The Cox ring of an algebraic variety with torus action

Citation for published version:

Digital Object Identifier (DOI):
10.1016/j.aim.2010.03.010

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Advances in Mathematics

Publisher Rights Statement:
The final publication is available at ScienceDirect via http://dx.doi.org/10.1016/j.aim.2010.03.010

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
THE COX RING OF AN ALGEBRAIC VARIETY WITH TORUS ACTION

JÜRGEN HAUSEN AND HENDRIK SÜSS

Abstract. We investigate the Cox ring of a normal complete variety \( X \) with algebraic torus action. Our first results relate the Cox ring of \( X \) to that of a maximal geometric quotient of \( X \). As a consequence, we obtain a complete description of the Cox ring in terms of generators and relations for varieties with torus action of complexity one. Moreover, we provide a combinatorial approach to the Cox ring using the language of polyhedral divisors. Applied to smooth \( K^* \)-surfaces, our results give a description of the Cox ring in terms of Orlik-Wagreich graphs. As examples, we explicitly compute the Cox rings of all Gorenstein del Pezzo \( K^* \)-surfaces with Picard number at most two and the Cox rings of projectivizations of rank two vector bundles as well as cotangent bundles over toric varieties in terms of Klyachko's description.

1. Introduction

Let \( X \) be a normal complete algebraic variety defined over some algebraically closed field \( K \) of characteristic zero and suppose that the divisor class group \( \text{Cl}(X) \) is finitely generated. The Cox ring of \( X \) is the graded \( K \)-algebra

\[
\mathcal{R}(X) = \bigoplus_{\mathcal{O}(X)} \Gamma(X, \mathcal{O}_X(D)),
\]

see Section 2 for a detailed reminder. A basic problem is to present \( \mathcal{R}(X) \) in terms of generators and relations. Besides the applications in number theory, see e.g. [9], the knowledge of generators and relations also opens a combinatorial approach to geometric properties of \( X \), see [6] and [11].

In the present paper, we investigate the case that \( X \) comes with an effective algebraic torus action \( T \times X \to X \). Our first result relates the Cox ring of \( X \) to that of a maximal orbit space of the \( T \)-action. For a point \( x \in X \), denote by \( T_x \) its isotropy group and consider the non-empty \( T \)-invariant open subset \( X_0 := \{ x \in X; \dim(T_x) = 0 \} \subseteq X \).

There is a geometric quotient \( q: X_0 \to X_0/T \) with an irreducible normal but possibly non-separated orbit space \( X_0/T \), see [22], and also for \( X_0/T \) one can define a Cox ring. Denote by \( E_1, \ldots, E_m \subseteq X \) the (\( T \)-invariant) prime divisors supported in \( X \setminus X_0 \) and by \( D_1, \ldots, D_n \subseteq X \) those \( T \)-invariant prime divisors who have a finite generic isotropy group of order \( l_j \geq 1 \). Moreover, let \( 1_{E_k} \) and \( 1_{D_j} \) denote the canonical sections of the divisors \( E_k \) and \( D_j \) respectively, and let \( 1_{q(D_j)} \in \mathcal{R}(X_0/T) \) be the canonical section of \( q(D_j) \).

**Theorem 1.1.** There is a graded injection \( q^*: \mathcal{R}(X_0/T) \to \mathcal{R}(X) \) of Cox rings and the assignments \( S_k \mapsto 1_{E_k} \) and \( T_j \mapsto 1_{D_j} \) induce an isomorphism of \( \text{Cl}(X) \)-graded rings

\[
\mathcal{R}(X) \cong \mathcal{R}(X_0/T)[S_1, \ldots, S_m, T_1, \ldots, T_n] / \langle T_j^{l_j} - 1_{q(D_j)}; 1 \leq j \leq n \rangle,
\]
where \( Cl(X) \)-grading on the right hand side is defined by associating to \( S_k \) the class of \( E_k \) and to \( T_{ij} \) the class of \( D_{ij} \). In particular, \( R(X) \) is finitely generated if and only if \( R(X_0/T) \) is so.

If the dimension of \( T \) equals that of \( X \), then our \( X \) is a toric variety, the subset \( X_0 \subseteq X \) is the open \( T \)-orbit, the divisors \( E_1, \ldots, E_m \) are the invariant prime divisors of \( X \) and there are no divisors \( D_j \). Thus, for toric varieties, the above Theorem shows that the Cox ring is the polynomial ring in the canonical section \( s \) of the invariant prime divisors and hence gives the result obtained by D. Cox in \([7]\).

The Cox ring \( R(X) \) can be further evaluated by using the fact that \( X_0/T \) admits a separation, i.e., a rational map \( \pi: X_0/T \rightarrow Y \) to a variety \( Y \), which is a local isomorphism in codimension one. After suitably shrinking, we may assume that there are prime divisors \( C_0, \ldots, C_r \) on \( Y \) such that each inverse image \( \pi^{-1}(C_i) \) is a disjoint union of prime divisors \( C_{ij} \), where \( 1 \leq j \leq n_i \), the map \( \pi \) is an isomorphism over \( Y \setminus (C_0 \cup \ldots \cup C_r) \) and all the \( D_j \) occur among the \( D_{ij} := q^{-1}(C_{ij}) \). Let \( i_{ij} \in \mathbb{Z}_{\geq 1} \) denote the order of the generic isotropy group of \( D_{ij} \).

**Theorem 1.2.** There is a graded injection \( R(Y) \rightarrow R(X) \) of Cox rings and the assignments \( S_k \mapsto 1_{E_k} \) and \( T_{ij} \mapsto 1_{q^{-1}(D_{ij})} \) induce an isomorphism of \( Cl(X) \)-graded rings

\[
R(X) \cong R(Y)[S_1, \ldots, S_m, T_{ij}; 0 \leq i \leq r, 1 \leq j \leq n_i] / \langle T_{ij}^{l_{ij}} - 1_{C_{ij}}; 0 \leq i \leq r \rangle.
\]

where \( T_{ij}^{l_{ij}} := T_{i1}^{l_{i1}} \cdots T_{in_i}^{l_{in_i}} \), and the \( Cl(X) \)-grading on the right hand side is defined by associating to \( S_k \) the class of \( E_k \) and to \( T_{ij} \) the class of \( D_{ij} \). In particular, \( R(X) \) is finitely generated if and only if \( R(Y) \) is so.

Now suppose that the \( T \)-action on \( X \) is of complexity one, i.e., its biggest \( T \)-orbits are of codimension one in \( X \). Then \( X_0/T \) is of dimension one and has a separation \( \pi: X_0/T \rightarrow \mathbb{P}_1 \). Choose \( r \geq 1 \) and \( a_0, \ldots, a_r \in \mathbb{P}_1 \) such that \( \pi \) is an isomorphism over \( \mathbb{P}_1 \setminus \{a_0, \ldots, a_r\} \) and all the divisors \( D_j \) occur among the \( D_{ij} := q^{-1}(y_{ij}) \), where \( \pi^{-1}(a_i) = \{y_{i1}, \ldots, y_{in_i}\} \). Let \( i_{ij} \in \mathbb{Z}_{\geq 1} \) denote the order of the generic isotropy group of \( D_{ij} \). For every \( 0 \leq i \leq r \), define a monomial

\[
f_i := T_{i1}^{l_{i1}} \cdots T_{in_i}^{l_{in_i}} \in \mathbb{K}[T_{ij}; 0 \leq i \leq r, 1 \leq j \leq n_i].
\]

Moreover, write \( a_i = [b_i, c_i] \) with \( b_i, c_i \in \mathbb{K} \) and for every \( 0 \leq i \leq r - 2 \) set \( k = j + 1 = i + 2 \) and define a trinomial

\[
g_i := (c_kb_j - c_jb_k)f_i + (c_kb_k - c_kb_j)f_j + (c_jb_i - c_ib_j)f_k.
\]

**Theorem 1.3.** Let \( X \) be a normal complete variety with finitely generated divisor class group and an effective algebraic torus action \( T \times X \rightarrow X \) of complexity one. Then, in terms of the data defined above, the Cox ring of \( X \) is given as

\[
R(X) \cong \mathbb{K}[S_1, \ldots, S_m, T_{ij}; 0 \leq i \leq r, 1 \leq j \leq n_i] / \langle g_i; 0 \leq i \leq r - 2 \rangle,
\]

where \( 1_{E_k} \) corresponds to \( S_k \), and \( 1_{D_{ij}} \) to \( T_{ij} \), and the \( Cl(X) \)-grading on the right hand side is defined by associating to \( S_k \) the class of \( E_k \) and to \( T_{ij} \) the class of \( D_{ij} \). In particular, \( R(X) \) is finitely generated.

Note that finite generation of the Cox ring for a complexity one torus action with \( X_0/T \) rational may as well be deduced from \([15]\).

In Section \([4]\) we combine the results just presented with the description of torus actions in terms of polyhedral divisors given in \([2]\) and \([3]\) and that way obtain a combinatorial approach to the Cox ring, see Theorem \([4.5]\). Similarly to the toric case \([7]\), the advantage of the combinatorial treatment is that the divisor class group is easily accessible via the defining data and thus one has a simple approach to the grading of the Cox ring.
In Section 5 we give some applications. The description of the Cox ring given in Theorem 1.3 allows us to apply the language of bunched rings presented in [6] and [11] in order to investigate complete normal rational varieties \( X \) with a complexity one torus action. For example, in Corollary 5.2 we realize \( X \) as an invariant complete intersection in a toric variety \( X' \), provided that any two points of \( X \) admit a common affine neighborhood. Moreover, in Corollary 5.3 we obtain explicit descriptions of the cone of movable divisor classes and the canonical divisor in terms of the divisors \( E_k \) and \( D_{ij} \).

The first non-trivial examples of complexity one torus actions are complete normal rational \( \mathbb{K} \)-surfaces \( X \). An important data is the Orlik-Wagreich graph associated to \( X \), which describes the intersection theory of a canonical resolution \( \overline{X} \) of \( X \), see [17]. In Theorem 5.4 we show how to extract the Cox ring of \( \overline{X} \) from the Orlik-Wagreich graph, which in turn allows to compute the Cox ring of \( X \). In Theorem 5.6 we explicitly compute the Cox rings of all Gorenstein del Pezzo surfaces of Picard number at most two.

Finally, we consider in Section 5 projectivizations of equivariant vector bundles over complete toric varieties. We explicitly compute the Cox ring for the case of rank two bundles and for the case of the cotangent bundle over a smooth toric variety, see Theorems 5.7 and 5.9.

We would like to thank the referee for carefully reading the manuscript and for many helpful remarks and corrections.

2. Cox rings and universal torsors

Here we provide basic ingredients for the proofs of Theorems 1.1 to 1.3 which also might be of independent interest. For example, in Proposition 2.3 we determine the Cox ring of a prevariety \( X \) in terms of that of a separation \( X \to Y \) and Proposition 2.6 is a lifting statement for torus actions to the universal torsor in the case of torsion in the class group.

We work over an algebraically closed field \( \mathbb{K} \) of characteristic zero. We will not only deal with varieties over \( \mathbb{K} \) but more generally with prevarieties, i.e., possibly non-separated spaces. Recall that a (\( \mathbb{K} \))-prevariety is a space \( X \) with a sheaf \( \mathcal{O}_X \) of \( \mathbb{K} \)-valued functions such that \( X = X_1 \cup \ldots \cup X_r \) holds with open subspaces \( X_i \), each of which is an affine (\( \mathbb{K} \))-variety.

In the sequel, \( X \) denotes an irreducible normal prevariety. As in the separated case, the group of Weil divisors is the free abelian group \( \text{WDiv}(X) \) generated by all prime divisors, i.e., irreducible subvarieties of codimension one. The divisor class group \( \text{Cl}(X) \) is the factor group of \( \text{WDiv}(X) \) modulo the subgroup of principal divisors. We define the Cox ring of \( X \) following [11, Sec. 2]. Suppose that \( \Gamma(X, \mathcal{O}_X^*) = \mathbb{K}^* \) holds and that the divisor class group \( \text{Cl}(X) \) is finitely generated. Let \( \mathcal{D} \subseteq \text{WDiv}(X) \) be a finitely generated subgroup mapping onto \( \text{Cl}(X) \) and consider the sheaf of \( \mathcal{D} \)-graded algebras

\[
S := \bigoplus_{D \in \mathcal{D}} S_D, \quad S_D := \mathcal{O}_X(D),
\]

where multiplication is defined via multiplying homogeneous sections as rational functions on \( X \). Let \( \mathcal{D}^0 \subseteq \mathcal{D} \) be the kernel of \( \mathcal{D} \to \text{Cl}(X) \). Fix a shifting family, i.e., a family of \( \mathcal{O}_X \)-module isomorphisms \( g_D : \mathcal{S} \to \mathcal{S} \), where \( D^0 \in \mathcal{D}^0 \), such that

- \( g_{D^0}(S_D) = S_{D+D^0} \) for all \( D \in \mathcal{D}, D^0 \in \mathcal{D}^0 \),
- \( g_{D^0+D^0} = g_{D^0} \circ g_{D^0} \) for all \( D^0, D^0 \in \mathcal{D}^0 \),
- \( g_{D^0}(fg) = f g_{D^0}(g) \) for all \( D^0 \in \mathcal{D}^0 \) and any two homogeneous \( f, g \).

Consider the quasicoherent sheaf \( \mathcal{I} \) of ideals of \( \mathcal{S} \) generated by all sections of the form \( f - g_{D^0}(f) \), where \( f \) is homogeneous and \( D^0 \) runs through \( \mathcal{D}^0 \). Then \( \mathcal{I} \) is
homogeneous with respect to the coarsened grading
\[ S = \bigoplus_{[D] \in \Cl(X)} S_{[D]}, \quad S_{[D]} = \bigoplus_{D' \in D + D^0} O_X(D'). \]
Moreover, it turns out that \( \mathcal{I} \) is a sheaf of radical ideals. Dividing the \( \Cl(X) \)-graded algebra \( S \) by the homogeneous ideal \( \mathcal{I} \) we obtain a quasicoherent sheaf of \( \Cl(X) \)-graded \( O_X \)-algebras, the Cox sheaf: set \( \mathcal{R} := S/\mathcal{I} \), let \( \pi: S \to \mathcal{R} \) be the projection and define the grading by
\[ \mathcal{R} = \bigoplus_{[D] \in \Cl(X)} \mathcal{R}_{[D]}, \quad \mathcal{R}_{[D]} = \pi(S_{[D]}). \]
One can show that, up to isomorphism, the graded \( O_X \)-algebra \( \mathcal{R} \) does not depend on the choices of \( D \) and the shifting family. We define the Cox ring \( \mathcal{R}(X) \) of \( X \), also called the total coordinate ring of \( X \), to be the \( \Cl(X) \)-graded algebra of global sections of the Cox sheaf:
\[ \mathcal{R}(X) := \Gamma(X;\mathcal{R}) \cong \Gamma(X,S)/\Gamma(X,\mathcal{I}). \]

We are ready to perform first computations of Cox rings. Our aim is to relate the Cox ring of a prevariety \( X \) to that of a (separated) variety arising in a canonical way from \( X \). We say that an open subset \( U \subseteq X \) is big if the complement \( X \setminus U \) is of codimension at least two in \( X \).

**Definition 2.1.** By a separation of a prevariety \( X \) we mean a rational map \( \varphi: X \dashrightarrow Y \) to a (separated) variety \( Y \), which is defined on a big open subset \( U \subseteq X \) and maps \( U \) locally isomorphic onto a big open subset \( V \subseteq Y \).

**Remark 2.2.** Let \( \varphi: X \dashrightarrow Y \) be a separation. Then there are big open subsets \( U \subseteq X \) and \( V \subseteq Y \) such that \( \varphi: U \to V \) is a local isomorphism and moreover there are prime divisors \( C_0, \ldots, C_r \) on \( V \) such that
\begin{enumerate}[(i)]  
  \item \( \varphi \) maps \( U \setminus \varphi^{-1}(C_0 \cup \ldots \cup C_r) \) isomorphically onto \( V \setminus (C_0 \cup \ldots \cup C_r) \),  
  \item Each \( \varphi^{-1}(C_i) \) is a disjoint union of prime divisors \( C_{ij} \) of \( U \).  
\end{enumerate}

As we will see in Proposition 3.3 every prevariety \( X \) with finitely generated divisor class group admits a separation \( X \to Y \). Here comes how the Cox rings \( \mathcal{R}(X) \) and \( \mathcal{R}(Y) \) are related to each other; for the sake of a simple notation, we identify prime divisors of the big open subsets \( U \subseteq X \) and \( V \subseteq Y \) with their closures in \( X \) and \( Y \) respectively.

