3. The construction of a birational group

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The map $D \mapsto (\mathcal{L}(D), s_D)$ defines a one-to-one correspondence between the set of relative effective Cartier divisors on X/T and the isomorphism classes of pairs $(\mathcal{L}, s)$, where $\mathcal{L}$ is an invertible sheaf on X and s is a global section of $\mathcal{L}$ such that the map $s\colon \mathcal{O}_X \to \mathcal{L}$ induced by the section s is injective and $\mathcal{L}/s\mathcal{O}_X$ is $\mathcal{O}_T$-flat.

The proof of the following lemma is straightforward and is left to the reader:

LEMMA 2.2.

(a) *If* D_1 *and* D_2 *are relative effective Cartier divisors on* X/T, *then so is* $D_1 + D_2$.

(b) *Let* D_1 *and* D_2 *be two relative effective Cartier divisors on* X/T *and let* $\mathcal{I}(D_1)$ *and* $\mathcal{I}(D_2)$ *be their ideal sheaves. If* $\mathcal{I}(D_1) \subset \mathcal{I}(D_2)$, *then* $D_1 - D_2$ *is also a relative effective Cartier divisor on* X/T.

(c) *Let* $T' \to T$ *be a base extension and let* $X' = X \times_T T'$. *If* D *is a relative effective Cartier divisor on* X/T, *then its pull-back to a closed subscheme* D' *of* X' *is a relative effective Cartier divisor on* X'/T'.

LEMMA 2.3. *Assume* $q\colon X \to T$ *is flat. Let* $\mathcal{I}$ *be a coherent sheaf of ideals of* $\mathcal{O}_X$ *and let* D *be the closed subscheme of* X *defined by* $\mathcal{I}$. *If for every point* $x \in D$, *the ideal* $\mathcal{I}_x$ *of* $\mathcal{O}_{X,x}$ *is generated by one element* g_x *whose image in* $\mathcal{O}_{X,x} \otimes_{\mathcal{O}_{T,q(x)}} k(q(x))$ *is not a zero divisor, then* D *is a relative effective Cartier divisor.*

Proof. It suffices to show that g_x is not a zero divisor in $\mathcal{O}_{X,x}$ and that $\mathcal{O}_{X,x}/(g_x)$ is flat over $\mathcal{O}_{T,q(x)}$. This follows from [EGA] §0.10.2.4 by taking $A = \mathcal{O}_{T,q(x)}$, $B = \mathcal{O}_{X,x}$, $M = N = \mathcal{O}_{X,x}$, and $u\colon M \to N$ to be the homomorphism $g_x\colon \mathcal{O}_{X,x} \to \mathcal{O}_{X,x}$ defined by the multiplication by g_x.

3. THE CONSTRUCTION OF A BIRATIONAL GROUP

Let X be a nonsingular irreducible projective curve over an algebraically closed field k. A *modulus* $\mathfrak{m}$ supported on a finite subset S of X is a divisor of the form $\mathfrak{m} = \sum_{P \in S} n_P P$ with each $n_P > 0$. For any rational function f on X, we write $f \equiv 0 \mod \mathfrak{m}$ if $v_P(f) \geq n_P$ for every $P \in S$, where v_P is the valuation defined by P. Two divisors D_1 and D_2 on X prime to S are called $\mathfrak{m}$*-equivalent* if there exists a rational function f satisfying $f - 1 \equiv 0 \mod \mathfrak{m}$ such that $D_1 - D_2 = (f)$. If this holds, we write $D_1 \sim_{\mathfrak{m}} D_2$. Define a ringed space $(X_{\mathfrak{m}}, \mathcal{O}_{X_{\mathfrak{m}}})$ as follows: The underlying set of $X_{\mathfrak{m}}$ is $(X-S)\cup\{Q\}$. Define

$$\mathcal{O}_{X_{\mathfrak{m}},Q} = k + \{f \mid f \equiv 0 \mod \mathfrak{m}\}$$

and for every $x \in X - S$, define $\mathcal{O}_{X_{\mathfrak{m}},x} = \mathcal{O}_{X,x}$. One can show that when $\deg(\mathfrak{m}) \geq 2$, the ringed space $X_{\mathfrak{m}}$ is a singular curve with a unique singular point Q and its normalization is X. (It is easy to see that when $\deg(\mathfrak{m}) < 2$, the ringed space $X_{\mathfrak{m}}$ is identified with X itself.) For a divisor D of X prime to S, we put

