057M

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1. Introduction

In this chapter, we discuss some advanced results on flat modules and flat morphisms of schemes and applications. Most of the results on flatness can be found in the paper [GR71] by Raynaud and Gruson.

Before reading this chapter we advise the reader to take a look at the following results (this list also serves as a pointer to previous results):

1. General discussion on flat modules in Algebra, Section 38.
2. The relationship between Tor-groups and flatness, see Algebra, Section 74.
3. Criteria for flatness, see Algebra, Section 98 (Noetherian case), Algebra, Section 100 (Artinian case), Algebra, Section 127 (non-Noetherian case), and finally More on Morphisms, Section 16.
4. Generic flatness, see Algebra, Section 117 and Morphisms, Section 26.
5. Openness of the flat locus, see Algebra, Section 128 and More on Morphisms, Section 15.
6. Flattening, see More on Algebra, Sections 16, 17, 18, 19, and 20.

As applications of the material on flatness we discuss the following topics: a non-Noetherian version of Grothendieck’s existence theorem, blowing up and flatness, Nagata’s theorem on compactifications, the h topology, blow up squares and descent, weak normalization, descent of vector bundles in positive characteristic, and the local structure of perfect complexes in the h topology.

2. Lemmas on étale localization

In this section we list some lemmas on étale localization which will be useful later in this chapter. Please skip this section on a first reading.

**Lemma 2.1.** Let $i : Z \to X$ be a closed immersion of affine schemes. Let $Z' \to Z$ be an étale morphism with $Z'$ affine. Then there exists an étale morphism $X' \to X$ with $X'$ affine such that $Z' \cong Z \times_X X'$ as schemes over $Z$.

**Proof.** See Algebra, Lemma 142.10. □

**Lemma 2.2.** Let

\[
\begin{array}{ccccc}
X & \leftarrow & X' \\
\downarrow & & \downarrow \\
S & \leftarrow & S'
\end{array}
\]
be a commutative diagram of schemes with $X' \to X$ and $S' \to S$ étale. Let $s' \in S'$ be a point. Then

$$X' \times_{S'} \text{Spec}(\mathcal{O}_{S', s'}) \to X \times_{S} \text{Spec}(\mathcal{O}_{S', s'})$$

is étale.

**Proof.** This is true because $X' \to X_{S'}$ is étale as a morphism of schemes étale over $X$, see Morphisms, Lemma 34.18 and the base change of an étale morphism is étale, see Morphisms, Lemma 34.4. □

**Lemma 2.3.** Let $X \to T \to S$ be morphisms of schemes with $T \to S$ étale. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module. Let $x \in X$ be a point. Then

$$\mathcal{F} \text{ flat over } S \text{ at } x \iff \mathcal{F} \text{ flat over } T \text{ at } x$$

In particular $\mathcal{F}$ is flat over $S$ if and only if $\mathcal{F}$ is flat over $T$.

**Proof.** As an étale morphism is a flat morphism (see Morphisms, Lemma 34.12) the implication “$\Rightarrow$” follows from Algebra, Lemma 38.4. For the converse assume that $\mathcal{F}$ is flat at $x$ over $S$. Denote $\tilde{x} \in X \times S T$ the point lying over $x$ in $X$ and over the image of $x$ in $T$ in $T$. Then $(X \times_S T \to X)^* \mathcal{F}$ is flat at $\tilde{x}$ over $T$ via $\text{pr}_2 : X \times_S T \to T$, see Morphisms, Lemma 24.7. The diagonal $\Delta_{T/S} : T \to T \times_S T$ is an open immersion; combine Morphisms, Lemmas 33.13 and 34.5. So $X$ is identified with open subscheme of $X \times S T$, the restriction of $\text{pr}_2$ to this open is the given morphism $X \to T$, the point $\tilde{x}$ corresponds to the point $x$ in this open, and $(X \times_S T \to X)^* \mathcal{F}$ restricted to this open is $\mathcal{F}$. Whence we see that $\mathcal{F}$ is flat at $x$ over $T$. □

**Lemma 2.4.** Let $T \to S$ be an étale morphism. Let $t \in T$ with image $s \in S$. Let $M$ be a $\mathcal{O}_{T, t}$-module. Then

$$M \text{ flat over } \mathcal{O}_{S, s} \iff M \text{ flat over } \mathcal{O}_{h, S, s}.$$ 

**Proof.** We may replace $S$ by an affine neighbourhood of $s$ and after that $T$ by an affine neighbourhood of $t$. Set $\mathcal{F} = (\text{Spec}(\mathcal{O}_{T, t}) \to T)_* M$. This is a quasi-coherent sheaf (see Schemes, Lemma 24.1 or argue directly) on $T$ whose stalk at $t$ is $M$ (details omitted). Apply Lemma 2.3. □

**Lemma 2.5.** Let $S$ be a scheme and $s \in S$ a point. Denote $\mathcal{O}^{h}_{S, s}$ (resp. $\mathcal{O}^{th}_{S, s}$) the henselization (resp. strict henselization), see Algebra, Definition 151.3 Let $M^{th}$ be a $\mathcal{O}^{th}_{S, s}$-module. The following are equivalent

1. $M^{sh}$ is flat over $\mathcal{O}_{S, s}$,
2. $M^{sh}$ is flat over $\mathcal{O}^{h}_{S, s}$, and
3. $M^{sh}$ is flat over $\mathcal{O}^{h}_{S, s}$.

If $M^{sh} = M^{h} \otimes_{\mathcal{O}_{S, s}} \mathcal{O}^{h}_{S, s}$ this is also equivalent to

4. $M^{h}$ is flat over $\mathcal{O}_{S, s}$, and
5. $M^{h}$ is flat over $\mathcal{O}^{h}_{S, s}$.

If $M^{h} = M \otimes_{\mathcal{O}_{S, s}} \mathcal{O}^{h}_{S, s}$ this is also equivalent to

6. $M$ is flat over $\mathcal{O}_{S, s}$.
Proof. By More on Algebra, Lemma 44.1 the local ring maps \( \mathcal{O}_{S, s} \to \mathcal{O}_{S, s}^h \to \mathcal{O}_{S, s}^{sh} \) are faithfully flat. Hence (3) \( \Rightarrow \) (2) \( \Rightarrow \) (1) and (5) \( \Rightarrow \) (4) follow from Algebra, Lemma 38.4. By faithful flatness the equivalences (6) \( \Leftrightarrow \) (5) and (5) \( \Leftrightarrow \) (3) follow from Algebra, Lemma 38.8. Thus it suffices to show that (1) \( \Rightarrow \) (2) \( \Rightarrow \) (3) and (4) \( \Rightarrow \) (5). To prove these we may assume \( S \) is an affine scheme.

Assume (1). By Lemma 2.4 we see that \( M^{sh} \) is flat over \( T, t \) for any étale neighbourhood \((T, t) \to (S, s)\). Since \( \mathcal{O}_{S, s}^h \) and \( \mathcal{O}_{S, s}^{sh} \) are directed colimits of local rings of the form \( \mathcal{O}_{T, t} \) (see Algebra, Lemmas 151.7 and 151.13) we conclude that \( M^{sh} \) is flat over \( \mathcal{O}_{S, s}^h \) and \( \mathcal{O}_{S, s}^{sh} \) by Algebra, Lemma 38.6. Thus (1) implies (2) and (3). Of course this implies also (2) \( \Rightarrow \) (3) by replacing \( \mathcal{O}_{S, s} \) by \( \mathcal{O}_{S, s}^h \). The same argument applies to prove (4) \( \Rightarrow \) (5). \( \square \)

Lemma 2.6. Let \( S \) be a scheme and \( s \in S \) a point. Denote \( \mathcal{O}_{S, s}^h \) (resp. \( \mathcal{O}_{S, s}^{sh} \)) the henselization (resp. strict henselization), see Algebra, Definition 151.3. Let \( M^{sh} \) be an object of \( D(\mathcal{O}_{S, s}^{sh}) \). Let \( a, b \in \mathbb{Z} \). The following are equivalent

1. \( M^{sh} \) has tor amplitude in \([a, b]\) over \( \mathcal{O}_{S, s} \),
2. \( M^{sh} \) has tor amplitude in \([a, b]\) over \( \mathcal{O}_{S, s}^h \), and
3. \( M^{sh} \) has tor amplitude in \([a, b]\) over \( \mathcal{O}_{S, s}^{sh} \).