**Proposition 2.3.** Let \( \varphi: X \dashrightarrow Y \) be a separation, \( C_0, \ldots, C_r \) prime divisors on \( Y \) as in 2.2 and \( \varphi^{-1}(C_i) = C_{i1} \cup \ldots \cup C_{ir_i} \) with pairwise disjoint prime divisors \( C_{ij} \) on \( X \). Then \( \varphi^*: \Cl(Y) \to \Cl(X) \) is injective, and we have
\[ \Cl(X) = \varphi^* \Cl(Y) \oplus \bigoplus_{1 \leq j \leq r_i, \ 1 \leq i \leq r} \mathbb{Z}[C_{ij}]. \]
If \( \Gamma(X,\mathcal{O}^*) = \mathbb{K}^* \) holds and \( \Cl(X) \) is finitely generated, then there is a canonical injective pullback homomorphism \( \varphi^*: \mathcal{R}(Y) \to \mathcal{R}(X) \) of Cox rings. Moreover, with \( \deg(T_{ij}) := [C_{ij}] \) and \( T_i := T_{i1} \cdots T_{ir_i} \), the assignment \( T_{ij} \mapsto 1_{C_{ij}} \) defines a \( \Cl(X) \)-graded isomorphism
\[ \mathcal{R}(Y)[T_{ij}; \ 0 \leq i \leq r, \ 1 \leq j \leq n_i] / \langle T_i - 1_{C_i}; \ 0 \leq i \leq r \rangle \to \mathcal{R}(X). \]

**Proof.** Since divisor class group and Cox ring do not change when passing to big open subsets, we may assume \( U = X \) and \( V = Y \) in the setting of Remark 2.2.

The assertion on the divisor class group follows immediately from the facts that the principal divisors of \( X \) are precisely the pull backs of principal divisors on \( Y \) and that the divisor class group of \( X \) is generated by all pullback divisors and the classes \([C_{ij}]\), where \( 0 \leq i \leq r \) and \( 1 \leq j \leq n_i - 1 \).
We turn to the Cox rings. Let $\mathcal{D}_Y \subseteq \text{WDiv}(Y)$ be a finitely generated subgroup containing $C_0, \ldots, C_r$ and mapping onto $\text{Cl}(Y)$. Moreover, let $\mathcal{D}_X \subseteq \text{WDiv}(X)$ be the subgroup generated by $\varphi^*(\mathcal{D}_Y)$ and the divisors $C_{ij}$, where $0 \leq i < r$ and $1 \leq j \leq n_i - 1$; note that $C_{in_i} \in \mathcal{D}_X$ holds. Consider the associated graded sheaves

$$
\mathcal{S}_Y := \bigoplus_{E \in \mathcal{D}_Y} \mathcal{O}_Y(E), \quad \mathcal{S}_X := \bigoplus_{D \in \mathcal{D}_X} \mathcal{O}_X(D).
$$

Then we have a graded injective pullback homomorphism $\varphi^* : \mathcal{S}_Y \to \mathcal{S}_X$, which in turn extends to a homomorphism

$$
\psi : \mathcal{S}_Y[T_{ij} : 0 \leq i \leq r, 1 \leq j \leq n_i] \to \mathcal{S}_X, \quad T_{ij} \mapsto 1_{C_{ij}}.
$$

We show that $\psi$ is surjective. Given a section $h$ of $\mathcal{S}_X$ of degree $D \in \mathcal{D}_X$, consider its divisor $D(h) = \text{div}(h) + D$. If there occurs a $C_{ij} \in \mathcal{D}_X$ in $D(h)$, then we may divide $h$ in $\mathcal{S}_X$ by the corresponding $1_{C_{ij}}$. Doing this as often as possible, we arrive at some section $h'$ of $\mathcal{S}_X$, homogeneous of some degree $D' \in \mathcal{D}_X$, such that $D(h') = \text{div}(h') + D'$ has no components $C_{ij}$. But then $D'$ is a pullback divisor and $h'$ is a pullback section. This in turn means that $h'$ is a polynomial over $\varphi^* \mathcal{S}_Y$ and the $1_{C_{ij}}$.

Next, we determine the kernel of $\psi$, which amounts to determining the relations among the sections $s_{ij} := 1_{C_{ij}}$. Consider two coprime monomials $F, F'$ in the $s_{ij}$ and two homogeneous pullback sections $h, h'$ of $\varphi^*(\mathcal{S}_Y)$. If $\deg(hF) = \deg(h'F')$ holds in $\mathcal{D}_X$, then the difference $\deg(F') - \deg(F)$ must be a linear combination of some $\varphi^*(C_i) \in \mathcal{D}_X$ and hence $F$ and $F'$ are products of some $\varphi^* 1_{C_i}$. As a consequence, we obtain that any homogeneous (and hence any) relation among the $s_{ij}$ is generated by the relations $T_i - 1_{C_i}$.

Finally, fix a shifting family $\varphi_Y$ for $\mathcal{S}_Y$. Since $\mathcal{D}_X^0 = \varphi^*(\mathcal{D}_Y^0)$ holds, the pullback family $\varphi^* \mathcal{D}_Y$ extends uniquely to a shifting family $\varphi_X$ for $\mathcal{S}_X$. We have $\mathcal{I}_X = \varphi^*(\mathcal{I}_Y)$ and hence obtain a well defined graded pullback homomorphism $\varphi^* : \mathcal{R}(Y) \to \mathcal{R}(X)$, which is injective, because $\varphi^* : \mathcal{D}_Y/\mathcal{D}_Y^0 \to \mathcal{D}_X/\mathcal{D}_X^0$ is so and $\varphi^* : \mathcal{S}_Y \to \mathcal{S}_X$ is an isomorphism when restricted to homogeneous components. Now one directly verifies that the above epimorphism $\varphi$ induces the desired isomorphism.

We apply this result to compute the Cox ring of the prevariety occurring as non-separated orbit space for torus actions of complexity one. Consider the projective line $\mathbb{P}_1$, a tuple $A = (a_0, \ldots, a_r)$ of pairwise different points $a_i$ on $\mathbb{P}_1$, and a tuple $n = (n_0, \ldots, n_r) \in \mathbb{Z}^r_{\geq 1}$, where $r \geq 1$. Set

$$
X_{ij} := \mathbb{P}_1 \setminus \bigcup_{k \neq i} a_k, \quad 0 \leq i \leq r, \quad 1 \leq j \leq n_i.
$$

Then, gluing the $X_{ij}$ along the common open subset $\mathbb{P}_1 \setminus \{a_0, \ldots, a_r\}$, one obtains an irreducible smooth prevariety $\mathbb{P}_1(A, n)$ of dimension one. The inclusion maps $X_{ij} \to \mathbb{P}_1$ glue together to a morphism $\pi : \mathbb{P}_1(A, n) \to \mathbb{P}_1$, which is a separation. Writing $a_{ij}$ for the point in $\mathbb{P}_1(A, n)$ stemming from $a_i \in X_{ij}$, we obtain the fiber over a point $a \in \mathbb{P}_1$ as

$$
\pi^{-1}(a) = \begin{cases} \{a_1, \ldots, a_{in_i}\} & a = a_i \text{ for some } 0 \leq i \leq r, \\
\{a\} & a \neq a_i \text{ for all } 0 \leq i \leq r.
\end{cases}
$$

For every $0 \leq i \leq r$, define a monomial $T_i := T_{i1} \cdots T_{in_i}$ in the polynomial ring $\mathbb{K}[T_{ij} : 0 \leq i \leq r, 1 \leq j \leq n_i]$. Moreover, for every $a_i \in \mathbb{P}_1$ fix a presentation $a_i = [b_i, c_i]$ with $b_i, c_i \in \mathbb{K}$ and for every $0 \leq i \leq r - 2$ set $k = j + 1 = i + 2$ and define a trinomial

$$
g_i := (c_kb_j - c_jb_k)T_i + (c_kb_k - c_kb_i)T_j + (c_jb_i - c_ib_j)T_k.
$$
Proposition 2.4. The divisor class group of \( \mathbb{P}_1(A, n) \) is free of rank \( n_0 + \ldots + n_r - r \) and there is a decomposition

\[
\text{Cl}(\mathbb{P}_1(A, n)) = \bigoplus_{j=1}^{n_0} \mathbb{Z} \cdot [a_{0j}] \oplus \bigoplus_{i=1}^{r} \left( \bigoplus_{j=1}^{n_i-1} \mathbb{Z} \cdot [a_{ij}] \right).
\]

Moreover, in terms of the above data and with \( \deg(T_{ij}) := [a_{ij}] \), the Cox ring of \( \mathbb{P}_1(A, n) \) is given as

\[
\mathcal{R}(\mathbb{P}_1(A, n)) \cong \mathbb{K}[T_{ij}; 0 \leq i \leq r, 1 \leq j \leq n_i] / \langle g_i; 0 \leq i \leq r - 2 \rangle.
\]

Proof. The statement on the divisor class group is clear. The description of the Cox ring follows from Proposition 2.3 and the fact that the Cox ring \( \mathcal{R}(\mathbb{P}_1) \) of the projective line is generated by the canonical sections \( s_i := 1 a_i \) and has the relations

\[
(c_k b_j - c_j b_k) s_i + (c_i b_k - c_k b_i) s_j + (c_j b_i - c_i b_j) s_k = 0,
\]

where \( 0 \leq i \leq r - 2 \), and \( k = j + 1 = i + 2 \); note that the dependence of these relations on the choice of the \( b_i, c_i \) reflects the choice of a shifting family. \( \square \)

Now we discuss some geometric aspects of the Cox ring. As before, let \( X \) be a normal prevariety with \( \Gamma(X, \mathcal{O}^*) = \mathbb{K}^* \) and finitely generated divisor class group, and let \( \mathcal{R} \) be a Cox sheaf. Suppose that \( \mathcal{R} \) is locally of finite type; this holds for example if \( X \) is locally factorial or if \( \mathcal{R}(X) \) is finitely generated. Then we may consider the relative spectrum

\[
\hat{X} := \text{Spec}_X(\mathcal{R}).
\]

The \( \text{Cl}(X) \)-grading of the sheaf \( \mathcal{R} \) of \( \mathcal{O}_X \)-algebras defines an action of the diagonalizable group \( H_X := \text{Spec} \mathbb{K}[\text{Cl}(X)] \) on \( \hat{X} \), and the canonical morphism \( p : \hat{X} \to X \) is a good quotient, i.e., it is an \( H_X \)-invariant affine morphism satisfying

\[
\mathcal{O}_X = (p_* \mathcal{O}_{\hat{X}})^{H_X}.
\]

We call \( p : \hat{X} \to X \) the universal torsor associated to \( \mathcal{R} \). If the Cox ring \( \mathcal{R}(X) \) is finitely generated, then we define the total coordinate space of \( X \) to be the affine variety \( \overline{X} = \text{Spec}(\mathcal{R}(X)) \) together with the \( H_X \)-action defined by the \( \text{Cl}(X) \)-grading of \( \mathcal{R}(X) \).

As usual, we say that a Weil divisor \( \sum a_D D \), where \( D \) runs through the irreducible hypersurfaces, on a prevariety \( Y \) with an action of a group \( G \) is \( G \)-invariant if \( a_D = q_g D \) holds for all \( g \in G \). We say that \( Y \) is \( G \)-factorial if every \( G \)-invariant divisor on \( G \) is principal. Moreover, we say that a prevariety \( Y \) is of affine intersection if for any two affine open subsets \( V, V' \subseteq Y \) the intersection \( V \cap V' \) is again affine.

Proposition 2.5. Let \( X \) be an irreducible smooth prevariety of affine intersection with \( \Gamma(X, \mathcal{O}^*) = \mathbb{K}^* \) and finitely generated divisor class group. Let \( \mathcal{R} \) be a Cox sheaf and denote by \( p : \hat{X} \to X \) the associated universal torsor.

(i) \( \hat{X} \) is a normal quasiaffine variety, and every homogeneous invertible function on \( \hat{X} \) is constant. If \( \Gamma(X, \mathcal{O}) = \mathbb{K} \) holds or \( \text{Cl}(X) \) is free, then every invertible function on \( \hat{X} \) is constant.

(ii) The action of \( H_X \) on \( \hat{X} \) is free and \( \hat{X} \) is \( H_X \)-factorial. If \( \text{Cl}(X) \) is free, then \( \hat{X} \) is even factorial.

Proof. Normality of \( \hat{X} \) follows from \([5] \) Lemma 3.10. Since \( X \) is of affine intersection, it can be covered by open affine subsets, the complements of which are of pure codimension one. Together with smoothness this implies that \( X \) is divisorial in the sense of \([5] \) Sec. 4. Thus, we infer from \([6] \) Prop. 6.3 that \( \hat{X} \) a quasiaffine variety. The fact that every homogeneous invertible function on \( \hat{X} \) is constant is seen as
Proposition 2.6. Let $X$ be an irreducible smooth prevariety of affine intersection with $\Gamma(X, \mathcal{O}) = \mathbb{K}^*$ and finitely generated divisor class group. Let $\mathcal{R}$ be a Cox sheaf on $X$ and $p: \tilde{X} \to X$ the associated universal torsor. Assume that $T \times X \to X$ is an effective algebraic torus action.

(i) There is a $T$-action on $\tilde{X}$ and an epimorphism $\varepsilon : T \to T$ such that for all $h \in H_X$, $t \in T$ and $z \in \tilde{X}$ one has

$$t \cdot h \cdot z = h \cdot t \cdot z, \quad p(t \cdot z) = \varepsilon(t) \cdot p(z).$$

If the divisor class group $\text{Cl}(X)$ is free, then one may take the homomorphism $\varepsilon : T \to T$ to be the identity.

(ii) Let $T \times H_X$ act on $\tilde{X}$ as in (i); let $G' \subseteq T \times H_X$ be the trivially acting subgroup and consider the induced effective action of $G := (T \times H_X)/G'$ on $\tilde{X}$. Then for any $z \in \tilde{X}$, there is an isomorphism of isotropy groups $G_z \cong T_{p(z)}$.

Proof. We prove (i). Take a group $\mathcal{D} \subseteq \text{WDiv}(X)$ of Weil divisors mapping onto the divisor class group, and let $D_1, \ldots , D_r \in \text{WDiv}(X)$ be a basis of $\mathcal{D}$ such that the kernel $\mathcal{D}_0 \subseteq \mathcal{D}$ of $\mathcal{D} \to \text{Cl}(X)$ has a basis of the form $a_i D_i$, where $1 \leq i \leq s$ with some $s \leq r$.

For every $D_i$ choose a $T$-linearization, and via tensoring these linearizations, define a $T$-linearization of the whole group $\mathcal{D}$, compare [10, Sec. 1]. Note that the $T$-linearization of the trivial divisor $a_i D_i$ is given by a character $\chi_i$. Set $b := a_1 \cdots a_s$ and consider the epimorphism $\varepsilon : T \to T$, $t \mapsto t^b$. Then we have a new $T$-action

$$T \times X \to X, \quad (t, x) \mapsto \varepsilon(t) \cdot x.$$

The divisors $D \in \mathcal{D}$ are as well linearized with respect to this new action. Twisting each $T$-linearization of $D_i$ with $\chi_i^{-h/a_i}$, we achieve that each $a_i D_i$ is trivially $T$-linearized with respect to the new $T$-action on $X$. Thus, we may choose $T$-equivariant isomorphisms $g_i : \mathcal{O}_X \to \mathcal{O}_X(a_i D_i)$.

Let $\mathcal{S}$ denote the $\mathcal{D}$-graded sheaf defined by $\mathcal{D}$. Using the isomorphisms $g_i$, we construct a $T$-equivariant shifting family: for $D^0 = b_1 a_1 D_1 + \cdots + b_s a_s D_s$, define a $T$-equivariant isomorphism $g_{D^0} : \mathcal{S} \to \mathcal{S}$ by sending a $\mathcal{D}$-homogeneous $f$ to

$$g_{D^0}(f) := g_1(1)^{b_1} \cdots g_s(1)^{b_s} f.$$

The ideal $\mathcal{I}$ of $\mathcal{S}$ associated to this shifting family is $T$-homogeneous. This means that the $T$-action on $\text{Spec}_X \mathcal{S}$ defined by the $T$-linearization of $\mathcal{D}$ leaves $\tilde{X}$ invariant. By construction, the torsor $p : \tilde{X} \to X$ is $T$-equivariant, when we take the new $T$-action on $X$.

We turn to (ii). Let $\varepsilon : T \to T$ be as in (i). A first step is to show that for any given point $z \in \tilde{X}$, the kernel of ineffectivity $G' \subseteq T \times H_X$ can be written as

$$G' = \{(t, h) \in (T \times H_X)_z; \varepsilon(t) = 1\}.$$

In order to verify the inclusion “$\subseteq$”, let $(t, h) \in G'$ be given. Then $(t, h) \cdot z' = z'$ holds for every point $z' \in \tilde{X}$. In particular, $(t, h)$ belongs to $(T \times H_X)_z$. Moreover, we obtain $\varepsilon(t) \cdot p(z') = p(z')$ for every $z' \in \tilde{X}$. Since $p : \tilde{X} \to X$ is surjective and $T$ acts effectively on $X$, this implies $\varepsilon(t) = 1$.