$$L_{\mathfrak{m}}(D) = H^0(X_{\mathfrak{m}}, \mathcal{L}_{\mathfrak{m}}), \quad I_{\mathfrak{m}}(D) = H^1(X_{\mathfrak{m}}, \mathcal{L}_{\mathfrak{m}}),$$

where $\mathcal{L}_{\mathfrak{m}}$ is the invertible sheaf on $X_{\mathfrak{m}}$ corresponding to D. Denote the dimensions of $L_{\mathfrak{m}}(D)$ and $I_{\mathfrak{m}}(D)$ by $l_{\mathfrak{m}}(D)$ and $i_{\mathfrak{m}}(D)$, respectively. The Riemann-Roch theorem states that

$$l_{\mathfrak{m}}(D) - i_{\mathfrak{m}}(D) = \deg(D) + 1 - \pi .$$

In this formula, π is the sum $\pi = g + \delta$, where g is the genus of X and $\delta = \deg(\mathfrak{m}) - 1$. All these results are proved in [S], Chapter IV.

For convenience, a closed point on a scheme is just called a point.

Let T be a connected k-scheme. Consider the Cartesian square

$$\begin{array}{ccc} X_{\mathfrak{m}} \times T & \longrightarrow & X_{\mathfrak{m}} \\ {\scriptstyle q}\downarrow & & \downarrow \\ T & \longrightarrow & \operatorname{spec}(k) . \end{array}$$

Since $X_{\mathfrak{m}}$ is proper and flat over $\operatorname{spec}(k)$, the morphism q is also proper and flat. Let D be a relative effective Cartier divisor on $(X_{\mathfrak{m}} \times T)/T$ supported on $(X_{\mathfrak{m}} - Q) \times T$ and let $\mathcal{L}$ be the invertible sheaf corresponding to D. Applying Theorem 1.1 (a) to the morphism q and the invertible sheaf $\mathcal{L}$, we conclude that $t \mapsto \chi(\mathcal{L}_t)$ is a constant function on T. By the Riemann-Roch theorem, we have $\chi(\mathcal{L}_t) = \deg D_t + 1 - \pi$. So $\deg(D_t)$ is also a constant. This constant is called the *degree* of D. Denote by $\mathrm{Div}^{(n)}(T)$ the set of all relative effective Cartier divisors of degree n on $(X_{\mathfrak{m}} \times T)/T$ supported on $(X_{\mathfrak{m}} - Q) \times T$.

Let $(X-S)^{(n)}$ be the n-th symmetric power of $X - S$, i.e., the quotient of $(X-S)^n$ by the action of the n-th symmetric group $\mathfrak{S}_n$, where $\mathfrak{S}_n$ acts on $(X-S)^n$ by permuting the factors. In the Appendix we show that there exists a relative effective Cartier divisor $\mathcal{D} \in \mathrm{Div}^{(n)}\big((X-S)^{(n)}\big)$, called the *universal relative effective Cartier divisor*, whose restriction to the fiber of the projection $X_{\mathfrak{m}} \times (X-S)^{(n)} \to (X-S)^{(n)}$ at $P_1 + \cdots + P_n \in (X-S)^{(n)}$ is the divisor $P_1 + \cdots + P_n$ of $X_{\mathfrak{m}}$. Moreover, we have

PROPOSITION 3.1. *The functor* $T \mapsto \mathrm{Div}^{(n)}(T)$ *from the category of* k*-schemes to the category of sets is represented by the symmetric power* $(X-S)^{(n)}$*. More precisely, for any relative effective Cartier divisor* D *of degree* n *on* $(X_{\mathfrak{m}} \times T)/T$ *supported on* $(X_{\mathfrak{m}} - Q) \times T$*, there exists a unique morphism* $f\colon T \to (X-S)^{(n)}$ *such that the pull-back of* $\mathcal{D}$ *by* $\mathrm{id} \times f$ *is* D*.*

The proof of this proposition is given in the Appendix. The morphism $T \to (X-S)^{(n)}$ can be described as follows: For every $t \in T$, identifying the fiber of $q\colon X_{\mathfrak{m}} \times T \to T$ at t with $X_{\mathfrak{m}}$, we may regard the restriction D_t of D to the fiber at t as an effective divisor of degree n on $X_{\mathfrak{m}}$ supported on $X_{\mathfrak{m}} - Q$. But this kind of divisor can be thought of as a point in $(X-S)^{(n)}$. The morphism $T \to (X-S)^{(n)}$ is just $t \mapsto D_t$.

