Note for the Virtual Fundamental Class

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Contents

1 Introduction

We will follows [BF97][AB84][GP99] and we will also use [Ric22].

We need [Har77][Ful98][EH16].

Here we will consider $\mathbb{P}(-) = \mathbf{Proj}\,\mathrm{Sym}(-)^\vee$ for bundles and the vector bundle is both space and sheaf via $\mathbf{Spec}\,\mathrm{Sym}(-)^\vee$. For a cone $C = \mathbf{Spec}_X \mathscr{S}^*$, we define $\mathbb{P}(C) := \mathbf{Proj}_X \mathscr{S}^*$ and $\mathbb{P}(C \oplus \mathscr{O}) := \mathbf{Proj}_X \mathscr{S}^*[z]$

which is the projective cone and projective completion, respectively. For more details we refer Appendix B.5 of [Ful98].

2 Review of Basic Intersection Theory

We will follows [Ful98]. We will omit the basic things such as Segre classes of bundles and cones, Chern classes of bundles and the technique of the deformation to the normal cone. We refer Chapter 1-5 in [Ful98]. We work over schemes of finite type over some field k.

2.1 Basic Facts of Refined Gysin Pullback

Here we will follows Chapter 6,8,9 of [Ful98]. We will state the results without the most of the proof.

Definition 2.1 (Intersection Product)**.** *Let $i : X \hookrightarrow Y$ be a closed regular embedding of codimension d with normal bundle $N_{X/Y}$. Pick V be a scheme of pure dimension k. Consider the cartesian diagram*

$$\begin{tikzcd} W \arrow[r, hook, "j"] \arrow[d, "g"'] \arrow[dr, phantom, "\ulcorner", very near start] & V \arrow[d, "f"] \\ X \arrow[r, hook, "i"] & Y \end{tikzcd}$$

Let $\mathscr{I}$ be the ideal of i and $\mathscr{J}$ be the ideal of j, then we have surjection

$$\bigoplus_n f^*(\mathscr{I}^n/\mathscr{I}^{n+1}) \to \bigoplus_n \mathscr{J}^n/\mathscr{J}^{n+1} \to 0$$

which induce embedding $C_{W/V} \hookrightarrow g^*N_{X/Y}$. Note that $C_{W/V}$ is also a scheme of pure dimension k since $\mathbb{P}(C_{W/V} \oplus \mathscr{O})$ is the exceptional divisor of $\mathrm{Bl}_W(Y \times \mathbb{A}^1)$. Let $0 : W \to g^*N_{X/Y}$ be the zero-section of $\pi : g^*N_{X/Y} \to W$, then we define

$$X \cdot V := 0^*[C_{W/V}] := (\pi^*)^{-1}[C_{W/V}] \in \mathsf{CH}_{k-d}(W)$$

as the intersection class.

Proposition 2.2. *Consider the situation of Definition 2.1.*

(a) We have $X \cdot V = \{c(g^*N_{X/Y}) \cap s(W, V)\}_{k-d}$.

(b) Let $\mathscr{Q}$ be the universal quotient bundle of $q : \mathbb{P}(g^*N_{X/Y} \oplus \mathscr{O}) \to W$, then

$$X \cdot V = q_*(c_d(\mathscr{Q}) \cap [\mathbb{P}(C_{W/V} \oplus \mathscr{O})]).$$

(c) *If $j : W \hookrightarrow V$ is a regular embedding of codimension d', then $X \cdot V = c_{d-d'}(g^* N_{X/Y}/N_{W/V}) \cap [W]$.*

Proof. Easy, one omitted. See Proposition 6.1 and Example 6.1.7 in [Ful98]. □

Definition 2.3 (Refined Gysin Pullback)**.** *Let $i : X \hookrightarrow Y$ be a closed regular embedding of codimension d with normal bundle $N_{X/Y}$. Pick $f : Y' \to Y$ be a morphism. Consider the cartesian diagram*

$$\begin{tikzcd} X' \arrow[r, hook, "j"] \arrow[d, "g"'] \arrow[dr, phantom, "\ulcorner", very near start] & Y' \arrow[d, "f"] \\ X \arrow[r, hook, "i"] & Y \end{tikzcd}$$

Then we define $i^! : \mathsf{Z}_k\, Y' \to \mathsf{CH}_{k-d}\, X'$ as $\sum_i n_i[V_i] \mapsto \sum_i n_i X \cdot V_i$. Now $i^!$ can be decomposed as:

$$i^! : \mathsf{Z}_k\, Y' \xrightarrow{\sigma} \mathsf{Z}_k\, C_{X'/Y'} \to \mathsf{CH}_k(g^* N_{X/Y}) \xrightarrow{0^*} \mathsf{CH}_{k-d}\, X'$$

where $\sigma : \mathsf{Z}_k\, Y' \to \mathsf{Z}_k\, C_{X'/Y'}$ given by $[V] \mapsto [C_{V \cap X'/V}]$. By the technique of deformation to the normal cone, this can be descend to the Chow-group level as $\sigma : \mathsf{CH}_k\, Y' \to \mathsf{CH}_k\, C_{X'/Y'}$ (see Proposition 5.2 in [Ful98]) which is called the specialization to the normal cone*. Hence this induce the* refined Gysin pullback

$$i^! : \mathsf{CH}_k\, Y' \to \mathsf{CH}_{k-d}\, X', \quad \sum_i n_i[V_i] \mapsto \sum_i n_i X \cdot V_i.$$

Proposition 2.4. *Consider the situation of Definition 2.3. Consider*

$$\begin{tikzcd} X'' \arrow[r, hook, "i''"] \arrow[d, "q"'] \arrow[dr, phantom, "\ulcorner", very near start] & Y'' \arrow[d, "p"] \\ X' \arrow[r, hook, "i'"] \arrow[d, "g"'] \arrow[dr, phantom, "\ulcorner", very near start] & Y' \arrow[d, "f"] \\ X \arrow[r, hook, "i"] & Y \end{tikzcd}$$

(a) *If p proper and $\alpha \in \mathsf{CH}_k(Y'')$, then $i^! p_*(\alpha) = q_* i^!(\alpha) \in \mathsf{CH}_{k-d}(X')$.*

(b) *If p is flat of relative dimension n and $\alpha \in \mathsf{CH}_k(Y'')$, then $i^! p^*(\alpha) = q^* i^!(\alpha) \in \mathsf{CH}_{k+n-d}(X'')$.*

(c) *If i' is also a regular embedding of codimension d and $\alpha \in \mathsf{CH}_k(Y'')$, then $i^! \alpha = (i')^!(\alpha) \in \mathsf{CH}_{k-d}(X'')$.*

(d) *If i' is a regular embedding of codimension d', then for $\alpha \in \mathsf{CH}_k(Y'')$ we have*

$$i^!(\alpha) = c_{d-d'}(q^*(g^*N_{X/Y}/N_{X'/Y'})) \cap (i')^!(\alpha) \in \mathsf{CH}_{k-d}(X'').$$

We call $g^*N_{X/Y}/N_{X'/Y'}$ the excess normal bundle.

(e) *Let F be any vector bundle on Y', then for $\alpha \in \mathsf{CH}_k(Y'')$ we have*

$$i^!(c_m(F) \cap \alpha) = c_m((i')^*F) \cap i^!(\alpha) \in \mathsf{CH}_{k-d-m}(X').$$

Proof. See Theorem 6.2, Theorem 6.3 and Proposition 6.3 in [Ful98]. □

Corollary 2.5. *Let $i : X \hookrightarrow Y$ be a regular embedding of codimension d, then*

$$i^*i_*(\alpha) = c_d(N_{X/Y}) \cap \alpha \in \mathsf{CH}_*(X).$$

Proof. By Proposition 2.4(d) directly. □

Proposition 2.6. *The refined Gysin pullback have the following properties.*

(a) *Let $i : X \hookrightarrow Y$ and $j : S \hookrightarrow T$ are regular embeddings of codimension d, e, respectively. Consider cartesians:*

$$\begin{tikzcd}
X'' \arrow[r, hook] \arrow[d, hook] \arrow[dr, phantom, "\ulcorner"] & Y'' \arrow[r] \arrow[d, hook, "j'"'] \arrow[dr, phantom, "\ulcorner"] & S \arrow[d, hook, "j"] \\
X' \arrow[r, hook, "i'"] \arrow[d] \arrow[dr, phantom, "\ulcorner"] & Y' \arrow[r, "g"'] \arrow[d, "f"'] & T \\
X \arrow[r, hook, "i"] & Y &
\end{tikzcd}$$

Then for any $\alpha \in \mathsf{CH}_k(Y'')$, we have

$$j^!i^!(\alpha) = i^!j^!(\alpha) \in \mathsf{CH}_{k-d-e}(X'').$$

(b) *Let $i : X \hookrightarrow Y$ and $j : Y \hookrightarrow Z$ are regular embeddings of codimension d, e, respectively. Consider cartesians:*

$$\begin{tikzcd}
X' \arrow[r, hook, "i'"] \arrow[d, "h"] \arrow[dr, phantom, "\ulcorner"] & Y' \arrow[r, hook, "j'"] \arrow[d, "g"'] \arrow[dr, phantom, "\ulcorner"] & Z' \arrow[d, "f"'] \\
X \arrow[r, hook, "i"] & Y \arrow[r, hook, "j"] & Z
\end{tikzcd}$$