For checking the inclusion “$\supseteq$”, consider $(t, h) \in (T \times H_X)_z$ with $\varepsilon(t) = 1$. Then, for every $z' \in \tilde{X}$, we have $p((t, h) \cdot z') = p(z')$. Consequently $t \cdot z' = h(t, z') \cdot z'$ holds with a uniquely determined $h(t, z') \in H_X$. Consider the assignment

$$\eta : \tilde{X} \to H_X, \quad z' \mapsto h(t, z').$$
Since $H_X$ acts freely we may choose for any $z'$ homogeneous functions $f_1, \ldots, f_r$, defined near $z'$ with $f_i(z') = 1$ such that their weights $\chi_1, \ldots, \chi_r$ form a basis of the character group of $H_X$. Then, near $z'$, we have a commutative diagram

\[
\begin{array}{ccc}
H_X & \xrightarrow{\sim} & (\mathbb{K}^*)^r \\
\eta & \downarrow & \\
\hat{X} & \xrightarrow{\beta} & T_p(z)
\end{array}
\]

Consequently, the map $\eta$ is is a morphism. Moreover, pulling back characters of $H_X$ via $\eta$ gives invertible $H_X$-homogeneous functions on $\hat{X}$, which by Proposition 2.5 (i) are constant. Thus, $\eta$ is constant, which means that $h(t) := h(t, z')$ does not depend on $z'$. By construction, $(t, h(t)^{-1})$ belongs to $G'$. Moreover, $t z = h^{-1} z$ and freeness of the $H_X$-action give $h(t) = h^{-1}$. This implies $(t, h) \in G'$.

We are ready to prove the assertion. Note that $(t, h) \mapsto \varepsilon(t)$ defines a homomorphism $\beta: (T \times H_X)_z \to T_{p(z)}$. We claim that $\beta$ is surjective. Given $t \in T_{p(z)}$, choose $t' \in T$ with $\varepsilon(t') = t$. Then we have

\[
p(t' \cdot z) = \varepsilon(t') \cdot p(z) = t \cdot p(z) = p(z).
\]

Consequently, $t' \cdot z = h \cdot z$ holds for some $h \in H_X$. Thus, $(t', h^{-1}) \in (T \times H_X)_z$ is mapped by $\beta$ to $t \in T_{p(z)}$. By the first step, the kernel of $\beta$ is just $G'$. This gives a commutative diagram

\[
\begin{array}{ccc}
(T \times H_X)_z & \xrightarrow{\beta} & T_{p(z)} \\
\downarrow & & \downarrow \\
G_z & \xrightarrow{\sim} & G_z
\end{array}
\]

\[\square\]

In the sequel, we mean by a universal torsor for $X$ more generally any good quotient $q: \mathcal{X} \to X$ for an action of $H_X$ on a variety $\mathcal{X}$ such that there is an equivariant isomorphism $i: \mathcal{X} \to \hat{X}$ with $q = p \circ i$.

**Proposition 2.7.** Let $\mathcal{X}$ be a normal quasiaffine variety with a free action of a diagonalizable group $H$. If every invertible function on $\mathcal{X}$ is constant and $X$ is $H$-factorial, then the quotient $q: \mathcal{X} \to X$ is a universal torsor for $X := \mathcal{X}/H$.

**Proof.** We have $H = \text{Spec} \mathbb{K}[K]$ with the character lattice $K$ of $H$. A first step is to provide an isomorphism $K \to \text{Cl}(X)$. Cover $\mathcal{X}$ by $H$-invariant affine open subsets $W_j$ such that, for every $w \in K$ and every $j$, there is a $w$-homogeneous $h_{w,j} \in \Gamma(W_j, \mathcal{O}_\mathcal{X}^*)$. Moreover, for every $w \in K$, fix a $w$-homogeneous $h_w \in \mathbb{K}(\mathcal{X})^*$. Then the $H$-invariant local equations $h_w/h_{w,j}$ define a Weil divisor $D(h_w)$ on $X$ satisfying

\[
D(h_w) = \text{div}(h_w/h_{w,j}) \text{ on } q(W_j), \quad q^*(D(h_w)) = \text{div}(h_w).
\]

We claim that the assignment $w \mapsto D(h_w)$ induces an isomorphism from $K$ onto $\text{Cl}(X)$, not depending on the choice of $h_w$:

\[K \to \text{Cl}(X), \quad w \mapsto D(w) := [D(h_w)].\]

To see that the class $\overline{D}(w)$ does not depend on the choice of $h_w$, consider a further $w$-homogeneous $g_w \in \mathbb{K}(\mathcal{X})^*$. Then $f := h_w/g_w$ is an invariant rational function descending to $X$, where we obtain

\[
D(h_w) - D(g_w) = \text{div}(f).
\]

Thus, $K \to \text{Cl}(X)$ is a well defined homomorphism. To verify injectivity, let $D(h_w) = \text{div}(f)$ for some $f \in \mathbb{K}(\mathcal{X})^*$. Then we obtain $\text{div}(h_w) = \text{div}(q^*(f))$. 

Thus, $h_w/q^*(f)$ is an invertible homogeneous function on $\mathcal{X}$ and hence is constant. This implies $w = 0$. For surjectivity, let any $D \in WDiv(X)$ be given. Then $q^*(D)$ is an $H$-invariant divisor on $\mathcal{X}$ and hence we have $q^*(D) = \text{div}(h)$ with some rational function $h$ on $\mathcal{X}$, which is homogeneous of some degree $w$. This means $D = D(h)$.

Now, choose a group $\mathcal{D} \subseteq WDiv(X)$ of Weil divisors mapping onto the divisor class group $\text{Cl}(X)$, and let $D_1, \ldots, D_r \in WDiv(X)$ be a basis of $\mathcal{D}$ such that the kernel $\mathcal{D}_0 \subseteq \mathcal{D}$ of $\mathcal{D} \to \text{Cl}(X)$ is generated by multiples $a_iD_i$, where $1 \leq i \leq s$ with some $s \leq r$. Set

$$S := \bigoplus_{D \in \mathcal{D}} S_D, \quad S_D := \mathcal{O}_X(D).$$

By the preceding consideration, we may assume $D_i = D(h_i)$ for $1 \leq i \leq r$. Then, for $D = b_1D_1 + \ldots + b_rD_r$, we have $D = D(h_w)$ with $h_w = h_i^{b_i} \cdots h_r^{b_r}$, where $w = [D]$ is the class of $D = D(h_w)$ in $K = \text{Cl}(X)$. For any open $U \subseteq X$, we have an isomorphism of $\mathbb{K}$-vector spaces

$$\Phi_{U,D}: \Gamma(U, \mathcal{O}(D(h_w))) \to \Gamma(q^{-1}(U), \mathcal{O}_w), \quad g \mapsto q^*(g)h_w.$$

In fact, on each $U_j := q(W_j) \cap U$ the section $g$ is given as $g = g_jh_j/h_w$ with a regular function $g_j \in \mathcal{O}(U_j)$. Consequently, the function $q^*(g)h_w$ is regular on $q^{-1}(U)$. In particular, the assignment is a well defined homomorphism. Moreover, $f \mapsto f/h_w$ defines an inverse homomorphism.

The $\Phi_{U,D}$ fit together to an epimorphism of sheaves $\Phi: S \to q_*(\mathcal{O}_X)$. We claim that the kernel $\mathcal{I}$ of $\Phi$ is the ideal of a shifting family $g$. Indeed, for any $D^0 \in \mathcal{D}^0$, consider

$$h^0 := \Phi_{X,D^0}^{-1}(\Phi_{X,0}(1)) \in \Gamma(X, S_{D^0}).$$

Then $g_{D^0}: S_D \to S_{D+D^0}$, $g \mapsto h^0g$ is as wanted. Thus, we obtain an induced isomorphism $\mathcal{R} \to q_*(\mathcal{O}_X)$, where $\mathcal{R} = S/\mathcal{I}$ is the associated Cox sheaf. This in turn defines the desired isomorphism $\mathcal{X} \to \hat{X}$. $\Box$

### 3. Proof of Theorems 1.1, 1.2 and 1.3

We begin with a couple of elementary observations. Let a diagonalizable group $G$ act effectively on a normal quasiaffine variety $U$. Recall that a function $f \in \Gamma(U, \mathcal{O})$ is said to be $G$-homogeneous of weight $\chi \in \mathbb{X}(G)$ if one has $f(g \cdot x) = \chi(g)f(x)$ for all $g \in G$ and $x \in X$.

**Lemma 3.1.** If there is a $G$-fixed point $x \in U$, then every $G$-homogeneous function $f \in \Gamma(U, \mathcal{O})$ with $f(x) \neq 0$ is $G$-invariant.

**Proof.** Let $\chi \in \mathbb{X}(G)$ be the weight of $f \in \Gamma(U, \mathcal{O})$. Then, for every $g \in G$, we have $f(x) = \chi(g)f(x)$, which implies $\chi(g) = 1$. Thus, $\chi$ is the trivial character. $\Box$

By a $G$-prime divisor on $U$ we mean a $G$-invariant Weil divisor $\sum a_D D$, where $D$ runs through the prime divisors, we always have $a_D \in \{0,1\}$ and $G$ permutes transitively the $D$ with $a_D = 1$. Let $B_1, \ldots, B_m \subseteq U$ be $G$-prime divisors and suppose that there are homogeneous functions $f_1, \ldots, f_m \in \Gamma(U, \mathcal{O})$ that satisfy $\text{div}(f_i) = B_i$. Let $\chi_i \in \mathbb{X}(G)$ be the weight of $f_i$.

**Lemma 3.2.** For $i = 1, \ldots, m$, let $G_i \subseteq G$ be the generic isotropy group of $B_i$ and set $G_0 := G_1 \cdots G_m \subseteq G$.

(i) The restriction of $\chi_i$ to $G_i$ generates the character group $\mathbb{X}(G_i)$.

(ii) For any two $i, j$ with $j \neq i$, the function $f_i$ is $G_j$-invariant.

(iii) The group $G_0$ is isomorphic to the direct product of the $G_i \subseteq G$.

(iv) $\Gamma(U, \mathcal{O})$ is generated by $f_1, \ldots, f_m$ and the $G_0$-invariant functions of $U$. 


Proof. Choose $G$-invariant affine open subsets $U_i \subseteq U$ such that $A_i := U_i \cap B_i$ is non-empty and $U_i \cap B_j$ is empty for every $j \neq i$.

To prove (i), let $\xi_i \in X(G_i)$ be given. Then $\xi_i$ is the restriction of some $\eta_i \in X(G)$. Let $V_i \subseteq U_i$ be a $G$-invariant affine open subset on which $G$ acts freely, and choose a non-trivial $G$-homogeneous function $h_i$ of weight $\eta_i$ on $V_i$. Suitably shrinking $U_i$, we achieve that $h_i$ is regular without zeroes on $U_i \setminus A_i$. Then, on $U_i$, the divisor $\text{div}(h_i)$ is a multiple of the $G$-prime divisor $A_i = \text{div}(f_i)$ and hence $h_i = a_if_i^k$ holds with a $G$-homogeneous invertible function $a_i$ on $U_i$ and some $k \in \mathbb{Z}$. By Lemma \ref{lem:weights}, the function $a_i$ is $G_i$-invariant. We conclude $\eta_i = k\chi_i$ on $G_i$.

Assertion (ii) is clear by Lemma \ref{lem:weights}. To obtain (iii), it suffices to show that $\chi_i$ is trivial on $G_j$ for any two $i, j$ with $j \neq i$. But, according to (ii), we have $f_i = \chi_i(g) f_i$ for every $g \in G_j$, which gives the claim. Finally, we verify (iv). Given a $G$-homogeneous function $f \in \Gamma(U, \mathcal{O})$, we may write $f = f_1^{\nu_1} \cdots f_m^{\nu_m}$ with $\nu_i \in \mathbb{Z}_{\geq 0}$ and a regular function $f'$ on $U$, which is homogeneous with respect to some weight $\chi' \in X(G)$ and has order zero along each $G$-prime divisor $B_i$. By Lemma \ref{lem:weights}, the function $f'$ is invariant under every $G_i$ and thus under $G_0$.

Now we specialize to the case that $B_1, \ldots, B_m \subseteq U$ are precisely the $G$-prime divisors of $U$, which are contained in $U \setminus U_0$, where we set

$$U_0 := \{z \in U; \dim(Gz) = 0\} \subseteq U.$$ 

Proposition 3.3. For $i = 1, \ldots, m$, let $G_i \subseteq G$ be the generic isotropy group of $B_i$ and set $G_0 := G_1 \cdots G_m \subseteq G$.

(i) Each $G_i$ is a one-dimensional torus. Moreover, there is a non-empty $G_0$-invariant open subset $U' \subseteq U$ such that each $B_i$ intersects the closure of any orbit $G_i \cdot z \subseteq U'$.

(ii) The $G_0$-action on $U_0$ is free, admits a geometric quotient $\lambda_0: U_0 \to V_0$ and the isotropy groups of the induced action of $H := G/G_0$ on $V_0$ satisfy $H_{\lambda_0(x)} \cong G_x$ for every $x \in U_0$.

(iii) $V_0$ is quasiaffine and, moreover, if $U$ is $G$-factorial (admits only constant invertible functions), then $V_0$ is $H$-factorial (admits only constant invertible functions).

(iv) Every $G_0$-invariant rational function of $U$ has neither poles nor zeroes along outside $U_0$. Moreover, there is an isomorphism

$$\Gamma(U_0, \mathcal{O})^{G_0}[S_1, \ldots, S_m] \to \Gamma(U, \mathcal{O}), \quad S_i \mapsto f_i.$$ 

Proof. We prove (i). By Lemma \ref{lem:weights} (i), every $G_i$ is a one-dimensional torus. To proceed, take any $G_0$-equivariant affine closure $U \subseteq \overline{U}$ and consider the quotient $\lambda_i: \overline{U} \to \overline{U}/G_i$. It maps the fixed point set of the $G_i$-action isomorphically onto its image in the quotient space $\overline{U}/G_i$. Since $\overline{U}/G_i$ is irreducible and of dimension at most $\dim(\overline{U}) - 1$, we obtain $\lambda_i(\overline{B}_i) = \overline{U}/G_i$ for the closure $\overline{B}_i$ of $B_i$ in $\overline{U}$. It follows that $\overline{B}_i$ is irreducible, equals the whole fixed point set of $G_i$ in $\overline{U}$ and any $G_i$-orbit of $\overline{U}$ has a point of $\overline{B}_i$ in its closure.

We turn to (ii). Since none of the $f_i$ has a zero inside $U_0$, we infer from Lemma \ref{lem:weights} that $G_0$ acts freely on $U_0$. In particular, the action of $G_0$ on $U_0$ admits a geometric quotient $\lambda_0: U_0 \to V_0$ with a prevariety $V_0$. The statement on the isotropy groups of the $H$-action on $V_0$ is obvious.

We prove the statements made in (iii) and (iv). Denoting by $T^m$ the standard $m$-torus $(\mathbb{C}^*)^m$, we have a well defined morphism of normal prevarieties

$$\varphi: U_0 \to V_0 \times T^m, \quad x \mapsto (\lambda_0(x), f_1(x), \ldots, f_m(x)).$$

According to Lemma \ref{lem:weights} the weight $\chi_i$ of $f_i$ generates the character group of $G_i$ for $i = 1, \ldots, m$. Using this and the fact that $G_0$ is the direct product of $G_1, \ldots, G_m$,
we conclude that \( \varphi \) is bijective and thus an isomorphism. In particular, we conclude that \( V_0 \) is quasiaffine, because \( U \) and hence \( U_0 \) is so.

Now, endow \( V_0 \) with the induced action of \( H = G/G_0 \) and \( \mathbb{T}^m \) with the diagonal \( G_0 \)-action given by the weights \( \chi_1, \ldots, \chi_m \) of \( f_1, \ldots, f_m \). Then \( \varphi \) becomes \( G \)-equivariant, where \( G \) acts via the splitting \( G = H \times G_0 \) on \( V_0 \times \mathbb{T}^m \). Using this, we see that \( G \)-factoriality of \( U_0 \) implies \( H \)-factoriality of \( V_0 \).

We show now that every \( G_0 \)-invariant rational function \( f \in \mathbb{K}(U_0) \) has neither zeroes nor poles outside \( U_0 \). Recall that \( U \setminus U_0 \) is the union of the zero sets \( B_i \) of \( f_i \), which in turn are the fixed point sets of the \( G_i \)-actions on \( U \). Since the general orbit \( G_0 \cdot x \subseteq U \) has a point \( x_i \in B_i \) in its closure, we see that \( f \) has neither poles nor zeroes along the \( B_i \). In particular, if \( f \) is regular on \( U_0 \) then it is so on the whole \( U \). As a consequence, we obtain that every invertible function on \( V_0 \) is constant provided the same holds for \( U \).

Finally, according to Lemma 3.2 (iv), the homomorphism of (iv) is surjective. Moreover, since the weights \( \chi_1, \ldots, \chi_m \) of the \( f_1, \ldots, f_m \) are a basis of the character group of \( G_0 \), there are no relations among the \( f_i \).

Let a diagonalizable group \( H \) act effectively with at most finite isotropy groups on a quasiaffine variety \( V \). Suppose that \( V \) is \( H \)-factorial and admits only constant invertible functions. Denote by \( C_1, \ldots, C_n \subseteq V \) those \( H \)-prime divisors of \( V \), on which \( H \) acts with a non-trivial generic isotropy group \( H_j \) of order \( l_j > 1 \) and let \( g_1, \ldots, g_n \) be homogeneous functions on \( V \) with \( \text{div}(g_j) = C_j \).

