k](g_i - 1) + 1 \]

which is what the lemma says too. \( \square \)

**Lemma 11.3.** In Situation 9.3 with \( \kappa_i = H^0(C_i, \mathcal{O}_{C_i}) \) and \( g_i \) the genus of \( C_i \) the data

\[ n, m_i, (C_i \cdot C_j), [\kappa_i : k], g_i \]

is a numerical type of genus equal to the genus of \( C \).

**Proof.** (In the proof of Lemma 11.2 we have seen that the quantities used in the statement of the lemma are well defined.) We have to verify the conditions (1) – (5) of Definition 3.1.

Condition (1) is immediate.

Condition (2). Symmetry of the matrix \((C_i \cdot C_j)\) follows from Equation 9.6.1 and Lemma 9.6. Nonnegativity of \((C_i \cdot C_j)\) for \( i \neq j \) is part (1) of Lemma 9.7.

Condition (3) is part (3) of Lemma 9.7.
Condition (4) is part (2) of Lemma 9.7.
Condition (5) follows from the fact that \((C_i \cdot C_j)\) is the degree of an invertible module on \(C_i\) which is divisible by \([\kappa_i : k]\), see Varieties, Lemma 13.10.

The genus formula proved in Lemma 11.2 tells us that the numerical type has the genus as stated, see Definition 3.4.

**Definition 11.4.** In Situation 9.3 the numerical type associated to \(X\) is the numerical type described in Lemma 11.3.

Now we match minimality of the model with minimality of the type.

**Lemma 11.5.** In Situation 9.3. The following are equivalent

1. \(X\) is a minimal model, and
2. the numerical type associated to \(X\) is minimal.

**Proof.** If the numerical type is minimal, then there is no \(i\) with \(g_i = 0\) and \((C_i \cdot C_i) = [\kappa_i : k]\), see Definition 3.12. Certainly, this implies that none of the curves \(C_i\) are exceptional curves of the first kind.

Conversely, suppose that the numerical type is not minimal. Then there exists an \(i\) such that \(g_i = 0\) and \((C_i \cdot C_i) = [\kappa_i : k]\). We claim this implies that \(C_i\) is an exceptional curve of the first kind. Namely, the invertible sheaf \(\mathcal{O}_X(-C_i)\) has degree \(-(C_i \cdot C_i) = [\kappa_i : k]\) when \(C_i\) is viewed as a proper curve over \(k\), hence has degree 1 when \(C_i\) is viewed as a proper curve over \(\kappa_i\). Applying Algebraic Curves, Proposition 10.4 we conclude that \(C_i \cong \mathbb{P}^1_{\kappa_i}\) as schemes over \(\kappa_i\). Since the Picard group of \(\mathbb{P}^1\) over a field is \(\mathbb{Z}\), we see that the normal sheaf of \(C_i\) in \(X\) is isomorphic to \(\mathcal{O}_{\mathbb{P}^1_{\kappa_i}}(-1)\) and the proof is complete.

**Remark 11.6.** Not every numerical type comes from a model for the silly reason that there exist numerical types whose genus is negative. There exist a minimal numerical types of positive genus which are not the numerical type associated to a model (over some dvr) of a smooth projective geometrically irreducible curve (over the fraction field of the dvr). A simple example is \(n = 1, m_1 = 1, a_{11} = 0, w_1 = 6, g_1 = 1\). Namely, in this case the special fibre \(X_k\) would not be geometrically connected because it would live over an extension \(\kappa\) of degree 6. This is a contradiction with the fact that the generic fibre is geometrically connected (see More on Morphisms, Lemma 48.6). Similarly, \(n = 2, m_1 = m_2 = 1, a_{11} = -a_{22} = a_{12} = a_{21} = 6, w_1 = w_2 = 6, g_1 = g_2 = 1\) would be an example for the same reason (details omitted). But if the gcd of the \(w_i\) is 1 we do not have an example.

**Lemma 11.7.** In Situation 9.3 assume \(C\) has a \(K\)-rational point. Then

1. \(X_k\) has a \(k\)-rational point \(x\) which is a smooth point of \(X_k\) over \(k\),
2. if \(x \in C_i\), then \(H^0(C_i, \mathcal{O}_{C_i}) = k\) and \(m_i = 1\), and
3. \(H^0(X_k, \mathcal{O}_{X_k}) = k\) and \(X_k\) has genus equal to the genus of \(C\).

**Proof.** Since \(X \to \text{Spec}(R)\) is proper, the \(K\)-rational point extends to a morphism \(a : \text{Spec}(R) \to X\) by the valuative criterion of properness (Morphisms, Lemma 40.1). Let \(x \in X\) be the image under \(a\) of the closed point of \(\text{Spec}(R)\). Then \(a\) corresponds to an \(R\)-algebra homomorphism \(\psi : \mathcal{O}_{X,x} \to R\) (see Schemes, Section 13). It follows that \(\pi \not\in \mathfrak{m}_x^2\) (since the image of \(\pi\) in \(R\) is not in \(\mathfrak{m}_R^2\)). Hence \(\mathcal{O}_{X_k,x} = \mathcal{O}_{X,x}/\pi \mathcal{O}_{X,x}\) is regular (Algebra, Lemma 105.3). Then \(X_k \to \text{Spec}(k)\) is
smooth at \( x \) by Algebra, Lemma 138.5. It follows that \( x \) is contained in a unique irreducible component \( C_i \) of \( X_k \), that \( \mathcal{O}_{C_i,x} = \mathcal{O}_{X_k,x} \), and that \( m_i = 1 \). The fact that \( C_i \) has a \( k \)-rational point implies that the field \( \kappa_i = H^0(C_i, \mathcal{O}_{C_i}) \) (Varieties, Lemma 26.2) is equal to \( k \). This proves (1). We have \( H^0(X_k, \mathcal{O}_{X_k}) = k \) because \( H^0(X_k, \mathcal{O}_{X_k}) \) is a field extension of \( k \) (Lemma 9.9) which maps to \( H^0(C_i, \mathcal{O}_{C_i}) = k \). The genus equality follows from Lemma 9.10.

\[ \square \]

Lemma 11.8. In Situation 9.3, assume \( X \) is a minimal model, \( \gcd(m_1, \ldots, m_n) = 1 \), and \( H^0((X_k)_{\text{red}}, \mathcal{O}) = k \). Then the map

\[ H^1(X_k, \mathcal{O}_{X_k}) \to H^1((X_k)_{\text{red}}, \mathcal{O}_{(X_k)_{\text{red}}}) \]

is surjective and has a nontrivial kernel as soon as \( (X_k)_{\text{red}} \neq X_k \).

Proof. By vanishing of cohomology in degrees \( \geq 2 \) over \( X_k \) (Cohomology, Proposition 21.7) any surjection of abelian sheaves on \( X_k \) induces a surjection on \( H^1 \). Consider the sequence

\[ (X_k)_{\text{red}} = Z_0 \subset Z_1 \subset \ldots \subset Z_m = X_k \]

of Lemma 9.9. Since the field maps \( H^0(Z_j, \mathcal{O}_{Z_j}) \to H^0((X_k)_{\text{red}}, \mathcal{O}_{(X_k)_{\text{red}}}) = k \) are injective we conclude that \( H^0(Z_j, \mathcal{O}_{Z_j}) = k \) for \( j = 0, \ldots, m \). It follows that \( H^0(X_k, \mathcal{O}_{X_k}) \to H^0(Z_{m-1}, \mathcal{O}_{Z_{m-1}}) \) is surjective. Let \( C = C_{im} \). Then \( X_k = Z_{m-1} + C \). Let \( \mathcal{L} = \mathcal{O}_X(-Z_{m-1})|_C \). Then \( \mathcal{L} \) is an invertible \( \mathcal{O}_C \)-module. As in the proof of Lemma 9.9 there is an exact sequence

\[ 0 \to \mathcal{L} \to \mathcal{O}_{X_k} \to \mathcal{O}_{Z_{m-1}} \to 0 \]

of coherent sheaves on \( X_k \). We conclude that we get a short exact sequence

\[ 0 \to H^1(C, \mathcal{L}) \to H^1(X_k, \mathcal{O}_{X_k}) \to H^1(Z_{m-1}, \mathcal{O}_{Z_{m-1}}) \to 0 \]

The degree of \( \mathcal{L} \) on \( C \) over \( k \) is

\[ (C \cdot Z_{m-1}) = (C \cdot C - X_k) = (C \cdot C) \]

Set \( \kappa = H^0(C, \mathcal{O}_C) \) and \( w = [\kappa : k] \). By definition of the degree of an invertible sheaf we see that

\[ \chi(C, \mathcal{L}) = \chi(C, \mathcal{O}_C) + (C \cdot C) = w(1 - g_C) + (C \cdot C) \]

where \( g_C \) is the genus of \( C \). This expression is \( < 0 \) as \( X \) is minimal and hence \( C \) is not an exceptional curve of the first kind (see proof of Lemma 11.5). Thus \( \dim_k H^1(C, \mathcal{L}) > 0 \) which finishes the proof. \( \square \)

Lemma 11.9. In Situation 9.3, assume \( X_k \) has a \( k \)-rational point \( x \) which is a smooth point of \( X_k \) \( \to \text{Spec}(k) \). Then

\[ \dim_k H^1((X_k)_{\text{red}}, \mathcal{O}_{(X_k)_{\text{red}}}) \geq g_{\text{top}} + g_{\text{geom}}(X_k/k) \]

where \( g_{\text{geom}} \) is as in Algebraic Curves, Section 18 and \( g_{\text{top}} \) is the topological genus (Definition 11.1) of the numerical type associated to \( X_k \) (Definition 11.4).