LEMMA 3.2. *Let* D *be a divisor of* X *prime to* S *such that* $i_{\mathfrak{m}}(D) \geq 1$*. Then there exists an open subset* U *of* $X-S$ *such that for every* $P \in U$*, we have* $i_{\mathfrak{m}}(D+P) = i_{\mathfrak{m}}(D) - 1$*.*

Proof. If $P \notin \mathrm{Supp}(D) \cup S$, then the dual vector space $I_{\mathfrak{m}}(D+P)^*$ of $I_{\mathfrak{m}}(D+P)$ is identified with the subspace of $I_{\mathfrak{m}}(D)^*$ formed by differential forms $\omega \in I_{\mathfrak{m}}(D)^*$ vanishing at P. Let $\{\omega_1, \ldots, \omega_{i_{\mathfrak{m}}(D)}\}$ be a basis of $I_{\mathfrak{m}}(D)^*$. We can then take U to be the complement of

$$\mathrm{Supp}(D) \cup S \cup \{P \mid \omega_i(P) = 0 \text{ for } i = 1, \ldots, i_{\mathfrak{m}}(D)\}.$$

LEMMA 3.3. *Let* D_0 *be a divisor of* X *prime to* S *of degree* 0*. Then the set*

$$V_{D_0} = \{D \in (X-S)^{(\pi)} \mid l_{\mathfrak{m}}(D+D_0) = 1 \text{ and } l(D+D_0-\mathfrak{m}) = 0\}$$

is non-empty and open in $(X-S)^{(\pi)}$*.*

Proof. Consider the Cartesian square

$$\begin{array}{ccc} X_{\mathfrak{m}} \times (X-S)^{(\pi)} & \xrightarrow{\ p\ } & X_{\mathfrak{m}} \\ {\scriptstyle q}\downarrow & & \downarrow \\ (X-S)^{(\pi)} & \longrightarrow & \mathrm{spec}(k)\,. \end{array}$$

Applying Theorem 1.1 (b) to q and the invertible sheaf $\mathcal{L}$ on $X_{\mathfrak{m}} \times (X-S)^{(\pi)}$ corresponding to the divisor $\mathcal{D} + p^*(D_0)$, where $\mathcal{D}$ is the universal relative effective Cartier divisor, we conclude that the set

$$V_1 = \{t \in (X-S)^{(\pi)} \mid \dim H^0(X_{\mathfrak{m}}, \mathcal{L}_t) \leq 1\}$$

is open, that is,

$$V_1 = \{D \in (X-S)^{(\pi)} \mid l_{\mathfrak{m}}(D+D_0) \leq 1\}$$

is open. By the Riemann-Roch theorem we have, for any $D \in (X-S)^{(\pi)}$,

$$l_{\mathfrak{m}}(D+D_0) \geq \deg(D+D_0) + 1 - \pi = 1.$$

So we must have

$$V_1 = \{D \in (X-S)^{(\pi)} \mid l_{\mathfrak{m}}(D+D_0) = 1\}.$$

If $l_{\mathfrak{m}}(D_0) \neq 0$, then there exists a rational function f on X such that $(f)+D_0$ is an effective divisor on X prime to S. This effective divisor must be 0 since it is of degree 0. Hence $l_{\mathfrak{m}}(D_0) = l_{\mathfrak{m}}((f)+D_0) = l_{\mathfrak{m}}(0) = 1$. So in any case we have $l_{\mathfrak{m}}(D_0) \leq 1$. By the Riemann-Roch theorem, we have $i_{\mathfrak{m}}(D_0) \leq \pi$. Applying Lemma 3.2 repeatedly, we can find $P_1, \ldots, P_{i_{\mathfrak{m}}(D_0)}$ in $X-S$ so that $i_{\mathfrak{m}}(D_0 + P_1 + \cdots + P_{i_{\mathfrak{m}}(D_0)}) = 0$. Choose $P_{i_{\mathfrak{m}}(D_0)+1}, \ldots, P_\pi$ in $X-S$ arbitrarily. We have

$$i_{\mathfrak{m}}(D_0+P_1+\cdots+P_{i_{\mathfrak{m}}(D_0)}) \geq i_{\mathfrak{m}}(D_0+P_1+\cdots+P_{i_{\mathfrak{m}}(D_0)}+P_{i_{\mathfrak{m}}(D_0)+1}+\cdots+P_\pi).$$