If \( M^{sh} = M^h \otimes_{\mathcal{O}_{S, s}^h} \mathcal{O}_{S, s}^{sh} \) for \( M^h \in D(\mathcal{O}_{S, s}^h) \) this is also equivalent to

4. \( M^h \) has tor amplitude in \([a, b]\) over \( \mathcal{O}_{S, s} \), and
5. \( M^h \) has tor amplitude in \([a, b]\) over \( \mathcal{O}_{S, s}^h \).

If \( M^h = M \otimes_{\mathcal{O}_{S, s}} \mathcal{O}_{S, s}^h \) for \( M \in D(\mathcal{O}_{S, s}) \) this is also equivalent to

6. \( M \) has tor amplitude in \([a, b]\) over \( \mathcal{O}_{S, s} \).

Proof. By More on Algebra, Lemma 44.1 the local ring maps \( \mathcal{O}_{S, s} \to \mathcal{O}_{S, s}^h \to \mathcal{O}_{S, s}^{sh} \) are faithfully flat. Hence (3) \( \Rightarrow \) (2) \( \Rightarrow \) (1) and (5) \( \Rightarrow \) (4) follow from More on Algebra, Lemma 63.11. By faithful flatness the equivalences (6) \( \Leftrightarrow \) (5) and (5) \( \Leftrightarrow \) (3) follow from More on Algebra, Lemma 63.17. Thus it suffices to show that (1) \( \Rightarrow \) (3), (2) \( \Rightarrow \) (3), and (4) \( \Rightarrow \) (5).

Assume (1). In particular \( M^{sh} \) has vanishing cohomology in degrees \(< a \) and \( > b \). Hence we can represent \( M^{sh} \) by a complex \( P^\bullet \) of free \( \mathcal{O}_{X, x} \)-modules with \( P^i = 0 \) for \( i > b \) (see for example the very general Derived Categories, Lemma 15.4). Note that \( P^n \) is flat over \( \mathcal{O}_{S, s} \) for all \( n \). Consider \( \text{Coker}(d^n_{P}^{-1}) \). By More on Algebra, Lemma 63.2 this is a flat \( \mathcal{O}_{S, s} \)-module. Hence by Lemma 2.5 this is a flat \( \mathcal{O}_{S, s}^{sh} \)-module. Thus \( \tau_{\geq a}P^\bullet \) is a complex of flat \( \mathcal{O}_{S, s}^{sh} \)-modules representing \( M^{sh} \) in \( D(\mathcal{O}_{S, s}^{sh}) \), and we find that \( M^{sh} \) has tor amplitude in \([a, b]\), see More on Algebra, Lemma 63.3. Thus (1) implies (3). Of course this implies also (2) \( \Rightarrow \) (3) by replacing \( \mathcal{O}_{S, s} \) by \( \mathcal{O}_{S, s}^h \). The same argument applies to prove (4) \( \Rightarrow \) (5). \( \square \)

Lemma 2.7. Let \( g : T \to S \) be a finite flat morphism of schemes. Let \( \mathcal{G} \) be a quasi-coherent \( \mathcal{O}_T \)-module. Let \( t \in T \) be a point with image \( s \in S \). Then

\[ t \in \text{WeakAss}(g^*\mathcal{G}) \Leftrightarrow s \in \text{WeakAss}(\mathcal{G}) \]

Proof. The implication \( \leftarrow \) follows immediately from Divisors, Lemma 6.4. Assume \( t \in \text{WeakAss}(g^*\mathcal{G}) \). Let \( \text{Spec}(A) \subset S \) be an affine open neighbourhood of \( s \). Let \( \mathcal{G} \) be the quasi-coherent sheaf associated to the \( A \)-module \( M \). Let \( p \subset A \) be the
prime ideal corresponding to $s$. As $g$ is finite flat we have $g^{-1}(\text{Spec}(A)) = \text{Spec}(B)$ for some finite flat $A$-algebra $B$. Note that $g^*\mathcal{G}$ is the quasi-coherent $\mathcal{O}_{\text{Spec}(B)}$-module associated to the $B$-module $M \otimes_A B$ and $g_*g^*\mathcal{G}$ is the quasi-coherent $\mathcal{O}_{\text{Spec}(A)}$-module associated to the $A$-module $M \otimes_A B$. By Algebra, Lemma 27.5 we have $B_p \cong A_p^{\oplus n}$ for some integer $n \geq 0$. Note that $n \geq 1$ as we assumed there exists at least one point of $T$ lying over $s$. Hence we see by looking at stalks that 

$$s \in \text{WeakAss}(\mathcal{G}) \Leftrightarrow s \in \text{WeakAss}(g_*g^*\mathcal{G}).$$

Now the assumption that $t \in \text{WeakAss}(g^*\mathcal{G})$ implies that $s \in \text{WeakAss}(g_*g^*\mathcal{G})$ by Divisors, Lemma 6.3 and hence by the above $s \in \text{WeakAss}(\mathcal{G})$. \hfill $\square$

**Lemma 2.8.** Let $h : U \to S$ be an étale morphism of schemes. Let $\mathcal{G}$ be a quasi-coherent $\mathcal{O}_S$-module. Let $u \in U$ be a point with image $s \in S$. Then

$$u \in \text{WeakAss}(h^*\mathcal{G}) \Leftrightarrow s \in \text{WeakAss}(\mathcal{G}).$$

**Proof.** After replacing $S$ and $U$ by affine neighbourhoods of $s$ and $u$ we may assume that $g$ is a standard étale morphism of affines, see Morphisms, Lemma 34.14. Thus we may assume $S = \text{Spec}(A)$ and $X = \text{Spec}(A[x, 1/g]/(f))$, where $f$ is monic and $f'$ is invertible in $A[x, 1/g]$. Note that $A[x, 1/g]/(f) = (A[x]/(f))_g$ is also the localization of the finite free $A$-algebra $A[x]/(f)$. Hence we may think of $U$ as an open subscheme of the scheme $T = \text{Spec}(A[x]/(f))$ which is finite locally free over $S$. This reduces us to Lemma 2.7 above. \hfill $\square$

**Lemma 2.9.** Let $S$ be a scheme and $s \in S$ a point. Denote $\mathcal{O}_{S,s}^h$ (resp. $\mathcal{O}_{S,s}^{sh}$) the henselization (resp. strict henselization), see Algebra, Definition 151.3. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_S$-module. The following are equivalent

1. $s$ is a weakly associated point of $\mathcal{F}$,
2. $\mathfrak{m}_s$ is a weakly associated prime of $\mathcal{F}_s$,
3. $\mathfrak{m}_s^h$ is a weakly associated prime of $\mathcal{F}_s \otimes_{\mathcal{O}_S} \mathcal{O}_{S,s}^h$, and
4. $\mathfrak{m}_s^{sh}$ is a weakly associated prime of $\mathcal{F}_s \otimes_{\mathcal{O}_S} \mathcal{O}_{S,s}^{sh}$.