**Proposition 3.4.** Consider the action of \( H_0 := H_1 \cdots H_n \subseteq H \) on \( V \), and let \( \kappa \colon V \to W \) be the associated quotient.

(i) \( W \) is a quasiaffine variety with an effective induced action of \( H/H_0 \), and 
\[
h \mapsto \kappa^*(h) \quad \text{and} \quad T_j \mapsto g_j
\]
define an isomorphism
\[
\Gamma(W, \mathcal{O})[T_1, \ldots, T_n]/(T_j^l_j - g_j^l_j; \ j = 1, \ldots, n) \to \Gamma(V, \mathcal{O}).
\]

(ii) \( W \) admits an \( (H/H_0) \)-factorial big open subset \( W_0 \subseteq W \) such that \( H/H_0 \) acts freely on \( W_0 \) and \( W_0 \) has only constant invertible functions.

**Proof.** We prove (i). By Lemma 3.2 (i), every \( H_j \) is cyclic. Moreover, Lemma 3.2 (iv) tells us that there is an epimorphism
\[
\Gamma(W, \mathcal{O})[T_1, \ldots, T_n] \to \Gamma(V, \mathcal{O}), \quad h \mapsto \kappa^*(h), \quad T_j \mapsto g_j.
\]

From Lemma 3.2 (iii) we infer that \( H_0 \subseteq H \) is the direct product of \( H_1, \ldots, H_n \subseteq H \). Thus, the quotient \( \kappa \colon V \to W \) can as well be obtained by dividing stepwise by effective actions of the \( H_j \). Using this, one directly checks that the kernel of this epimorphism is the ideal generated by \( T_j^l_j - g_j^l_j \), where \( 1 \leq j \leq n \).

We turn to (ii). Note that \( W \) admits only constant invertible functions. Let \( V_0 \subseteq V \) denote the subset consisting of all points \( y \in V \) that have either trivial isotropy group \( H_{0,y} \) or belong to some \( C_j \) and have isotropy group \( H_{0,y} = H_j \). Note that \( V_0 \subseteq V \) is big, \( H \)-invariant and open. Set \( W_0 := \kappa(V_0) \). Then \( W_0 \subseteq W \) is big and the restriction \( \kappa \colon V_0 \to W_0 \) is a quotient for the action of \( H_0 \). By construction, \( H/H_0 \) acts freely on \( W_0 \).

We show that \( W_0 \) is \( H/H_0 \)-factorial. Since \( V_0 \) and \( W_0 \) are normal, there is a smooth \( (H/H_0) \)-invariant big open subset \( W_1 \subseteq W_0 \) such that \( V_1 := \kappa^{-1}(W_1) \) is also smooth and big in \( V_0 \). We have to show that every \( (H/H_0) \)-linearizable bundle on \( W_1 \) is trivial. According to [14, Cor. 5.3], we have two exact sequences fitting
into the following diagram

\[
\begin{array}{ccc}
1 & \xrightarrow{\kappa^*} & \text{Pic}(W_1) \\
\downarrow & & \downarrow \\
\chi(H_0) & \xrightarrow{\alpha} & \text{Pic}_{H_0}(V_1) \\
\downarrow & & \downarrow \\
\prod_{i=1}^n \chi(H_i) & \xrightarrow{\delta} & \text{Pic}(V_1)
\end{array}
\]

where the isotropy groups \(H_1, \ldots, H_n\) generate \(H_0\) and hence \(\beta \circ \kappa^* \) and \(\delta \circ \alpha\) are injective. Given an \((H/H_0)\)-linearized bundle \(L\) on \(W_1\), the pullback \(\kappa^*(L)\) is trivial by assumption, which means \(\beta(\kappa^*(L)) = 1\). Consequently, \(L\) is trivial. \(\square\)

**Proof.** Proof of Theorem 1.1 We prove the statement more generally for the cases that \(\Gamma(X, O) = \mathbb{K}\) holds or that \(\Gamma(X, O^*) = \mathbb{K}^*\) holds and \(\text{Cl}(X)\) is free. Since the Cox ring of \(X\) and that of its smooth locus coincide, we may assume that \(X\) is smooth. Consider the universal torsor \(p: \hat{X} \to X\). By Proposition 2.5 this is a geometric quotient for a free action of the diagonalizable group \(H_X := \text{Spec} \mathbb{K}[\text{Cl}(X)]\) on \(\hat{X}\) and \(\hat{X}\) has only constant globally invertible functions. Fix a lifting of the \(T\)-action to \(\hat{X}\) as in Proposition 2.6 (i) and, as in Proposition 2.6 (ii), let \(G\) be the quotient of \(T \times H_X\) by the kernel of ineffectivity of its action on \(\hat{X}\). Then \(G\) acts effectively on \(\hat{X}\) and Proposition 2.5 (ii) tells us that \(\hat{X}\) is \(G\)-factorial.

Consider the \(T\)-invariant prime divisors \(E_1, \ldots, E_m \subseteq X\) supported in \(X \setminus X_0\). Their inverse images \(\hat{E}_k := p^{-1}(E_k)\) are \(G\)-prime divisors and, since \(\hat{X}\) is \(G\)-factorial, we have \(\hat{E}_k = \text{div}(f_k)\) with some \(G\)-homogeneous \(f_k \in \mathcal{R}(X)\). According to Proposition 2.6 (ii), the \(\hat{E}_k\) are precisely the \(G\)-prime divisors supported in \(\hat{X} \setminus \hat{X}_0\). Moreover, consider the \(T\)-invariant prime divisors \(D_1, \ldots, D_n \subseteq X\) along which \(T\) acts with a finite generic isotropy group of order \(l_j > 1\) and their (\(G\)-prime) inverse images \(\hat{D}_j := p^{-1}(D_j)\). As before, we see that \(\hat{D}_j = \text{div}(g_j)\) holds with some \(G\)-homogeneous \(g_j \in \mathcal{R}(X)\) and the generic isotropy group of the \(G\)-action on \(\hat{D}_j\) has order \(l_j\). Note that none of the \(\hat{D}_j\) equals one of the \(\hat{E}_k\). Moreover, we may view the functions \(f_k\) and \(g_j\) as the canonical sections of the divisors \(E_k\) and \(D_j\).

Let \(G_k \subseteq G\) denote the generic isotropy group of \(\hat{E}_k \subseteq \hat{X}_k\). The action of \(G_0 := G_1 \cdots G_m\) on \(\hat{X}_0 = p^{-1}(X_0)\) admits a geometric quotient \(\lambda_0: \hat{X}_0 \to \hat{Y}_0\). The factor group \(H := G/G_0\) acts with at most finite isotropy groups on \(\hat{Y}_0\) and, by Proposition 3.3 (ii), has generic isotropy group \(H_j \subseteq H\) of order \(l_j\) along the divisors \(\hat{C}_j := \lambda_0(\hat{D}_j)\). Set \(H_0 := H_1 \cdots H_n\) and let \(\hat{\gamma}_0: \hat{Y}_0 \to \hat{Z}_0\) denote the quotient for the action of \(H_0\) on \(\hat{Y}_0\). The induced action of \(F := H/H_0\) on \(\hat{Z}_0\) admits again a geometric quotient \(\hat{Z}_0 \to Z_0\) and the whole situation fits into the following commutative diagram.

\[
\begin{array}{ccc}
\hat{X} & \xrightarrow{G_0} & \hat{Y}_0 \\
\downarrow /H_X & & \downarrow /H_X \\
X & \xrightarrow{H_0} & \hat{Z}_0 \\
\downarrow /T & & \downarrow /F \\
x \subseteq X_0 & \xrightarrow{H_0} & Z_0
\end{array}
\]

Replacing \(Z_0\) and \(X_0\) as well as \(\hat{Z}_0, \hat{Y}_0\) and \(\hat{X}_0\) with suitable big open subsets, we achieve that the group \(F\) acts freely on \(\hat{Z}_0\).
We show that \( \tilde{Z}_0 \to Z_0 \) is a universal torsor for \( Z_0 \). According to Proposition \ref{prop:universal_torsor}, this means to verify that \( \tilde{Z}_0 \) is an \( F \)-factorial quasiaffine variety with only constant invertible functions. Proposition \ref{prop:toric_prevariety} provides the corresponding properties for the \( H \)-variety \( \tilde{Y}_0 \). Moreover, by Lemma \ref{lem:G_0_invariant}, every \( g_j \) is \( G_0 \)-invariant, hence \( g_j \) descends to a function on \( \tilde{Y}_0 \), where we have \( \text{div}(g_j) = \hat{C}_j \). Thus, we can apply Proposition \ref{prop:toric_prevariety} to obtain the desired properties for \( \tilde{Z}_0 \) and the action of \( F \).

The final task is to relate the Cox rings \( \mathcal{R}(X) = \Gamma(\tilde{X}, \mathcal{O}) \) and \( \mathcal{R}(Z_0) = \Gamma(\tilde{Z}_0, \mathcal{O}) \) to each other. Note that we have canonical inclusions of graded algebras

\[
\Gamma(\tilde{X}, \mathcal{O}) \supseteq \Gamma(\tilde{X}, \mathcal{O})^{G_0} = \Gamma(\tilde{Y}_0, \mathcal{O}) \supseteq \Gamma(\tilde{Y}_0, \mathcal{O})^{H_0} = \Gamma(\tilde{Z}_0, \mathcal{O}),
\]

where the first one is due to Proposition \ref{prop:toric_prevariety}. This allows us in particular to view \( \Gamma(\tilde{Z}_0, \mathcal{O}) \) as a graded subalgebra of \( \Gamma(\tilde{X}, \mathcal{O}) \). The assertion now follows from Proposition \ref{prop:toric_prevariety} (iv) and Proposition \ref{prop:toric_prevariety} (i).

In the above proof, we realized a big open subset of \( X_0/T \) as a quotient of a quasiaffine variety with only constant invertible functions by a free action of a diagonalizable group, see the diagram \ref{diagram:main}. According to Proposition \ref{prop:toric_prevariety} this allowed us to define a Cox ring for \( X_0/T \). Moreover, we use this now to show that \( X_0/T \) admits a separation.

**Proposition 3.5.** Let \( X \) be a normal quasiaffine variety with a free action of a diagonalizable group \( H \). Suppose that every invertible function on \( X \) is constant and that \( X \) is \( H \)-factorial. Then \( X := X/H \) admits a separation.

**Proof.** We first treat the case of a certain toric variety. Consider the standard action of \( T^r = (\mathbb{K}^*)^r \) on \( \mathbb{K}^r \), let \( Z \subseteq \mathbb{K}^r \) be the union of all orbits of the big torus \( T^r \subseteq \mathbb{K}^r \) of dimension at least \( r - 1 \), and let \( H \subseteq T^r \) be a closed subgroup acting freely on \( Z \). The fan \( \Sigma \) of \( Z \) has the extremal rays of the positive orthant \( \mathbb{Q}^r_{>0} \) as its maximal cones and \( Z := Z/H \) is the toric prevariety obtained by gluing the orbit spaces \( Z_0/H \) along their common big torus \( T/H \), where \( Z_0 \subseteq Z \) denotes the affine toric chart corresponding to \( \varrho \in \Sigma \). The embedding \( H \to T^r \) corresponds to a surjection \( \mathbb{Z}^r \to K \) of the respective character groups. Let \( P : \mathbb{Z}^r \to N \) be a map having \( \text{Hom}(K, \mathbb{Z}) \) as its kernel. Then we obtain a canonical separation \( Z \to Z' \) onto a toric variety \( Z' \), the fan of which lives in \( N \) and consists of the cones \( P(\varrho) \), where \( \varrho \in \Sigma \).

In the general case, choose a finitely generated graded subalgebra \( A \subseteq \Gamma(X, \mathcal{O}) \) such that we obtain an open embedding \( \hat{X} \subseteq \hat{X} \), where \( \hat{X} := \text{Spec} A \). Properly enlarging \( A \), we may assume that it admits a system \( f_1, \ldots, f_r \) of homogeneous generators such that each \( \text{div}(f_i) \) is \( H \)-prime in \( \hat{X} \). Consider the \( H \)-equivariant closed embedding \( \hat{X} \to \mathbb{K}' \) defined by \( f_1, \ldots, f_r \) and let \( Z \subseteq \mathbb{K}' \) be as above. By construction, \( U := Z \cap X \) is a big \( H \)-invariant open subset of \( X \), and we obtain a commutative diagram

\[
\begin{array}{ccc}
U & \to & Z \\
\downarrow H & & \downarrow H \\
U & \to & Z \\
\end{array}
\]

where the induced map \( U \to Z \) of quotients is a locally closed embedding and \( Z \) is a toric prevariety. Again by construction, the intersection of the invariant prime divisors of \( Z \) with \( U \) are prime divisors on \( U \). Consequently, the restriction of \( Z \to Z' \) defines the desired separation \( U \to U' \).

**Proof.** Proof of Theorem \ref{thm:main} We prove the statement more generally for the cases that \( \Gamma(X, \mathcal{O}) = K \) holds or that \( \Gamma(X, \mathcal{O}^*) = K^* \) holds and \( \text{Cl}(X) \) is free. By Proposition \ref{prop:toric_prevariety}, the orbit space \( X_0/T \) admits a separation \( \pi: X_0/T \to Y \). According to Remark \ref{rem:prime_divisors}, we may assume that there are prime divisors \( C_0, \ldots, C_r \) on \( Y \) such that
each \( \pi^{-1}(C_i) \) is a disjoint union of prime divisors \( C_{ij} \subseteq X_0/T \), where \( 1 \leq j \leq n_i \), the map \( \pi \) is an isomorphism over \( Y \setminus (C_0 \cup \ldots \cup C_r) \) and all the \( D_j \) occur among the divisors \( D_{ij} := q^{-1}(C_{ij}) \). Then, according to Proposition 2.3 we have

\[
\mathcal{R}(X_0/T) \cong \mathcal{R}(Y)[T_{ij}; \ 0 \leq i \leq r, \ 1 \leq j \leq n_i] / \langle T_i - 1_{C_i}; \ 0 \leq i \leq r \rangle,
\]

where the variables \( T_{ij} \) correspond to the canonical sections \( 1_{C_{ij}} \) and we define \( T_i := T_{i1} \cdots T_{im_i} \). Let \( l_{ij} \in \mathbb{Z}_{\geq 1} \) denote the order of the generic isotropy group of \( D_{ij} = q^{-1}(C_{ij}) \). Then, by Theorem 1.1 we have

\[
\mathcal{R}(X) \cong \mathcal{R}(X_0/T)[S_1, \ldots, S_m; T_{ij}] / \langle T_{ij}^{l_{ij}} - 1_{C_{ij}} \rangle,
\]

where the variables \( T_{ij} \) correspond to the canonical sections \( 1_{C_{ij}} \); note that \( 1_{C_{ij}} \) and \( 1_{D_{ij}} \) are identified for \( l_{ij} = 1 \). Putting these two presentations of Cox ring together, we arrive at the assertion. \( \square \)

**Proof.** Proof of Theorem 3.3. We prove the statement more generally for the case that \( \Gamma(X, \mathcal{O}) = \mathbb{K} \) holds. Since the \( T \)-action on \( X \) is of complexity one, the orbit space \( X_0/T \) is of dimension one and smooth. Moreover, using the diagram 3.1 and Proposition 3.3 we see that \( X_0/T \) admits only constant global functions and has a finitely generated divisor class group. It follows that \( X_0/T \) is isomorphic to \( \mathbb{P}_1(A, n) \), with \( A = (a_0, \ldots, a_r) \) and \( n = (n_0, \ldots, n_r) \) defined as in Theorem 1.3. By Proposition 2.3 the Cox ring \( \mathbb{P}_1(A, n) \) is given by

\[
(3.3) \quad \mathcal{R}(\mathbb{P}_1(A, n)) \cong \mathbb{K}[T_{ij}] / \langle g_i; \ 0 \leq i \leq r - 2 \rangle,
\]

where the variables \( T_{ij} \) correspond to the canonical sections of points \( a_{ij} \) in \( X_0/T \cong \mathbb{P}_1(A, n) \). Their inverse images \( D_{ij} = q^{-1}(a_{ij}) \) under \( q : X_0 \to X_0/T \) are prime divisors with generic isotropy group of order \( l_{ij} \geq 1 \); note that \( l_{ij} = 1 \) is allowed. Applying Theorem 1.1 gives

\[
(3.3) \quad \mathcal{R}(X) \cong \mathcal{R}(\mathbb{P}_1(A, n))[S_1, \ldots, S_m; T_{ij}] / \langle T_{ij}^{l_{ij}} - T_{ij} \rangle,
\]

where the variables \( S_i \) correspond to the divisors of \( X \) having a one-dimensional generic isotropy group, the variables \( T_{ij} \) are the canonical sections of the divisors \( D_{ij} \), and the \( T_{ij} \) are identified with their pullbacks under \( X_0 \to X_0/T \); note that the pullback \( q'(a_{ij}) \) equals \( l_{ij} D_{ij} \). Now, putting the descriptions (3.2) and (3.3) together gives the assertion. \( \square \)

**Remark 3.6.** Note that for factorial affine varieties with a complexity one torus action, D. Panov observed in [15] Remark 2.12 a presentation of the algebra of global functions by generators and trinomial relations.