(This can be seen by interpreting $i_{\mathfrak{m}}(D)$ as the dimension of the vector space of differential forms ω regular at Q satisfying $(\omega) \geq D$.) So we have $i_{\mathfrak{m}}(D_0 + P_1 + \cdots + P_\pi) = 0$. By the Riemann-Roch theorem, we have $l_{\mathfrak{m}}(D_0 + P_1 + \cdots + P_\pi) = 1$. Hence $P_1 + \cdots + P_\pi$ is in the set V_1 and V_1 is not empty.

Similarly by Theorem 1.1 (b) applied to the projection $q\colon X \times (X-S)^{(\pi)} \to (X-S)^{(\pi)}$ and the invertible sheaf on $X \times (X-S)^{(\pi)}$ corresponding to the divisor $\mathcal{D} + p^*(D_0 - \mathfrak{m})$, where $p\colon X \times (X-S)^{(\pi)} \to X$ is another projection, we see that the set

$$V_2 = \{D \in (X-S)^{(\pi)} \mid l(D+D_0-\mathfrak{m}) = 0\}$$

is open. Since $\deg(D_0 - \mathfrak{m}) < 0$, we have $l(D_0 - \mathfrak{m}) = 0$. By the Riemann-Roch theorem, we have $i(D_0 - \mathfrak{m}) = \pi$. Applying Lemma 3.2 repeatedly (but taking $\mathfrak{m} = 0$), we can find $P_1, \ldots, P_\pi \in X-S$ such that $i(D_0 - \mathfrak{m} + P_1 + \cdots + P_\pi) = 0$. Then by the Riemann-Roch theorem we have $l(D_0 - \mathfrak{m} + P_1 + \cdots + P_\pi) = 0$. So $P_1 + \cdots + P_\pi$ is in V_2 and V_2 is not empty.

Since $(X-S)^{(\pi)}$ is irreducible, the set $V_{D_0} = V_1 \cap V_2$ is open and non-empty.

LEMMA 3.4. *Fix a point* P_0 *in* S.

(a) *The set*

$$U = \{(D_1, D_2) \in (X-S)^{(\pi)} \times (X-S)^{(\pi)} \mid l_{\mathfrak{m}}(D_1 + D_2 - \pi P_0) = 1, \quad l(D_1 + D_2 - \pi P_0 - \mathfrak{m}) = 0\}$$

is a non-empty open subset of $(X-S)^{(\pi)} \times (X-S)^{(\pi)}$.

(b) *The set*

$$V = \{(D_1, D_2) \in (X-S)^{(\pi)} \times (X-S)^{(\pi)} \mid l_{\mathfrak{m}}(D_2 - D_1 + \pi P_0) = 1, \quad l(D_2 - D_1 + \pi P_0 - \mathfrak{m}) = 0\}$$

is a non-empty open subset of $(X-S)^{(\pi)} \times (X-S)^{(\pi)}$.

Proof. (a) Let $p_1, p_2 \colon (X-S)^{(\pi)} \times (X-S)^{(\pi)} \to (X-S)^{(\pi)}$ be the projections and let E_i $(i=1,2)$ be the pull-backs by $\mathrm{id} \times p_i$ of the universal relative effective Cartier divisor $\mathcal{D}$ on $X_{\mathfrak{m}} \times (X-S)^{(\pi)}$. Put $E = E_1 + E_2$. This is a divisor on $X_{\mathfrak{m}} \times (X-S)^{(\pi)} \times (X-S)^{(\pi)}$.