Proof. We are going to prove the inequality

\[ \dim_k H^1(D, \mathcal{O}_D) \geq g_{\text{top}}(D) + g_{\text{geom}}(D/k) \]

for all connected reduced effective Cartier divisors \( D \subset (X_k)_{\text{red}} \) containing \( x \) by induction on the number of irreducible components of \( D \). Here \( g_{\text{top}}(D) = 1 - m + e \) where \( m \) is the number of irreducible components of \( D \) and \( e \) is the number of unordered pairs of components of \( D \) which meet.
Base case: $D$ has one irreducible component. Then $D = C_i$ is the unique irreducible component containing $x$. In this case $\dim_k H^1(D, \mathcal{O}_D) = g_i$ and $g_{\text{top}}(D) = 0$. Since $C_i$ has a $k$-rational smooth point it is geometrically integral (Varieties, Lemma 25.10). It follows that $g_i$ is the genus of $C_{i, \overline{k}}$ (Algebraic Curves, Lemma 8.2). It also follows that $g_{\text{geom}}(D/k)$ is the genus of the normalization $C'_{i, \overline{k}}$ of $C_{i, \overline{k}}$. Applying Algebraic Curves, Lemma 18.4 to the normalization morphism $C'_{i, \overline{k}} \to C_{i, \overline{k}}$ we get

0CEB (11.9.1) genus of $C_{i, \overline{k}} \geq \text{genus of } C'_{i, \overline{k}}$

Combining the above we conclude that $\dim_k H^1(D, \mathcal{O}_D) \geq g_{\text{top}}(D) + g_{\text{geom}}(D/k)$ in this case.

Induction step. Suppose we have $D$ with more than 1 irreducible component. Then we can write $D = C_i + D'$ where $x \in D'$ and $D'$ is still connected. This is an exercise in graph theory we leave to the reader (hint: let $C_i$ be the component of $D$ which is farthest from $x$). We compute how the invariants change. As $x \in D'$ we have $H^0(D, \mathcal{O}_D) = H^0(D', \mathcal{O}_{D'}) = k$. Looking at the short exact sequence of sheaves

$$0 \to \mathcal{O}_D \to \mathcal{O}_{C_i} \oplus \mathcal{O}_{D'} \to \mathcal{O}_{C_i \cup D'} \to 0$$

(Morphisms, Lemma 4.6) and using additivity of euler characteristics we find

$$\dim_k H^1(D, \mathcal{O}_D) - \dim_k H^1(D', \mathcal{O}_{D'}) = -\chi(\mathcal{O}_{C_i}) + \chi(\mathcal{O}_{C_i \cup D'})$$

$$= w_i(g_i - 1) + \sum_{C_j \subset D'} a_{ij}$$

Here as in Lemma 11.3 we set $w_i = [\kappa_i : k]$, $\kappa_i = H^0(C_i, \mathcal{O}_{C_i})$, $g_i$ is the genus of $C_i$, and $a_{ij} = (C_i \cdot C_j)$. We have

$$g_{\text{top}}(D) - g_{\text{top}}(D') = -1 + \sum_{C_j \subset D'} \text{meeting } C_i, 1$$

We have

$$g_{\text{geom}}(D/k) - g_{\text{geom}}(D'/k) = g_{\text{geom}}(C_i/k)$$

by Algebraic Curves, Lemma 18.4. Combining these with our induction hypothesis, we conclude that it suffices to show that

$$w_i g_i - g_{\text{geom}}(C_i/k) + \sum_{C_j \subset D'} \text{meets } C_i(a_{ij} - 1) - (w_i - 1)$$

is nonnegative. In fact, we have

0CEC (11.9.2) $w_i g_i \geq [\kappa_i : k], g_i \geq g_{\text{geom}}(C_i/k)$

The second inequality by Algebraic Curves, Lemma 18.5. On the other hand, since $w_i$ divides $a_{ij}$ (Varieties, Lemma 43.10) it is clear that

0CED (11.9.3) $\sum_{C_j \subset D'} \text{meets } C_i(a_{ij} - 1) - (w_i - 1) \geq 0$

because there is at least one $C_j \subset D'$ which meets $C_i$. □

0CEE Lemma 11.10. If equality holds in Lemma 11.9 then

1. the unique irreducible component of $X_k$ containing $x$ is a smooth projective geometrically irreducible curve over $k$,
2. if $C \subset X_k$ is another irreducible component, then $\kappa = H^0(C, \mathcal{O}_C)$ is a finite separable extension of $k$, $C$ has a $\kappa$-rational point, and $C$ is smooth over $\kappa$
The following lemma tells us what happens with the intersection numbers when we contract an exceptional curve of the first kind. Let $f$ be the contraction of $C_1$ in a regular proper model. We put $C_{i,\overline{k}}$ be the irreducible component containing $x$. Equality in (11.9.1) shows via Algebraic Curves, Lemma [18.4] that $C_{i,\overline{k}} \to C_{i,\overline{k}}$ is an isomorphism. Hence $C_{i,\overline{k}}$ is smooth and part (1) holds.

Next, let $C_i \subset X_k$ be another irreducible component. Then we may assume we have $D = D' + C_i$ as in the induction step in the proof of Lemma [11.9]. Equality in (11.9.2) immediately implies that $\kappa_i/k$ is finite separable. Equality in (11.9.3) implies either $a_{ij} = 1$ for some $j$ or that there is a unique $C_j \subset D'$ meeting $C_i$ and $a_{ij} = w_i$. In both cases we find that $C_i$ has a $\kappa_i$-rational point $c$ and $c = C_i \cap C_j$ scheme theoretically. Since $O_{X,c}$ is a regular local ring, this implies that the local equations of $C_i$ and $C_j$ form a regular system of parameters in the local ring $O_{X,c}$. Then $O_{C_{i,c}}$ is regular by (Algebra, Lemma [105.3]). We conclude that $C_i \to \Spec(\kappa_i)$ is smooth at $c$ (Algebra, Lemma [138.5]). It follows that $C_i$ is geometrically integral over $\kappa_i$ (Varieties, Lemma [25.10]). To finish we have to show that $C_i$ is smooth over $\kappa_i$. Observe that

\[ C_{i,\overline{k}} = C_i \times_{\Spec(k)} \Spec(\overline{k}) = \coprod_{\kappa_i \to \kappa} C_i \times_{\Spec(\kappa_i)} \Spec(\overline{k}) \]

where there are $[\kappa_i : k]$-summands. Thus if $C_i$ is not smooth over $\kappa_i$, then each of these curves is not smooth, then these curves are not normal and the normalization morphism drops the genus (Algebraic Curves, Lemma [18.4]) which is disallowed because it would drop the geometric genus of $C_i/k$ contradicting $[\kappa_i : k]g_i = g_{\text{geom}}(C_i/k)$.

### 12. Blowing down exceptional curves

0CEF The following lemma tells us what happens with the intersection numbers when we contract an exceptional curve of the first kind in a regular proper model. We put this here mostly to compare with the numerical contractions introduced in Lemma [3.9]. We will compare the geometric and numerical contractions in Remark [12.3].

0C6C **Lemma 12.1.** In Situation [9.3] assume that $C_n$ is an exceptional curve of the first kind. Let $f : X \to X'$ be the contraction of $C_n$. Let $C'_i = f(C_i)$. Write $X'_i = \sum m'_i C_i'$. Then $X', C'_i, i = 1, \ldots, n' = n - 1$, and $m'_i = m_i$ is as in Situation [9.3] and we have

1. for $i, j < n$ we have $(C'_i \cdot C'_j) = (C_i \cdot C_j) - (C_i \cdot C_n)(C_j \cdot C_n)/(C_n \cdot C_n)$,
2. for $i < n$ if $C_i \cap C_n \neq \emptyset$, then there are maps $\kappa_i \to \kappa'_i$.

Here $\kappa_i = H^0(C_i, O_{C_i})$ and $\kappa'_i = H^0(C'_i, O_{C'_i})$.