**Proof.** The equivalence of (1) and (2) is the definition, see Divisors, Definition 5.1. The implications (2) $\Rightarrow$ (3) $\Rightarrow$ (4) follows from Divisors, Lemma 6.4 applied to the flat (More on Algebra, Lemma 44.1) morphisms

$$\text{Spec}(\mathcal{O}_{S,s}^h) \to \text{Spec}(\mathcal{O}_{S,s}^h) \to \text{Spec}(\mathcal{O}_{S,s})$$

and the closed points. To prove (4) $\Rightarrow$ (2) we may replace $S$ by an affine neighbourhood. Suppose that $x \in \mathcal{F}_s \otimes_{\mathcal{O}_S} \mathcal{O}_{S,s}^{sh}$ is an element whose annihilator has radical equal to $\mathfrak{m}_s^{sh}$. (See Algebra, Lemma 65.2) Since $\mathcal{O}_{S,s}^{sh}$ is equal to the limit of $\mathcal{O}_{U,u}$ over étale neighbourhoods $f : (U, u) \to (S, s)$ by Algebra, Lemma 151.13 we may assume that $x$ is the image of some $x' \in \mathcal{F}_s \otimes_{\mathcal{O}_S} \mathcal{O}_{U,u}$. The local ring map $\mathcal{O}_{U,u} \to \mathcal{O}_{S,s}^{sh}$ is faithfully flat (as it is the strict henselization), hence universally injective (Algebra, Lemma 81.11). It follows that the annihilator of $x'$ is the inverse image of the annihilator of $x$. Hence the radical of this annihilator is equal to $\mathfrak{m}_s$. Thus $u$ is a weakly associated point of $f^*\mathcal{F}$. By Lemma 2.8 we see that $s$ is a weakly associated point of $\mathcal{F}$. \hfill $\square$
3. The local structure of a finite type module

057P The key technical lemma that makes a lot of the arguments in this chapter work is the geometric Lemma 3.2.

057Q Lemma 3.1. Let \( f : X \to S \) be a finite type morphism of affine schemes. Let \( \mathcal{F} \) be a finite type quasi-coherent \( \mathcal{O}_X \)-module. Let \( x \in X \) with image \( s = f(x) \) in \( S \). Set \( \mathcal{F}_s = \mathcal{F}|_{X_s} \). Then there exist a closed immersion \( i : Z \to X \) of finite presentation, and a quasi-coherent finite type \( \mathcal{O}_Z \)-module \( \mathcal{G} \) such that \( i_* \mathcal{G} = \mathcal{F} \) and \( Z_s = \text{Supp}(\mathcal{F}_s) \).

Proof. Say the morphism \( f : X \to S \) is given by the ring map \( A \to B \) and that \( \mathcal{F} \) is the quasi-coherent sheaf associated to the \( B \)-module \( M \). By Morphisms, Lemma 14.2 we know that \( A \to B \) is a finite type ring map, and by Properties, Lemma 16.1 we know that \( M \) is a finite \( B \)-module. In particular the support of \( \mathcal{F} \) is the closed subscheme of \( \text{Spec}(B) \) cut out by the annihilator \( I = \{ x \in B \mid x \cdot m = 0 \ \forall m \in M \} \) of \( M \), see Algebra, Lemma 39.5. Let \( q \subset B \) be the prime ideal corresponding to \( x \) and let \( p \subset A \) be the prime ideal corresponding to \( s \). Note that \( X_s = \text{Spec}(B \otimes_A \kappa(p)) \) and that \( \mathcal{F}_s \) is the quasi-coherent sheaf associated to the \( B \otimes_A \kappa(p) \) module \( M \otimes_A \kappa(p) \). By Morphisms, Lemma 5.3 the support of \( \mathcal{F}_s \) is equal to \( V(I(B \otimes_A \kappa(p))) \). Since \( B \otimes_A \kappa(p) \) is of finite type over \( \kappa(p) \) there exist finitely many elements \( f_1, \ldots, f_m \in I \) such that \[ I(B \otimes_A \kappa(p)) = (f_1, \ldots, f_m)(B \otimes_A \kappa(p)). \]

Denote \( i : Z \to X \) the closed subscheme cut out by \( (f_1, \ldots, f_m) \), in a formula \( Z = \text{Spec}(B/(f_1, \ldots, f_m)) \). Since \( M \) is annihilated by \( I \) we can think of \( M \) as an \( B/(f_1, \ldots, f_m) \)-module. In other words, \( \mathcal{F} \) is the pushforward of a finite type module on \( Z \). As \( Z_s = \text{Supp}(\mathcal{F}_s) \) by construction, this proves the lemma.

057S Lemma 3.2. Let \( f : X \to S \) be morphism of schemes which is locally of finite type. Let \( \mathcal{F} \) be a finite type quasi-coherent \( \mathcal{O}_X \)-module. Let \( x \in X \) with image \( s = f(x) \) in \( S \). Set \( \mathcal{F}_s = \mathcal{F}|_{X_s} \) and \( n = \dim_s(\text{Supp}(\mathcal{F}_s)) \). Then we can construct

1. elementary étale neighbourhoods \( g : (X', x') \to (X, x) \), \( e : (S', s') \to (S, s) \),
2. a commutative diagram

\[
\begin{array}{ccc}
X & \xleftarrow{g} & X' & \xleftarrow{i} & Z' \\
\downarrow{f} & & \downarrow{\pi} & & \downarrow{h} \\
S & \xleftarrow{e} & S' & & \\
\end{array}
\]

3. a point \( z' \in Z' \) with \( i(z') = x', y' = \pi(z'), h(y') = s' \),
4. a finite type quasi-coherent \( \mathcal{O}_{Z'} \)-module \( \mathcal{G} \),

such that the following properties hold

1. \( X', Z', Y', S' \) are affine schemes,
2. \( i \) is a closed immersion of finite presentation,
3. \( i_* (\mathcal{G}) \cong g^* \mathcal{F} \),
4. \( \pi \) is finite and \( \pi^{-1}(\{ y' \}) = \{ z' \} \),
5. the extension \( \kappa(s') \subset \kappa(y') \) is purely transcendental,
(6) $h$ is smooth of relative dimension $n$ with geometrically integral fibres.

**Proof.** Let $V \subset S$ be an affine neighbourhood of $s$. Let $U \subset f^{-1}(V)$ be an affine neighbourhood of $x$. Then it suffices to prove the lemma for $f|_U : U \to V$ and $\mathcal{F}|_U$. Hence in the rest of the proof we assume that $X$ and $S$ are affine.

First, suppose that $X_s = \text{Supp}(\mathcal{F}_s)$, in particular $n = \dim_x(X_s)$. Apply More on Morphisms, Lemmas 42.2 and 42.3. This gives us a commutative diagram

$$
\begin{array}{ccc}
X & \xrightarrow{g} & X' \\
\downarrow & & \downarrow \pi \\
Y' & \xrightarrow{h} & S' \\
\downarrow & & \downarrow e \\
S & \xleftarrow{i} & S'
\end{array}
$$

and point $x' \in X'$. We set $Z' = X'$, $i = \text{id}$, and $\mathcal{G} = g^*\mathcal{F}$ to obtain a solution in this case.