Consider the Cartesian square

$$\begin{array}{ccc} X_{\mathfrak{m}} \times (X-S)^{(\pi)} \times (X-S)^{(\pi)} & \xrightarrow{\;p\;} & X_{\mathfrak{m}} \\ {\scriptstyle q}\downarrow & & \downarrow \\ (X-S)^{(\pi)} \times (X-S)^{(\pi)} & \longrightarrow & \mathrm{spec}(k)\,. \end{array}$$

By the Riemann-Roch theorem, for any $(D_1, D_2) \in (X-S)^{(\pi)} \times (X-S)^{(\pi)}$, we have

$$l_{\mathfrak{m}}(D_1 + D_2 - \pi P_0) \geq \deg(D_1 + D_2 - \pi P_0) + 1 - \pi = 1\,,$$

that is, for any $t \in (X-S)^{(\pi)} \times (X-S)^{(\pi)}$, we have $l_{\mathfrak{m}}(E_t - \pi P_0) \geq 1$. Applying Theorem 1.1 (b) to the projection q and the invertible sheaf corresponding to the divisor $E - p^*(P_0)$, we see that the set

$$U_1 = \{t \in (X-S)^{(\pi)} \times (X-S)^{(\pi)} \mid l_{\mathfrak{m}}(E_t - \pi P_0) = 1\}$$

is open. Similarly the set

$$U_2 = \{t \in (X-S)^{(\pi)} \times (X-S)^{(\pi)} \mid l(E_t - \pi P_0 - \mathfrak{m}) = 0\}$$

is also open. Hence the set $U = U_1 \cap U_2$ is open.

Applying Lemma 3.3 to $D_0 = 0$, we see that there exists a $D \in (X-S)^{(\pi)}$ such that $l_{\mathfrak{m}}(D) = 1$ and $l(D - \mathfrak{m}) = 0$. Then $(D, \pi P_0)$ is in U. So U is non-empty. This proves (a).

The proof of (b) is similar and is omitted.

DEFINITION 3.5. A *birational group* over k is a nonsingular variety V together with a rational map $m\colon V \times V \to V$, $(a,b) \mapsto ab$ such that

(a) $(ab)c = a(bc)$ when both sides are defined;

(b) the rational maps $\Phi\colon (a,b) \mapsto (a,ab)$ and $\Psi\colon (a,b) \mapsto (b,ab)$ on $V \times V$ are birational.

PROPOSITION 3.6. *There exists a unique rational map*

$$m\colon (X-S)^{(\pi)} \times (X-S)^{(\pi)} \to (X-S)^{(\pi)}$$

whose domain of definition contains the set U *in* 3.4 (a) *such that* $m(D_1,D_2)$ *is the unique effective divisor that is* $\mathfrak{m}$*-equivalent to* $D_1+D_2-\pi P_0$ *for any* $(D_1,D_2)\in U$. *Moreover* m *makes* $(X-S)^{(\pi)}$ *a birational group.*

Proof. Keep the notations in the proof of Lemma 3.4. Consider the Cartesian squares

$$\begin{array}{ccccccc}
X_{\mathfrak{m}} = q^{-1}(t) & \longrightarrow & X_{\mathfrak{m}} \times U & \subset & X_{\mathfrak{m}} \times (X-S)^{(\pi)} \times (X-S)^{(\pi)} & \xrightarrow{p} & X_{\mathfrak{m}} \\
\downarrow & & \downarrow{\scriptstyle q} & & \downarrow & & \downarrow \\
\operatorname{spec}(k(t)) & \longrightarrow & U & \subset & (X-S)^{(\pi)} \times (X-S)^{(\pi)} & \longrightarrow & \operatorname{spec}(k).
\end{array}$$