Then ji is a regular embedding of codimension $d+e$ and for all $\alpha \in \mathsf{CH}_k(Z')$ we have

$$(ji)^!(\alpha) = i^!j^!(\alpha) \in \mathsf{CH}_{k-d-e}(X').$$

Proof. See Theorem 6.4 and Theorem 6.5 in [Ful98]. ☐

Proposition 2.7. *Consider cartesians:*

$$\begin{tikzcd} X' \arrow[r, "i'"] \arrow[d, "h"] \arrow[dr, phantom, "\ulcorner"] & Y' \arrow[r, "p'"] \arrow[d, "g"'] \arrow[dr, phantom, "\ulcorner"] & Z' \arrow[d, "f"'] \\ X \arrow[r, "i"] & Y \arrow[r, "p"] & Z \end{tikzcd}$$

(a) *If i is a regular embedding of codimension d and p and pi are flat of relative dimension $n, n-d$, respectively. Then i' is a regular embedding of codimension d and $p', p'i'$ are flat, and for $\alpha \in \mathsf{CH}_k(Z')$ we have*

$$(p'i')^*(\alpha) = (i')^*((p')^*\alpha) = i^!((p')^*\alpha).$$

(b) *If i is a regular embedding of codimension d and p is smooth of relative dimension n, and pi is a regular embedding of codimension $d-n$ Then for $\alpha \in \mathsf{CH}_k(Z')$ we have*

$$(pi)^!(\alpha) = i^!((p')^*\alpha).$$

Proof. See Proposition 6.5 in [Ful98]. ☐

Remark 2.8. *Some remarks.*

(a) *For local complete intersection morphism $f : X \to Y$, we can decompose it into $f : X \xrightarrow{i} P \xrightarrow{p} Y$ where i is a closed regular embedding of constant codimension and p is smooth of constant relative dimension. Then we can define $f^! := i^!(p')^*$. See Section 6.6 in [Ful98] for more properties.*

(b) *If Y is nonsingular of dimension n, then we can define the following intersection product: Let $f : X \to Y$ and $p : X' \to X$ and $q : Y' \to Y$. Let $x \in \mathsf{CH}_k(X')$ and $y \in \mathsf{CH}_l(Y')$, consider the cartesian*

$$\begin{tikzcd} X' \times_Y Y' \arrow[r] \arrow[d] \arrow[dr, phantom, "\ulcorner"] & X' \times Y' \arrow[d, "p\times q"] \\ X \arrow[r, "\gamma_f"] & X \times Y \end{tikzcd}$$

and define $x \cdot_f y := \gamma_f^!(x \times y) \in \mathsf{CH}_{k+l-n}(X' \times_Y Y')$.

So when $x, y \in \mathsf{CH}_*(Y)$, then let $X = Y$ and $X' = |x|, Y' = |y|$, then we get the new intersection product. Note that this is compactible as the definition before. See Chapter 8 in [Ful98] for more properties. In this case $CH_*(Y)$ is a ring which is called Chow ring.

Finally we will discuss something about equivalence and supportness.

Definition 2.9. *Let $i : X \hookrightarrow Y$ be a closed regular embedding of codimension d with normal bundle $N_{X/Y}$. Pick V be a scheme of pure dimension k. Consider the cartesian diagram*

$$\begin{tikzcd} W \arrow[r, hook, "j"] \arrow[d, "g"'] \arrow[dr, phantom, "\ulcorner", very near start] & V \arrow[d, "f"] \\ X \arrow[r, hook, "i"] & Y \end{tikzcd}$$

Let $C_1, ..., C_r$ be the irreducible components of $C_{W/V}$, then $[C_{W/V}] = \sum_{i=1}^r m_i[C_i]$. Let $Z_i = \pi(C_i)$ where $\pi : g^*N_{X/Y} \to W$ and we call them the distinguished varieties *of the intersection of V by X. Let $N_i := (g^*N_{X/Y})|_{Z_i}$ and let $0_i : Z_i \to N_i$ be the zero-sections. Let $\alpha_i := 0_i^*[C_i] \in \mathsf{CH}_{k-d}(Z_i)$ and hence we have $X \cdot V = \sum_{i=1}^r m_i\alpha_i \in \mathsf{CH}_{k-d}(W)$.*

Pick any closed set $S \subset W$, we define

$$(X \cdot V)^S := \sum_{Z_i \subset S} m_i\alpha_i \in \mathsf{CH}_{k-d}(S)$$

as the part of $X \cdot V$ supported on S.

Definition 2.10. *Let $X_i \hookrightarrow Y$ be closed regular embeddings of codimension d_i. Let $V \subset Y$ be a k-dimensional subvariety. Consider*

$$\begin{tikzcd} \bigcap_i X_i \cap V \arrow[r, hook] \arrow[d, hook] \arrow[dr, phantom, "\ulcorner", very near start] & V \arrow[d, hook, "\delta"] \\ X_1 \times \cdots \times X_r \arrow[r, hook] & Y \times \cdots \times Y \end{tikzcd}$$

Then we can get $X_1 \cdot \ldots \cdot x_r \cdot V \in \mathsf{CH}_{\dim V - \sum_i d_i}(\bigcap_i X_i \cap V)$.

Let Z be a connected component of $\bigcap_i X_i \cap V$, we will consider

$$(X_1 \cdot \ldots \cdot X_r \cdot V)^Z \in \mathsf{CH}_{\dim V - \sum_i d_i}(Z)$$

as before.

Proposition 2.11. *As in the previous situation, we have*

$$(X_1 \cdot \ldots \cdot X_r \cdot V)^Z = \left\{ \prod_{i=1}^r c(N_{X_i/Y}|_Z) \cap s(Z, V) \right\}_{\dim V - \sum_i d_i}.$$

If $Z \hookrightarrow V$ is a regular embedding, then

$$(X_1 \cdot \ldots \cdot X_r \cdot V)^Z = \left\{ \prod_{i=1}^r c(N_{X_i/Y}|_Z) \cdot c(N_{Z/V})^{-1} \cap [Z] \right\}_{\dim V - \sum_i d_i}.$$

If V, Z are both non-singular, then

$$(X_1 \cdot \ldots \cdot X_r \cdot V)^Z = \left\{ \prod_{i=1}^{r} c(N_{X_i/Y}|_Z) c(T_V|_Z)^{-1} c(T_Z) \cap [Z] \right\}_{\dim V - \sum_i d_i}.$$

Proof. See Proposition 9.1.1 in [Ful98]. □

2.2 Localized Chern Class

Here we will follows Chapter 14.1 of [Ful98]. This is the most important part which is the local case of the virtual fundamental class.

Definition 2.12. *Let $E \to X$ be a vector bundle of rank e over a purely n-dimensional scheme X. Let $s : X \to E$ be a section, consider the cartesian*

$$\begin{tikzcd} Z(s) \arrow[r] \arrow[d, "i"'] \arrow[dr, phantom, "\ulcorner"] & X \arrow[d, hook, "s"'] \\ X \arrow[r, hook, "0"] & E \end{tikzcd}$$

with zero-section $0 : X \to E$ which is a regular section by trivial reason. We define

$$c_{\mathrm{loc}}(E, s) := 0^!([X]) = 0^*(C_{Z(s)/X}) \in \mathsf{CH}_{n-e}(Z(s))$$

be the localized (top) Chern class of E with respect to s.

Proposition 2.13. *Consider the situation of Definition 2.12.*

(a) We have $i_*(c_{\mathrm{loc}}(E, s)) = c_e(E) \cap [X]$.

(b) Each irreducible component of $Z(s)$ has codimension at most e in X. If $\mathrm{codim}_{Z(s)} X = e$, then $c_{\mathrm{loc}}(E, s)$ is a positive cycle whose support is $Z(s)$.

(c) If s is a regular section, then $c_{\mathrm{loc}}(E, s) = [Z(s)]$.

(d) Let $f : X' \to X$ be a morphism, $s' = f^*s$ be a induced section of f^*E. Let $g : Z(s') \to Z(s)$ be the induced morphism.

(d1) If f flat, then $g^* c_{\mathrm{loc}}(E, s) = c_{\mathrm{loc}}(f^*E, s')$.

(d2) If f is proper of varieties, then $g_* c_{\mathrm{loc}}(f^*E, s') = \deg(X'/X) c_{\mathrm{loc}}(E, s)$.