**Proof.** By Resolution of Surfaces, Lemma [16.8] we can contract $C_n$ by a morphism $f : X \to X'$ such that $X'$ is regular and is projective over $R$. Thus we see that $X'$ is as in Situation [9.3]. Let $x \in X'$ be the image of $C_n$. Since $f$ defines an isomorphism $X \setminus C_n \to X' \setminus \{x\}$ it is clear that $m'_i = m_i$ for $i < n$.

Part (2) of the lemma is immediately clear from the existence of the morphisms $C_i \to C'_i$ and $C_n \to x \to C'_i$.

By Divisors, Lemma [32.11] the pullback $f^{-1}C'_i$ is defined. By Divisors, Lemma [15.11] we see that $f^{-1}C'_i = C_i + e_i C_n$ for some $e_i \geq 0$. Since $O_X(C_i + e_i C_n) = O_X(C_i) \oplus O_X(e_i C_n)$, we have

\[ f^{-1}C'_i = C_i + e_i C_n. \]
\(O_X(f^{-1}C_j') = f^*O_X(C_j')\) (Divisors, Lemma 14.5) and since the pullback of an invertible sheaf restricts to the trivial invertible sheaf on \(C_n\), we see that

\[0 = \deg_{C_n}(O_X(C_i + e_iC_n)) = (C_i + e_iC_n \cdot C_n) = (C_i \cdot C_n) + e_i(C_n \cdot C_n)\]

As \(f_j = f|_{C_j} : C_j \to C_j\) is a proper birational morphism of proper curves over \(k\), we see that \(\deg_{C_j}(O_X(C_i')|_{C_j})\) is the same as \(\deg_{C_j}(f_j^*O_X(C_i')|_{C_j})\) (Varieties, Lemma 43.4). Looking at the commutative diagram

\[
\begin{array}{ccc}
C_j & \xrightarrow{f_j} & X \\
\downarrow & & \downarrow f \\
C_j' & \xrightarrow{f} & X'
\end{array}
\]

and using Divisors, Lemma 14.5 we see that

\[(C_i', C_j') = \deg_{C_j}(O_X(C_i')|_{C_j}) = \deg_{C_j}(O_X(C_i + e_iC_n)) = (C_i + e_iC_n \cdot C_j)\]

Plugging in the formula for \(e_i\) found above we see that (1) holds. \(\square\)

**Remark 12.2.** In the situation of Lemma 12.1 we can also say exactly how the genus \(g_i\) of \(C_i\) and the genus \(g_i'\) of \(C_i'\) are related. The formula is

\[g_i' = \frac{w_i}{w_i'}(g_i - 1) + 1 + \frac{(C_i \cdot C_n)^2 - w_n(C_i \cdot C_n)}{2w_i'w_n}\]

where \(w_i = [\kappa_i : k]\), \(w_n = [\kappa_n : k]\), and \(w_i' = [\kappa_i' : k]\). To prove this we consider the short exact sequence

\[0 \to O_X(-C_i) \to O_{X'} \to O_{C_i} \to 0\]

and its pullback to \(X\) which reads

\[0 \to O_X(-C_i' - e_iC_n) \to O_X \to O_{C_i + e_iC_n} \to 0\]

with \(e_i\) as in the proof of Lemma 12.1. Since \(Rf_*f^*L = L\) for any invertible module \(L\) on \(X'\) (details omitted), we conclude that

\[Rf_*O_{C_i + e_iC_n} = O_{C_i'}\]

as complexes of coherent sheaves on \(X'_k\). Hence both sides have the same Euler characteristic and this agrees with the Euler characteristic of \(O_{C_i + e_iC_n}\) on \(X_k\). Using the exact sequence

\[0 \to O_{C_i + e_iC_n} \to O_{C_i} \oplus O_{e_iC_n} \to O_{C_i \cap e_iC_n} \to 0\]

and further filtering \(O_{e_iC_n}\) (details omitted) we find

\[\chi(O_{C_i'}) = \chi(O_{C_i}) - \left(\frac{e_i + 1}{2}\right)(C_n \cdot C_n) - e_i(C_i \cdot C_n)\]

Since \(e_i = -(C_i \cdot C_n)/(C_n \cdot C_n)\) and \((C_n \cdot C_n) = -w_n\) this leads to the formula stated at the start of this remark. If we ever need this we will formulate this as a lemma and provide a detailed proof.

**Remark 12.3.** Let \(f : X \to X'\) be as in Lemma 12.1. Let \(n, m_i, a_{ij}, w_i, g_i\) be the numerical type associated to \(X\) and let \(n', m_{ij}', a_{ij}', w_i', g_i'\) be the numerical type associated to \(X'\). It is clear from Lemma 12.1 and Remark 12.2 that this agrees with the contraction of numerical types in Lemma 3.9 except for the value of \(w_i'\). In the geometric situation \(w_i'\) is some positive integer dividing both \(w_i\) and \(w_n\). In the
numerical case we chose $w'_i$ to be the largest possible integer dividing $w_i$ such that $g'_i$ (as given by the formula) is an integer. This works well in the numerical setting in that it helps compare the Picard groups of the numerical types, see Lemma \(4.4\) (although only injectivity is every used in the following and this injectivity works as well for smaller $w'_i$).

**Lemma 12.4.** Let $C$ be a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$ and genus 0. If there is more than one minimal model for $C$, then the special fibre of every minimal model is isomorphic to $\mathbb{P}^1_k$.

This lemma can be improved to say that the birational transformation between two nonisomorphic minimal models can be factored as a sequence of elementary transformations as in Example \[10.3\]. If we ever need this, we will precisely formulate and prove this here.

**Proof.** Let $X$ be some minimal model of $C$. The numerical type associated to $X$ has genus 0 and is minimal (Definition \[11.4\] and Lemma \[11.5\]). Hence by Lemma \[6.1\] we see that $X_k$ is reduced, irreducible, has $H^0(X_k, \mathcal{O}_{X_k}) = k$, and has genus 0. Let $Y'$ be a second minimal model for $C$ which is not isomorphic to $X$. By Resolution of Surfaces, Lemma \[17.2\] there exists a diagram of $S$-morphisms

$$X = X_0 \leftarrow X_1 \leftarrow \ldots \leftarrow X_n = Y_m \rightarrow \ldots \rightarrow Y_1 \rightarrow Y_0 = Y$$

where each morphism is a blowup in a closed point. We will prove the lemma by induction on $m$. The base case is $m = 0$; it is true in this case because we assumed that $Y$ is minimal hence this would mean $n = 0$, but $X$ is not isomorphic to $Y$, so this does not happen, i.e., there is nothing to check.

Before we continue, note that $n + 1 = m + 1$ is equal to the number of irreducible components of the special fibre of $X_n = Y_m$ because both $X_k$ and $Y_k$ are irreducible.

Another observation we will use below is that if $X' \rightarrow X''$ is a morphism of regular proper models for $C$, then $X' \rightarrow X''$ is an isomorphism over an open set of $X''$ whose complement is a finite set of closed points of the special fibre of $X''$, see Varieties, Lemma \[17.3\]. In fact, any such $X' \rightarrow X''$ is a sequence of blowing ups in closed points (Resolution of Surfaces, Lemma \[17.1\]) and the number of blowups is the difference in the number of irreducible components of the special fibres of $X'$ and $X''$.

Let $E_i \subset Y_i$, $m \geq i \geq 1$ be the curve which is contracted by the morphism $Y_i \rightarrow Y_{i-1}$. Let $i$ be the biggest index such that $E_i$ has multiplicity $> 1$ in the special fibre of $Y_i$. Then the further blowups $Y_m \rightarrow \ldots \rightarrow Y_{i+1} \rightarrow Y_i$ are isomorphisms over $E_i$ since otherwise $E_j$ for some $j > i$ would have multiplicity $> 1$. Let $E \subset Y_m$ be the inverse image of $E_i$. By what we just said $E \subset Y_m$ is an exceptional curve of the first kind. Let $Y_m \rightarrow Y'$ be the contraction of $E$ (which exists by Resolution of Surfaces, Lemma \[16.9\]). The morphism $Y_m \rightarrow X$ has to contract $E$, because $X_k$ is reduced. Hence there are morphisms $Y' \rightarrow Y$ and $Y' \rightarrow X$ (by Resolution of Surfaces, Lemma \[16.1\]) which are compositions of at most $n-1 = m-1$ contractions of exceptional curves (see discussion above). We win by induction on $m$. Upshot: we may assume that the special fibres of all of the curves $X_i$ and $Y_i$ are reduced.