In general choose a closed immersion $Z \to X$ and a sheaf $\mathcal{G}$ on $Z$ as in Lemma 3.1. Applying the result of the previous paragraph to $Z \to S$ and $\mathcal{G}$ we obtain a diagram

$$
\begin{array}{ccc}
X & \xleftarrow{g} & Z' \\
\downarrow & & \downarrow \pi \\
Y' & \xrightarrow{h} & S' \\
\downarrow & & \downarrow e \\
S & \xrightarrow{f} & S'
\end{array}
$$

and point $z' \in Z'$ satisfying all the required properties. We will use Lemma 2.1 to embed $Z'$ into a scheme étale over $X$. We cannot apply the lemma directly as we want $X'$ to be a scheme over $S'$. Instead we consider the morphisms

$$
Z' \longrightarrow Z \times_S S' \longrightarrow X \times_S S'
$$

The first morphism is étale by Morphisms, Lemma 34.18. The second is a closed immersion as a base change of a closed immersion. Finally, as $X$, $S$, $S'$, $Z$, $Z'$ are all affine we may apply Lemma 2.1 to get an étale morphism of affine schemes $X' \to X \times_S S'$ such that

$$
Z' = (Z \times_S S') \times_{(X \times_S S')} X' = Z \times_X X'.
$$

As $Z \to X$ is a closed immersion of finite presentation, so is $Z' \to X'$. Let $x' \in X'$ be the point corresponding to $z' \in Z'$. Then the completed diagram

$$
\begin{array}{ccc}
X & \xleftarrow{i} & Z' \\
\downarrow & & \downarrow \pi \\
Y' & \xrightarrow{h} & S' \\
\downarrow & & \downarrow e \\
S & \xrightarrow{e} & S'
\end{array}
$$
Lemma 3.3. Assumptions and notation as in Lemma 3.2. If \( f \) is locally of finite presentation then \( \pi \) is of finite presentation. In this case the following are equivalent

\begin{enumerate}
  \item \( F \) is an \( \mathcal{O}_X \)-module of finite presentation in a neighbourhood of \( x \),
  \item \( G \) is an \( \mathcal{O}_{Z'} \)-module of finite presentation in a neighbourhood of \( z' \), and
  \item \( \pi_*G \) is an \( \mathcal{O}_{Y'} \)-module of finite presentation in a neighbourhood of \( y' \).
\end{enumerate}

Still assuming \( f \) locally of finite presentation the following are equivalent to each other

\begin{enumerate}
  \item \( F \) is an \( \mathcal{O}_{X,x} \)-module of finite presentation in a neighbourhood of \( x \),
  \item \( G \) is an \( \mathcal{O}_{Z',z'} \)-module of finite presentation in a neighbourhood of \( z' \), and
  \item \( \pi_*G \) is an \( \mathcal{O}_{Y',y'} \)-module of finite presentation in a neighbourhood of \( y' \).
\end{enumerate}

**Proof.** Assume \( f \) locally of finite presentation. Then \( Z' \to S \) is locally of finite presentation as a composition of such, see Morphisms, Lemma 20.3. Note that \( Y' \to S \) is also locally of finite presentation as a composition of a smooth and an étale morphism. Hence Morphisms, Lemma 20.11 implies \( \pi \) is locally of finite presentation. Since \( \pi \) is finite we conclude that it is also separated and quasi-compact, hence \( \pi \) is actually of finite presentation.

To prove the equivalence of (1), (2), and (3) we also consider: (4) \( g^*F \) is a \( \mathcal{O}_{X'} \)-module of finite presentation in a neighbourhood of \( x' \). The pullback of a module of finite presentation is of finite presentation, see Modules, Lemma 11.4. Hence (1) \( \Rightarrow \) (4). The étale morphism \( g \) is open, see Morphisms, Lemma 34.13. Hence for any open neighbourhood \( U' \subset X' \) of \( x' \) the map \( \{U' \to g(U')\} \) is an étale covering. Thus (4) \( \Rightarrow \) (1) by Descent, Lemma 7.3. Using Descent, Lemma 7.10 and some easy topological arguments (see More on Morphisms, Lemma 42.4) we see that (4) \( \Leftrightarrow \) (2) \( \Leftrightarrow \) (3).

To prove the equivalence of (a), (b), (c) consider the ring maps

\[ \mathcal{O}_{X,x} \to \mathcal{O}_{X',x'} \to \mathcal{O}_{Z',z'} \leftarrow \mathcal{O}_{Y',y'}. \]

The first ring map is faithfully flat. Hence \( F_x \) is of finite presentation over \( \mathcal{O}_{X,x} \) if and only if \( g^*F_{x'} \) is of finite presentation over \( \mathcal{O}_{X',x'} \), see Algebra, Lemma 82.2.

The second ring map is surjective (hence finite) and finitely presented by assumption, hence \( g^*F_{x'} \) is of finite presentation over \( \mathcal{O}_{X',x'} \) if and only if \( G_{z'} \) is of finite presentation over \( \mathcal{O}_{Z',z'} \), see Algebra, Lemma 35.23. Because \( \pi \) is finite, of finite presentation, and \( \pi^{-1}(\{y'\}) = \{x'\} \) the ring homomorphism \( \mathcal{O}_{Y',y'} \leftarrow \mathcal{O}_{Z',z'} \) is finite and of finite presentation, see More on Morphisms, Lemma 42.4. Hence \( G_{z'} \) is of finite presentation over \( \mathcal{O}_{Z',z'} \) if and only if \( \pi_*G_{y'} \) is of finite presentation over \( \mathcal{O}_{Y',y'} \), see Algebra, Lemma 35.23. \( \square \)

Lemma 3.4. Assumptions and notation as in Lemma 3.2. The following are equivalent

\begin{enumerate}
  \item \( F \) is flat over \( S \) in a neighbourhood of \( x \),
  \item \( G \) is flat over \( S' \) in a neighbourhood of \( z' \), and
  \item \( \pi_*G \) is flat over \( S' \) in a neighbourhood of \( y' \).
\end{enumerate}

The following are equivalent also

\begin{enumerate}
  \item \( F_x \) is flat over \( \mathcal{O}_{S,s} \),
  \item \( G_{z'} \) is flat over \( \mathcal{O}_{S',s'} \), and
\end{enumerate}
(c) \((\pi_*G)_{y'}\) is flat over \(O_{S',s'}\).

**Proof.** To prove the equivalence of (1), (2), and (3) we also consider: (4) \(g^*F\) is flat over \(S\) in a neighbourhood of \(x'\). We will use Lemma 24.13 to equate flatness over \(S\) and \(S'\) without further mention. The étale morphism \(g\) is flat and open, see Morphisms, Lemma 34.13. Hence for any open neighbourhood \(U' \subset X'\) of \(x'\), the image \(g(U')\) is an open neighbourhood of \(x\) and the map \(U' \to g(U')\) is surjective and flat. Thus (4) \(\Leftrightarrow\) (1) by Morphisms, Lemma 24.13. Note that

\[
\Gamma(X', g^*F) = \Gamma(Z', G) = \Gamma(Y', \pi_*G)
\]

Hence the flatness of \(g^*F\), \(G\) and \(\pi_*G\) over \(S'\) are all equivalent (this uses that \(X', Z', Y', \) and \(S'\) are all affine). Some omitted topological arguments (compare More on Morphisms, Lemma 42.4) regarding affine neighbourhoods now show that (4) \(\Leftrightarrow\) (2) \(\Leftrightarrow\) (3).

To prove the equivalence of (a), (b), (c) consider the commutative diagram of local ring maps

\[
\begin{array}{ccccccccc}
O_{X',x'} & \xrightarrow{i} & O_{Z',z'} & \xleftarrow{\alpha} & O_{Y',y'} & \xrightarrow{\beta} & O_{S',s'} \\
\gamma & & & & \alpha & & \beta \\
O_{X,x} & \xleftarrow{\varphi} & O_{Z,z} & \xrightarrow{\epsilon} & O_{S,s}
\end{array}
\]

We will use Lemma 24.13 to equate flatness over \(O_{S,s}\) and \(O_{S',s'}\) without further mention. The map \(\gamma\) is faithfully flat. Hence \(F_x\) is flat over \(O_{S,s}\) if and only if \(g^*F_{x'}\) is flat over \(O_{S',s'}\), see Algebra, Lemma 38.9. As \(O_{S',s'}\)-modules the modules \(g^*F_{x'}, G_{z'}, \) and \(\pi_*G_{y'}\) are all isomorphic, see More on Morphisms, Lemma 42.4. This finishes the proof. \(\square\)

## 4. One step dévissage

In this section we explain what is a one step dévissage of a module. A one step dévissage exist étale locally on base and target. We discuss base change, Zariski shrinking and étale localization of a one step dévissage.