Proof. For (a), by Proposition 2.4(a) and Corollary 2.5, we have

$$i_* 0^! [X] = 0^* s_* [X] = s^* s_* [X] = c_e(E) \cap [X].$$

For (b),(c), these follows from the trivial arguments of intersection multiplicities, see Lemma 7.1 and Proposition 7.1 in [Ful98]. Finally (d) follows from the following cartesians

$$\begin{tikzcd} Z(s') \arrow[r] \arrow[d] \arrow[dr, phantom, "\ulcorner"] & X' \arrow[d, "s'"] \\ X' \arrow[r, hook, "0_{f^*E}"] \arrow[d] \arrow[dr, phantom, "\ulcorner"] & f^*E \arrow[d] \\ X \arrow[r, hook, "0_E"] & E \end{tikzcd}$$

and Proposition 2.4. □

3 A Brief of Cotangent Complexes

Here we will give a quike introduction of cotangent complexes. We will consider Deligne-Mumford stacks locally of finite type over k. Morphisms are quasicompact and quasiseparated. We work over étale site.

Theorem 3.1. *For every morphism $f : X \to Y$ of DM-stacks (resp. finite type morphism of noetherian DM-stacks), there exists a complex*

$$\mathbb{L}_{X/Y} : \cdots \to \mathbb{L}^{-1}_{X/Y} \to \mathbb{L}^0_{X/Y} \to 0$$

of flat $\mathscr{O}_X$-modules with quasi-coherent (resp., coherent) cohomology, whose image $\mathbf{D}^-_{\mathrm{Qcoh}}(X_{ét})$ (resp. $\mathbf{D}^-_{\mathrm{Coh}}(X_{ét})$) is also denoted by $\mathbb{L}_{X/Y}$. This is called the cotangent complex of f. It satisfies the following properties.

(a) $H^0(X, \mathbb{L}_{X/Y}) = \Omega^1_{X/Y}$.

(b) The morphism f is smooth if and only if f is locally of finite presentation and $\mathbb{L}_{X/Y}$ is a perfect complex supported in degree 0. In this case, there is a quasi-isomorphism $\mathbb{L}_{X/Y} \cong \Omega^1_{X/Y}[0]$.

(c) If f is flat and finitely presented, then f is syntomic if and only if $\mathbb{L}_{X/Y}$ is a perfect complex supported in degrees $[-1, 0]$. Explicitly, if f factors as a complete intersection $X \hookrightarrow Z$ defined by a sheaf of ideals $\mathscr{I}$ and a smooth morphism $Z \to Y$, then

$$\mathbb{L}_{X/Y} \cong [0 \to \mathscr{I}/\mathscr{I}^2 \to \Omega^1_{Z/Y}|_X \to 0]$$

in $\mathbf{D}^-_{\mathrm{Qcoh}}(X_{ét})$ with $\Omega^1_{X/Y}$ in degree 0. If in addition f is generically smooth, then $\mathbb{L}_{X/Y} \cong \Omega^1_{X/Y}[0]$.

(d) *If we have a cartesian diagram*

$$\begin{tikzcd} X' \arrow[r, "g'"] \arrow[d] \arrow[dr, phantom, "\ulcorner", very near start] & X \arrow[d, "f"] \\ Y' \arrow[r, "g"] & Y \end{tikzcd}$$

then there is a morphism $(\mathbf{L}g')^*\mathbb{L}_{X/Y} \to \mathbb{L}_{X'/Y'}$. *When* f *or* g *is flat, then it is a quasi-isomorphism.*

(e) *If* $X \xrightarrow{f} Y \to Z$ *is a composition of morphisms of DM-stacks, then there is an exact triangle*

$$\mathbf{L}f^*\mathbb{L}_{Y/Z} \to \mathbb{L}_{X/Z} \to \mathbb{L}_{X/Y} \to \mathbf{L}f^*\mathbb{L}_{Y/Z}[1]$$

in $\mathbf{D}^-_{\mathrm{Qcoh}}(X_{\acute{e}t})$. *This induces a long exact sequence on cohomology*

$$\cdots \to H^{-1}(\mathbb{L}_{X/Z}) \to H^{-1}(\mathbb{L}_{X/Y}) \to f^*\Omega^1_{Y/Z} \to \Omega^1_{X/Z} \to \Omega^1_{X/Y} \to 0.$$

Proof. In the level of ring maps $A \to B$, this constructed by standard simplicial free A-resolution $B \to P(B)_*$ where $P(B)_n = A[\cdots[A[B]]\cdots]$ as

$$\mathbb{L}_{B/A} := \Omega_{P(B)_*/A} \otimes_{P(B)_*} B.$$

See Tag 08UV Tag 0D0N Tag 0FK3 Tag 08QQ Tag 08T4. □

Remark 3.2. *For the general algebraic stacks, any quasicompact and quasiseparated* 1*-morphism* $f : \mathscr{X} \to \mathscr{Y}$ *there exists a relative cotangent complex*

$$\mathbb{L}_f \in \mathbf{D}^{\leq 1}_{\mathrm{Coh}}(\mathscr{X}_{\textit{lis-ét}})$$

over lisse-étale site of $\mathscr{X}$. *Existence is good, but the fact that the cotangent complex trespasses to positive degree forces one to pay more attention when performing the cutoff. If the diagonal of* f *is unramified (as we consider now), then this problem goes away, in the sense that* $\mathbb{L}_f \in \mathbf{D}^{\leq 0}_{\mathrm{Coh}}(\mathscr{X}_{\textit{lis-ét}})$. *We refer section C.3 in [Ric22] for more comments about this and the generalization of the properties as above.*

4 Fundations of Virtual Fundamental Class

We will follows [BF97]. Here an algebraic stack (or Artin stack) over a field k is assumed to be quasi-separated and locally of finite type over k.

4.1 About Cones

We will let X be a Deligne-Mumford stack now.

Definition 4.1. *Let X be a DM-stack.*

(a) We call an affine X-scheme $C = \underline{\mathrm{Spec}}_X \mathscr{S}$ is a cone over X *if the quasi-coherent algebra $\mathscr{S}$ is graded as $\mathscr{S} = \bigoplus_{i \geq 0} \mathscr{S}^i$ with $\mathscr{S}^0 = \mathscr{O}_X$ and $\mathscr{S}^1$ is coherent and $\mathscr{S}$ is generated by $\mathscr{S}^1$.*

(b) A morphism of cones over X *is an X-morphism induced by a graded morphism of graded sheaves of $\mathscr{O}_X$-algebras. A* closed subcone *is the image of a closed immersion of cones.*

Remark 4.2. *(a) The fiber product of cones over X is still a cone over X.*

(b) For every cone $C \to X$, it has a zero section $0 : X \to C$ induced by $\mathscr{S} \to \mathscr{S}^0$.

(c) For every cone $C \to X$, the grade induce a $\mathbb{G}_m$-action $\mathbb{G}_m \times C = \underline{\mathrm{Spec}}_X \mathscr{S}[t, t^{-1}] \to C$ induced by $\mathscr{S} \to \mathscr{S}[t, t^{-1}]$ via $s_0 + \cdots s_d \mapsto \sum_i a_i t^i$ where $s_i \in \mathscr{S}^i$. Since no negative power of t occurs, we can in fact replace $\mathbb{G}_m$ by $\mathbb{A}^1$. So we have the $\mathbb{A}^1$-action $\gamma : \mathbb{A}^1 \times C \to C$ induced by $\mathscr{S} \to \mathscr{S}[x]$ via $\mathscr{S}^i \ni s \mapsto sx^i$. Note that here $\mathbb{A}^1$ is not a group scheme and the action *here, as expected, to be the commutativity of the following diagrams:*

$$\begin{tikzcd} C \arrow[r, "{(1,\mathrm{id})/(0,\mathrm{id})}"] \arrow[dr, "\mathrm{id}/0"'] & \mathbb{A}^1 \times C \arrow[d, "\gamma"] \\ & C \end{tikzcd} \qquad \begin{tikzcd} \mathbb{A}^1 \times \mathbb{A}^1 \times C \arrow[r, "\mathrm{id}\times\gamma"] \arrow[d, "m\times\mathrm{id}"'] & \mathbb{A}^1 \times \mathbb{A}^1 \times C \arrow[d, "\gamma"] \\ \mathbb{A}^1 \times C \arrow[r, "\gamma"'] & C \end{tikzcd}$$

where $m(x, y) = xy$.

(d) So a morphism of cones $f : C \to D$ over X is just the $\mathbb{A}^1$-equivariant X-morphism respecting the zero section, that is, the following commutativity of the diagram:

$$\begin{tikzcd} \mathbb{A}^1 \times C \arrow[r] \arrow[d, "\mathrm{id}\times f"'] & C \arrow[d, "f"'] \arrow[r, shift right] & X \arrow[l, shift right, "0_C"'] \arrow[dl, shift left, "0_D"] \\ \mathbb{A}^1 \times D \arrow[r] & D \arrow[ur, shift left] \end{tikzcd}$$

Definition 4.3. *Let $\mathscr{F}$ be a coherent sheaf of X, then we can define $C(\mathscr{F}) := \underline{\mathrm{Spec}}_X \mathrm{Sym}(\mathscr{F})$ which is a group scheme over X since it can be represented as $C(\mathscr{F})(T) = \mathrm{Hom}(\mathscr{F}_T, \mathscr{O}_T)$. We call a cone of this form is an* abelian cone over X.