Since the fibres of $X_i$ and $Y_i$ are reduced, it has to be the case that the blowups $X_i \rightarrow X_{i-1}$ and $Y_i \rightarrow Y_{i-1}$ happen in closed points which are regular points of the special fibres. Namely, if $X''$ is a regular model for $C$ and if $x \in X''$ is a
closed point of the special fibre, and \( \pi \in \mathfrak{m}^2 \), then the exceptional fibre \( E \) of the blowup \( X' \to X'' \) at \( x \) has multiplicity at least 2 in the special fibre of \( X' \) (local computation omitted). Hence \( \mathcal{O}_{X'' x} = \mathcal{O}_{X'' x}/\pi \) is regular (Algebra, Lemma \[105.3\]) as claimed. In particular \( x \) is a Cartier divisor on the unique irreducible component \( Z' \) of \( X'' \) it lies on (Varieties, Lemma \[43.16\]). It follows that the strict transform \( Z \subset X' \) of \( Z' \) maps isomorphically to \( Z' \) (use Divisors, Lemmas \[33.2\] and \[32.7\]). In other words, if an irreducible component \( Z \) of \( X \) is not contracted under the map \( X_i \to X_j \) \((i > j)\) then it maps isomorphically to its image.

Now we are ready to prove the lemma. Let \( E \subset Y_m \) be the exceptional curve of the first kind which is contracted by the morphism \( Y_m \to Y_{m-1} \). If \( E \) is contracted by the morphism \( Y_m = X_n \to X \), then there is a factorization \( Y_{m-1} \to X \) (Resolution of Surfaces, Lemma \[16.1\]) and moreover \( Y_{m-1} \to X \) is a sequence of blowups in closed points (Resolution of Surfaces, Lemma \[17.1\]). In this case we lower \( m \) and we win by induction. Finally, assume that \( E \) is not contracted by the morphism \( Y_m \to X \). Then \( E \to X_k \) is surjective as \( X_k \) is irreducible and by the above this means it is an isomorphism. Hence \( X_k \) is isomorphic to a projective line as desired. \( \square \)

### 13. Picard groups of models

0CAA Assume \( R, K, k, \pi, C, X, n, C_1, \ldots, C_n, m_1, \ldots, m_n \) are as in Situation \[9.3\]. In Lemma \[9.5\] we found an exact sequence

\[ 0 \to Z \to Z^\oplus n \to \text{Pic}(X) \to \text{Pic}(C) \to 0 \]

We want to use this sequence to study the \( \ell \)-torsion in the Picard groups for suitable primes \( \ell \).

0CAB **Lemma** \[13.1\]. In Situation \[9.3\] let \( d = \gcd(m_1, \ldots, m_n) \). If \( \mathcal{L} \) is an invertible \( \mathcal{O}_X \)-module which

1. restricts to the trivial invertible module on \( C \), and
2. has degree 0 on each \( C_i \),

then \( \mathcal{L}^\oplus n \cong \mathcal{O}_X \).

**Proof.** By Lemma \[9.5\] we have \( \mathcal{L} \cong \mathcal{O}_X(\sum a_i C_i) \) for some \( a_i \in \mathbb{Z} \). The degree of \( \mathcal{L}|_{C_i} \) is \( \sum a_j (C_i \cdot C_j) \). In particular \( \sum a_i C_i \cdot \sum a_i C_i = 0 \). Hence we see from Lemma \[9.7\] that \( (a_1, \ldots, a_n) = q(m_1, \ldots, m_n) \) for some \( q \in \mathbb{Q} \). Thus \( \mathcal{L} = \mathcal{O}_X(ID) \) for some \( I \in \mathbb{Z} \) where \( D = \sum (m_i/d) C_i \) is as in Lemma \[9.8\] and we conclude. \( \square \)

0CAC **Lemma** \[13.2\]. In Situation \[9.3\] let \( T \) be the numerical type associated to \( X \). There exists a canonical map

\[ \text{Pic}(C) \to \text{Pic}(T) \]

whose kernel is exactly those invertible modules on \( C \) which are the restriction of invertible modules \( \mathcal{L} \) on \( X \) with \( \deg_{C_i}(\mathcal{L}|_{C_i}) = 0 \) for \( i = 1, \ldots, n \).

**Proof.** Recall that \( w_i = [\kappa_i : k] \) where \( \kappa_i = H^0(C_i, \mathcal{O}_{C_i}) \) and recall that the degree of any invertible module on \( C_i \) is divisible by \( w_i \) (Varieties, Lemma \[13.10\]). Thus we can consider the map

\[ \frac{\deg}{w} : \text{Pic}(X) \to \mathbb{Z}^\oplus n, \quad \mathcal{L} \mapsto \left( \frac{\deg(\mathcal{L}|_{C_1})}{w_1}, \ldots, \frac{\deg(\mathcal{L}|_{C_n})}{w_n} \right) \]
The image of $\mathcal{O}_X(C_j)$ under this map is

$$( (C_j \cdot C_j)/w_1, \ldots, (C_j \cdot C_n)/w_n ) = (a_{1j}/w_1, \ldots, a_{nj}/w_n)$$

which is exactly the image of the $j$th basis vector under the map $(a_{ij}/w_i) : \mathbb{Z}^{\oplus n} \to \mathbb{Z}^{\oplus n}$ defining the Picard group of $T$, see Definition 4.1. Thus the canonical map of the lemma comes from the commutative diagram

$$\begin{array}{ccc}
\mathbb{Z}^{\oplus n} & \longrightarrow & \text{Pic}(X) \\
\text{id} & \downarrow & \uparrow \\
\mathbb{Z}^{\oplus n} & \longrightarrow & \text{Pic}(T)
\end{array}$$

with exact rows (top row by Lemma 9.5). The description of the kernel is clear. □

0CAD Lemma 13.3. In Situation 9.3 let $d = \gcd(m_1, \ldots, m_n)$ and let $T$ be the numerical type associated to $X$. Let $h \geq 1$ be an integer prime to $d$. There exists an exact sequence

$$0 \to \text{Pic}(X)[h] \to \text{Pic}(C)[h] \to \text{Pic}(T)[h]$$

Proof. Taking $h$-torsion in the exact sequence of Lemma 9.5 we obtain the exactness of $0 \to \text{Pic}(X)[h] \to \text{Pic}(C)[h]$ because $h$ is prime to $d$. Using the map Lemma 13.1 we get a map $\text{Pic}(C)[h] \to \text{Pic}(T)[h]$ which annihilates elements of $\text{Pic}(X)[h]$. Conversely, if $\xi \in \text{Pic}(C)[h]$ maps to zero in $\text{Pic}(T)[h]$, then we can find an invertible $\mathcal{O}_X$-module $\mathcal{L}$ with $\deg(\mathcal{L}[\xi]) = 0$ for all $\xi$ whose restriction to $C$ is $\xi$. Then $\mathcal{L}^{\oplus h}$ is $d$-torsion by Lemma 13.1. Let $d'$ be an integer such that $dd' \equiv 1 \mod h$. Such an integer exists because $h$ and $d$ are coprime. Then $\mathcal{L}^{\oplus dd'}$ is an $h$-torsion invertible sheaf on $X$ whose restriction to $C$ is $\xi$. □

0CAE Lemma 13.4. In Situation 9.3 let $h$ be an integer prime to the characteristic of $k$. Then the map

$$\text{Pic}(X)[h] \to \text{Pic}((X_\text{red})[h]$$

is injective.

Proof. Observe that $X \times \text{Spec}(R) \text{Spec}(R/\pi^n)$ is a finite order thickening of $(X_\text{red})$ (this follows for example from Cohomology of Schemes, Lemma 10.2). Thus the canonical map $\text{Pic}(X \times \text{Spec}(R) \text{Spec}(R/\pi^n)) \to \text{Pic}((X_\text{red}))$ identifies $h$ torsion by More on Morphisms, Lemma 13.2 and our assumption on $h$. Thus if $\mathcal{L}$ is an $h$-torsion invertible sheaf on $X$ which restricts to the trivial sheaf on $(X_\text{red})$ then $\mathcal{L}$ restricts to the trivial sheaf on $X \times \text{Spec}(R) \text{Spec}(R/\pi^n)$ for all $n$. We find

$$H^0(X, \mathcal{L})^h = \lim H^0(X \times \text{Spec}(R) \text{Spec}(R/\pi^n), \mathcal{L}|_{X \times \text{Spec}(R) \text{Spec}(R/\pi^n)})$$

$$\cong \lim H^0(X \times \text{Spec}(R) \text{Spec}(R/\pi^n), \mathcal{O}_{X \times \text{Spec}(R) \text{Spec}(R/\pi^n)})$$

$$= R^h$$

using the theorem on formal functions (Cohomology of Schemes, Theorem 20.5) for the first and last equality and for example More on Algebra, Lemma 90.4 for the middle isomorphism. Since $H^0(X, \mathcal{L})$ is a finite $R$-module and $R$ is a discrete valuation ring, this means that $H^0(X, \mathcal{L})$ is free of rank 1 as an $R$-module. Let $s \in H^0(X, \mathcal{L})$ be a basis element. Then tracing back through the isomorphisms above we see that $s|_{X \times \text{Spec}(R) \text{Spec}(R/\pi^n)}$ is a trivialization for all $n$. Since the vanishing locus of $s$ is closed in $X$ and $X \to \text{Spec}(R)$ is proper we conclude that the vanishing locus of $s$ is empty as desired. □
14. Semistable reduction

0CDB In this section we carefully define what we mean by semistable reduction.