4. COX RING VIA POLYHEDRAL DIVISORS

In this section, we combine Theorem 1.2 with the description of algebraic torus actions in terms of polyhedral divisors presented in [2] and [3] and provide a combinatorial approach to the Cox ring of an algebraic variety with torus action. We begin with a brief reminder on the language of polyhedral divisors.

In the sequel, \( N \) is a free finitely generated abelian group, and \( M = \text{Hom}(N, \mathbb{Z}) \) is its dual. The associated rational vector spaces are denoted by \( N_\mathbb{Q} := N \otimes \mathbb{Q} \) and \( M_\mathbb{Q} := M \otimes \mathbb{Q} \). Moreover, \( \sigma \subseteq N_\mathbb{Q} \) is a pointed convex polyhedral cone, and \( \omega \subseteq M_\mathbb{Q} \) is its dual cone. The relative interior of \( \sigma \) is denoted by \( \sigma^\circ \), and if \( \tau \) is a face of \( \sigma \), then we write \( \tau \subseteq \sigma \).

We consider convex polyhedra \( \Delta \subseteq N_\mathbb{Q} \) admitting a decomposition \( \Delta = \Pi + \sigma \) with a (bounded) polytope \( \Pi \subseteq N_\mathbb{Q} \); we refer to \( \sigma \) as the tail cone of \( \Delta \) and refer to \( \Delta \) as a \( \sigma \)-polyhedron. With respect to Minkowski addition, the set \( \text{Pol}^\star_\sigma(N) \) of all \( \sigma \)-polyhedra is a monoid with neutral element \( \sigma \). We consider also the empty set as an element of \( \text{Pol}^\star_\sigma(N) \) and set \( \Delta + \emptyset := \emptyset + \Delta := \emptyset \).
We are ready to enter the description of affine varieties with an action of the torus \( T = \text{Spec} \mathbb{K}[M] \). Let \( Y \) be a normal variety and fix a pointed convex polyhedral cone \( \sigma \subseteq N_\mathbb{Q} \). A polyhedral divisor on \( Y \) is a formal finite sum
\[
D = \sum_{Z} \Delta_Z \cdot Z,
\]
where \( Z \) runs over the prime divisors of \( Y \) and the coefficients \( \Delta_Z \) belong to \( \text{Pol}^+_\sigma(N) \); finiteness of the sum means that only finitely many coefficients \( \Delta_Z \) differ from the tail cone \( \sigma \).

The locus of a polyhedral divisor \( D \) on \( Y \) is the open subset \( Y(D) \subseteq Y \) obtained by removing all prime divisors \( Z \subseteq Y \) with \( \Delta_Z = \emptyset \). For every \( u \in \omega \cap M \) we have the evaluation
\[
D(u) := \sum_{Z} \min_{v \in \Delta_Z} \langle u, v \rangle \cdot Z,
\]
which is an ordinary rational divisor living on \( Y(D) \). We call the polyhedral divisor \( D \) on \( Y \) proper if its locus is semiprojective, i.e., projective over some affine variety, and its evaluations \( D(u) \), where \( u \in \omega \cap M \), have the following properties

(i) \( D(u) \) has a base point free multiple,
(ii) \( D(u) \) is big for \( u \in \omega \cap M \).

Remark 4.1. Suppose that we have \( Y = \mathbb{P}_n \), and consider a polyhedral divisor \( D = \sum \Delta_Z \cdot Z \). The degree of \( D \) is the polyhedron
\[
\text{deg}(D) := \sum Z \Delta_Z \cdot \text{deg}(Z) \in \text{Pol}^+_\sigma(N).
\]
It provides a simple criterion for properness: if \( \text{deg}(D) \) is a proper subset of the tail cone of \( D \), then \( D \) is a proper polyhedral divisor, see [2, Ex. 2.12].

By construction, every polyhedral divisor \( D \) on a normal variety \( Y \) defines a sheaf \( A(D) \) of \( M \)-graded \( \mathcal{O}_Y \)-algebras and its ring \( A(D) \) of global sections:
\[
A(D) := \bigoplus_{u \in \omega \cap M} \mathcal{O}(D(u)), \quad A(D) := \Gamma(Y(D), A(D)).
\]
Now suppose that \( D \) is proper. Then [2, Thm. 3.1] guarantees that \( A(D) \) is a normal affine algebra. Thus, we obtain an affine variety \( X(D) := \text{Spec} A(D) \), which comes with an effective action of the torus \( T = \text{Spec} \mathbb{K}[M] \). By [2, Thm. 3.4], every normal affine variety with an effective torus action is isomorphic to some \( X(D) \).

Example 4.2. Set \( N = \mathbb{Z}^2 \), let \( \sigma \subseteq N_\mathbb{Q} \) be the cone generated by the vectors \((1, 1)\) and \((0, 1)\), and consider the \( \sigma \)-polyhedra \( \Delta_0 \) and \( \Delta_\infty \) given as follows:
\[
\begin{align*}
\Delta_0 & := (0, 1) + \sigma \\
\Delta_\infty & := (0, 1] \times 0 + \sigma
\end{align*}
\]
Then we have a polyhedral divisor \( D := \Delta_0 \cdot \{0\} + \Delta_\infty \cdot \{\infty\} \) on \( Y = \mathbb{P}_1 \). Its degree \( \text{deg}(D) \) and tail cone \( \text{tail}(D) \) are given as
\[
\text{deg}(D) \quad \text{tail}(D)
\]
In particular, deg(D) is a proper subset of tail(D), and thus Remark 4.1 says that D is proper. The associated T-variety is \( \mathbb{K}^3 \) with the action

\[
t \cdot z = (t_1^{-1}t_2z_1, t_1z_2, t_2z_3).
\]

As in the case of toric varieties, general T-varieties are obtained by gluing affine ones. In the combinatorial picture, the gluing leads to the concept of a divisorial fan, which we recall now. As before, let \( N \) be a finitely generated free abelian group, fix a pointed convex polyhedral cone \( \sigma \in N_\mathbb{Q} \), and let \( Y \) be a normal variety. Consider two polyhedral divisors

\[
D = \sum Z \Delta Z, \quad D' = \sum Z' \Delta Z.
\]

both living on \( Y \). The intersection of \( D \) and \( D' \) is the polyhedral divisor \( D \cap D' \) on \( Y \) given by

\[
D \cap D' := \sum Z (\Delta' \cap \Delta) \cdot Z.
\]

Moreover, given a (not necessarily closed) point \( y \in Y \), we define the slice of \( D \) at \( y \) to be the polyhedron

\[
D_y := \sum y \Delta Z.
\]

Note that the slice \( D_y \) is the empty sum and hence equals the tail cone of \( D \). We say that \( D' \) is a face of \( D \) and write \( D' \preceq D \) if \( D'_y \preceq D_y \) holds for all \( y \in Y \) and the T-equivariant morphism \( X(D') \rightarrow X(D) \) given by the inclusion \( A(D') \supseteq A(D) \) is an open embedding.

**Remark 4.3.** Suppose that in the above setting, we have \( Y = \mathbb{P}^n \). As a consequence of [3, Lem. 6.7] the relation \( D' \preceq D \) holds if and only if we have

\[
D_y' \preceq D_y \text{ for all } y \in Y, \quad \text{deg}(D) \cap \text{tail}(D') = \text{deg}(D').
\]

A divisorial fan is a finite set \( \Xi \) of polyhedral divisors such that for any two \( D, D' \in \Xi \) we have \( D \geq D' \cap D \preceq D' \). For any \( y \in Y \), we call the polyhedral complex \( \Xi_y \) defined by the slices \( D_y \) the slice of \( \Xi \) at \( y \). We say that the divisorial fan \( \Xi \) is complete if \( Y \) is complete and each of its slices \( \Xi_y \) is a complete subdivision of \( N_\mathbb{Q} \). The locus of \( \Xi \) is the open subset

\[
Y(\Xi) := \bigcup_{D \in \Xi} Y(D) \subseteq Y.
\]

Given a divisorial fan \( \Xi \) consisting of proper polyhedral divisors, [3, Thm. 5.3] guarantees that we can equivariantly glue the affine T-varieties \( X(D) \) along the open subsets \( X(D \cap D') \), where \( D, D' \in \Xi \), to a T-prevariety \( X(\Xi) \). If the divisorial fan \( \Xi \) is complete, then \( X(\Xi) \) is a complete normal T-variety. By [3, Thm. 5.6], every normal variety with torus action is isomorphic to some \( X(\Xi) \).

**Example 4.4.** Set \( N := \mathbb{Z}^2 \) and \( Y := \mathbb{P}^1 \). Consider the six polyhedral divisors \( D^1, \ldots, D^6 \) with coefficients over the points 0, 1 and \( \infty \) as indicated below.
The collections of degrees \( \deg(D^i) \) and tail cones \( \text{tail}(D^i) \) of these polyhedral divisors are given as

\[
\begin{align*}
\text{deg}(D^i) & \quad \text{tail}(D^i)
\end{align*}
\]

Remarks 4.1 and 4.3 yield that \( D^1, \ldots, D^n \) are proper and form a divisorial fan \( \Sigma \). The \( T \)-variety \( X(\Sigma) \) is the projectivized cotangent bundle over \( \mathbb{P}_2 \).

For the description of the Cox ring of the \( T \)-variety \( X \) defined by a divisorial fan, we first of all need a description of the invariant prime divisors of \( X \) and their generic isotropy groups. For this, we introduce the following data.

**Definition 4.5.** Consider a divisorial fan \( \Sigma \) on a normal projective variety \( Y \), and let \( Z \subseteq Y \) be a prime divisor.

(i) The **index** of a vertex \( v \in \Sigma_Z \) is the minimal positive integer \( \mu(v) \) such that \( \mu(v) \cdot v \in N \) holds.

(ii) We call a vertex \( v \in \Sigma_Z \) **extremal** if there is a \( D \in \Sigma \) with \( v \in D_Z \) such that \( O(D(u)) \) is big on \( Z \) for any \( u \in (D_Z - v) \). The set of all extremal vertices \( v \in \Sigma_Z \) is denoted by \( \Sigma_Z^\times \).

(iii) We call a ray \( \rho \in \Sigma_Y \) **extremal** if there is a \( D \in \Sigma \) with \( \rho \in D_Y \) such that \( O(D(u)) \) is big on \( Y \) for any \( u \in (\rho^\perp \cap \omega)^\circ \). The set of all extremal rays \( \rho \in \Sigma_Y \) is denoted by \( \Sigma_Y^\times \).

(iv) We say that the prime divisor \( Z \) is **irrelevant** if \( \Sigma_Z^\times \) is empty, and we denote it by \( \Sigma_Y^\times \). The open subset obtained by removing all irrelevant \( Z \).

**Remark 4.6.** Let \( \Sigma \) be a divisorial fan on \( Y = \mathbb{P}_n \) and \( Z \subseteq \mathbb{P}_n \) a prime divisor. Then every vertex \( v \in \Sigma_Z \) is extremal and a ray \( \rho \in \Sigma_Y \) is extremal if and only if \( \rho \cap \deg(D) = 0 \) holds for some \( D \in \Sigma \) with \( \rho \in D_Y \).

As shown in [20], the extremal vertices of \( \Sigma \) are in bijection with the invariant prime divisors of \( X = X(\Sigma) \) intersecting \( X_0 \) and the extremal rays correspond to those contained in \( X \setminus X_0 \); see also Propositions 4.11 and 4.12. We will denote by \( D_v \) the divisors given by extremal vertices \( v \in \Sigma_Z^\times \) and by \( E_\rho \) those given by extremal rays \( \rho \in \Sigma_Y^\times \). Then the divisor class group \( \text{Cl}(X) \) can be described as follows, see [20 Cor. 3.17].

**Proposition 4.7.** Let \( \Sigma \) be a divisorial fan on \( Y \) and set \( X = X(\Sigma) \). Then \( \text{Cl}(X) \) is generated by the classes \([D_v]\), \( v \in \Sigma_Z^\times \) and \([E_\rho]\), \( \rho \in \Sigma_Y^\times \) and the image of a canonical homomorphism \( \text{Cl}(Y^\circ) \to \text{Cl}(X) \). The relations among these generators are

\[
\sum_{v \in \Sigma_Z^\times} \mu(v)D_v = [Z], \quad \sum_{\rho \in \Sigma_Y^\times} (u, v_\rho)E_\rho + \sum_{Z} \sum_{v \in \Sigma_Z^\times} \mu(v)(u, v)D_v = 0,
\]

where \( Z \) runs through the prime divisors of \( Y \), \( u \) runs through (a basis of) the lattice \( M \) and \( v_\rho \in \rho \) denotes the primitive lattice vector.

We are ready to compute the Cox ring of a \( T \)-variety \( X = X(\Sigma) \) in terms of its defining divisorial fan \( \Sigma \) and the projective variety \( Y \) carrying \( \Sigma \). Let \( Z_0, \ldots, Z_r \subseteq Y \) be the prime divisors having nontrivial slices \( \Sigma_{Z_0}, \ldots, \Sigma_{Z_r} \). 

THE COX RING OF A T-VARIETY 17
Theorem 4.8. There is a Cl(X)-graded inclusion of Cox rings $\mathcal{R}(Y^o) \to \mathcal{R}(X)$ and a Cl(X)-graded isomorphism

$$\mathcal{R}(X) \cong \mathcal{R}(Y^o)[S_0, T_v; \varrho \in \Xi^X, v \in \Xi^X, 0 \leq i \leq r] / \langle T^{\mu_i} - 1 Z_i; i = 0, \ldots, r \rangle,$$

where we set $T^{\mu_i} := \prod_{v \in \Xi^X} T^v_{\mu_i}$ and $1 Z_i \in \mathcal{R}(Y^o)$ denotes the canonical section of the prime divisor $Z_i \subseteq Y$. The grading is given by $\deg T_v = [D_v]$ and $\deg S_0 = [E_0]$. As a direct consequence, we obtain the following description of the Cox ring of a $T$-variety of complexity one.

Corollary 4.9. Let $\Xi$ be a divisorial fan on $Y = \mathbb{P}^1$ having non-trivial slices $\Xi_{a_0}, \ldots, \Xi_{a_r}$. Then the Cox ring of $X = X(\Xi)$ is given by

$$\mathbb{K}[S_v, T_v; \varrho \in \Xi^V, v \in \Xi^V, T_v^0, T_v^1, \ldots, T_v^r] / \left\langle \sum_{i=0}^r \beta_i T^{\mu_i}; \beta \in \text{Rel}(\bar{a}_0, \ldots, \bar{a}_r) \right\rangle,$$

where $\bar{a}_i \in \mathbb{K}^2$ represents $a_i \in \mathbb{P}^1$. We set $T^{\mu_i} := \prod_{v \in \Xi^V} T^v_{\mu_i}$ and $\text{Rel}(\bar{a}_0, \ldots, \bar{a}_r)$ is a basis for the space of linear relations among $\bar{a}_0, \ldots, \bar{a}_r$.

Note that an appropriate choice of a basis for the space of linear relations among $\bar{a}_0, \ldots, \bar{a}_r$ in $\mathbb{K}^2$ gives a trinomial representation of the Cox ring as in Theorem 4.8.

Example 4.10. Consider once more the divisorial fan $\Xi$ and its associated variety $X(\Xi)$ of Example 4.4. According to Remark 4.6, there are no extremal rays and all six vertices

$$v_1, v_2 \in \Xi(0), \quad v_3, v_4 \in \Xi(1), \quad v_5, v_6 \in \Xi(\infty)$$

are extremal, where we have $v_1 = v_3 = v_5 = 0 \in N$. Proposition 4.7 shows that Cl($X(\Xi)$) is freely generated by the classes of $D_{v_1}$ and $D_{v_2}$. By Corollary 4.9, the Cox ring of $X(\Xi)$ is

$$\mathcal{R}(X(\Xi)) = \mathbb{K}[T_1, \ldots, T_6] / \langle T_1 T_2 + T_3 T_4 + T_5 T_6 \rangle$$

with $\deg T_1 = \deg T_3 = \deg T_5 = [D_{v_1}]$ and $\deg T_2 = \deg T_4 = \deg T_6 = [D_{v_2}]$. Note that this presentation of the Cox ring shows that $X(\Xi)$ can be obtained as a $\mathbb{K}^*$-quotient of the Grassmannian $G(2, 4)$.