Remark 4.4. *(a) A fibered product of abelian cones is an abelian cone.*

(b) A vector bundle $E = \underline{\mathrm{Spec}}_X \operatorname{Sym}(\mathscr{E}^\vee)$ is a special case.

(c) Any cone $C = \underline{\mathrm{Spec}}_X \bigoplus_{i \geq 0} \mathscr{S}^i$ is canonically a closed subcone of an abelian cone $A(C) = \underline{\mathrm{Spec}}_X \operatorname{Sym} \mathscr{S}^1$, called the abelian hull of C. *The abelian hull is a vector bundle if and only if $\mathscr{S}^1$ is locally free.*

(d) The abelianization *$C \mapsto A(C)$ is a functor has the forgetful functor as a right adjoint. So we have*

$$\mathrm{Hom}_{\mathbf{AbCone}_X}(A(C), A) \cong \mathrm{Hom}_{\mathbf{Cone}_X}(C, A).$$

(e) Let $\mathbf{Alg}_X^o$ as the category of quasicoherent graded $\mathscr{O}_X$-algebras satisfying the condition in the definition of cones. So we have the following commutative diagram of functors:

$$\begin{tikzcd}
\mathbf{Alg}_X^o \arrow[r, "\underline{\mathrm{Spec}}_X"] & \mathbf{Cone}_X^{\mathrm{op}} \\
\mathbf{LocFree}_X \arrow[u, "\mathrm{Sym}"] \arrow[r, "\underline{\mathrm{Spec}}_X \operatorname{Sym}(-)^\vee"] \arrow[d, hook] & \mathbf{Vect}_X^{\mathrm{op}} \arrow[u, hook] \arrow[d, hook] \\
\mathbf{Coh}_X \arrow[r, "\underline{\mathrm{Spec}}_X \operatorname{Sym}"] & \mathbf{AbCone}_X^{\mathrm{op}}
\end{tikzcd}$$

Example 4.5. *Tow important examples. Let $X \hookrightarrow Y$ be a closed immersion of ideal $\mathscr{I}$. Then $C_{X/Y} := \underline{\mathrm{Spec}}_X \bigoplus_{n \geq 0} \mathscr{I}^n / \mathscr{I}^{n+1}$ is called the* normal cone of X in Y. *The associated abelian cone $N_{X/Y} = \underline{\mathrm{Spec}}_X \operatorname{Sym} \mathscr{I}/\mathscr{I}^2$ is called the* normal sheaf of X in Y.

Lemma 4.6. *About smoothness:*

(a) Let $C = \underline{\mathrm{Spec}}_X \mathscr{S}$ be a cone over X. Then $C_{X/C} \cong \mathscr{S}^1 \cong 0^* \Omega_{C/X}$.

(b) A cone C over X is a vector bundle if and only if it is smooth over X.

(c) Let $C \to D$ be a smooth morphism of cones of relative dimension n over X. Then the induced morphism $A(C) \to A(D)$ is also smooth of relative dimension n.

Proof. For (a), note that $C_{X/C} \cong \mathscr{S}^1$ is trivial by definition. Morever, $0 : X \to C$ is the zero section and we have $0 \to C_{X/C} \to 0^*\Omega_{C/X} \to \Omega_{X/X} = 0$ exact (see Tag 0474). Well done.

For (b), let $C = \underline{\mathrm{Spec}}_X \bigoplus_{i \geq 0} \mathscr{S}^i$ and assume that $C \to X$ has constant relative dimension r. Then $\mathscr{S}^1 = 0^*\Omega_{C/X}$ is locally free of rank r. As $C \hookrightarrow A(C)$ where $A(C)$ is a vector bundle and $\dim C = \dim A(C)$, we know that C is a vector bundle.

For (c), apply the exact triangle of cotangent complex to $X \to C \to D$ and (a), we have an exact sequence

$$0 \to \mathscr{T}^1 \to \mathscr{S}^1 \to 0_C^*\Omega_{C/D} \to 0$$

where $C = \underline{\mathrm{Spec}}_X \mathscr{S}$ and $D = \underline{\mathrm{Spec}}_X \mathscr{T}$. So locally we have $A(C) = A(D) \times_X \underline{\mathrm{Spec}}_X \,\mathrm{Sym}(0_C^*\Omega_{C/D})$. Well done. ☐

Definition 4.7. *A sequence of cone morphisms*

$$0 \to E \xrightarrow{i} C \to D \to 0$$

is called exact *if E is a vector bundle and locally over X there is a morphism of cones $C \to E$ splitting i and inducing an isomorphism $C \cong E \times_X D$.*

Remark 4.8. *As $E \to X$ is smooth and surjective by Lemma 4.6, if $0 \to E \xrightarrow{i} C \to D \to 0$ then locally we have $C \cong E \times_X D$ which force that $C \to D$ is smooth and surjective! Similarly $i : E \to C$ is a closed embedding.*

Lemma 4.9. *We have the following useful results.*

(a) Given a short exact sequence $0 \to \mathscr{F}' \to \mathscr{F} \to \mathscr{E} \to 0$ of coherent sheaves on X, with $\mathscr{E}$ locally free, then $0 \to C(\mathscr{E}) \to C(\mathscr{F}) \to C(\mathscr{F}') \to 0$ is exact, and conversely is also true.

(b) Let $0 \to E \to F \xrightarrow{f} G \to 0$ be an exact sequence of abelian cones over X with E a vector bundle. Assume that $D \subset G$ is a closed subcone, then the induced sequence $0 \to E \to f^{-1}(D) =: C \to D \to 0$ is exact.

(c) Let $f : C \to D$ be a morphisms of cones over X which is smooth surjective, then the induced diagram

$$\begin{tikzcd} C \arrow[r, "f"] \arrow[d, hook] & D \arrow[d, hook] \\ A(C) \arrow[r, "A(f)"] & A(D) \end{tikzcd}$$

is cartesian. Moreover, we have $D = [C/E]$ (see Lemma 4.12(a)) and $A(D) = [A(C)/E]$, where $E := C \times_{D,0} X = A(C) \times_{A(D),0} X$.

(d) Let E be a vector bundle over X and then the sequence $0 \to E \to C \to D \to 0$ is exact if and only if the abelian hulls $0 \to E \to A(C) \to A(D) \to 0$ is exact and $C \to D$ is smooth and surjective.

Proof. For (a), we refer Example 4.1.6 and Example 4.1.7 in [Ful98]. As exactness is local, we may assume $\mathscr{E}$ is free. Then the first sequence is exact if and only if $\mathscr{F}' \oplus \mathscr{E} = \mathscr{F}$ if and only if the second sequence is exact as cones, since $\mathrm{Sym}(\mathscr{F}' \oplus \mathscr{E}) = \mathrm{Sym}(\mathscr{F}') \otimes \mathrm{Sym}(\mathscr{E}) = \mathrm{Sym}(\mathscr{F})$.

For (b), note that this can be checked locally, so we can let we can assume that $\mathscr{F} = \mathscr{G} \oplus \mathscr{E}^\vee$ where $E = \underline{\mathrm{Spec}}_X \operatorname{Sym} \mathscr{E}^\vee$ and $F = \underline{\mathrm{Spec}}_X \operatorname{Sym} \mathscr{F}$ and $G = \underline{\mathrm{Spec}}_X \operatorname{Sym} \mathscr{G}$. Let $D = \underline{\mathrm{Spec}}_X \mathscr{T}$, then we have surjection $\mathrm{Sym}(\mathscr{G}) \to \mathscr{T}$. By definition, we have

$$\begin{aligned} C = F \times_G D &= \underline{\mathrm{Spec}}_X(\mathrm{Sym}(\mathscr{F}) \otimes_{\mathrm{Sym}(\mathscr{G})} \mathscr{T}) \\ &= \underline{\mathrm{Spec}}_X((\mathrm{Sym}(\mathscr{G}) \otimes \operatorname{Sym} \mathscr{E}^\vee) \otimes_{\mathrm{Sym}(\mathscr{G})} \mathscr{T}) \\ &= \underline{\mathrm{Spec}}_X(\operatorname{Sym} \mathscr{E}^\vee \otimes \mathscr{T}). \end{aligned}$$

This means locally $C = E \oplus D$ and the splitting $C \to E$ is induced by $F \to E$. Well done.

For (c), let $E := C \times_{D,0} X$ and $E' := A(C) \times_{A(D)} D$ with embedding $E \hookrightarrow E'$, then both of them are vector bundles by Lemma 4.6(b)(c) and hence $E = E'$. We have cartesians

$$\begin{tikzcd} E \arrow[r] \arrow[d] \arrow[dr, phantom, "\ulcorner", very near start] & X \arrow[d, hook] \\ C \arrow[r] & D \end{tikzcd} \qquad \begin{tikzcd} E \arrow[r] \arrow[d] \arrow[dr, phantom, "\ulcorner", very near start] & X \arrow[d, hook] \\ A(C) \arrow[r] & A(D) \end{tikzcd}$$

By the properties of commutative affine group schemes, we have $A(D) = [A(C)/E]$. But how about $[C/E]$? Now we have

$$\begin{tikzcd} & & D \arrow[d, hook] \\ C \arrow[urr] \arrow[r] \arrow[d, hook] \arrow[dr, phantom, "\ulcorner", very near start] & {[C/E]} \arrow[d, hook] & \\ A(C) \arrow[r] & A(D) & \end{tikzcd}$$

Since $C \to [C/E]$ and $C \to D$ are both smooth and surjective, we know that $[C/E] \to D$ is flat and surjective. But by closed embeddings $[C/E] \to A(D)$ and $D \to A(D)$, we know that $[C/E] \to D$ is also a closed embedding. Thus $D = [C/E]$, well done.