Let $\mathcal{L}$ be the restriction to $X_{\mathfrak{m}} \times U$ of the invertible sheaf corresponding to the divisor $E_1+E_2-p^*(\pi P_0)$. By Theorem 1.1 (c) and the choice of U, the sheaf $q_*\mathcal{L}$ is invertible. The canonical homomorphism $q^*q_*\mathcal{L} \to \mathcal{L}$ gives rise to $s\colon \mathcal{O}_{X_{\mathfrak{m}}\times U} \to \mathcal{L}\otimes(q^*q_*\mathcal{L})^{-1}$. We claim that the pair $(\mathcal{L}\otimes(q^*q_*\mathcal{L})^{-1}, s)$ defines a relative effective Cartier divisor on $(X_{\mathfrak{m}} \times U)/U$. According to Remark 2.1, it is enough to check that s is injective and $\operatorname{coker}(s)$ is $\mathcal{O}_U$-flat. Since $\mathcal{L}\otimes(q^*q_*\mathcal{L})^{-1}$ is invertible, it is enough to verify s_t is injective for all $t\in U$ by [EGA] §0.10.2.4, where s_t is the homomorphism obtained by restricting s to the fiber of q at t. It suffices to show that the restriction of the canonical homomorphism $q^*q_*\mathcal{L} \to \mathcal{L}$ to the fiber of q at t is injective. By Theorem 1.1 (c) we have $q_*\mathcal{L}\otimes_{\mathcal{O}_U} k(t) = H^0(X_{\mathfrak{m}}, \mathcal{L}_t)$. So the restriction of the canonical homomorphism to the fiber is $H^0(X_{\mathfrak{m}},\mathcal{L}_t)\otimes_k \mathcal{O}_{X_{\mathfrak{m}}} \to \mathcal{L}_t$. Denote this map by s'_t; we need to show it is injective. But we have $\dim H^0(X_{\mathfrak{m}},\mathcal{L}_t)=1$ since $t\in U$. If we fix a nonzero element $g\in H^0(X_{\mathfrak{m}},\mathcal{L}_t)$, then s'_t is identified with $\mathcal{O}_{X_{\mathfrak{m}}} \to \mathcal{L}_t$, $a\mapsto ag$. This last map is injective since $X_{\mathfrak{m}}$ is an integral scheme and g can be thought of as a rational function. So s_t is injective. Hence $(\mathcal{L}\otimes(q^*q_*\mathcal{L})^{-1}, s)$ defines a relative effective Cartier divisor. The restriction of this divisor to the fiber of q at t is the divisor on $X_{\mathfrak{m}}$ defined by the pair $(\mathcal{L}_t, g)$, which is supported on $X_{\mathfrak{m}}-Q$. So the divisor defined by

$(\mathcal{L}\otimes(q^*q_*\mathcal{L})^{-1}, s)$ is supported on $(X_{\mathfrak{m}} - Q)\times U$. By Proposition 3.1 there exists a unique morphism of varieties $m\colon U \to (X-S)^{(\pi)}$ such that the divisor defined by $(\mathcal{L}\otimes(q^*q_*\mathcal{L})^{-1}, s)$ is the pull-back by $\mathrm{id}\times m$ of the universal relative effective Cartier divisor $\mathcal{D}$ on $X_{\mathfrak{m}}\times(X-S)^{(\pi)}$. For any $(D_1, D_2)\in U$, we have $l_{\mathfrak{m}}(D_1+D_2-\pi P_0)=1$ and $l(D_1+D_2-\pi P_0-\mathfrak{m})=0$. So there is one and only one effective divisor $\mathfrak{m}$-equivalent to $D_1+D_2-\pi P_0$ and it is simply $m(D_1, D_2)$.

Similarly, using Lemma 3.4 (b) and Proposition 3.1, one can show that there exists a morphism $r\colon V\to(X-S)^{(\pi)}$ such that $r(D_1, D_2)$ is the unique effective divisor $\mathfrak{m}$-equivalent to $D_2-D_1+\pi P_0$ for any $(D_1, D_2)\in V$.

Let us verify that m defines a birational group on $(X-S)^{(\pi)}$. First we show

$$m(m(D_1, D_2), D_3) = m(D_1, m(D_2, D_3))$$

when (D_1, D_2), (D_2, D_3), $(m(D_1, D_2), D_3)$ and $(D_1, m(D_2, D_3))$ all belong to U. Indeed $m(m(D_1, D_2), D_3)$ is the unique effective divisor $\mathfrak{m}$-equivalent to $m(D_1, D_2)+D_3-\pi P_0$, and $m(D_1, m(D_2, D_3))$ is the unique effective divisor $\mathfrak{m}$-equivalent to $D_1+m(D_2, D_3)-\pi P_0$. But $m(D_1, D_2)+D_3-\pi P_0$ and $D_1+m(D_2, D_3)-\pi P_0$ are $\mathfrak{m}$-equivalent since both are $\mathfrak{m}$-equivalent to $D_1+D_2+D_3-2\pi P_0$. So we have $m(m(D_1, D_2), D_3)=m(D_1, m(D_2, D_3))$.

One can also verify $m(D_1, D_2) = m(D_2, D_1)$ when both (D_1, D_2) and (D_2, D_1) are in U, that is, the operation m is commutative.

Next we show that $\Theta\colon (D_1, D_2)\mapsto(D_1, r(D_1, D_2))$ is the birational inverse of $\Phi\colon (D_1, D_2)\mapsto(D_1, m(D_1, D_2))$ so that Φ is birational. Since the operation m is commutative, the rational map $\Psi\colon (D_1, D_2)\mapsto(D_2, m(D_1, D_2))$ is also birational. Therefore m makes $(X-S)^{(\pi)}$ a birational group.