The rest of the section is devoted to proving Theorem 4.8, which basically means to express the input data of Theorem 1.2 in terms of polyhedral divisors. For this, we first have to recall further details of the construction of the $T$-variety $X(\Xi)$ associated to a divisorial fan $\Xi$ on a projective variety $Y$. For every $D \in \Xi$, we have the sheaf $\mathcal{A}(D)$ of normal $M$-graded $\mathcal{O}_Y$-algebras. Its relative spectrum $\tilde{X}(D) := \text{Spec}_Y \mathcal{A}(D)$ comes with a $T$-action and we have canonical morphisms

$$\tilde{X}(D) \to Y, \quad \tilde{X}(D) \to X(D)$$

defined by $\mathcal{O}_Y \subseteq \mathcal{A}(D)$ and $\mathcal{A}(D) = \Gamma(\tilde{X}(D), \mathcal{O})$. The $T$-varieties glue together $\tilde{X}(D)$ along the open subsets $\tilde{X}(D \cap D')$ to a $T$-variety $\tilde{X}(\Xi)$. These gluings are compatible with the above maps and one obtains a commutative diagram

$$\tilde{X}(\Xi) \xrightarrow{r} X(\Xi) \xrightarrow{\pi} Y$$

where $r: \tilde{X}(\Xi) \to X(\Xi)$ is $T$-equivariant, birational and proper, $\tilde{\pi}: \tilde{X}(\Xi) \to Y$ is $T$-invariant and the rational map $\pi: X(\Xi) \to Y$ is defined in codimension two. Note that image of $\tilde{\pi}$ is given by

$$\tilde{\pi}(\tilde{X}(\Xi)) = \bigcup_{D \in \Xi} Y(D) \subseteq Y.$$
The next step is a precise description of the $T$-invariant prime divisors $X(\Xi)$, see also [20] Prop. 3.13. Consider an extremal vertex $v \in \Xi^\vee_Z$ of $D \in \Xi$, where $Z \subseteq Y(D)$ is a prime divisor. These data define a homogeneous ideal
\[ I_v := \bigoplus_{u \in D_v \cap M} \Gamma(Y, O(D(u))) \cap \{ f \in K(Y); \text{ord}_Z(f) > -\langle u, v \rangle \} \subseteq \Gamma(X(D), O), \]
which turns out to be a prime ideal of height one. We define the corresponding prime divisor $D_v \subseteq X(\Xi)$ to be the closure of the zero set of $I_v$.

**Proposition 4.11.** Set $X := X(\Xi)$. The assignment $v \mapsto D_v$ induces a bijection between the extremal vertices of $\Xi$ and the invariant prime divisors of $X$ intersecting $X_0$. The extremal vertices of $\Xi_Z$ correspond to the invariant prime divisors contained in $\pi^{-1}(Z)$ and the generic isotropy group of $D_v$ is cyclic of order $\mu(v)$.

**Proof.** We may restrict to the affine case. Consider a proper polyhedral divisor $D$, the corresponding sheaf of algebras $A := A(D)$ and its algebra of global sections $A := A(D)$. First we calculate the ideal of $\pi^{-1}(Z) = r(\pi^{-1}(Z))$. The inverse image ideal sheaf of $O(-Z)$ is given by
\[ O(-Z) \cdot A = \bigoplus_{u \in D_v \cap M} O([D(u)] - Z). \]

The radical of the ideal $\Gamma(Y, O(-Z) \cdot A) \subseteq A$ is exactly the ideal we are looking for. It is given by
\[
I_Z = \bigoplus_{u \in D_v \cap M} \Gamma(Y, O(D(u))) \cap \{ f \in K(Y); \text{ord}_Z(f) > -\min\langle u, D_Z \rangle \}
\]
\[ = \bigcap_{v \in D_Z} I_v. \]

Note that we have $(I_v)_u = A_u$ if $\langle u, v \rangle \notin Z$. Denote by $\kappa: \tilde{Z} \rightarrow Z$ the normalization. If $\psi: \tilde{Y} \rightarrow Y$ is a desingularization, then we have $A(D) = A(\psi^* D)$ and $I_v = I_u$, where $I_u$ is the ideal in $A(\psi^* D)$ corresponding to the vertex $v$ in $(\psi^* D)|_{\tilde{Z}}^{-1} Z$. Hence, in the following we may assume that $Y$ is smooth and thus every prime divisor is Cartier. Then, for the corresponding affine subschemes $V(I_v)$ we obtain the coordinate rings
\[
A/I_v = \bigoplus_{u \in (D_Z - v)^* \cap M_v} \Gamma(Y, A_u)/\Gamma(Y, A_u(-Z))
\[
\subseteq \bigoplus_{u \in (D_Z - v)^* \cap M_v} \Gamma(Y, A_u/A_u(-Z))
\[
\cong \bigoplus_{u \in (D_Z - v)^* \cap M_v} \Gamma(Z, A_u|_Z)
\[
\subseteq \bigoplus_{u \in (D_Z - v)^* \cap M_v} \Gamma(\tilde{Z}, \kappa^*(A_u|_Z))
\[
\cong A(D_v).
\]

Here, we write $A_u(-Z) := A_u \otimes O(-Z)$ as usual, $M_v \subseteq M$ is the sublattice consisting of all $u \in M$ with $\langle u, v \rangle \in Z$ and $D_v$ is a polyhedral divisor on $\tilde{Z}$ with tail cone $\sigma_v := \mathbb{Q}_{\geq 0} \cdot (D_Z - v)$ and lattice $M_v^* \supset N$ defined via the inclusion $\iota: Z \rightarrow Y$ as follows
\[
D_v := \sum_W (D_W + \sigma_v) \cdot (\kappa \circ \iota)^* W.
\]

Note that $(\kappa \circ \iota)^* Z$ is defined only up to linear equivalence as a divisor on $\tilde{Z}$ but every choice will give isomorphic algebras $A(D_v)$, compare [2] Cor. 8.9]. Our condition on
the bigness of \( \mathcal{D}(u) \) for \( u \in \sigma^\vee_v \) implies that \( \mathcal{D}_v \) is indeed proper for any extremal \( v \). Hence, \( X(\mathcal{D}_v) \) is irreducible and of dimension (\( \dim X - 1 \)) in this case. If \( v \) is not extremal then \( \mathcal{D}_v \) is the pullback of a proper polyhedral divisor on

\[
Y_v := \text{Proj} \bigoplus_k \Gamma(Y, \mathcal{O}(k \cdot \sum_i \mathcal{D}_v(u_i)))
\]

for some \( u_i \in (\sigma^\vee_v)^{\circ} \). But \( Y_v \) is of smaller dimension than \( Y \), since \( \mathcal{O}(\mathcal{D}_v(u_i)) \cong \mathcal{O}(\mathcal{D}(u_i))|_Z \) is not big. This implies, that \( X(\mathcal{D}_v) \) is of dimension

\[
\dim Y_v + \dim T < \dim Y + \dim T = \dim X - 1.
\]

Since \( \mathcal{D}(u) \) is semi-ample and \( \mathcal{A}_u = \mathcal{O}(\mathcal{D}(u)) \) holds, \( \oplus_{k \geq 0} H^1(\mathcal{A}_k(-Z)) \) is finitely generated as a module over the ring \( \oplus_{k \geq 0} \Gamma(Y, \mathcal{A}_k(-Z)) \) shows that \( \oplus_{k \geq 0} \Gamma(Y, \mathcal{A}_k(-Z)) \) is finitely generated over the ring \( \oplus_{k \geq 0} \Gamma(Y, \mathcal{A}_k(-Z)) \). The fact that \( \Gamma(\bar{Z}, u^* \oplus_{k \geq 0} \mathcal{A}_k(-Z)) \) is finitely generated over \( \Gamma(Z, u^* \mathcal{A}_k) \) follows from the properties of the normalization map. Thus, \( A(\mathcal{D}_v) \) is finitely generated over \( A(\mathcal{D}) \) and \( \mathcal{D}_v \) is the image of \( X(\mathcal{D}_v) \) under a finite morphism \( f \), hence, \( \mathcal{D}_v \) is irreducible and of codimension one; it is not hard to see that \( f \) even is the normalization map.

The fact that all homogeneous functions of weights \( u \notin M_v \) vanish on \( \mathcal{D}_v \) implies, that \( T \) does not act effectively on \( \mathcal{D}_v \) but with generic isotropy group \( M/M_v \cong \mathbb{Z}/\mu(v) \mathbb{Z} \).

Now take an extremal ray \( \rho \in \Xi^\vee_{\mathcal{Y}} \) with \( \rho \in \mathcal{D}_{\mathcal{Y}} \), where \( \mathcal{D} \in \Xi \). Then define the associated invariant prime divisor \( E_\rho \) of \( X(\Xi) \) to be the closure of the zero set of \( V(\mathcal{X}(\mathcal{D}), I_{\rho}) \), where \( I_{\rho} \) is the homogeneous prime ideal of height one given by

\[
I_{\rho} := \bigoplus_{u \in \mathcal{D} \setminus \rho^\perp} \Gamma(Y, \mathcal{O}(\mathcal{D}(u))) \subseteq \Gamma(X(\mathcal{D}), \mathcal{O}).
\]

**Proposition 4.12.** Set \( X := X(\Xi) \). The assignment \( \rho \to E_\rho \) induces a bijection between the set of extremal rays of \( \Xi \) and the invariant prime divisors of \( X \) contained in \( X \setminus X_0 \).

**Proof.** For a polyhedral divisor \( \mathcal{D} \), the invariant prime divisors of \( \bar{X} \) contained in \( \bar{X}/X_0 \) correspond to the prime ideal sheaves given by not necessarily extremal rays \( \rho \in \mathcal{D}_{\mathcal{Y}}(1) \) as follows

\[
I_{\rho} := \bigoplus_{u \in \mathcal{D} \setminus \rho^\perp} \mathcal{O}(\mathcal{D}(u)).
\]

This can be seen locally. Consider an affine open subset \( U \subset Y \) such that \( \mathcal{D}|_U \) is trivial. Then \( \bar{X}(\mathcal{D}|_U) \subseteq \bar{X}(\mathcal{D}) \) is an open inclusion and we have

\[
A(\mathcal{D}|_U) = \Gamma(U, \mathcal{O}_Y)|_{\mathcal{D}^\vee_{\mathcal{Y}} \cap M}.
\]

Now the claim follows from standard toric geometry, since the considered prime divisors correspond to ideals \( I \subset A(\mathcal{D}|_U) \) with \( I \cap \Gamma(U, \mathcal{O}_Y) = 0 \).

The image under \( r \) corresponds to the ideal \( I_{\rho} = \Gamma(I_{\rho}) \) and for the coordinate ring of the corresponding subvariety we obtain

\[
A(\mathcal{D})/I_{\rho} = \bigoplus_{u \in \rho^\perp \cap \mathcal{D}^\vee_{\mathcal{Y}} \cap M} \Gamma(Y, \mathcal{D}(u)) = A(\mathcal{D}_v).
\]

Here, \( \mathcal{D}_v := \sum_{\mathbb{Z}} p(\mathcal{D}_Z) \cdot Z \) is a polyhedral divisor on \( Y \) with tail cone \( p(\mathcal{D}_{\mathcal{Y}}) \) and lattice \( p(N) \), where \( p \) is the projection \( N_{\mathbb{Q}} \to N_{\mathbb{Q}}/\mathbb{Q} \cdot \rho \).

The fact that \( \rho \) is extremal ensures that \( \mathcal{D}_v \) is proper, which in turn implies that \( V(I_{\rho}) \) has codimension one. \( \square \)
Proof. Proof of Theorem 4.8 We first construct big open subsets $Y' \subseteq Y^0$ and $X' \subseteq X_0$. The set $Y'$ is obtained by removing from $Y^0$ all the intersections $Z_i \cap Z_j$, where $0 \leq i < j \leq r$. To define $X'$, denote by $\tilde{E} \subseteq \tilde{X}$ the exceptional locus of the contraction $r: \tilde{X} \to X$ and set

$$\tilde{X}' := (\pi^{-1}(Y') \setminus \tilde{X}_0) \setminus \tilde{E} \subseteq \tilde{X}_0, \quad X' := r(\tilde{X}') \subseteq X_0.$$

Then $\pi: \tilde{X}' \to Y'$ is surjective and $r: \tilde{X}' \to X'$ is an isomorphism. Moreover, the $T$-invariant map $\pi' := \pi \circ r^{-1}$ factors as

$$X' \xrightarrow{\pi'} Y' \quad \xrightarrow{\varphi} \quad X'/T.$$

Note that $\varphi$ is birational and injective. Thus, $\varphi$ is a local isomorphism and hence a separation for $X'/T$.

By Proposition 4.11 the prime divisors corresponding to the extremal vertices $v \in \mathbb{Z}^d_2$ are precisely the irreducible components of the inverse image $(\pi')^{-1}(Z_i)$, and their generic $T$-isotropy is of order $\mu(v)$. Moreover, by Proposition 4.12 the prime divisors in $X \setminus X_0$ correspond to the extremal rays of $\Xi$. Now the assertion follows from Theorem 1.2. \hfill \Box

5. Applications and Examples

We first note some algebraic properties of the Cox ring of a variety with complexity one torus action. Recall the following concepts from [11, Def. 3.1]. Let $K$ be a finitely generated abelian group and $R = \bigoplus_{w \in K} R_w$ any $K$-graded integral $K$-algebra with $R^* = K^*$.

(i) We say that a nonzero nonunit $f \in R$ is $K$-prime if it is homogeneous and $f|gh$ with homogeneous $g, h \in R$ always implies $f|g$ or $f|h$.

(ii) We say that an ideal $a \subset R$ is $K$-prime if it is homogeneous and for any two homogeneous $f, g \in R$ with $fg \in a$ one has $f \in a$ or $g \in a$.

(iii) We say that a homogeneous prime ideal $a \subset R$ has $K$-height $d$ if $d$ is maximal admitting a chain $a_0 \subset a_1 \subset \ldots \subset a_d = a$ of $K$-prime ideals.

(iv) We say that the ring $R$ is factorially graded if every $K$-prime ideal of $K$-height one is principal.

Now, let $X$ be a complete normal variety with finitely generated divisor class group and an algebraic torus action $T \times X \to X$ of complexity one. Then Theorem 4.3 provides a presentation of the Cox ring of $X$ as

$$\mathcal{R}(X) \cong K[S_1, \ldots, S_m, T_{ij}; 0 \leq i \leq r, 1 \leq j \leq n_i] / \langle g_i; 0 \leq i \leq r-2 \rangle,$$

where the variables $S_j$ and $T_{ij}$ are homogeneous with respect to the $\text{Cl}(X)$-grading and the relations $g_i$ are $\text{Cl}(X)$-homogeneous trinomials all having the same degree.

**Proposition 5.1.** The Cox ring $\mathcal{R}(X)$ is factorially $\text{Cl}(X)$-graded. In the presentation of Theorem 4.3, the generators $S_k$ and $T_{ij}$ define pairwise nonassociated $\text{Cl}(X)$-prime elements and $\mathcal{R}(X)$ is a complete intersection.

**Proof.** The fact that $\mathcal{R}(X)$ is factorially $\text{Cl}(X)$-graded holds for any complete variety with a finitely generated Cox ring, use for example [11, Prop. 3.2]. Moreover, the variables $S_k$ and $T_{ij}$ define pairwise nonassociated $\text{Cl}(X)$-prime elements, because their divisors are pairwise different $H_X$-prime divisors, where $H_X = \text{Spec } K[\text{Cl}(X)]$, use again [11, Prop. 3.2].

We show that $\mathcal{R}(X)$ is a complete intersection. This means to verify that $\mathcal{R}(X)$ is of dimension $m + n_0 + \ldots + n_r - (r-1)$. Consider the torsor $\tilde{X} \to X$, and recall
from the proof of Theorem 1.1 diagram 5.1 that we have quotients
\[ \hat{\mathcal{Y}}_0 = \hat{X}_0/G_0, \quad \hat{Z}_0 = \hat{Y}_0/H_0, \quad X_0/T \cong \hat{Z}_0/F \]
where \( G_0 \) is an \( m \)-dimensional torus acting freely, \( H_0 \) is a finite group, and \( F \) is a diagonalizable group acting freely and having the rank of \( \text{Cl}(X_0/T) \) as its dimension. In our situation, \( X_0/T \cong \mathbb{P}_1(A, n) \) is of dimension one and, by Proposition 2.13, has a divisor class group of rank \( n_0 + \ldots + n_r - r \). Thus, the dimension of \( \mathcal{R}(X) \) equals
\[ \dim(\hat{X}_0) = m + \dim(\hat{\mathcal{Y}}_0) = m + \dim(\hat{Z}_0) = m + n_0 + \ldots + n_r - r + 1. \]

We come to geometric applications of this observation. Note that each complete normal variety \( X \) with finitely generated divisor class group and a complexity one torus action is rational, because \( X_0/T \cong \mathbb{P}_1(A, n) \) is so. Thus, the varieties \( X \) in question are precisely the complete normal rational ones with a torus action of complexity one. If we impose additionally the condition that any two points of \( X \) admit a common affine neighbourhood, which holds e.g. for projective \( X \), then Proposition 5.1 and [11, Thm. 4.19] ensure that \( X \) arises from a "bunched ring" \((R, \mathfrak{g}, \Phi)\), see [11, Def. 3.3, Constr. 3.4], where we may take \( R = \mathcal{R}(X) \) and \( \mathfrak{g} = (S_k, T_{ij}) \). This allows us to apply the results provided in [11].