For (d), note that all the question is locally on X. First we assume $0 \to E \xrightarrow{i} C \xrightarrow{f} D \to 0$ is exact. Then by (a), to show that $0 \to E \to A(C) \to A(D) \to 0$ is exact, we only need to show that $0 \to \mathscr{T}^1 \to \mathscr{S}^1 \to \mathscr{E}^\vee \to 0$ is exact where $E = \underline{\mathrm{Spec}}_X \operatorname{Sym} \mathscr{E}^\vee$ and $C = \underline{\mathrm{Spec}}_X \mathscr{S}$ and $D = \underline{\mathrm{Spec}}_X \mathscr{T}$. First since f is faithfully flat and quasi-compact, we know that $\mathscr{T}^1 \to \mathscr{S}^1$ is injective. And since i is a closed embedding, $\mathscr{S}^1 \to \mathscr{E}^\vee$ is surjective. Now by local splitting, we know that locally we have $\mathrm{Sym}(E^\vee) \otimes \mathscr{T} = \mathscr{S}$. In particular, we have $\mathscr{T}^1 \oplus \mathscr{E}^\vee = \mathscr{S}^1$. Thus the exactness of $0 \to \mathscr{T}^1 \to \mathscr{S}^1 \to \mathscr{E}^\vee \to 0$ is obtained. Conversely we assume that after taking abelian hull, the sequence is exact. Now the result follows from (a) and (c). $\square$

Proposition 4.10. *Let $C \to D$ be a smooth, surjective morphism of cones. If we let $E = C \times_{D,0} X$, then the sequence*

$$0 \to E \to C \to D \to 0$$

is exact. Conversely if $0 \to E \to C \to D \to 0$ is exact, then $E \cong C \times_{D,0} X$.

Proof. Let $C = \underline{\mathrm{Spec}}_X \bigoplus_{i \geq 0} \mathscr{S}^i$ and $D = \underline{\mathrm{Spec}}_X \bigoplus_{i\geq 0} \mathscr{T}^i$.

Let $E = C \times_{D,0} X = \underline{\mathrm{Spec}}_X \mathrm{Sym}\,\mathscr{E}^\vee$, by Lemma 4.9(d) we just need to show that $0 \to E \to A(C) \to A(D) \to 0$ is exact, that is, $0 \to \mathscr{T}^1 \to \mathscr{S}^1 \to \mathscr{E}^\vee \to 0$ is exact by Lemma 4.9(a). Note that $\mathrm{Sym}\,\mathscr{E}^\vee = \mathscr{S} \otimes_{\mathscr{T}} (\mathscr{T}/\mathscr{T}^{\geq 1})$ which force $\mathscr{E}^\vee \cong \mathscr{S}^1/\mathscr{T}^1$. Well done.

Conversely, assume that the sequence $0 \to E \to C \to D \to 0$ is exact and $F = C \times_{D,0} X$. Then by the universal property of fibre product, we get a morphism $E \to F$. From the construction, it is easy to see that $\mathscr{F}^\vee \to \mathscr{E}^\vee$ surjective. Since they are both bundles of the same rank over X, we know that $E = F$. $\square$

Definition 4.11. *(a) If E is a vector bundle and $f : E \to C(\mathscr{F})$ a morphism of abelian cones. The there is an E-action as $E \times_X C(\mathscr{F}) \to C(\mathscr{F})$ as $(\nu, \gamma) \mapsto f\nu + \gamma$.*

(b) If E is a vector bundle and $d : E \to C$ a morphism of cones, we say that C is an E-cone, if C is invariant under the action of E on $A(C)$.

(c) A morphism ϕ from an E-cone C to an F-cone D is a commutative diagram of cones

$$\begin{tikzcd} E \arrow[r, "d_E"] \arrow[d, "\phi"] & C \arrow[d, "\phi"] \\ F \arrow[r, "d_F"] & D \end{tikzcd}$$

(d) If $\phi : (E, d_E, C) \to (F, d_F, D)$ and $\psi : (E, d_E, C) \to (F, d_F, D)$ are morphisms, we call them homotopic, if there exists a morphism of cones $k : C \to F$, such that $kd_E = \psi - \phi = d_F k$.

Lemma 4.12. *Some useful lemmas:*

(a) Let $f : C \to D$ be a smooth surjective cone morphism with $E = C \times_{D,0} X$, then C is an E-cone.

(b) *Let* $0 \to E \xrightarrow{i} C \xrightarrow{f} D = [C/E] \to 0$ *be a sequence of algebraic* X*-spaces with* E *a bundle,* C *is a* E*-cone,* i *a closed embedding and* $f : C \to D = [C/E]$ *is the universal family. Then locally on* X*, there is a* $j : C \to E$ *split* i *and induces an isomorphism* $(f, j) : C \to D \times_X E$*.*

(c) *Let* $0 \to E \xrightarrow{i} C \xrightarrow{f} D \to 0$ *be a sequence of algebraic* X*-spaces with sections and* $\mathbb{A}^1$*-actions such that* E *a bundle,* C *is a* E*-cone,* i *is a closed embedding and* f *is* $\mathbb{A}^1$*-equivariant. Then* D *is a cone with the sequence exact if and only if* $D \cong [C/E]$*.*

Proof. For (a), this follows from directly check. We omit it.

For (b), since the question is local we can assume that E is a trivial bundle and X is a scheme. Let $i' : E \to A(C)$ and $C = \underline{\mathrm{Spec}}_X \mathscr{S}$ and $E = \underline{\mathrm{Spec}}_X \operatorname{Sym} \mathscr{E}^\vee$. Then the surjection $\mathscr{S}^1 \twoheadrightarrow \mathscr{E}^\vee$ has a splitting $\mathscr{E}^\vee \hookrightarrow \mathscr{S}^1$, which gives $j' : A(C) \to E$ such that $j' \circ i' = \mathrm{id}_E$. Then we just define $j : C \to E$ as composition with $C \to A(C)$ and j'. Hence $j \circ i = \mathrm{id}_E$.

Now since $C \to D$ is also a principal E-bundle, and we have a E-equivariant D-morphism $(f, j) : C \to D \oplus E$ from C to the trivial principal bundle. Since they are both E-principal bundle, we know that (f, j) is an isomorphism.

For (c), let $D = [C/E]$. We know that $D \to X$ is affine since locally on X we have $C \cong D \times_X E \to E$ is affine and (b) and faithfully flat descent. By construction we have $E = C \times_{D,0} X$, hence by Proposition 4.10 we just need to show D is a cone. Now as $D \to X$ affine we have $D = \underline{\mathrm{Spec}}_X \mathscr{T}$. If $C = \underline{\mathrm{Spec}}_X \mathscr{S}$, then $\mathscr{T} \subset \mathscr{S}$ as $C \to D$ is faithfully flat. Hence it has graded structure $\mathscr{T} = \bigoplus_{i \geq 0} \mathscr{T} \cap \mathscr{S}^i$ as f is $\mathbb{A}^1$-equivariant. As it have zero section, we have $\mathscr{T}^0 = \mathscr{O}_X$. Finally we have $\mathbb{A}^1$-equivariant embedding $D \hookrightarrow [A(C)/E]$ and $[A(C)/E]$ is a cone by Lemma 4.9(c). Hence $\mathscr{T}$ generated by the coherent sheaf $\mathscr{T}^1$.

Conversely, we assume D is a cone and that sequence is exact. Let $D' = [C/E]$. By the universal property of quotient, we have a natural map $g : D' \to D$. Since $0 \to E \to C \to D' \to 0$ is also exact by the first case, by exactness we have locally $C \cong E \times_X D \cong E \times_X D'$. Note that these isomorphisms compatible with $g : D' \to D$, hence by faithfully flat descent we have g is an isomorphism. $\square$

Proposition 4.13. *Let* X *be a DM-stack.*

(a) *Let* E *be a vector bundle. Consider the sequence of cone morphisms* $0 \to E \xrightarrow{i} C \xrightarrow{\phi} D \to 0$ *with* i *a closed embedding. Then it is exact if* *and only if C is a E-cone, $\phi : C \to D$ is faithfully flat and the diagram*

$$\begin{tikzcd} E \times C \arrow[r, "\sigma"] \arrow[d, "p"] \arrow[dr, phantom, "\ulcorner", very near start] & C \arrow[d, "\phi"] \\ C \arrow[r, "\phi"] & D \end{tikzcd}$$

is cartesian with projection p and action σ.