0CDC Example 14.1. Let $R$ be a discrete valuation ring with uniformizer $\pi$. Given $n \geq 0$, consider the ring map

$$R \rightarrow A = R[x, y]/(xy - \pi^n)$$

Set $X = \text{Spec}(A)$ and $S = \text{Spec}(R)$. If $n = 0$, then $X \rightarrow S$ is smooth. For all $n$ the morphism $X \rightarrow S$ is at-worst-nodal of relative dimension 1 as defined in Algebraic Curves, Section 20. If $n = 1$, then $X$ is regular, but if $n > 1$, then $X$ is not regular as $(x, y)$ no longer generate the maximal ideal $m = (\pi, x, y)$. To ameliorate the situation in case $n > 1$ we consider the blowup $b : X' \rightarrow X$ of $X$ in $m$. See Divisors, Section 32. By construction $X'$ is covered by three affine pieces corresponding to the blowup algebras $A[\frac{m}{x}], A[\frac{m}{x}], A[\frac{m}{y}]$.

The algebra $A[\frac{m}{x}]$ has generators $x' = x/\pi$ and $y' = y/\pi$ and $x'y' = \pi^{n-2}$. Thus this part of $X'$ is the spectrum of $R[x', y']/(x'y' - \pi^{n-2})$.

The algebra $A[\frac{m}{y}]$ has generators $x, u = \pi/x$ subject to the relation $xu = \pi$. Note that this ring contains $y/x = \pi^n/x^2 = u^2\pi^{n-2}$. Thus this part of $X'$ is regular.

By symmetry the case of the algebra $A[\frac{m}{y}]$ is the same as the case of $A[\frac{m}{x}]$.

Thus we see that $X' \rightarrow S$ is at-worst-nodal of relative dimension 1 and that $X'$ is regular, except for one point which has an affine open neighbourhood exactly as above but with $n$ replaced by $n - 2$. Using induction on $n$ we conclude that there is a sequence of blowing ups in closed points

$$X_{[n/2]} \rightarrow \ldots \rightarrow X_1 \rightarrow X_0 = X$$

such that $X_{[n/2]} \rightarrow S$ is at-worst-nodal of relative dimension 1 and $X_{[n/2]}$ is regular.

0CDD Lemma 14.2. Let $R$ be a discrete valuation ring. Let $X$ be a scheme which is at-worst-nodal of relative dimension 1 over $R$. Let $x \in X$ be a point of the special fibre of $X$ over $R$. Then there exists a commutative diagram

$$
\begin{array}{ccc}
X & \leftarrow & U \\
\downarrow & & \downarrow \\
\text{Spec}(R) & \leftarrow & \text{Spec}(R')
\end{array}
$$

where $R \subset R'$ is an étale extension of discrete valuation rings, the morphism $U \rightarrow X$ is étale, there is a point $x' \in U$ mapping to $x$, and

$$A = R'[u, v]/(uv) \quad \text{or} \quad A = R'[u, v]/(uv - \pi^n)$$

where $n \geq 0$ and $\pi \in R'$ is a uniformizer.

Proof. We have already proved this lemma in much greater generality, see Algebraic Curves, Lemma 20.12. All we have to do here is to translate the statement given there into the statement given above.

First, if the morphism $X \rightarrow \text{Spec}(R)$ is smooth at $x$, then we can find an étale morphism $U \rightarrow \mathbf{A}^1_R = \text{Spec}(R[u])$ for some affine open neighbourhood $U \subset X$ of $x$. This is Morphisms, Lemma 34.20. After replacing the coordinate $u$ by $u + 1$ if
necessary, we may assume that $x$ maps to a point in the standard open $D(u) \subset \mathbb{A}^1_R$. Then $D(u) = \text{Spec}(A)$ with $A = R[u,v]/(uv - 1)$ and we see that the result is true in this case.

Next, assume that $x$ is a singular point of the fibre. Then we may apply Algebraic Curves, Lemma 20.12 to get a diagram

$$
\begin{array}{ccc}
X & \leftarrow & U \\
\downarrow & & \downarrow \\
\text{Spec}(R) & \leftarrow & V \\
\downarrow & & \downarrow \\
W & \rightarrow & \text{Spec}(\mathbb{Z}[u,v]/(uv - a))
\end{array}
$$

with all the properties mentioned in the statement of the cited lemma. Let $x' \in U$ be the point mapping to $x$ promised by the lemma. First we shrink $V$ to an affine neighbourhood of the image of $x'$. Say $V = \text{Spec}(R')$. Then $R \to R'$ is étale. Since $R$ is a discrete valuation ring, we see that $R'$ is a finite product of quasi-local Dedekind domains (use More on Algebra, Lemma [43.4]). Hence (for example using prime avoidance) we find a standard open $D(f) \subset V = \text{Spec}(R')$ containing the image of $x'$ such that $R'_f$ is a discrete valuation ring. Replacing $R'$ by $R'_f$ we reach the situation where $V = \text{Spec}(R')$ with $R \subset R'$ an étale extension of discrete valuation rings (extensions of discrete valuation rings are defined in More on Algebra, Definition [99.1]).

The morphism $V \to \text{Spec}(\mathbb{Z}[a])$ is determined by the image $h$ of $a$ in $R'$. Then $W = \text{Spec}(R'[u,v]/(uv - h))$. Thus the lemma holds with $A = R'[u,v]/(uv - h)$. If $h = 0$ then we clearly obtain the first case mentioned in the lemma. If $h \neq 0$ then we may write $h = \epsilon \pi^n$ for some $n \geq 0$ where $\epsilon$ is a unit of $R'$. Changing coordinates $u_{\text{new}} = \epsilon u$ and $v_{\text{new}} = v$ we obtain the second isomorphism type of $A$ listed in the lemma. □

**Lemma 14.3.** Let $R$ be a discrete valuation ring. Let $X$ be a quasi-compact scheme which is at-worst-nodal of relative dimension 1 with smooth generic fibre over $R$. Then there exists $m \geq 0$ and a sequence

$$X_m \to \ldots \to X_1 \to X_0 = X$$

such that

1. $X_{i+1} \to X_i$ is the blowing up of a closed point $x_i$ where $X_i$ is singular,
2. $X_i \to \text{Spec}(R)$ is at-worst-nodal of relative dimension 1,
3. $X_m$ is regular.

A slightly stronger statement (also true) would be that no matter how you blow up in singular points you eventually end up with a resolution and all the intermediate blowups are at-worst-nodal of relative dimension 1 over $R$.

**Proof.** Since $X$ is quasi-compact we see that the special fibre $X_k$ is quasi-compact. Since the singularities of $X_k$ are at-worst-nodal, we see that $X_k$ has a finite number of nodes and is otherwise smooth over $k$. As $X \to \text{Spec}(R)$ is flat with smooth generic fibre it follows that $X$ is smooth over $R$ except at the finite number of nodes of $X_k$ (use Morphisms, Lemma [32.14]). It follows that $X$ is regular at every point except for possibly the nodes of its special fibre (see Algebra, Lemma [157.10]).
Let $x \in X$ be such a node. Choose a diagram

\[
\begin{array}{ccc}
X & \leftarrow & U \\
\downarrow & & \downarrow \\
\text{Spec}(R) & \leftarrow & \text{Spec}(R')
\end{array}
\]

as in Lemma \[14.2\]. Observe that the case $A = R'[u,v]/(uv)$ cannot occur, as this would mean that the generic fibre of $X/R$ is singular (tiny detail omitted). Thus $A = R'[u,v]/(uv - \pi^n)$ for some $n \geq 0$. Since $x$ is a singular point, we have $n \geq 2$, see discussion in Example \[14.1\].

After shrinking $U$ we may assume there is a unique point $u \in U$ mapping to $x$. Let $w \in \text{Spec}(A)$ be the image of $u$. We may also assume that $u$ is the unique point of $U$ mapping to $w$. Since the two horizontal arrows are étale we see that $u$, viewed as a closed subscheme of $U$, is the scheme theoretic inverse image of $x \in X$ and the scheme theoretic inverse image of $w \in \text{Spec}(A)$. Since blowing up commutes with flat base change (Divisors, Lemma \[32.3\]) we find a commutative diagram

\[
\begin{array}{ccc}
X' & \leftarrow & U' \\
\downarrow & & \downarrow \\
X & \leftarrow & U \\
\downarrow & & \downarrow \\
\text{Spec}(A)
\end{array}
\]

with cartesian squares where the vertical arrows are the blowing up of $x, u, w$ in $X, U, \text{Spec}(A)$. The scheme $W'$ was described in Example \[14.1\]. We saw there that $W'$ is at-worst-nodal of relative dimension 1 over $R'$. Thus $W''$ is at-worst-nodal of relative dimension 1 over $R$ (Algebraic Curves, Lemma \[20.7\]). Hence $U'$ is at-worst-nodal of relative dimension 1 over $R$ (see Algebraic Curves, Lemma \[20.8\]). Since $X' \to X$ is an isomorphism over the complement of $x$, we conclude the same thing is true of $X'/R$ (by Algebraic Curves, Lemma \[20.8\] again).