**Definition 4.1.** Let \(S\) be a scheme. Let \(X\) be locally of finite type over \(S\). Let \(\mathcal{F}\) be a quasi-coherent \(O_X\)-module of finite type. Let \(s \in S\) be a point. A one step dévissage of \(\mathcal{F}/X/S\) over \(s\) is given by morphisms of schemes over \(S\)

\[
\begin{array}{ccc}
X & \xrightarrow{i} & Z & \xrightarrow{\pi} & Y
\end{array}
\]

and a quasi-coherent \(O_Z\)-module \(\mathcal{G}\) of finite type such that

1. \(X, S, Z\) and \(Y\) are affine,
2. \(i\) is a closed immersion of finite presentation,
3. \(\mathcal{F} \cong i_*\mathcal{G}\),
4. \(\pi\) is finite, and
5. the structure morphism \(Y \to S\) is smooth with geometrically irreducible fibres of dimension \(\dim({\text{Supp}}(\mathcal{F}_s))\).

In this case we say \((Z,Y,i,\pi,\mathcal{G})\) is a one step dévissage of \(\mathcal{F}/X/S\) over \(s\).

Note that such a one step dévissage can only exist if \(X\) and \(S\) are affine. In the definition above we only require \(X\) to be (locally) of finite type over \(S\) and we continue working in this setting below. In [CRII] the authors use consistently the
setup where \( X \rightarrow S \) is locally of finite presentation and \( \mathcal{F} \) quasi-coherent \( \mathcal{O}_X \)-module of finite type. The advantage of this choice is that it “makes sense” to ask for \( \mathcal{F} \) to be of finite presentation as an \( \mathcal{O}_X \)-module, whereas in our setting it “does not make sense”. Please see More on Morphisms, Section 50 for a discussion; the observations made there show that in our setup we may consider the condition of “locally of finite presentation relative to \( S \)”, and we could work consistently with this notion. Instead however, we will rely on the results of Lemma 3.3 and the observations in Remark 6.3 to deal with this issue in an ad hoc fashion whenever it comes up.

**Definition 4.2.** Let \( S \) be a scheme. Let \( X \) be locally of finite type over \( S \). Let \( \mathcal{F} \) be a quasi-coherent \( \mathcal{O}_X \)-module of finite type. Let \( x \in X \) be a point with image \( s \) in \( S \). A one step dévissage of \( \mathcal{F}/X/S \) at \( x \) is a system \((Z,Y,i,\pi,\mathcal{G},z,y)\), where \((Z,Y,i,\pi,\mathcal{G})\) is a one step dévissage of \( \mathcal{F}/X/S \) over \( s \) and

1. \( \dim_x(\text{Supp}(\mathcal{F}_s)) = \dim(\text{Supp}(\mathcal{F}_s)) \),
2. \( z \in Z \) is a point with \( i(z) = x \) and \( \pi(z) = y \),
3. we have \( \pi^{-1}(\{y\}) = \{z\} \),
4. the extension \( \kappa(s) \subset \kappa(y) \) is purely transcendental.

A one step dévissage of \( \mathcal{F}/X/S \) at \( x \) can only exist if \( X \) and \( S \) are affine. Condition (1) assures us that \( Y \rightarrow S \) has relative dimension equal to \( \dim_x(\text{Supp}(\mathcal{F}_s)) \) via condition (5) of Definition 4.1.

**Lemma 4.3.** Let \( f : X \rightarrow S \) be morphism of schemes which is locally of finite type. Let \( \mathcal{F} \) be a finite type quasi-coherent \( \mathcal{O}_X \)-module. Let \( x \in X \) with image \( s = f(x) \) in \( S \). Then there exists a commutative diagram of pointed schemes

\[
\begin{array}{ccc}
(X,x) & \xrightarrow{g} & (X',x') \\
\downarrow f & & \downarrow \\
(S,s) & \xleftarrow{g'} & (S',s')
\end{array}
\]

such that \((S',s') \rightarrow (S,s)\) and \((X',x') \rightarrow (X,x)\) are elementary étale neighbourhoods, and such that \( g^*\mathcal{F}/X'/S' \) has a one step dévissage at \( x' \).

**Proof.** This is immediate from Definition 4.2 and Lemma 3.2.

**Lemma 4.4.** Let \( S, X, \mathcal{F}, s \) be as in Definition 4.1. Let \((Z,Y,i,\pi,\mathcal{G})\) be a one step dévissage of \( \mathcal{F}/X/S \) over \( s \). Let \((S',s') \rightarrow (S,s)\) be any morphism of pointed schemes. Given this data let \( X',Z',Y',i',\pi' \) be the base changes of \( X,Z,Y,i,\pi \) via \( S' \rightarrow S \). Let \( \mathcal{F}' \) be the pullback of \( \mathcal{F} \) to \( X' \) and let \( \mathcal{G}' \) be the pullback of \( \mathcal{G} \) to \( Z' \). If \( S' \) is affine, then \((Z',Y',i',\pi',\mathcal{G}')\) is a one step dévissage of \( \mathcal{F}'/X'/S' \) over \( s' \).

**Proof.** Fibre products of affines are affine, see Schemes, Lemma 17.2. Base change preserves closed immersions, morphisms of finite presentation, finite morphisms, smooth morphisms, morphisms with geometrically irreducible fibres, and morphisms of relative dimension \( n \), see Morphisms, Lemmas 2.4, 20.4, 42.6, 32.5 and More on Morphisms, Lemma 25.2. We have \( i'^*\mathcal{G} \cong \mathcal{F}' \) because push-forward along the finite morphism \( i \) commutes with base change, see Cohomology of Schemes, Lemma 7.1. We have \( \dim(\text{Supp}(\mathcal{F}_s)) = \dim(\text{Supp}(\mathcal{F}'_{s'})) \) by Morphisms, Lemma 27.3 because

\[
\text{Supp}(\mathcal{F}_s) \times_S s' = \text{Supp}(\mathcal{F}'_{s'}).
\]
This proves the lemma. □

Lemma 4.5. Let \( S, X, F, x, s \) be as in Definition 4.2. Let \((Z, Y, i, \pi, G, z, y)\) be a one step dévissage of \( F/X/S \) at \( x \). Let \((S', s') \to (S, s)\) be a morphism of pointed schemes which induces an isomorphism \( \kappa(s) = \kappa(s') \). Let \((Z', Y', i', \pi', G')\) be as constructed in Lemma 4.4 and let \( x' \in X' \) (resp. \( z' \in Z', y' \in Y' \)) be the unique point mapping to both \( x \in X \) (resp. \( z \in Z, y \in Y \)) and \( s' \in S' \). If \( S' \) is affine, then \((Z', Y', i', \pi', G', z', y')\) is a one step dévissage of \( F'/X'/S' \) at \( x' \).

Proof. By Lemma 4.4 \((Z', Y', i', \pi', G')\) is a one step dévissage of \( F'/X'/S' \) over \( S' \). Properties (1) – (4) of Definition 4.2 hold for \((Z', Y', i', \pi', G', z', y')\) as the assumption that \( \kappa(s) = \kappa(s') \) insures that the fibres \( X'_s, Z'_s \), and \( Y'_s \) are isomorphic to \( X, Z_s \), and \( Y_s \).

Definition 4.6. Let \( S, X, F, x, s \) be as in Definition 4.2. Let \((Z, Y, i, \pi, G, z, y)\) be a one step dévissage of \( F/X/S \) at \( x \). Let us define a standard shrinking of this situation to be given by standard opens \( S' \subset S, X' \subset X, Z' \subset Z, \) and \( Y' \subset Y \) such that \( s \in S', x \in X', z \in Z', \) and \( y \in Y' \) and such that

\[
(Z', Y', i, Z'_s, \pi|Z'_s, G|Z'_s, z, y)
\]

is a one step dévissage of \( F|X'/X'/S' \) at \( x \).