First we verify $\Phi\Theta(D_1, D_2) = (D_1, D_2)$ whenever the left-hand side is defined. We have

$$\Phi\Theta(D_1, D_2) = \Phi(D_1, r(D_1, D_2)) = (D_1, m(D_1, r(D_1, D_2)))\,.$$

Moreover $m(D_1, r(D_1, D_2))$ is the unique effective divisor $\mathfrak{m}$-equivalent to $D_1+r(D_1, D_2)-\pi P_0$. But D_2 is also an effective divisor $\mathfrak{m}$-equivalent to $D_1+r(D_1, D_2)-\pi P_0$ since we have

$$D_1+r(D_1, D_2)-\pi P_0 \sim_{\mathfrak{m}} D_1+(D_2-D_1+\pi P_0)-\pi P_0 = D_2\,.$$

Hence $m(D_1, r(D_1, D_2)) = D_2$ and $\Phi\Theta(D_1, D_2) = (D_1, D_2)$.

Similarly one can show that $\Theta\Phi(D_1, D_2) = (D_1, D_2)$ when the left-hand side is defined.

Note that Φ is a regular morphism defined on U and Θ is a regular morphism defined on V. Since

$$\Phi\,\Theta(D_1,D_2)=(D_1,D_2) \quad \text{and} \quad \Theta\,\Phi(D_1,D_2)=(D_1,D_2)$$

whenever the left-hand sides are defined, the maps Φ and Θ induce regular morphisms $\Phi\colon U\cap\Phi^{-1}(V)\to V\cap\Theta^{-1}(U)$ and $\Theta\colon V\cap\Theta^{-1}(U)\to U\cap\Phi^{-1}(V)$. To show that Φ and Θ are birational inverses to each other, it is enough to check that $U\cap\Phi^{-1}(V)$ and $V\cap\Theta^{-1}(U)$ are non-empty.

Note that $(D_1,D_2)\in U\cap\Phi^{-1}(V)$ if and only if $(D_1,D_2)\in U$ and

$$l_{\mathfrak{m}}(m(D_1,D_2)-D_1+\pi P_0)=1, \quad l(m(D_1,D_2)-D_1+\pi P_0-\mathfrak{m})=0\,.$$

Since $m(D_1,D_2)\sim_{\mathfrak{m}} D_1+D_2-\pi P_0$, the above equations are equivalent to

$$l_{\mathfrak{m}}(D_2)=1, \quad l(D_2-\mathfrak{m})=0\,.$$

Applying Lemma 3.3 to the divisor $D_0=0$, we conclude that the set

$$V_0=\{D\in(X-S)^{(\pi)}\mid l_{\mathfrak{m}}(D)=0, \quad l(D-\mathfrak{m})=0\}$$

is open and non-empty. Since $(X-S)^{(\pi)}\times(X-S)^{(\pi)}$ is irreducible, the set $U\cap((X-S)^{(\pi)}\times V_0)$ is also open and non-empty. This set is exactly $U\cap\Phi^{-1}(V)$. So $U\cap\Phi^{-1}(V)$ is non-empty.

Similarly $V\cap\Theta^{-1}(U)$ is also non-empty. This completes the proof of the proposition.

4. From birational groups to algebraic groups

Let k be an algebraically closed field, let V be a connected nonsingular variety over k, and let $m\colon V\times V\to V$, $(a,b)\mapsto ab$ be a rational map satisfying $(ab)c=a(bc)$. Assume the rational maps $\Phi(a,b)=(a,ab)$ and $\Psi(a,b)=(b,ab)$ are birational. Then there exist open subsets X_Φ, Y_Φ, X_Ψ and Y_Ψ in $V\times V$ such that Φ induces an isomorphism $X_\Phi\cong Y_\Phi$ and Ψ induces an isomorphism $X_\Psi\cong Y_\Psi$. Put $Z=X_\Phi\cap Y_\Phi\cap X_\Psi\cap Y_\Psi$.

It is convenient to write the formulae for Φ^{-1} and Ψ^{-1} as $\Phi^{-1}(a,b)=(a,a^{-1}b)$ and $\Psi^{-1}(a,b)=(ba^{-1},a)$.