**Corollary 5.2.** Let \( X \) be a complete normal rational variety with an effective algebraic torus action \( T \times X \rightarrow X \) of complexity one and suppose that any two points of \( X \) admit a common affine neighbourhood. Then there exists a closed embedding \( \iota : X \rightarrow X' \) into a toric variety \( X' \) with big torus \( T' \subseteq X' \) such that

(i) \( \iota : X \rightarrow X' \) is equivariant with respect to a \( T \)-action on \( X' \) given by a monomorphism \( T \rightarrow T' \);

(ii) the image \( \iota(X) \subseteq X' \) intersects \( T' \) and is a complete intersection of \( T' \)-invariant hypersurfaces of \( X' \);

(iii) for every \( T' \)-invariant prime divisor \( D' \subseteq X' \), the inverse image \( \iota^{-1}(D') \subseteq X \) is a prime divisor,

(iv) \( \iota : X \rightarrow X' \) defines a pullback isomorphism \( \iota^* : \text{Cl}(X') \rightarrow \text{Cl}(X) \) on the level of divisor class groups.

**Proof.** Apply the construction of a toric embedding given in [11, Constr. 3.13 and Prop. 3.14] to the defining bunched ring \((R, \mathfrak{g}, \Phi)\) of \( X \), where \( R = \mathcal{R}(X) \) and \( \mathfrak{g} = (S_k, T_{ij}) \), and use the fact that the \( S_k \) as well as the \( T_{ij} \) are homogeneous with respect to a lifting of the \( T \)-action to the torsor. \( \square \)

Recall from the introduction that \( E_k \subseteq X \) are the prime divisors supported in \( X \setminus X_0 \), that \( D_{ij} \subseteq X \) are prime divisors intersecting \( X_0 \) and lying over a point \( a_i \in X_0/T \) and \( l_{ij} \) is the order of the generic isotropy group of \( T \) along \( D_{ij} \).

**Corollary 5.3.** Let \( X \) be a complete normal rational variety with an effective algebraic torus action \( T \times X \rightarrow X \) of complexity one.

(i) The cone of divisor classes without fixed components is given by
\[ \bigcap_{1 \leq k \leq m} \text{cone}(\{E_s\}, \{D_{ij}\}; s \neq k) \cap \bigcap_{0 \leq s \leq r} \text{cone}(\{E_k\}, \{D_{st}\}; (s, t) \neq (i, j)). \]

(ii) For any \( 0 \leq i \leq r \), one obtains a canonical divisor for \( X \) by
\[ \max(0, r - 1) \cdot \sum_{j=0}^{n_i} I_{ij}D_{ij} - \sum_{k=1}^{m} E_k - \sum_{i,j} D_{ij}. \]

**Proof.** By [3, Thm. 2.3], there is a small birational transformation \( X \rightarrow X' \) with a projective \( X' \). As \( X \) and \( X' \) share the same Cox ring, we may assume that \( X \) is projective. The assertions then follow from [11, Prop. 4.1 and Prop. 4.15]. \( \square \)
Note that [20] Thm. 3.19 provides an equivalent description of the canonical divisor in terms of the defining divisorial fan.

The first non-trivial examples of torus actions of complexity one are $\mathbb{K}^*$-surfaces. Let us look at their Cox rings. Orlik and Wagreich associate in [17] to any smooth complete $\mathbb{K}^*$-surface $X$ without elliptic fixed points a graph of the following shape:

![Graph](image)

The vertices of this graph represent certain invariant curves. The two (smooth) fixed point curves of $X$ occur as $F^+$ and $F^-$ in the graph. The other vertices represent the invariant irreducible contractible curves $D_{ij} \subseteq X$ different from $F^+$ and $F^-$. The label $-b_j^i$ is the self intersection number of $D_{ij}$, and two of the $D_{ij}$ are joined by an edge if and only if they have a common (fixed) point. Every $D_{ij}$ is the closure of a non-trivial $\mathbb{K}^*$-orbit.

We show how to read off the Cox ring from the Orlik-Wagreich graph. Suppose that $X$ is rational. Then $F^+$ is rational as well and hence is a $\mathbb{P}_1$. Define $l_{ij}$ to be the numerator of the canceled continued fraction

$$\frac{1}{b_1^i - \frac{1}{b_2^i - \frac{1}{\ldots - \frac{1}{b_{j-1}^i}}}}.$$  

Moreover, let $a_i$ be the point in $F^+ \cap D_{ij}$ and write $a_i = [b_i, c_i]$ with $b_i, c_i \in \mathbb{K}$. Then, for every $0 \leq i \leq r$, set $k = j + 1 = i + 2$ and define a trinomial in $\mathbb{K}[T_{ij}; 0 \leq i \leq r, 1 \leq j \leq n_i]$ as follows

$$g_i := (c_k b_j - c_j b_k) f_k + (c_i b_j - c_j b_i) f_j + (c_j b_i - c_i b_j) f_k,$$

where $f_s := T_{s_1}^{l_{s_1}} \cdots T_{s_{n_s}}^{l_{s_{n_s}}}$.

**Theorem 5.4.** Let $X$ be a smooth complete rational $\mathbb{K}^*$-surface without elliptic fixed points. Then the assignments $S^\pm \mapsto 1_{F^\pm}$ and $T_{ij} \mapsto 1_{D_{ij}}$ define an isomorphism

$$\mathcal{R}(X) \cong \mathbb{K}[S^+, S^-, T_{ij}; 0 \leq i \leq r, 1 \leq j \leq n_i] / \langle g_i; 0 \leq i \leq r - 2 \rangle$$

of Cl$(X)$-graded rings, where the Cl$(X)$-grading on the right hand side is defined by associating to $S^\pm$ the class of $F^\pm$ and to $T_{ij}$ the class of $D_{ij}$.

**Proof.** The open set $X_0 \subseteq X$ is obtained by removing $F^+$, $F^-$ and the isolated fixed points. By [17] Sec. 3.5, the number $l_{ij}$ is the order of the isotropy group of the nontrivial $\mathbb{K}^*$-orbit in $D_{ij}$. Moreover, we have a canonical morphism $\pi: X_0/\mathbb{K}^* \rightarrow F^+$, with exceptional fibers $\pi^{-1}(a_i) = \{a_{i1}, \ldots, a_{in_i}\}$, where $a_{ij}$ represents the nontrivial $\mathbb{K}^*$-orbit of $D_{ij}$. Thus, the assertion follows from Theorem [1,3].

For (possibly singular) $\mathbb{K}^*$-surfaces $X$ with elliptic fixed points, the Cox ring can be computed as follows. Suitably resolving gives a $\mathbb{K}^*$-surface $\tilde{X}$, called canonical resolution, where the elliptic fixed points are replaced with fixed point curves. Having computed the Cox ring $\mathcal{R}(\tilde{X})$ as above, we easily obtain the Cox ring $\mathcal{R}(X)$. According to Theorem [1,3] we need the divisors of the type $E_k$ and $D_{ij}$ in $X$ and the orders $l_{ij}$ of the generic isotropy groups of $D_{ij}$. Each of these divisors is the image of a non-exceptional divisor of the same type in $\tilde{X}$; to see this for the $D_{ij}$, note that $X_0$ is the open subset of $\tilde{X}_0$ obtained by removing the exceptional locus.
of $\tilde{X} \to X$ and thus $X_0/\mathbb{K}^*$ is an open subset of $\tilde{X}_0/\mathbb{K}^*$. Moreover, by equivariance, the orders $t_{ij}$ in $X$ are the same as in $\tilde{X}$. Consequently, the Cox ring $\mathcal{R}(X)$ is obtained from $\mathcal{R}(\tilde{X})$ by removing those generators that correspond to the exceptional curves arising from the resolution.

As the intersection graphs of their resolutions are known, see [1], the methods just outlined provide Cox rings of (possibly singular) Gorenstein del Pezzo $\mathbb{K}^*$-surfaces $X$; note that Derenthal computed in [8] the Cox rings of the minimal resolutions $\tilde{X}$ without assuming existence of a $\mathbb{K}^*$-action for the cases that $X$ is of degree at least 3 and $\mathcal{R}(\tilde{X})$ is defined by a single relation. Moreover, the divisorial fans of Gorenstein del Pezzo $\mathbb{K}^*$-surfaces $X$ are provided in [21], which allows us to use as well the approach via polyhedral divisors.

**Example 5.5.** We consider the family $X_\lambda$ of Gorenstein Del Pezzo $\mathbb{K}^*$-surfaces over $\mathbb{K} \setminus \{0, 1\}$ of degree one and singularity type $2D_4$. The canonical resolution $\tilde{X}_\lambda$ of $X_\lambda$ is obtained by minimally resolving the two singularities and, by [1] Thm. 8.3, its Orlik-Wagreich graph is given as

![Orlik-Wagreich graph](image)

We have four points $a_0, \ldots, a_3$, where $\{a_i\} = D_3 \cap F^+$. Note that the positions of these four points on $F^+ \cong \mathbb{P}_1$ may vary and the parameter $\lambda$ is the cross ratio of $a_0, a_1, a_2, a_3$. The Cox rings of $\tilde{X}_\lambda$ and $X_\lambda$ are given by

$$
\mathcal{R}(\tilde{X}_\lambda) = \mathbb{K}[S_1, S_2, T_{01}, \ldots, T_{33}] / \langle T_{01}T_{02} + T_{12}T_{13} + T_{23}T_{24}T_{23}, \lambda T_{12}T_{13} + T_{23}T_{24}T_{23} + T_{31}T_{32}T_{33} \rangle,
$$

$$
\mathcal{R}(X_\lambda) = \mathbb{K}[T_1, \ldots, T_5] / \langle T_1T_2 + T_2^2 + T_3^2, \lambda T_1^2 + T_2^2 + T_3^2 \rangle.
$$

Now let us look at $X_\lambda$ via its divisorial fan $\Xi_\lambda$. According to [21] Thm. 4.8, the divisorial fan $\Xi_\lambda$ lives on $Y = \mathbb{P}_1$. Its non-trivial slices lie over the points $a_0, \ldots, a_3 \in Y$ and are given in $N = \mathbb{Z}$ as follows:

![Slices of divisorial fan](image)

We compute the divisor class group $\text{Cl}(X_\lambda)$. According to Remark 4.6 we have two extremal vertices $v_1, v_2$ in $\Xi_{a_0}$ and one extremal vertex $v_{i+2}$ in $\Xi_{a_i}$ for $i = 1, 2, 3$. Let $D_i$ be the prime divisor associated to $v_i$ for $i = 1, \ldots, 5$ and denote by $D_0$ the positive generator of $\text{Cl}(Y) = \mathbb{Z}$. Then Proposition 4.7 tells us that the divisor class group $\text{Cl}(X_\lambda)$ is $\mathbb{Z}D_0 \oplus \ldots \oplus \mathbb{Z}D_5$ modulo the relations defined by the rows of the matrix

$$
A = \begin{pmatrix}
-1 & 1 & 0 & 0 & 0 \\
-1 & 0 & 2 & 0 & 0 \\
-1 & 0 & 0 & 0 & 2 \\
-1 & 0 & 0 & 0 & 2 \\
0 & -2 & -1 & 1 & 1 \\
\end{pmatrix}
$$
The Smith Normal Form \( S = U \cdot A \cdot V \) with unimodular transformation matrices \( U \) and \( V \) is given as

\[
S = \begin{pmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 2 & 0 \\
0 & 0 & 0 & 0 & 2
\end{pmatrix}
\]

In particular, we conclude \( \text{Cl}(X_\lambda) \cong \mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z} \). Moreover, computing \( V^{-1} \) we see that the class of \( D_4 \) generates the free part and the classes of \( D_3 - D_5 \) and \( D_4 - D_5 \) generate the cyclic parts. Consulting Theorem 4.8 gives the Cox ring

\[
\mathcal{R}(X_\lambda) = \mathbb{K}[T_1, \ldots, T_5] / (T_1 T_2 + T_3^2 + T_4^2, \lambda T_2^2 + T_4^2 + T_5^2)
\]

with the grading

\[
\deg(T_1) = \deg(T_2) = (1, \overline{1}, \overline{1}), \quad \deg(T_3) = (1, \overline{1}, \overline{1}), \\
\deg(T_4) = (1, \overline{1}, \overline{1}), \quad \deg(T_5) = (1, \overline{1}, \overline{1}).
\]

Proceeding as in this example, we are able to compute the Cox rings of all Gorenstein del Pezzo \( \mathbb{K}^* \)-surfaces and their minimal resolutions. Here comes the result for the cases of Picard number one and two.

**Theorem 5.6.** Let \( X \) be a Gorenstein del Pezzo surface of Picard number at most two admitting a nontrivial \( \mathbb{K}^* \)-action. The following table provides the Cox rings of \( X \) and its minimal resolution \( \tilde{X} \) ordered by the degree \( \deg(X) \) and the singularity type \( S(X) \).

<table>
<thead>
<tr>
<th>( S(X) )</th>
<th>( \mathcal{R}(X) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 2D_4 )</td>
<td>( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, \lambda T_2^2 + T_4^2 + T_5^2 \right) )</td>
</tr>
<tr>
<td>( E_6 A_2 )</td>
<td>( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) )</td>
</tr>
<tr>
<td>( E_7 A_1 )</td>
<td>( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) )</td>
</tr>
<tr>
<td>( E_8 )</td>
<td>( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) )</td>
</tr>
</tbody>
</table>

| \( \deg(X) = 2 \) |
|----------------|-----------------|
| \( S(X) \) | \( \mathcal{R}(X) \) |
| \( 2A_3 A_1 \) | \( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) \) |
| \( A_5 A_2 \) | \( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) \) |
| \( D_4 A_1 \) | \( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) \) |
| \( D_6 A_1 \) | \( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) \) |
| \( E_7 \) | \( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) \) |

| \( \deg(X) = 3 \) |
|----------------|-----------------|
| \( S(X) \) | \( \mathcal{R}(X) \) |
| \( 2A_3 \) | \( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, \lambda T_2^2 + T_4^2 + T_5^2 \right) \) |
| \( D_5 A_1 \) | \( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) \) |
| \( E_6 \) | \( \mathbb{K}[T_1, \ldots, T_5] / \left( T_1 T_2 + T_3^2 + T_4^2, T_3 T_4 T_5 + T_6 T_7 T_8 + T_9 T_{10} T_{11} \right) \) |
\begin{align*}
\mathbb{A}_2 \mathbb{A}_1 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1 \tau_2 + \tau_3 \tau_4 + \tau_5^2) \\
E_6 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 \tau_2^2 + \tau_1^2 \tau_3^2 + \tau_1^2 \tau_4^2 + \tau_5^2) \\
2A_2A_1 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1 \tau_2 + \tau_3 \tau_4 + \tau_5^2) \\
A_3A_1 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 \tau_2 + \tau_3 \tau_4 + \tau_5^2) \\
A_4 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 + \tau_3 \tau_4 + \tau_5^2) \\
D_5 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 + \tau_2 \tau_3 + \tau_4 + \tau_5^2) \\
S(X) & \quad R(X) \\
D_5 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 \tau_2 + \tau_1 \tau_3 \tau_4 + \tau_5^2) \\
A_3A_1 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1 \tau_2 + \tau_3 \tau_4 + \tau_5^2) \\
A_4 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 \tau_2 + \tau_3 \tau_4 + \tau_5^2) \\
D_4 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 + \tau_2 \tau_3 \tau_4 + \tau_5^2) \\
S(X) & \quad R(X) \\
D_5 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 \tau_2 + \tau_1 \tau_3 \tau_4 + \tau_5^2) \\
A_3 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 \tau_2 + \tau_3 \tau_4 + \tau_5^2) \\
A_4 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 + \tau_3 \tau_4 + \tau_5^2) \\
S(X) & \quad R(X) \\
D_5 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1^2 \tau_2 + \tau_1 \tau_3 \tau_4 + \tau_5^2) \\
A_2 & \quad \mathbb{K}[\tau_1, \ldots, \tau_5]/(\tau_1 \tau_2 + \tau_3 \tau_4 + \tau_5^2)
\end{align*}

Finally, we consider equivariant vector bundles over a toric variety \( X \) arising from a fan \( \Sigma \) and ask for the Cox rings of their projectivizations. We will use Klyachko’s description \cite{Klyachko} of equivariant reflexive sheaves over \( X \); we will follow Perling’s notation \cite{Perling} in terms of families of complete increasing filtrations.