Lemma 4.7. With assumption and notation as in Definition 4.6 we have:

1. If \( S' \subset S \) is a standard open neighbourhood of \( s \), then setting \( X' = X_{S'} \), \( Z' = Z_{S'} \) and \( Y' = Y_{S'} \) we obtain a standard shrinking.
2. Let \( W \subset Y \) be a standard open neighbourhood of \( y \). Then there exists a standard shrinking with \( Y' = W \times_S S' \).
3. Let \( U \subset X \) be an open neighbourhood of \( x \). Then there exists a standard shrinking with \( X' \subset U \).

Proof. Part (1) is immediate from Lemma 4.5 and the fact that the inverse image of a standard open under a morphism of affine schemes is a standard open, see Algebra, Lemma 16.4.

Let \( W \subset Y \) as in (2). Because \( Y \to S \) is smooth it is open, see Morphisms, Lemma 32.10 Therefore we can find a standard open neighbourhood \( S' \) of \( s \) contained in the image of \( W \). Then the fibres of \( W_{S'} \to S' \) are nonempty open subschemes of the fibres of \( Y \to S \) over \( S' \) and hence geometrically irreducible too. Setting \( Y' = W_{S'} \) and \( Z' = \pi^{-1}(Y') \) we see that \( Z' \subset Z \) is a standard open neighbourhood of \( z \). Let \( \overline{h} \in \Gamma(Z, \mathcal{O}_Z) \) be a function such that \( Z' = D(\overline{h}) \). As \( i : Z \to X \) is a closed immersion, we can find a function \( h \in \Gamma(X, \mathcal{O}_X) \) such that \( i^*(h) = \overline{h} \). Take \( X' = D(h) \subset X \). In this way we obtain a standard shrinking as in (2).

Let \( U \subset X \) be as in (3). We may after shrinking \( U \) assume that \( U \) is a standard open. By More on Morphisms, Lemma 42.4 there exists a standard open \( W \subset Y \) neighbourhood of \( y \) such that \( \pi^{-1}(W) \subset i^{-1}(U) \). Apply (2) to get a standard shrinking \( X', S', Z', Y' \) with \( Y' = W_{S'} \). Since \( Z' \subset \pi^{-1}(W) \subset i^{-1}(U) \) we may replace \( X' \) by \( X' \cap U \) (still a standard open as \( U \) is also standard open) without violating any of the conditions defining a standard shrinking. Hence we win. □
Lemma 4.8. Let $S, X, \mathcal{F}, x, s$ be as in Definition 4.2. Let $(Z, Y, i, \pi, G, z, y)$ be a one step dévissage of $\mathcal{F}/X/S$ at $x$. Let

$$(Y, y) \xleftarrow{(Y', y')} \xrightarrow{(Y'', y'')} (S, s)$$

be a commutative diagram of pointed schemes such that the horizontal arrows are elementary étale neighbourhoods. Then there exists a commutative diagram

$$(X, x) \xleftarrow{(X'', x'')} \xrightarrow{(X', x')} (Z, z) \xleftarrow{(Z'', z'')} (S', s') \xrightarrow{(S'', s'')} (Y, y)$$

of pointed schemes with the following properties:

1. $(S'', s'') \to (S', s')$ is an elementary étale neighbourhood and the morphism $S'' \to S$ is the composition $S'' \to S' \to S$,
2. $Y''$ is an open subscheme of $Y' \times_S S''$,
3. $Z'' = Z \times_Y Y''$,
4. $(X'', x'') \to (X, x)$ is an elementary étale neighbourhood, and
5. $(Z'', Y'', i'', \pi'', G'', z'', y'')$ is a one step dévissage at $x''$ of the sheaf $\mathcal{F}''$.

Here $\mathcal{F}''$ (resp. $G''$) is the pullback of $\mathcal{F}$ (resp. $G$) via the morphism $X'' \to X$ (resp. $Z'' \to Z$) and $i'' : Z'' \to X''$ and $\pi'' : Z'' \to Y''$ are as in the diagram.

Proof. Let $(S'', s'') \to (S', s')$ be any elementary étale neighbourhood with $S''$ affine. Let $Y'' \subset Y' \times_S S''$ be any affine open neighbourhood containing the point $y'' = (y', s'')$. Then we obtain an affine $(Z'', z'')$ by (3). Moreover $Z_{S''} \to X_{S''}$ is a closed immersion and $Z'' \to Z_{S''}$ is an étale morphism. Hence Lemma 2.1 applies and we can find an étale morphism $X'' \to X_{S'}$ of affines such that $Z'' \cong X'' \times_{X_{S'}} Z_{S'}$. Denote $i'' : Z'' \to X''$ the corresponding closed immersion. Setting $x'' = y''(z'')$ we obtain a commutative diagram as in the lemma. Properties (1), (2), (3), and (4) hold by construction. Thus it suffices to show that (5) holds for a suitable choice of $(S'', s'') \to (S', s')$ and $Y''$.

We first list those properties which hold for any choice of $(S'', s'') \to (S', s')$ and $Y''$ as in the first paragraph. As we have $Z'' = X'' \times_X Z$ by construction we see that $i''_! G'' = F''$ (with notation as in the statement of the lemma), see Cohomology of Schemes, Lemma 5.1. Set $n = \dim(\text{Supp}(F_\pi)) = \dim_S(\text{Supp}(F_\pi))$. The morphism $Y'' \to S''$ is smooth of relative dimension $n$ (because $Y' \to S'$ is smooth of relative dimension $n$ as the composition $Y' \to Y_{S'} \to S'$ of an étale and smooth morphism of relative dimension $n$ and because base change preserves smooth morphisms of relative dimension $n$). We have $\kappa(y'') = \kappa(y)$ and $\kappa(s) = \kappa(s'')$ hence $\kappa(y'')$ is a purely transcendental extension of $\kappa(s'')$. The morphism of fibres $X_{s''} \to X_s$ is an étale morphism of affine schemes over $\kappa(s) = \kappa(s'')$ mapping the point $x''$ to the
point $x$ and pulling back $\mathcal{F}_s$ to $\mathcal{F}'_{s''}$. Hence

$$\dim(\text{Supp}(\mathcal{F}'_{s''})) = \dim(\text{Supp}(\mathcal{F}_s)) = n = \dim_x(\text{Supp}(\mathcal{F}_s)) = \dim_x''(\text{Supp}(\mathcal{F}'_{s''}))$$

because dimension is invariant under étale localization, see Descent, Lemma 18.2. As $\pi'' : Z'' \to Y''$ is the base change of $\pi$ we see that $\pi''$ is finite and as $\kappa(y) = \kappa(y'')$ we see that $\pi^{-1}(\{y''\}) = \{z''\}$.