(b) Let $(C, 0, \gamma)$ and $(D, 0, \gamma)$ be algebraic X-spaces with sections and $\mathbb{A}^1$-actions and let $\phi : C \to D$ be an $\mathbb{A}^1$-equivariant X-morphism, which is smooth and surjective. Let $E = C \times_{D,0} X$. Assume that E is a vector bundle. Then C is an E-cone (resp. abelian cone, vector bundle) over X if and only if D is a cone (resp. abelian cone, vector bundle) over X and C is affine over X.

Proof. For (a), if it is exact, locally we have $C \cong E \times_X D$. So E act on C locally as $E \times E \times_X D \to E \times_X D$ given by $(f, (e, d)) \mapsto (i(f) + e, d)$. So C is a E-cone. Now $\phi : C \to D$ is trivially faithfully flat. The cartesian diagram follows from Lemma 4.12(c).

Conversely, since ϕ is fppf, this diagram is also cocartesian by Proposition V.1.3.1 in [Li18] which force $D = [C/E]$. Hence the results follows from Lemma 4.12(c).

For (b), let C is an E-cone over X. Then we have $g : [C/E] \to D$. We claim that g is an isomorphism. Indeed, by the diagram in (a), we know that g induces an isomorphism $g' : E \times_X C = C \times_{[C/E]} C \to C \times_D C$. Note that we have a cartesian diagram:

$$\begin{tikzcd} C \times_{[C/E]} C \arrow[r] \arrow[d] \arrow[dr, phantom, "\ulcorner", very near start] & C \times_D C \arrow[d] \\ {[C/E]} \arrow[r, hook] & {[C/E] \times_D [C/E]} \end{tikzcd}$$

where $C \times_D C \to [C/E] \times_D [C/E]$ is faithfully flat, hence $[C/E] \hookrightarrow [C/E] \times_D [C/E]$ is an isomorphism. So g is a monomorphism. But since $C \to [C/E]$ and $C \to D$ are faithfully flat, hence epimorphism. Thus g is also an epimorphism, hence an isomorphism. Thus $D \cong [C/E]$ and the result follows from Lemma 4.12(c).

Now assume that $C = A(C)$ is an abelian cone, then taking hull to $0 \to E \to C \to D = [C/E] \to 0$. By Lemma 4.9(c)(d) we have $A(D) = [A(C)/E] = [C/E] = D$. Hence D is also an abelian cone.

Finally assume that C is a bundle. Then by the previous case we know that D is an abelian cone. The $\mathscr{T}^1 = \ker(\mathscr{S}^1 \twoheadrightarrow \mathscr{E}^\vee)$ is clearly locally free since $\mathscr{C}^1$ and $\mathscr{E}$ are where $C = \underline{\operatorname{Spec}}_X \mathscr{S}$, $D = \underline{\operatorname{Spec}}_X \mathscr{T}$ and $E = \underline{\operatorname{Spec}}_X \operatorname{Sym} \mathscr{E}^\vee$.

Conversely we let D is a cone and C is affine over X. Hence we have $C = \underline{\mathrm{Spec}}_X \mathscr{S}$ where $\mathscr{S} = \bigoplus_{i\geq 0} \mathscr{S}^i$ and $\mathscr{S}^1 = \mathscr{O}_X$. By the same reason E is affine over X. Hence we have $C = \underline{\mathrm{Spec}}_X \mathscr{F}$ where $\mathscr{F} = \bigoplus_{i\geq 0} \mathscr{F}^i$ and $\mathscr{F}^1 = \mathscr{O}_X$. If we let $D = \underline{\mathrm{Spec}}_X \mathscr{T}$, then $\mathscr{F} = \mathscr{S}/(\mathscr{T}^{\geq 1}\mathscr{S})$.

Apply the exact triangle of cotangent complex to $X \xrightarrow{0_C} C \to D$, we have an exact sequence

$$0 \to \mathscr{T}^1 \to \mathscr{S}^{\geq 1}/(\mathscr{S}^{\geq 1})^2 = C_{X/C} \to \mathscr{E}^\vee := 0_C^* \Omega_{C/D} \to 0.$$

As $\mathscr{S}^{\geq 1}/(\mathscr{S}^{\geq 1})^2 = \mathscr{S}^1 \oplus \mathscr{S}^{\geq 2}/(\mathscr{S}^{\geq 1})^2$, we have a commutative diagram with exact rows and columns:

$$\begin{tikzcd}
 & & 0 \arrow[d] & 0 \arrow[d] & \\
0 \arrow[r] & \mathscr{T}^1 \arrow[r] \arrow[d, "="] & \mathscr{S}^1 \arrow[r] \arrow[d] & \mathscr{F}^1 \arrow[r] \arrow[d] & 0 \\
0 \arrow[r] & \mathscr{T}^1 \arrow[r] & \mathscr{S}^{\geq 1}/(\mathscr{S}^{\geq 1})^2 \arrow[r] \arrow[d] & \mathscr{E}^\vee \arrow[r] \arrow[d] & 0 \\
 & & \mathscr{S}^{\geq 2}/(\mathscr{S}^{\geq 1})^2 \arrow[r, "="] \arrow[d] & \mathscr{E}^\vee/\mathscr{F} \arrow[d] & \\
 & & 0 & 0 &
\end{tikzcd}$$

Locally on X we can assume that $\mathscr{E}$ is free and $\mathscr{T}^1 \oplus \mathscr{E}^\vee = \mathscr{S}^{\geq 1}/(\mathscr{S}^{\geq 1})^2$. Then as $\mathscr{F}^1 \subset \mathscr{E}^\vee$, we know that $\mathscr{F}^1$. Since $\mathscr{T}^1$ is also coherent, we know that so is $\mathscr{S}^1$. Finally we just need to show $\mathscr{S}$ generated by $\mathscr{S}^1$ as by Lemma 4.12(a) here C will be an E-cone.

Then locally on X we can choose generators of $\mathscr{T}^1, \mathscr{F}^1, \mathscr{E}^\vee/\mathscr{F}^1 = \mathscr{S}^{\geq 2}/(\mathscr{S}^{\geq 1})^2$ such that gives a surjective $\mathscr{O}_X$-algebra morphism $\phi : \mathscr{T} \oplus \mathrm{Sym}\, \mathscr{E}^\vee \twoheadrightarrow \mathscr{S}$ which induce $\mathscr{T} \oplus \mathrm{Sym}\, \mathscr{F}^1 \to \mathscr{T} \oplus \mathrm{Sym}\, \mathscr{E}^\vee \twoheadrightarrow \mathscr{S}$ is graded. Tensoring $(-) \otimes_{\mathscr{T}} \mathscr{O}_X$ with ϕ we get surjection $\phi' : \mathrm{Sym}\, \mathscr{E}^\vee \twoheadrightarrow \mathscr{F}$. This induce the closed immersion $E \hookrightarrow \underline{\mathrm{Spec}}_X \mathrm{Sym}\, \mathscr{E}^\vee$. Since they are both smooth of a same relative dimension over X and $\underline{\mathrm{Spec}}_X \mathrm{Sym}\, \mathscr{E}^\vee$ is a vector bundle, hence $E \cong \underline{\mathrm{Spec}}_X \mathrm{Sym}\, \mathscr{E}^\vee$ and ϕ' is an isomorphism. Hence $\mathscr{F} = \mathrm{Sym}(\mathscr{F}^1)$ and $\mathscr{F}^1$ is locally free. As $\mathrm{Sym}(\mathscr{F}^1) \subset \mathrm{Sym}\, \mathscr{E}^\vee \xrightarrow{\phi'} \mathscr{F} = \mathrm{Sym}(\mathscr{F}^1)$ is identity, this force $\mathscr{E}^\vee = \mathscr{F}^1$. As this can be check locally, we have $\mathscr{E}^\vee = \mathscr{F}^1$ in whole X. By the diagram above, we have $\mathscr{S}^{\geq 2}/(\mathscr{S}^{\geq 1})^2 = \mathscr{E}^\vee/\mathscr{F}^1 = 0$. This means $\mathscr{S}$ generated by $\mathscr{S}^1$. Well done. $\square$

Remark 4.14. *In the original paper [BF97] they claim (a) is enough for the surjectivity of f.*

4.2 Cone Stack

Let X be a Deligne-Mumford stack.

Definition 4.15. *Let $\mathfrak{C}$ be an algebraic stack over X, together with a section $0 : X \to \mathfrak{C}$. An $\mathbb{A}^1$-action on $(\mathfrak{C}, 0)$ is given by a morphism of X-stacks $\gamma : \mathbb{A}^1 \times \mathfrak{C} \to \mathfrak{C}$ and three 2-isomorphisms θ_1, θ_0 and θ_γ between the 1-morphisms in the following diagrams.*

$$\begin{tikzcd} \mathfrak{C} \arrow[rr, "(1,\mathrm{id})/(0,\mathrm{id})"] \arrow[dr, "\mathrm{id}/0"'] & \arrow[d, phantom, "\Rightarrow \theta_1/\theta_0"] & \mathbb{A}^1 \times \mathfrak{C} \arrow[dl, "\gamma"] \\ & \mathfrak{C} & \end{tikzcd}$$

$$\begin{tikzcd} \mathbb{A}^1 \times \mathbb{A}^1 \times \mathfrak{C} \arrow[r, "\mathrm{id}\times\gamma"] \arrow[d, "m\times\mathrm{id}"'] \arrow[dr, phantom, "\Rightarrow \theta_\gamma"] & \mathbb{A}^1 \times \mathfrak{C} \arrow[d, "\gamma"] \\ \mathbb{A}^1 \times \mathfrak{C} \arrow[r, "\gamma"'] & \mathfrak{C} \end{tikzcd}$$

The 2-isomorphisms θ_1, θ_0 and θ_γ are required to satisfy certain compatibilities.