Finally, we need to argue that after doing a finite number of these blowups we arrive at a regular model $X_m$. This is rather clear because the “invariant” $n$ decreases by 2 under the blowup described above, see computation in Example \[14.1\]. However, as we want to avoid precisely defining this invariant and establishing its properties, we in stead argue as follows. If $n = 2$, then $W'$ is regular and hence $X'$ is regular at all points lying over $x$ and we have decreased the number of singular points of $X$ by 1. If $n > 2$, then the unique singular point $w'$ of $W'$ lying over $w$ has $\kappa(w) = \kappa(w')$. Hence $U'$ has a unique singular point $u'$ lying over $u$ with $\kappa(u) = \kappa(u')$. Clearly, this implies that $X'$ has a unique singular point $x'$ lying over $x$, namely the image of $u'$. Thus we can argue exactly as above that we get a commutative diagram

\[
\begin{array}{ccc}
X'' & \leftarrow & U'' \\
\downarrow & & \downarrow \\
X' & \leftarrow & U' \\
\downarrow & & \downarrow \\
X & \leftarrow & U \\
\downarrow & & \downarrow \\
\text{Spec}(A)
\end{array}
\]

with cartesian squares where the vertical arrows are the blowing up of $x', u', w'$ in $X', U', W'$. Continuing like this we get a compatible sequence of blowups which stops after $\lfloor n/2 \rfloor$ steps. At the completion of this process the scheme $X(\lfloor n/2 \rfloor)$ will
have one fewer singular point than $X$. Induction on the number of singular points completes the proof. □

**Lemma 14.4.** Let $R$ be a discrete valuation ring with fraction field $K$ and residue field $k$. Assume $X \to \text{Spec}(R)$ is at-worst-nodal of relative dimension 1 over $R$. Let $X \to X'$ be the contraction of an exceptional curve $E \subset X$ of the first kind. Then $X'$ is at-worst-nodal of relative dimension 1 over $R$.

**Proof.** Namely, let $x' \in X'$ be the image of $E$. Then the only issue is to see that $X' \to \text{Spec}(R)$ is at-worst-nodal of relative dimension 1 in a neighbourhood of $x'$. The closed fibre of $X \to \text{Spec}(R)$ is reduced, hence $\pi \in R$ vanishes to order 1 on $E$. Since $\mathcal{O}_{X',x'}$ is regular of dimension 2 (by definition of contractions in Resolution of Surfaces, Section 16), this implies that $\mathcal{O}_{X',x'}$ is regular of dimension 1 (Algebra, Lemma 105.3). On the other hand, the curve $E$ has to meet at least one other component, say $C$ of the closed fibre $X_k$. Say $x \in E \cap C$. Then $x$ is a node of the special fibre $X_k$ and hence $\kappa(x)/k$ is finite separable, see Algebraic Curves, Lemma 19.7. By Algebra, Lemma 138.5 we conclude that $X' \to \text{Spec}(k)$ is smooth in an open neighbourhood of $x'$. Combined with flatness, this proves that $X' \to \text{Spec}(R)$ is smooth in a neighbourhood of $x'$ (Morphisms, Lemma 32.14). This finishes the proof as a smooth morphism of relative dimension 1 is at-worst-nodal of relative dimension 1 (Algebraic Curves, Lemma 20.3). □

**Lemma 14.5.** Let $R$ be a discrete valuation ring with fraction field $K$. Let $C$ be a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$. The following are equivalent

1. there exists a proper model of $C$ which is at-worst-nodal of relative dimension 1 over $R$,
2. there exists a minimal model of $C$ which is at-worst-nodal of relative dimension 1 over $R$, and
3. any minimal model of $C$ is at-worst-nodal of relative dimension 1 over $R$.

**Proof.** To make sense out of this statement, recall that a minimal model is defined as a regular proper model without exceptional curves of the first kind (Definition 8.4), that minimal models exist (Proposition 8.6), and that minimal models are unique if the genus of $C$ is $> 0$ (Lemma 10.1). Keeping this in mind the implications (2) $\Rightarrow$ (1) and (3) $\Rightarrow$ (2) are clear.

Assume (1). Let $X$ be a proper model of $C$ which is at-worst-nodal of relative dimension 1 over $R$. Applying Lemma 14.3 we see that we may assume $X$ is regular as well. Let

$$X = X_m \to X_{m-1} \to \ldots \to X_1 \to X_0$$

be as in Lemma 8.3. By Lemma 14.4 and induction this implies $X_0$ is at-worst-nodal of relative dimension 1 over $R$.

To finish the proof we have to show that (2) implies (3). This is clear if the genus of $C$ is $> 0$, since then the minimal model is unique (see discussion above). On the other hand, if the minimal model is not unique, then the morphism $X \to \text{Spec}(R)$ is smooth for any minimal model as its special fibre will be isomorphic to $\mathbb{P}^1_k$ by Lemma 12.3.
Let $R$ be a discrete valuation ring with fraction field $K$. Let $C$ be a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$. We say that $C$ has semistable reduction if the equivalent conditions of Lemma 14.5 are satisfied.

Lemma 14.7. Let $R$ be a discrete valuation ring with fraction field $K$. Let $C$ be a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$. The following are equivalent

1. there exists a proper smooth model for $C$,
2. there exists a minimal model for $C$ which is smooth over $R$,
3. any minimal model is smooth over $R$.

Proof. If $X$ is a smooth proper model, then the special fibre is connected (Lemma 9.4) and smooth, hence irreducible. This immediately implies that it is minimal. Thus (1) implies (2). To finish the proof we have to show that (2) implies (3). This is clear if the genus of $C$ is $> 0$, since then the minimal model is unique (Lemma 10.1). On the other hand, if the minimal model is not unique, then the morphism $X \to \text{Spec}(R)$ is smooth for any minimal model as its special fibre will be isomorphic to $\mathbb{P}^1_k$ by Lemma 12.4. □

Definition 14.8. Let $R$ be a discrete valuation ring with fraction field $K$. Let $C$ be a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$. We say that $C$ has good reduction if the equivalent conditions of Lemma 14.7 are satisfied.

15. Semistable reduction in genus zero

In this section we prove the semistable reduction theorem (Theorem 18.1) for genus zero curves.

Let $R$ be a discrete valuation ring with fraction field $K$. Let $C$ be a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$. If the genus of $C$ is 0, then $C$ is isomorphic to a conic, see Algebraic Curves, Lemma 10.3. Thus there exists a finite separable extension $K'/K$ of degree at most 2 such that $C(K') \neq \emptyset$, see Algebraic Curves, Lemma 9.4. Let $R' \subset K'$ be the integral closure of $R$, see discussion in More on Algebra, Remark 99.6. We will show that $C_{K'}$ has semistable reduction over $R'_m$ for each maximal ideal $m$ of $R'$ (of course in the current case there are at most two such ideals). After replacing $R$ by $R'_m$ and $C$ by $C_{K'}$ we reduce to the case discussed in the next paragraph.

In this paragraph $R$ is a discrete valuation ring with fraction field $K$, $C$ is a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$, of genus 0, and $C$ has a $K$-rational point. In this case $C \cong \mathbb{P}^1_K$ by Algebraic Curves, Proposition 10.4. Thus we can use $\mathbb{P}^1_R$ as a model and we see that $C$ has both good and semistable reduction.

Example 15.1. Let $R = \mathbb{R}[[\pi]]$ and consider the scheme

$$X = V(T^2_1 + T^2_2 - \pi T^2_3) \subset \mathbb{P}^2_R$$

The base change of $X$ to $\mathbb{C}[[\pi]]$ is isomorphic to the scheme defined in Example 10.3 because we have the factorization $T^2_1 + T^2_2 = (T_1 + iT_2)(T_1 - iT_2)$ over $\mathbb{C}$. Thus $X$ is regular and its special fibre is irreducible yet singular, hence $X$ is the unique minimal model of its generic fibre (use Lemma 12.4). It follows that an extension is needed even in genus 0.
16. Semistable reduction in genus one

In this section we prove the semistable reduction theorem (Theorem 18.1) for curves of genus one. We suggest the reader first read the proof in the case of genus \( \geq 2 \) (Section 17). We are going to use as much as possible the classification of minimal numerical types of genus 1 given in Lemma 6.2.