At this point we have verified all the conditions of Definition 4.1 except we have not verified that $Y'' \to S''$ has geometrically irreducible fibres. Of course in general this is not going to be true, and it is at this point that we will use that $\kappa(s) \subset \kappa(y)$ is purely transcendental. Namely, let $T \subset Y'_{s'}$ be the irreducible component of $Y'_{s'}$ containing $y' = (y, s')$. Note that $T$ is an open subscheme of $Y'_{s'}$ as this is a smooth scheme over $\kappa(s')$. By Varieties, Lemma 7.4 we see that $T$ is geometrically connected because $\kappa(s') = \kappa(s)$ is algebraically closed in $\kappa(y') = \kappa(y)$. As $T$ is smooth we see that $T$ is geometrically irreducible. Hence More on Morphisms, Lemma 41.4 applies and we can find an elementary étale morphism $(S'', s'') \to (S', s')$ and an affine open $Y'' \subset Y'_{s''}$ such that all fibres of $Y'' \to S''$ are geometrically irreducible and such that $T = T_{s''}$. After shrinking (first $Y''$ and then $S''$) we may assume that both $Y''$ and $S''$ are affine. This finishes the proof of the lemma. $\square$

**Lemma 4.9.** Let $S$, $X$, $\mathcal{F}$, $s$ be as in Definition 4.1. Let $(Z, Y, i, \pi, \mathcal{G})$ be a one step dévissage of $\mathcal{F}/X/S$ over $s$. Let $\xi \in Y_s$ be the (unique) generic point. Then there exists an integer $r > 0$ and an $\mathcal{O}_Y$-module map

$$\alpha : \mathcal{O}_Y^\oplus r \rightarrow \pi_* \mathcal{G}$$

such that

$$\alpha : (\mathcal{O}_Y^\oplus r)_{\xi} \otimes_{\mathcal{O}_Y, \xi} \kappa(\xi)$$

is an isomorphism. Moreover, in this case we have

$$\dim(\text{Supp}(\text{Coker}(\alpha)_s)) < \dim(\text{Supp}(\mathcal{F}_s)).$$

**Proof.** By assumption the schemes $S$ and $Y$ are affine. Write $S = \text{Spec}(A)$ and $Y = \text{Spec}(B)$. As $\pi$ is finite the $\mathcal{O}_Y$-module $\pi_* \mathcal{G}$ is a finite type quasi-coherent $\mathcal{O}_Y$-module. Hence $\pi_* \mathcal{G} = \widetilde{N}$ for some finite $B$-module $N$. Let $p \subset B$ be the prime ideal corresponding to $\xi$. To obtain a set $r = \dim_{\kappa(p)} N \otimes_B \kappa(p)$ and pick $x_1, \ldots, x_r \in N$ which form a basis of $N \otimes_B \kappa(p)$. Take $\alpha : B^\oplus r \rightarrow N$ to be the map given by the formula $\alpha(b_1, \ldots, b_r) = \sum b_i x_i$. It is clear that $\alpha : (\mathcal{O}_Y^\oplus r) \rightarrow N \otimes_B \kappa(p)$ is an isomorphism as desired. Finally, suppose $\alpha$ is any map with this property. Then $N' = \text{Coker}(\alpha)$ is a finite $B$-module such that $N' \otimes \kappa(p) = 0$. By Nakayama’s lemma (Algebra, Lemma 19.1) we see that $N'_p = 0$. Since the fibre $Y_s$ is geometrically irreducible of dimension $n$ with generic point $\xi$ and since we have just seen that $\xi$ is not in the support of $\text{Coker}(\alpha)$ the last assertion of the lemma holds. $\square$

5. Complete dévissage

In this section we explain what is a complete dévissage of a module and prove that such exist. The material in this section is mainly bookkeeping.

**Definition 5.1.** Let $S$ be a scheme. Let $X$ be locally of finite type over $S$. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module of finite type. Let $s \in S$ be a point. A complete
dévissage of $\mathcal{F}/X/S$ over $s$ is given by a diagram

\[
\begin{array}{ccc}
X & \xleftarrow{i_1} & Z_1 \\
\downarrow{\pi_1} & & \downarrow{\pi_2} \\
Y_1 & \xleftarrow{i_2} & Z_2 \\
\downarrow{\pi_2} & & \downarrow{\pi_2} \\
Y_2 & \xleftarrow{i_3} & Z_3 \\
\downarrow{\pi_2} & & \downarrow{\pi_2} \\
& \cdots & \\
& \cdots & \\
& Y_n &
\end{array}
\]

of schemes over $S$, finite type quasi-coherent $\mathcal{O}_{Z_k}$-modules $\mathcal{G}_k$, and $\mathcal{O}_{Y_k}$-module maps
\[
\alpha_k : \mathcal{O}_{Y_k}^{\oplus r_k} \to \pi_{k,*}\mathcal{G}_k, \quad k = 1, \ldots, n
\]
satisfying the following properties:

1. $(Z_1, Y_1, i_1, \pi_1, \mathcal{G}_1)$ is a one step dévissage of $\mathcal{F}/X/S$ over $s$,
2. the map $\alpha_k$ induces an isomorphism
\[
\kappa(\xi_k)^{\oplus r_k} \to (\pi_{k,*}\mathcal{G}_k)_{\xi_k} \otimes_{\mathcal{O}_{Y_k}, \xi_k} \kappa(\xi_k)
\]
where $\xi_k \in (Y_k)_s$ is the unique generic point,
3. for $k = 2, \ldots, n$ the system $(Z_k, Y_k, i_k, \pi_k, \mathcal{G}_k)$ is a one step dévissage of $\text{Coker}(\alpha_{k-1})/Y_{k-1}/S$ over $s$,
4. $\text{Coker}(\alpha_n) = 0$.

In this case we say that $(Z_k, Y_k, i_k, \pi_k, \mathcal{G}_k, \alpha_k)_{k=1, \ldots, n}$ is a complete dévissage of $\mathcal{F}/X/S$ over $s$.

**Definition 5.2.** Let $S$ be a scheme. Let $X$ be locally of finite type over $S$. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module of finite type. Let $x \in X$ be a point with image $s \in S$. A complete dévissage of $\mathcal{F}/X/S$ at $x$ is given by a system
\[
(Z_k, Y_k, i_k, \pi_k, \mathcal{G}_k, \alpha_k, z_k, y_k)_{k=1, \ldots, n}
\]
such that $(Z_k, Y_k, i_k, \pi_k, \mathcal{G}_k, \alpha_k)$ is a complete dévissage of $\mathcal{F}/X/S$ over $s$, and such that

1. $(Z_1, Y_1, i_1, \pi_1, \mathcal{G}_1, z_1, y_1)$ is a one step dévissage of $\mathcal{F}/X/S$ at $x$,
2. for $k = 2, \ldots, n$ the system $(Z_k, Y_k, i_k, \pi_k, \mathcal{G}_k, z_k, y_k)$ is a one step dévissage of $\text{Coker}(\alpha_{k-1})/Y_{k-1}/S$ at $y_{k-1}$.

Again we remark that a complete dévissage can only exist if $X$ and $S$ are affine.

**Lemma 5.3.** Let $S$, $X$, $\mathcal{F}$, $s$ be as in Definition 5.1. Let $(S', s') \to (S, s)$ be any morphism of pointed schemes. Let $(Z_k, Y_k, i_k, \pi_k, \mathcal{G}_k, \alpha_k)_{k=1, \ldots, n}$ be a complete dévissage of $\mathcal{F}/X/S$ over $s$. Given this data let $X', Z'_k, Y'_k, \mathcal{G}'_k, \alpha'_k$ be the base changes of $X, Z_k, Y_k, i_k, \pi_k$ via $S' \to S$. Let $\mathcal{F}'$ be the pullback of $\mathcal{F}$ to $X'$ and let $\mathcal{G}'_k$ be the pullback of $\mathcal{G}_k$ to $Z'_k$. Let $\alpha'_k$ be the pullback of $\alpha_k$ to $Y'_k$. If $S'$ is affine, then $(Z'_k, Y'_k, i'_k, \pi'_k, \mathcal{G}'_k, \alpha'_k)_{k=1, \ldots, n}$ is a complete dévissage of $\mathcal{F}'/X'/S'$ over $s'$. 
Proof. By Lemma 4.4 we know that the base change of a one step dévissage is a one step dévissage. Hence it suffices to prove that formation of $\text{Coker}(\alpha_k)$ commutes with base change and that condition (2) of Definition 5.1 is preserved by base change. The first is true as $\pi'_{k,s}G'_k$ is the pullback of $\pi_{k,s}G_k$ (by Cohomology of Schemes, Lemma 5.1) and because $\otimes$ is right exact. The second because by the same token we have

$$(\pi'_{k,s}G'_k)_{\xi_k} \otimes_{\mathcal{O}_{Y'_k,s}} \kappa(\xi_k) \otimes_{\kappa(s_x)} \kappa(\xi'_k) \cong (\pi'_{k,s}G'_k)_{\xi'_k} \otimes_{\mathcal{O}_{Y'_k,s}} \kappa(\xi'_k)$$

with obvious notation.