Definition 4.16. *Let $(\mathfrak{C}, 0, \gamma)$ and $(\mathfrak{D}, 0, \gamma)$ be X-stacks with sections and $\mathbb{A}^1$-actions. Then an $\mathbb{A}^1$-*equivariant morphism* $\phi : \mathfrak{C} \to \mathfrak{D}$ is a triple $(\phi, \eta_0, \eta_\gamma)$, where $\phi : \mathfrak{C} \to \mathfrak{D}$ is a morphism of algebraic X-stacks and η_0 and η_γ are 2-isomorphisms between the morphisms in the following diagrams.*

$$\begin{tikzcd} X \arrow[r, "0"] \arrow[dr, "0"'] \arrow[r, phantom, shift right=3, "\Rightarrow \eta_0"] & \mathfrak{C} \arrow[d, "\phi"] \\ & \mathfrak{D} \end{tikzcd}$$

$$\begin{tikzcd} \mathbb{A}^1 \times \mathfrak{C} \arrow[r, "\mathrm{id}\times\phi"] \arrow[d, "\gamma"'] \arrow[dr, phantom, "\Rightarrow \eta_\gamma"] & \mathbb{A}^1 \times \mathfrak{D} \arrow[d, "\gamma"] \\ \mathfrak{C} \arrow[r, "\phi"] & \mathfrak{D} \end{tikzcd}$$

Again, the 2-isomorphisms have to satisfy certain compatibilities.

Definition 4.17. *Let $(\phi, \eta_0, \eta_\gamma) : \mathfrak{C} \to \mathfrak{D}$ and $(\psi, \eta_0', \eta_\gamma') : \mathfrak{C} \to \mathfrak{D}$ be two $\mathbb{A}^1$-equivariant morphisms. An $\mathbb{A}^1$-*equivariant isomorphism* $\zeta : \phi \to \psi$ is a 2-isomorphism $\zeta : \phi \to \psi$ such that the diagrams*

$$\begin{tikzcd} 0 \arrow[r, "\eta_0"] \arrow[dr, "\eta_0'"'] & \phi \circ 0 \arrow[d, "\zeta\circ 0"] \\ & \psi \circ 0 \end{tikzcd} \qquad \begin{tikzcd} \phi\circ\gamma \arrow[r] \arrow[d, "\zeta\circ\gamma"] & \gamma\circ(\mathrm{id}\times\phi) \arrow[d, "\gamma\circ(\mathrm{id}\times\zeta)"] \\ \psi\circ\gamma \arrow[r] & \gamma\circ(\mathrm{id}\times\psi) \end{tikzcd}$$

commute.

Example 4.18. *Let C be a E-cone, then consider the quotient stack $[C/E]$. We claim that $[C/E]$ a zero section and an $\mathbb{A}^1$-action.*

Indeed, the zero section $0 : X \to [C/E]$ given by $X \leftarrow E \to C$. The $\mathbb{A}^1$-action of $\alpha \in \mathbb{A}^1(T)$ on $(P, f) \in [C/E](T)$ defined by $(\alpha P, \alpha f)$ where $\alpha P = P \times^{E,\alpha} E$ and $\alpha f : P \times^{E,\alpha} E \to C$ given by $[p, v] \mapsto \alpha f(p) + d(v)$ where $d : E \to C$.

Moreover, if $\phi : (E, C) \to (F, D)$ is a morphism of vector bundle cones we get an induced $\mathbb{A}^1$-equivariant morphism $\tilde{\phi} : [C/E] \to [D/F]$.

Lemma 4.19. *Some usrful results.*

(a) A homotopy $k : \phi \to \psi$ of two morphisms of vector bundle cones $\phi, \psi : (E, C) \to (F, D)$ gives rise to an $\mathbb{A}^1$-equivariant 2-isomorphism $\tilde{k} : \tilde{\phi} \to \tilde{\psi}$ of $\mathbb{A}^1$-equivariant morphisms of stacks with $\mathbb{A}^1$-action.

(b) Conversely, let two morphisms of vector bundle cones $\phi, \psi : (E, C) \to (F, D)$ with an $\mathbb{A}^1$-equivariant 2-isomorphism $\zeta : \tilde{\phi} \to \tilde{\psi}$ of $\mathbb{A}^1$-equivariant morphisms of stacks with $\mathbb{A}^1$-action. Then $\zeta = \tilde{k}$ for unique homotopy $k : \phi \to \psi$.

Proof. TBC... □

Proposition 4.20. *Let C be an E-cone and D an F-cone and let $\phi : (E, C) \to (F, D)$ be a morphism. If the diagram*

$$\begin{tikzcd} E \arrow[r] \arrow[d] \arrow[dr, phantom, "\ulcorner", very near start] & C \arrow[d, "\phi"] \\ F \arrow[r, "d"'] & D \end{tikzcd}$$

is cartesian and $F \times_X C \to D$ by $(\mu, \gamma) \mapsto d\mu + \phi(\gamma)$ is surjective, then $[C/E] \to [D/F]$ is an isomorphism of algebraic X-stacks with $\mathbb{A}^1$-action.

Proof. TBC... □

Definition 4.21. *(a) We call an algebraic stack $(\mathfrak{C}, 0, \gamma)$ over X with section and $\mathbb{A}^1$-action a* cone stack*, if, étale locally on X, there exists a cone C over X and an $\mathbb{A}^1$-equivariant morphism $C \to \mathfrak{C}$ that is smooth and surjective and such that $E = C \times_{\mathfrak{C},0} X$ is a vector bundle over X.*

(b) The morphism $C \to \mathfrak{C}$ is called a local presentation of $\mathfrak{C}$*. The section $0 : X \to \mathfrak{C}$ is called the vertex of $\mathfrak{C}$.*

(c) Let $\mathfrak{C}$ and $\mathfrak{D}$ be cone stacks over X. A morphism of cone stacks *$\phi : \mathfrak{C} \to \mathfrak{D}$ is an $\mathbb{A}^1$-equivariant morphism of algebraic X-stacks. A 2-*isomorphism of cone stacks *is just an $\mathbb{A}^1$-equivariant 2-isomorphism.*

(d) *A cone stack $\mathfrak{C}$ over X is called* abelian cone stack *(resp.* vector bundle stack*), if, locally in X, one can find presentations $C \to \mathfrak{C}$, where C is an abelian cone (resp. vector bundle).*

Remark 4.22. *Some basic properties of cone stacks.*

(a) *If $C \to \mathfrak{C}$ is a global presentation with $E = C \times_{\mathfrak{C},0} X$, then C is an E-cone with $\mathfrak{C} \cong [C/E]$ as stacks with $\mathbb{A}^1$-action. This follows from Proposition 4.10 and 4.13 and Lemma 4.12.*

(b) *If $\phi : \mathfrak{C} \to \mathfrak{D}$ is a morphism of cone stacks, then, étale locally on X, ϕ is $\mathbb{A}^1$-equivariantly isomorphic to $[C/E] \to [D/F]$, where $E \to F$ is a morphism of vector bundles over X and $C \to D$ is a morphism from the E-cone C to the F-cone D.*

(c) *A 2-isomorphism of cone stacks $\zeta : \phi \to \psi$, where $\phi, \psi : \mathfrak{C} \to \mathfrak{D}$, is étale locally over X given by a homotopy of morphisms of vector bundle cones. This follows from Lemma 4.19(b).*

(d) *Let $C \to \mathfrak{C}$ and $D \to \mathfrak{D}$ be two local presentation of a cone stack $\mathfrak{C}$ over X, then so is $C \times_{\mathfrak{C}} D \to \mathfrak{C}$.*

Indeed, we only need to show that $C \times_{\mathfrak{C}} D$ is a cone. Since $C \to \mathfrak{C}$ and $D \to X$ are affine, we know that $C \times_{\mathfrak{C}} D \to D \to X$ is also affine. Then $C \times_{\mathfrak{C}} D$ is a cone a by Proposition 4.13(b) and the result follows.