We recall the basic constructions. Let \( \mathcal{E} \) be an equivariant reflexive sheaf of rank \( r \) on \( X \). Then \( \mathcal{E} \) is trivial over the big torus \( T \subseteq X \). Moreover, for every ray \( \varrho \in \Sigma^{(1)} \), the sheaf \( \mathcal{E} \) splits over the affine chart \( X_{\varrho} \subseteq X \) and hence is even trivial there. This gives us identifications

\[ \Gamma(X_{\varrho}, \mathcal{E}) \subseteq \Gamma(T, \mathcal{E}) = E \otimes \Gamma(T, \mathcal{O}_X) = E \otimes \mathbb{K}[M] \]

with an \( r \)-dimensional vector space \( E \). Fix generators \( e_{\varrho, 1} \otimes \chi_{\varrho, 1}, \ldots, e_{\varrho, r} \otimes \chi_{\varrho, r} \) for every \( \Gamma(X_{\varrho}, \mathcal{E}) \). Then \( \mathcal{E} \) is determined by the family of complete increasing filtrations \( E^{\varrho}(i) \), where \( \varrho \in \Sigma^{(1)} \), of \( E \) defined by

\[ E^{\varrho}(i) := \text{lin}(e_{\varrho, j}; \langle u_{\varrho, j}, v_{\varrho} \rangle \leq i), \]

where \( v_{\varrho} \in \varrho \) denotes the primitive lattice vector. Conversely, given any family of complete increasing filtrations \( E^{\varrho}(i) \), where \( \varrho \in \Sigma^{(1)} \), of \( E = \mathbb{K}^r \), one obtains an equivariant reflexive sheaf \( \mathcal{E} \) of rank \( r \) over \( X \) by defining its sections over the affine
charts $X_{\sigma} \subseteq X$, where $\sigma \in \Sigma$, to be

$$\Gamma(X_{\sigma}, \mathcal{E}) := \bigoplus_{u \in M} \left( \bigcap_{\varrho \in \Sigma^{(1)}} E^\varrho((u, v_\varrho)) \right) \otimes \chi^u \subseteq E \otimes \mathbb{K}[M].$$

In our first result, we compute the Cox ring of the projectivization $\mathbb{P}(\mathcal{E})$, see [12, p. 162], of a locally free sheaf $\mathcal{E}$ of rank two over a complete toric variety $X$ arising from a fan $\Sigma$. Let $E^\varrho(i)$, where $\varrho \in \Sigma^{(1)}$, be the family of filtrations describing $\mathcal{E}$, let $\mathcal{L}$ be the set of one-dimensional subspaces of $E$ occurring in these filtrations, for every $L \in \mathcal{L}$ fix a generator $e_L$, and denote by $\text{Rel}(\mathcal{L})$ the space of linear relations among the $e_L$. Moreover, let $i^\varrho_k$ be the smallest integer such that $\dim E^\varrho(i^\varrho_k) > k$ and set $L^\varrho := E^\varrho(i^\varrho_k)$.

**Theorem 5.7.** Let $\mathcal{E}$ be an equivariant locally free sheaf of rank two over a complete toric variety $X$ defined by a fan $\Sigma$. Then the Cox ring of the projectivization $\mathbb{P}(\mathcal{E})$ is given as

$$\mathcal{R}(\mathbb{P}(\mathcal{E})) = \mathbb{K}[S_0, T_L; \varrho \in \Sigma^{(1)}, L \in \mathcal{L}] / \left( \sum_{L \in \mathcal{L}} \lambda_L S^L T_L; \lambda \in \text{Rel}(\mathcal{L}) \right),$$

where $S^L := \prod_{\varrho, L^\varrho \subseteq L} S^\varrho_{i^\varrho_k}$.

**Example 5.8.** Let $\mathcal{T}$ be the sheaf of sections of the tangent bundle of the projective plane $\mathbb{P}^2$; then $\mathbb{P}(\mathcal{T})$ is the projectivized cotangent bundle. As a toric variety, $\mathbb{P}^2$ is given by the complete fan in $\mathbb{Q}^2$ with the rays

$$\varrho_1 = \mathbb{Q}_{>0} \cdot e_1, \quad \varrho_2 = \mathbb{Q}_{>0} \cdot e_2, \quad \varrho_0 = \mathbb{Q}_{>0} \cdot e_0,$$

where $e_1, e_2 \in \mathbb{Q}^2$ are the canonical basis vectors and we set $e_0 := -e_1 - e_2$. The filtrations of the tangent sheaf are given as

$$E^\varrho(i) = \begin{cases} 0, & i < -1, \\ \mathbb{K}, & i = -1, \\ E, & i > -1. \end{cases}$$

As generators for the one-dimensional subspaces we may choose $e_1, e_2, e_0 \in \mathbb{K}^2$. The linear relations between them are spanned by $(1,1,1) \in \mathbb{K}^3$. Hence, as in Example 4.10 we obtain

$$\mathcal{R}(\mathbb{P}(\mathcal{T})) = \mathbb{K}[S_0, S_1, S_2, S_3, T_1, T_2, T_3] / (T_1 S_1 + T_2 S_2 + T_3 S_3).$$

More generally, we may calculate the Cox ring of the projectivized cotangent bundle on an arbitrary smooth complete toric variety $X$ arising from a fan $\Sigma$. We distinguish two types of rays $\varrho \in \Sigma^{(1)}$: those with $-\varrho \notin \Sigma^{(1)}$ and those with $-\varrho \in \Sigma^{(1)}$. Denote by $\mathcal{L}$ the set containing all rays of the first type and one representative for every pair of the second type. Moreover, let $\text{Rel}(\mathcal{L})$ denote the tuples $\lambda \in \mathbb{K}^\mathcal{L}$ such that $\sum_{\varrho \in \mathcal{L}} \lambda_{\varrho} v_\varrho = 0$, where $v_\varrho \in \varrho$ denote the primitive generator.

**Theorem 5.9.** Let $X$ be a smooth complete toric variety arising from a fan $\Sigma$, and denote by $\mathcal{T}_X$ the sheaf of sections of the tangent bundle over $X$. Then the Cox ring of the projectivization $\mathbb{P}(\mathcal{T}_X)$ is given by

$$\mathcal{R}(\mathbb{P}(\mathcal{T}_X)) = \mathbb{K}[S_\varrho, T_\tau; \varrho \in \Sigma^{(1)}, \tau \in \mathcal{L}] / \left( \sum_{\varrho \in \mathcal{L}} \lambda_\varrho S^\varrho T_\varrho; \lambda \in \text{Rel}(\mathcal{L}) \right),$$

where $S^\varrho := \begin{cases} S_\varrho S_{-\varrho}, & \varrho \in \Sigma^{(1)}, \\ S_\varrho, & \text{else.} \end{cases}$
Remark 5.10. Let $\Sigma$ be a fan in a lattice $N$ having rays $g_1, \ldots, g_s$ as its maximal cones, $Z$ the associated toric variety and $T \subseteq Z$ the acting torus. Given a primitive sublattice $L \subseteq N$, consider the action of the corresponding subtorus $H \subseteq T$ on $Z$. Let $P : N \to N' := N/L$ denote the projection. The generic isotropy group $H_\ell \subseteq H$ along the toric divisor $D_\ell \subseteq Z$ corresponding to a ray $g \in \Sigma$ is one-dimensional if $P(g) = 0$ holds and finite otherwise; in the latter case it is given by

$$X(H_\ell) = (\text{lin}(P(g)) \cap N') / P(\text{lin}(g) \cap N).$$

In particular, the set $Z_0 \subseteq Z$ is the toric subvariety corresponding to the subfan $\Sigma_0 \subseteq \Sigma$ obtained by removing all $g$ with $P(g) = \{0\}$. For an affine chart $Z_\ell \subseteq Z_0$, the orbit space $Z_0/H$ is the affine toric variety $Z'_{P(\ell)}$ corresponding to the ray $P(\ell)$ in $N'$. Gluing these $Z'_{P(\ell)}$ along their common big torus $T/H$ gives the toric prevariety $Z_0/H$.

There is a canonical separation $\pi : Z_0/H \to Z'$, where $Z'$ is the toric variety defined by the fan $P(\Sigma_0)$ in $N'$ having $\{P(g); g \in \Sigma_0\}$ as its set of maximal cones. Note that the inverse image $\pi^{-1}(D_{P(\ell)})$ of the divisor $D_{P(\ell)} \subseteq Z'$ corresponding to $P(\ell) \in P(\Sigma_0)$ is the disjoint union of all divisors $D_\ell \subseteq Z_0$ with $P(\tau) = P(\ell)$.

Proof. Proof of Theorem 5.7 and Theorem 5.9 In order to use Theorem 1.2, we have to study the map $\pi \circ q$ obtained by composing the quotient $q : \mathbb{P}(\mathcal{E})_0 \to \mathbb{P}(\mathcal{E})_0/T$ with the separation $\pi : \mathbb{P}(\mathcal{E})_0/T \to Y$. This done in three steps. First we cover $\mathbb{P}(\mathcal{E})$ by affine toric charts and describe the quotient map on these charts using Remark 5.10. Then we collect the data for Theorem 1.2 in every chart. In the last step we will see how this local data fit into the global picture.

Step 1: the toric charts. We may assume that the maximal cones of $\Sigma$ are just the rays $g \in \Sigma$. On an affine chart $X_\ell$ any equivariant locally free sheaf $\mathcal{E}$ is actually free with homogeneous generators $s_{g,0}, \ldots, s_{g,r}$ of the form $s_{g,i} = e_{g,i} \otimes \chi^{u_{g,i}}$. Choosing an appropriate order, we may achieve $(u_{g,k}, v_\ell) = i_k$. Then $\mathbb{P}(\mathcal{E}|_{X_\ell})$ is given as

$$\mathbb{P}(\mathcal{E}|_{X_\ell}) = \text{Proj}_{X_\ell}(S(\mathcal{E}|_{X_\ell})) = \text{Proj} \mathbb{K}[\mathcal{E}^\vee \cap M][s_{g,0}, \ldots, s_{g,r}],$$

where $\text{deg}(s_{g,i}) := 1$. So, $\mathbb{P}(\mathcal{E}|_{X_\ell})$ is $X_\ell \times \mathbb{P}^r$ but endowed with a special $T^n$-action. This action can be extended to an $T^{n+r}$-action by assigning to $s_i$ the weight $(u_i, b_i) \in M \times M'$ for $i = 0, \ldots, r$. Here, $M' \cong Z'$ and $b_1, \ldots, b_r$ is a basis and $b_0 := 0$. As a consequence we can describe $\mathbb{P}(\mathcal{E}|_{X_\ell})$ as a toric variety and the endowed $T^n$-action by an inclusion $T^n \hookrightarrow T^{n+r}$, which corresponds to the lattice inclusion $N \hookrightarrow N \times N'$, where $N' := (M')^\ast$.

We describe the corresponding fan in $N \times N'$. Denote by $b_1^\ast, \ldots, b_r^\ast$ the dual basis in $N'$ and set $b_0^\ast := -\sum b_i^\ast$. Moreover, set

$$g_\ell := \tilde{q} + \text{cone}(b_0^\ast, \ldots, b_{i-1}^\ast, b_{i+1}^\ast, \ldots, b_r^\ast), \quad \tilde{q} := (v_\ell, \sum_{k=0}^r i_k^s b_k^s).$$

Then $g_0, \ldots, g_r$ are the maximal cones of the fan we are looking for. Indeed, cover $\mathbb{P}(\mathcal{E}|_{X_\ell})$ by the affine charts $\text{Spec} \mathbb{K}[\mathcal{E}^\vee \cap M][\frac{a_s}{x_j}, \ldots, \frac{a_s}{x_j}]$. Then

$$\mathbb{K}[\mathcal{E}^\vee \cap M][\frac{a_s}{x_j}, \ldots, \frac{a_s}{x_j}] \to \mathbb{K}[\mathcal{E}^\vee \cap M \times M'], \quad \frac{s_j}{s_i} \mapsto \chi^{(u_j - u_i, b_j - b_i)}, \quad \chi^u \mapsto \chi^{(u,0)}$$

defines an equivariant isomorphism from $\mathbb{P}(\mathcal{E}|_{X_\ell})$ with the extended torus action onto the toric variety arising from the fan just defined, see also [16] pp. 58-59.

Step 2: local quotient maps. In the setting of Remark 5.10 the map $P : N \times N' \to N'$ is the projection to the second factor and we deduce that the separation of
\[ \mathbb{P}(\mathcal{E}|_{X_e})/T \] has the fan \( \Sigma' \) consisting of the rays \( \mathbb{Q}_{\geq 0} \cdot b_0', \ldots, \mathbb{Q}_{\geq 0} \cdot b_r', P(\tilde{q}) \) and the trivial cone.

If \( \mathcal{E} \) is an equivariant locally free sheaf of rank two, then we obtain \( \tilde{q} = \mathbb{Q}_{\geq 0} \cdot (v_0, (i_1 - i_0) b_0) \) and \( \Sigma' \) is the unique fan \( \Delta \) of \( \mathbb{P}^1 \). If \( \mathcal{E} \) is the sheaf of sections of the tangent bundle of \( X \), then we have \( E = N \otimes K \) and the filtrations

\[
E^0(i) = \begin{cases} 0, & i < -1, \\ \mathbb{K} \cdot \tilde{q}, & i = -1, \\ E, & i > -1. \end{cases}
\]

Thus, by the chosen order of the \( s_{\varphi, i} \), we obtain \( \tilde{q} = \mathbb{Q}_{\geq 0} \cdot (v_0, b_0) \) and \( \Sigma' = \{ 0, \mathbb{Q}_{\geq 0} \cdot b_0, \ldots, \mathbb{Q}_{\geq 0} \cdot b_r \} \). Hence, \( \Sigma' \) is a subfan of a fan \( \Delta \) with \( X_\Delta \cong \mathbb{P}^r \) and we have a rational toric map \( p_\varphi : \mathbb{P}(\mathcal{E}|_{X_e}) \to \mathbb{P}' \), which is defined on a big open subset.

Now we locally collect the data for Theorem 1.2 using Remark 5.10. In the preimage \( P^{-1}(\mathbb{Q}_{\geq 0} \cdot b_0) \), we find the rays \( \tau := \mathbb{Q}_{\geq 0} \cdot (0, b_0) \) and \( \tilde{q} \). Hence, the prime divisor in \( Y = X_{\Sigma'} \) corresponding to \( \mathbb{Q}_{\geq 0} \cdot b_0 \) has two invariant prime divisors in its preimage under the map \( \pi \circ q \).

The lattice elements of \( \tau \) are mapped onto the lattice elements of \( \mathbb{Q}_{\geq 0} \cdot b_0 \), hence \( T \) acts effectively on the corresponding prime divisor. The lattice generated by \( P(\tilde{q} \cap (N \times N')) \) has index \( i_1^0 - i_0^0 \) in \( \mathbb{Z} \cdot b_0 \). This implies that the corresponding prime divisor has a generic isotropy group of order \( i_1 - i_0 \) (which is equal to 1 in the case of \( T_X \)).

**Step 3: the global picture.** We identify \( \mathbb{P}(E^*) \) with \( X_\Delta \) via the isomorphism \( \varphi_\varphi \) induced by the following homomorphism of the homogeneous coordinate rings

\[
S(E) \to \mathbb{K}[\chi^{b_0}, \ldots, \chi^{b_r}], \quad e_i \mapsto \chi^{b_i}.
\]

Note that the map \( \varphi_\varphi \circ p_\varphi \) (considered as a rational map \( \mathbb{P}(\mathcal{E}) \to \mathbb{P}(E^*) \)) no longer depends on the choice of \( \varphi \) and \( s_{\varphi, 0}, \ldots, s_{\varphi, r} \), because over \( \mathbb{P}(\mathcal{E}|_{T}) \) it is just the projection \( \mathbb{P}(\mathcal{E}|_{T}) = \mathbb{P}(E^*) \times T \to \mathbb{P}(E^*) \) given by

\[
S(E) \to \mathbb{K}[M][s_{\varphi, 0}, \ldots, s_{\varphi, r}] = \Gamma(T, S(\mathcal{E}))
\]

\[
e_i \mapsto \chi^{-u_i} \cdot s_{\varphi, i} = e_i \otimes \chi^0.
\]

Note that \( \varphi_\varphi \) maps the prime divisor corresponding to the ray \( \mathbb{Q}_{\geq 0} \cdot b_0 \) onto \( E^0(i_0^0) = e_{\varphi, 0}^0 \subset \mathbb{P}(E^*) \). Putting things together we obtain

- A ray \( \varphi \) with \( i_0^0 = i_1^0 \) corresponding to a divisor outside of \( \mathbb{P}(\mathcal{E})_0 \).
- Since \( (\pi \circ q)|_{\mathbb{P}(\mathcal{E}|_{T})} \) is the equivariant projection \( \mathbb{P}(\mathcal{E}|_{T}) = \mathbb{P}(E^*) \times T \to \mathbb{P}(E^*) \) the closure \( (\pi \circ q)^{-1}(Z) \cap \mathbb{P}(\mathcal{E}|_{T}) \) is always a prime divisor with effective \( T \)-action.
- If \( i_0^0 < i_1^0 \) the ray \( \varphi \) corresponds to an additional invariant prime divisor in the preimage of \( E^0(i_0^0) \) with generic isotropy group of order \( i_1 - i_0 \).

Inspecting the filtrations for \( T_X \), we see that \( i_0^0 - i_0^0 = 1 \) for every ray \( \varphi \) and \( E^0(i_0^0) = E^0(i_1^0) \) if and only if \( \tau = \pm \tilde{q} \). Using Theorem 1.2 we obtain the desired results.

**References**


Mathematisches Institut, Universität Tübingen, Auf der Morgenstelle 10, 72076 Tübingen, Germany
E-mail address: hausen@mail.mathematik.uni-tuebingen.de

Institut für Mathematik, LS Algebra und Geometrie, Brandenburgische Technische Universität Cottbus, PF 10 13 44, 03013 Cottbus, Germany
E-mail address: suess@math.tu-cottbus.de