Let \( R \) be a discrete valuation ring with fraction field \( K \). Let \( C \) be a smooth projective curve over \( K \) with \( H^0(C, \mathcal{O}_C) = K \). Assume the genus of \( C \) is 1. Choose a prime \( \ell \geq 7 \) different from the characteristic of \( k \). Choose a finite separable extension \( K'/K \) of such that \( C(K') \neq \emptyset \) and such that \( \text{Pic}(C_{K'})[\ell] \cong (\mathbb{Z}/\ell\mathbb{Z})^{\oplus 2} \). See Algebraic Curves, Lemma 17.2 Let \( R' \subset K' \) be the integral closure of \( R \), see discussion in More on Algebra, Remark 99.6. We may replace \( R \) by \( R_m \) for some maximal ideal \( m \) in \( R' \) and \( C \) by \( C_{K'} \). This reduces us to the case discussed in the next paragraph.

In the rest of this section \( R \) is a discrete valuation ring with fraction field \( K \), \( C \) is a smooth projective curve over \( K \) with \( H^0(C, \mathcal{O}_C) = K' \), with genus 1, having a \( K \)-rational point, and with \( \text{Pic}(C)[\ell] \cong (\mathbb{Z}/\ell\mathbb{Z})^{\oplus 2} \) for some prime \( \ell \geq 7 \) different from the characteristic of \( k \). We will prove that \( C \) has semistable reduction.

Let \( X \) be a minimal model for \( C \), see Proposition 8.6. Let \( T = (n, m_i, (a_{ij}), w_i, g_i) \) be the numerical type associated to \( X \) (Definition 11.4). Then \( T \) is a minimal numerical type (Lemma 11.5). As \( C \) has a rational point, there exists an \( i \) such that \( m_i = w_i = 1 \) by Lemma 11.7. Looking at the classification of minimal numerical types of genus 1 in Lemma 6.2 we see that \( m = w = 1 \) and that cases \( 3, 4; 7, 9; 11, 13, 15, 18; 19; 21, 22, 23, 24; 26, 28, 30 \) are disallowed (because there is no index where both \( w_i \) and \( m_i \) is equal to 1). Let \( e \) be the number of pairs \( (i, j) \) with \( i < j \) and \( a_{ij} > 0 \). For the remaining cases we have

(A) \( e = n - 1 \) for cases \( 1, 2, 3, 8, 12, 14, 16, 17, 20, 22, 23, 27, 29, 31, 32, 33, \) and \( 34 \), and

(B) \( e = n \) for cases \( 4, 10, 16, \) and \( 25 \).

We will argue these cases separately.

Case (A). In this case \( \text{Pic}(T)[\ell] = \emptyset \) (the Picard group of a numerical type is defined in Section 4). The vanishing follows as \( \text{Pic}(T) \subset \text{Coker}(A) \) (Lemma 14.3) and \( \text{Coker}(A)[\ell] = 0 \) by Lemma 2.6 and the fact that \( \ell \) was chosen relatively prime to \( a_{ij} \) and \( m_i \). By Lemmas 13.3 and 13.4 we conclude that there is an embedding

\[ (\mathbb{Z}/\ell\mathbb{Z})^{\oplus 2} \subset \text{Pic}((X_{k, \text{red}})[\ell]) \]

By Algebraic Curves, Lemma 18.6 we obtain

\[ 2 \leq \dim_k H^1((X_{k, \text{red}}), \mathcal{O}_{(X_{k, \text{red}})}) + g_{\text{geom}}((X_{k, \text{red}})/k) \]

By Algebraic Curves, Lemmas 18.1 and 18.5 we see that \( g_{\text{geom}}((X_{k, \text{red}})/k) \leq \sum w_i g_i \). The assumptions of Lemma 11.8 hold by Lemma 11.7 and we conclude that we have \( \dim_k H^1((X_{k, \text{red}}), \mathcal{O}_{(X_{k, \text{red}})}) \leq g = 1 \). Combining these we see

\[ 2 \leq 1 + \sum w_i g_i \]

Looking at the list we conclude that the numerical type is given by \( n = 1, w_1 = m_1 = g_1 = 1 \). Because we have equality everywhere we see that \( g_{\text{geom}}(C_1/k) = 1 \). On the other hand, we know that \( C_1 \) has a \( k \)-rational point \( x \) such that \( C_1 \to \text{Spec}(k) \) is smooth at \( x \). It follows that \( C_1 \) is geometrically integral (Varieties,
Proposition 10.4. In particular, since Example 16.1. We conclude by Varieties, Lemma 30.3 and the above we still have we see that C is smooth over k as desired.

Case (B). Here we only conclude that there is an embedding

\[ \mathbb{Z}/\ell \mathbb{Z} \subset \text{Pic}(X_k)[\ell] \]

From the classification of types we see that each C_i is a genus zero curve over k. Moreover, for each i there is a j such that C_i ∩ C_j is a k-rational point. Then it follows that C_i ≅ P^1_k by Algebraic Curves, Proposition 10.4. In particular, since X_k is the scheme theoretic union of the C_i we see that \( X_\overline{k} \) is the scheme theoretic union of the C_{i, \overline{k}}. Hence \( X_\overline{k} \) is a reduced connected proper scheme of dimension 1 over \( \overline{k} \) with \( \dim_{\overline{k}} H^1(X_\overline{k}, \mathcal{O}_{X_\overline{k}}) = 1 \). Also, by Varieties, Lemma 30.3 this finishes the proof in case (B).

Example 16.1. Let k be an algebraically closed field. Let Z be a smooth projective curve over k of positive genus g. Let \( n \geq 1 \) be an integer prime to the characteristic of k. Let \( \mathcal{L} \) be an invertible \( \mathcal{O}_Z \)-module of order n, see Algebraic Curves, Lemma 17.1. Pick an isomorphism \( \varphi : \mathcal{L}^\otimes n \to \mathcal{O}_Z \). Set \( R = k[[\pi]] \) with fraction field \( \kappa = k((\pi)) \). Denote \( Z_R \) the base change of Z to R. Let \( \mathcal{L}_R \) be the pullback of \( \mathcal{L} \) to \( Z_R \). Consider the finite flat morphism

\[ p : X \to Z_R \]

such that

\[ p_* \mathcal{O}_X = \text{Sym}^n_{\mathcal{O}_{Z_R}}(\mathcal{L}_R)/(\varphi - \pi) = \mathcal{O}_{Z_R} \oplus \mathcal{L}_R^\otimes 2 \oplus \ldots \oplus \mathcal{L}_R^\otimes n-1 \]

More precisely, if \( U = \text{Spec}(A) \subset Z \) is an affine open such that \( \mathcal{L}|_U \) is trivialized by a section s with \( \varphi(s^\otimes n) = f \) (with f a unit), then

\[ p^{-1}(U_R) = \text{Spec}((A \otimes_R R[[\pi]])[[x]]/(x^n - \pi f)) \]

The reader verifies that the morphism \( X_K \to Z_K \) of generic fibres is finite étale. Looking at the description of the structure sheaf we see that \( H^0(X, \mathcal{O}_X) = R \) and \( H^0(X_K, \mathcal{O}_{X_K}) = K \). By Riemann-Hurwitz (Algebraic Curves, Lemma 12.4) the genus of \( X_K \) is \( n(g-1)+1 \). In particular \( X_K \) has genus 1, if Z has genus 1. On the other hand, the scheme X is regular by the local equation above and the special fibre \( X_k \) is n times the reduced special fibre as an effective Cartier divisor. It follows that any finite extension \( K'/K \) over which \( X_K \) attains semistable reduction has to ramify with ramification index at least n (some details omitted). Thus there does not exist a universal bound for the degree of an extension over which a genus 1 curve attains semistable reduction.
17. Semistable reduction in genus at least two

In this section we prove the semistable reduction theorem (Theorem 18.1) for curves of genus $g \geq 2$. Fix $g \geq 2$.

Let $R$ be a discrete valuation ring with fraction field $K$. Let $C$ be a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$. Assume the genus of $C$ is $g$. Choose a prime $\ell > 768g$ different from the characteristic of $k$. Choose a finite separable extension $K'/K$ of such that $C(K') \neq \emptyset$ and such that $\text{Pic}(C_{K'})[\ell] \cong (\mathbb{Z}/\ell\mathbb{Z})^{\oplus 2g}$. See Algebraic Curves, Lemma 17.2. Let $R' \subset K'$ be the integral closure of $R$, see discussion in More on Algebra, Remark 99.6. We may replace $R$ by $R'_{\mathfrak{m}}$ for some maximal ideal $\mathfrak{m}$ in $R'$ and $C$ by $C_{K'}$. This reduces us to the case discussed in the next paragraph.

In the rest of this section $R$ is a discrete valuation ring with fraction field $K$, $C$ is a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$, with genus $g$, having a $K$-rational point, and with $\text{Pic}(C)[\ell] \cong (\mathbb{Z}/\ell\mathbb{Z})^{\oplus 2g}$ for some prime $\ell \geq 768g$ different from the characteristic of $k$. We will prove that $C$ has semistable reduction.

In the rest of this section we will use without further mention that the conclusions of Lemma 11.7 are true.