(e) *Every fibered product of cone stacks is a cone stack.*

(f) *If $\mathfrak{C}$ is a representable cone stack over X, then it is a cone.*

Indeed, locally on X, $\mathfrak{C} \to X$ is $\mathbb{A}^1$-isomorphic to a cone. In particular, as $\mathfrak{C} \to X$ is representable, it is affine. Then we assume that $C = \underline{\operatorname{Spec}}_X \mathscr{S}$. Since there is a non-trivial $\mathbb{A}^1$-action on C and has a section, we know that $\mathscr{S}$ is a graded algebra with $\mathscr{S}^0 = \mathscr{O}_X$. To show C is a cone, we only need to show that $\mathscr{S}^1$ is coherent and $\mathscr{S}$ is locally generated by $\mathscr{S}^1$. These are both local property, then they hold since locally $\mathfrak{C} \to X$ is $\mathbb{A}^1$-isomorphic to a cone.

(g) *If $\mathfrak{C}$ is abelian (a vector bundle stack), then for every local presentation $C \to \mathfrak{C}$ the cone C will be abelian (a vector bundle).*

Example 4.23. *Note that all cones are cone stacks and all morphisms of cones are morphisms of cone stacks. For a vector bundle E on X, the classifying stack $\mathbf{B}_X E$ is a cone stack. Every homomorphism of vector bundles $\phi : E \to F$ gives rise to a morphism of cone stacks.*

Proposition 4.24. *Every cone stack is a closed subcone stack of an abelian cone stack. There exists a universal such abelian cone stack. It is called the* abelian hull.

Proof. Just glue the stacks obtained from the abelian hulls of local presentations. $\square$

Definition 4.25. *(a) Let $\mathfrak{E}$ be a vector bundle stack and $\mathfrak{E} \to \mathfrak{C}$ a morphism of cone stacks. We say that $\mathfrak{C}$ is an $\mathfrak{E}$-cone stack, if $\mathfrak{E} \to \mathfrak{C}$ is locally isomorphic (as a morphism of cone stacks) to the morphism $[E_1/E_0] \to [C/F]$ coming from a commutative diagram*

$$\begin{tikzcd} E_0 \arrow[r] \arrow[d] & F \arrow[d] \\ E_1 \arrow[r] & C \end{tikzcd}$$

where C is both E_1- and F-cone. The natural action $\mathfrak{E} \times_X \mathfrak{C} \to \mathfrak{C}$ induced by $E_1 \times C \to C$.

(b) Let $\mathfrak{E} \to \mathfrak{C} \to \mathfrak{D}$ be a sequence of morphisms of cone stacks where $\mathfrak{C}$ is an $\mathfrak{E}$-cone stack. If

(b1) $\mathfrak{C} \to \mathfrak{D}$ is a smooth epimorphism.

(b2) The diagram

$$\begin{tikzcd} \mathfrak{E} \times_X \mathfrak{C} \arrow[r, "\sigma"] \arrow[d, "p"'] \arrow[dr, phantom, "\ulcorner"] & \mathfrak{C} \arrow[d] \\ \mathfrak{C} \arrow[r] & \mathfrak{D} \end{tikzcd}$$

is cartesian where σ is action and p is projection.

Then we call $0 \to \mathfrak{E} \to \mathfrak{C} \to \mathfrak{D} \to 0$ is a short exact sequence of cone stacks. As before, this is equivalent to $\mathfrak{C}$ being locally isomorphic to $\mathfrak{E} \times_X \mathfrak{D}$.

Proposition 4.26. *The sequence $0 \to \mathfrak{E} \to \mathfrak{C} \to \mathfrak{D} \to 0$ of morphisms of cone stacks is exact if and only if locally in X there exist commutative diagrams*

$$\begin{tikzcd} 0 \arrow[r] & E_0 \arrow[r] \arrow[d] & F \arrow[r] \arrow[d] & G \arrow[r] \arrow[d] & 0 \\ 0 \arrow[r] & E_1 \arrow[r] & C \arrow[r] & D \arrow[r] & 0 \end{tikzcd}$$

where the top row is a short exact sequence of vector bundles and the bottom row is a short exact sequence of cones, such that $\mathfrak{E} \to \mathfrak{C} \to \mathfrak{D}$ is isomorphic to $[E_1/E_0] \to [C/F] \to [D/G]$.

Proof. The statement is local on X. To prove the only if part we can assume $\mathfrak{C} = \mathfrak{E} \times_X \mathfrak{D}$, and then it is trivial. To prove the if part, note that both short exact sequences are locally split. $\square$

4.3 A Picard Stack of Special Type

General Theory

Definition 4.27. *Let X be a topos.*

(a) Let $d : E^0 \to E^1$ a homomorphism of abelian sheaves on X, which we shall consider as a complex of abelian sheaves on X. Via d, the abelian sheaf E^0 acts on E^1 and we may consider the quotient stack of this action, denoted

$$\mathcal{H}^0/\mathcal{H}^1(E^\bullet) := [E^0/E^1]$$

which is a Picard stack over X.

(b) Now if $d : F^0 \to F^1$ is another homomorphism of abelian sheaves on X and $\phi : E^\bullet \to F^\bullet$ is a homomorphism of complexes, then we get an induced morphism of Picard stacks

$$\mathcal{H}^0/\mathcal{H}^1(\phi) : \mathcal{H}^0/\mathcal{H}^1(E^\bullet) \to \mathcal{H}^0/\mathcal{H}^1(F^\bullet)$$

given by $(P, f) \mapsto (P \times^{E^0,\phi^0} F^0, \phi^1(f))$ where $\phi^1(f)$ is the map

$$\phi^1(f) : P \times^{E^0,\phi^0} F^0 \to F^1, \quad [p, \nu] \mapsto \phi^1(f(p) + d(\nu)).$$

(c) Now, if $\psi : E^\bullet \to F^\bullet$ is another homomorphism of complexes, then the homotopy *$k : \phi \to \psi$ is a homomorphism of abelian sheaves $k : E^1 \to F^0$, such that $kd = \psi^0 - \phi^0$ and $dk = \psi^1 - \phi^1$.*

Proposition 4.28. *As in the considtion of definition, if we have a homotopy $k : \phi \to \psi$, then this can induce isomorphism $\theta : \mathcal{H}^0/\mathcal{H}^1(\phi) \to \mathcal{H}^0/\mathcal{H}^1(\psi)$ of morphisms of Picard stacks from $\mathcal{H}^0/\mathcal{H}^1(E^\bullet)$ to $\mathcal{H}^0/\mathcal{H}^1(F^\bullet)$.*

Proof. Pick object $U \in \mathrm{ob}(X)$ and $(P, f) \in \mathcal{H}^0/\mathcal{H}^1(E^\bullet)(U)$, then $\theta(U)(P, f) : \mathcal{H}^0/\mathcal{H}^1(\phi)(U)(P, f) \to \mathcal{H}^0/\mathcal{H}^1(\psi)(U)(P, f)$ in $\mathcal{H}^0/\mathcal{H}^1(F^\bullet)(U)$ is the isomorphism of $F^0|_U$-torsors

$$\theta(U)(P, f) : P \times^{E^0,\phi^0} F^0 \to P \times^{E^0,\psi^0} F^0$$

given by $[p, \nu] \mapsto [p, kf(p) + \nu]$ such that the diagram of $F^0|_U$-sheaves

$$\begin{tikzcd}
P \times^{E^0,\phi^0} F^0 \arrow[d, "\theta(U)(P,f)"'] \arrow[dr, "\phi^1(f)"] & \\
P \times^{E^0,\psi^0} F^0 \arrow[r, "\psi^1(f)"'] & F^1
\end{tikzcd}$$

commutes. □

Proposition 4.29. *Let $\phi : E^\bullet \to F^\bullet$ is a homomorphism of complexes of abelian sheaves in the topos X. If ϕ induces isomorphisms on kernels and cokernels (i.e. if ϕ is a quasi-isomorphism), then*

$$\mathcal{H}^0/\mathcal{H}^1(\phi) : \mathcal{H}^0/\mathcal{H}^1(E^\bullet) \to \mathcal{H}^0/\mathcal{H}^1(F^\bullet)$$

is an isomorphism of Picard stacks over X.

Proof. □

Application

4.4 Intrinsic Normal Cone

4.5 Obstruction Theory and Virtual Class

4.6 Examples

5 Atiyah-Bott Localization

We will follows [AB84].

6 Localization of Virtual Fundamental Class

We will follows [GP99].

References

[AB84] M. Atiyah and R. Bott. The moment map and equivariant cohomology. *Topology*, 23:1–28, 1984.

[BF97] K. Behrend and B. Fantechi. The intrinsic normal cone. *Invent. Math.*, 128:45–88, 1997.

[EH16] David Eisenbud and Joe Harris. *3264 and All That: A Second Course in Algebraic Geometry.* Cambridge University Press, 2016.

[Ful98] William Fulton. *Intersection Theory.* Springer New York, 1998.

[GP99] T. Graber and R. Pandharipande. Localization of virtual classes. *Invent. Math.*, 135:487–518, 1999.

[Har77] Robin Hartshorne. *Algebraic geometry.* Springer-Verlag, New York-Heidelberg, 1977.

[Li18] Kezheng Li. *Group Schemes and Their Actions (in Chinese)*. Tsinghua University Press, 2018.

[Ric22] Andrea Ricolfi. *An Invitation to Modern Enumerative Geometry.* Springer Cham, 2022.