Let $X$ be a minimal model for $C$, see Proposition 8.6. Let $T = (n, m_i, (a_{ij}), w_i, g_i)$ be the numerical type associated to $X$ (Definition 11.4). Then $T$ is a minimal numerical type of genus $g$ (Lemma 11.5). By Proposition 7.4 we have

$$\dim_{\mathbb{F}_\ell} \text{Pic}(T)[\ell] \leq g_{\text{top}}$$

By Lemmas 13.3 and 13.4 we conclude that there is an embedding

$$(\mathbb{Z}/\ell\mathbb{Z})^{\oplus 2g - g_{\text{top}}} \subset \text{Pic}(\mathcal{(X_k)}_{\text{red}})[\ell].$$

By Algebraic Curves, Lemma 18.6 we obtain

$$2g - g_{\text{top}} \leq \dim_k H^1(\mathcal{(X_k)}_{\text{red}}, \mathcal{O}_{\mathcal{(X_k)}_{\text{red}}}) + g_{\text{geom}}(X_k/k)$$

By Lemmas 11.8 and 11.9 we have

$$g \geq \dim_k H^1(\mathcal{(X_k)}_{\text{red}}, \mathcal{O}_{\mathcal{(X_k)}_{\text{red}}}) \geq g_{\text{top}} + g_{\text{geom}}(X_k/k)$$

Elementary number theory tells us that the only way these 3 inequalities can hold is if they are all equalities. Looking at Lemma 11.8 we conclude that $m_i = 1$ for all $i$. Looking at Lemma 11.10 we conclude that every irreducible component of $X_k$ is smooth over $k$.

In particular, since $X_k$ is the scheme theoretic union of its irreducible components $C_i$ we see that $X_k$ is the scheme theoretic union of the $C_{i,k}$. Hence $X_k$ is a reduced connected proper scheme of dimension 1 over $\overline{k}$ with $\dim_{\mathbb{F}_\ell} H^1(X_k, \mathcal{O}_{X_k}) = g$. Also, by Varieties, Lemma 30.3 and the above we still have

$$\dim_{\mathbb{F}_\ell} (\text{Pic}(X_k)) \geq 2g - g_{\text{top}} = \dim_{\mathbb{F}_\ell} H^1(X_k, \mathcal{O}_{X_k}) + g_{\text{geom}}(X_k)$$

By Algebraic Curves, Proposition 17.3 we see that $X_k$ has at only multicross singularities. But since $X_k$ is Gorenstein (Lemma 2.2), so is $X_k$ (Duality for Schemes, Lemma 25.1). We conclude $X_k$ is at-worst-nodal by Algebraic Curves, Lemma 16.4. This finishes the proof.
18. Semistable reduction for curves

In this section we finish the proof of the theorem. For $g \geq 2$ let $768g < \ell' < \ell$ be the first two primes $> 728g$ and set

$$B_g = (2g - 2)((2^g)!$$

The precise form of $B_g$ is unimportant; the point we are trying to make is that it depends only on $g$.

Theorem 18.1. Let $R$ be a discrete valuation ring with fraction field $K$. Let $C$ be a smooth projective curve over $K$ with $H^0(C, \mathcal{O}_C) = K$. Then there exists an extension of discrete valuation rings $R \subset R'$ which induces a finite separable extension of fraction fields $K \subset K'$ such that $C_{K'}$ has semistable reduction. More precisely, we have the following

1. If the genus of $C$ is zero, then there exists a degree 2 separable extension $K'/K$ such that $C_{K'} \cong \mathbb{P}_K^1$, and hence $C_{K'}$ is isomorphic to the generic fibre of the smooth projective scheme $\mathbb{P}_R^1$ over the integral closure $R'$ of $R$ in $K'$.

2. If the genus of $C$ is one, then there exists a finite separable extension $K'/K$ such that $C_{K'}$ has semistable reduction over $R'_m$ for every maximal ideal $m$ of the integral closure $R'$ of $R$ in $K'$. Moreover, the special fibre of the (unique) minimal model of $C_{K'}$ over $R'_m$ is either a smooth genus one curve or a cycle of rational curves.

3. If the genus $g$ of $C$ is greater than one, then there exists a finite separable extension $K'/K$ of degree at most $B_g$ (18.0.1) such that $C_{K'}$ has semistable reduction over $R'_m$ for every maximal ideal $m$ of the integral closure $R'$ of $R$ in $K'$.

Proof. For the case of genus zero, see Section 15. For the case of genus one, see Section 16. For the case of genus greater than one, see Section 17. To see that we have a bound on the degree $[K' : K]$ you can use the bound on the degree of the extension needed to make all $\ell$ or $\ell'$ torsion visible proved in Algebraic Curves, Lemma 17.2. (The reason for using $\ell$ and $\ell'$ is that we need to avoid the characteristic of the residue field $k$.)

Remark 18.2 (Improving the bound). Results in the literature suggest that one can improve the bound given in the statement of Theorem 18.1. For example, in [DM69] it is shown that semistable reduction of $C$ and its Jacobian are the same thing if the residue field is perfect and presumably this is true for general residue fields as well. For an abelian variety we have semistable reduction if the action of Galois on the $\ell$-torsion is trivial for any $\ell \geq 3$ not equal to the residue characteristic. Thus we can presumably choose $\ell = 5$ in the formula (18.0.1) for $B_g$ (but the proof would take a lot more work; if we ever need this we will make a precise statement and provide a proof here).

19. Other chapters

Preliminaries

(1) Introduction
(2) Conventions
(3) Set Theory
(4) Categories
(5) Topology
(6) Sheaves on Spaces
(7) Sites and Sheaves
(8) Stacks
(9) Fields
(10) Commutative Algebra
(11) Brauer Groups
(12) Homological Algebra
(13) Derived Categories
(14) Simplicial Methods
(15) More on Algebra
(16) Smoothing Ring Maps
(17) Sheaves of Modules
(18) Modules on Sites
(19) Injectives
(20) Cohomology of Sheaves
(21) Cohomology on Sites
(22) Differential Graded Algebra
(23) Divided Power Algebra
(24) Hypercoverings

Schemes
(25) Schemes
(26) Constructions of Schemes
(27) Properties of Schemes
(28) Morphisms of Schemes
(29) Cohomology of Schemes
(30) Divisors
(31) Limits of Schemes
(32) Varieties
(33) Topologies on Schemes
(34) Descent
(35) Derived Categories of Schemes
(36) More on Morphisms
(37) More on Flatness
(38) Groupoid Schemes
(39) More on Groupoid Schemes
(40) Étale Morphisms of Schemes

Topics in Scheme Theory
(41) Chow Homology
(42) Intersection Theory
(43) Picard Schemes of Curves
(44) Weil Cohomology Theories
(45) Adequate Modules
(46) Dualizing Complexes
(47) Duality for Schemes
(48) Discriminants and Differents
(49) Local Cohomology
(50) Algebraic and Formal Geometry
(51) Algebraic Curves
(52) Resolution of Surfaces
(53) Semistable Reduction

(54) Fundamental Groups of Schemes
(55) Étale Cohomology
(56) Crystalline Cohomology
(57) Pro-étale Cohomology
(58) More Étale Cohomology
(59) The Trace Formula

Algebraic Spaces
(60) Algebraic Spaces
(61) Properties of Algebraic Spaces
(62) Morphisms of Algebraic Spaces
(63) Decent Algebraic Spaces
(64) Cohomology of Algebraic Spaces
(65) Limits of Algebraic Spaces
(66) Divisors on Algebraic Spaces
(67) Algebraic Spaces over Fields
(68) Topologies on Algebraic Spaces
(69) Descent and Algebraic Spaces
(70) Derived Categories of Spaces
(71) More on Morphisms of Spaces
(72) Flatness on Algebraic Spaces
(73) Groupoids in Algebraic Spaces
(74) More on Groupoids in Spaces
(75) Bootstrap
(76) Pushouts of Algebraic Spaces

Topics in Geometry
(77) Chow Groups of Spaces
(78) Quotients of Groupoids
(79) More on Cohomology of Spaces
(80) Simplicial Spaces
(81) Duality for Spaces
(82) Formal Algebraic Spaces
(83) Restricted Power Series
(84) Resolution of Surfaces Revisited

Deformation Theory
(85) Formal Deformation Theory
(86) Deformation Theory
(87) The Cotangent Complex
(88) Deformation Problems

Algebraic Stacks
(89) Algebraic Stacks
(90) Examples of Stacks
(91) Sheaves on Algebraic Stacks
(92) Criteria for Representability
(93) Artin’s Axioms
(94) Quot and Hilbert Spaces
(95) Properties of Algebraic Stacks
(96) Morphisms of Algebraic Stacks
LIMITS OF ALGEBRAIC STACKS

COHOMOLOGY OF ALGEBRAIC STACKS

DEPRECATED CATEGORIES OF STACKS

INTRODUCING ALGEBRAIC STACKS

MORE ON MORPHISMS OF STACKS

THE GEOMETRY OF STACKS

MODULI STACKS

MODULI OF CURVES

REFERENCES