\[\square\]

05HK Lemma 5.4. Let $S$, $X$, $F$, $x$, $s$ be as in Definition 5.2. Let $(S', s') \to (S, s)$ be a morphism of pointed schemes which induces an isomorphism $\kappa(s) = \kappa(s')$. Let $(Z_k, Y_k, i_k, \pi_k, G_k, \alpha_k, z_k, y_k)_{k=1,...,n}$ be a complete dévissage of $\mathcal{F}/X/S$ at $x$. Let $(Z'_k, Y'_k, i'_k, \pi'_k, G'_k, \alpha'_k, z'_k, y'_k)_{k=1,...,n}$ be as constructed in Lemma 5.3 and let $x' \in X'$ (resp. $z'_k \in Z'_k$, $y'_k \in Y'_k$) be the unique point mapping to both $x \in X$ (resp. $z_k \in Z_k$, $y_k \in Y_k$) and $s' \in S'$. If $S'$ is affine, then $(Z'_k, Y'_k, i'_k, \pi'_k, G'_k, \alpha'_k, z'_k, y'_k)_{k=1,...,n}$ is a complete dévissage of $\mathcal{F}'/X'/S'$ at $x'$.

Proof. Combine Lemma 5.3 and Lemma 4.5.

\[\square\]

05HL Definition 5.5. Let $S$, $X$, $F$, $x$, $s$ be as in Definition 5.2. Consider a complete dévissage $(Z_k, Y_k, i_k, \pi_k, G_k, \alpha_k, z_k, y_k)_{k=1,...,n}$ of $\mathcal{F}/X/S$ at $x$. Let us define a standard shrinking of this situation to be given by standard opens $S' \subset S$, $X' \subset X$, $Z'_k \subset Z_k$, and $Y'_k \subset Y_k$ such that $s_k \in S'$, $x_k \in X'$, $z_k \in Z'$, and $y_k \in Y'$ and such that

$$(Z'_k, Y'_k, i'_k, \pi'_k, G'_k, \alpha'_k, z'_k, y'_k)_{k=1,...,n}$$

is a one step dévissage of $\mathcal{F}'/X'/S'$ at $x$ where $G'_k = G_k|_{Z'_k}$ and $\mathcal{F}' = \mathcal{F}|_{X'}$.

\[\square\]

05HM Lemma 5.6. With assumption and notation as in Definition 5.5 we have:

05HN (1) If $S' \subset S$ is a standard open neighbourhood of $s$, then setting $X' = X_{S'}$, $Z'_k = Z_{S'}$ and $Y'_k = Y_{S'}$ we obtain a standard shrinking.

05HP (2) Let $W \subset Y_n$ be a standard open neighbourhood of $y$. Then there exists a standard shrinking with $Y'_n = W \times_S S'$.

05HQ (3) Let $U \subset X$ be an open neighbourhood of $x$. Then there exists a standard shrinking with $X' \subset U$.

Proof. Part (1) is immediate from Lemmas 5.4 and 4.7.

Proof of (2). For convenience denote $X = Y_0$. We apply Lemma 4.7 (2) to find a standard shrinking $S', Y'_{n-1}, Z'_n, Y'_n$ of the one step dévissage of $\text{Coker}(\alpha_{n-1})/Y_{n-1}/S$ at $y_{n-1}$ with $Y'_n = W \times_S S'$. We may repeat this procedure and find a standard shrinking $S'', Y''_{n-2}, Z''_{n-1}, Y''_{n-1}$ of the one step dévissage of $\text{Coker}(\alpha_{n-2})/Y_{n-2}/S$ at $y_{n-2}$ with $Y''_{n-1} = Y_{n-1} \times_S S''$. We may continue in this manner until we obtain $S^{(n)}, Y^{(n)}_0, Z^{(n)}_n, Y^{(n)}_n$. At this point it is clear that we obtain our desired standard shrinking by taking $S^{(n)}, X^{(n)}, Z^{(n-k)}_k \times_S S^{(n)},$ and $Y^{(n-k)}_k \times_S S^{(n)}$ with the desired property.

Proof of (3). We use induction on the length of the complete dévissage. First we apply Lemma 4.7 (3) to find a standard shrinking $S', X', Z'_1, Y'_1$ of the one step dévissage of $\mathcal{F}/X/S$ at $x$ with $X' \subset U$. If $n = 1$, then we are done. If $n > 1$, then by induction we can find a standard shrinking $S'', Y''_1, Z'_k, Y'_k$ of
the complete dévissage \((Z_k, Y_k, i_k, \pi_k, G_k, \alpha_k, z_k, y_k)_{k=2,\ldots,n}\) of \(\text{Coker}(\alpha_1)/Y_1/S\) at \(x\) such that \(Y_1'' \subset Y_1'\). Using Lemma 4.7 (2) we can find \(S'' \subset S'\), \(X'' \subset X'\), \(Z_1''\) and \(Y_1'' = Y_1'' \times_S S''\) which is a standard shrinking. The solution to our problem is to take 

\[
S'' \times_S S'' \times_S \ldots \times_S S'' \times_S S'' \times_S S'' \times_S S'' \times_S S''
\]

This ends the proof of the lemma. □

**Proposition 5.7.** Let \(S\) be a scheme. Let \(X\) be locally of finite type over \(S\). Let \(x \in X\) be a point with image \(s \in S\). There exists a commutative diagram

\[
\begin{array}{c}
(X, x) \xrightarrow{g} (X', x') \\
\downarrow \\
(S, s) \xleftarrow{(S', s')}
\end{array}
\]

of pointed schemes such that the horizontal arrows are elementary étale neighbourhoods and such that \(g^* F/X'/S'\) has a complete dévissage at \(x\).

**Proof.** We prove this by induction on the integer \(d = \dim_x(\text{Supp}(F_s))\). By Lemma 4.3 there exists a diagram

\[
\begin{array}{c}
(X, x) \xrightarrow{g} (X', x') \\
\downarrow \\
(S, s) \xleftarrow{(S', s')}
\end{array}
\]

of pointed schemes such that the horizontal arrows are elementary étale neighbourhoods and such that \(g^* F/X'/S'\) has a one step dévissage at \(x\). The local nature of the problem implies that we may replace \((X, x) \rightarrow (S, s)\) by \((X', x') \rightarrow (S', s')\). Thus after doing so we may assume that there exists a one step dévissage \((Z_1, Y_1, i_1, \pi_1, G_1)\) of \(F/X/S\) at \(x\).

We apply Lemma 4.9 to find a map

\[\alpha_1 : O_{Y_1}^{\oplus r_1} \rightarrow \pi_1, \pi G_1\]

which induces an isomorphism of vector spaces over \(\kappa(\xi_1)\) where \(\xi_1 \in Y_1\) is the unique generic point of the fibre of \(Y_1\) over \(s\). Moreover \(\dim_{\kappa(\xi_1)}(\text{Supp}(\text{Coker}(\alpha_1)_s)) < d\). It may happen that the stalk of \(\text{Coker}(\alpha_1)_s\) at \(y_1\) is zero. In this case we may shrink \(Y_1\) by Lemma 4.7 (2) and assume that \(\text{Coker}(\alpha_1) = 0\) so we obtain a complete dévissage of length zero.

Assume now that the stalk of \(\text{Coker}(\alpha_1)_s\) at \(y_1\) is not zero. In this case, by induction, there exists a commutative diagram

\[
\begin{array}{c}
(Y_1, y_1) \xleftarrow{h} (Y_1', y_1') \\
\downarrow \\
(S, s) \xleftarrow{(S', s')}
\end{array}
\]

of pointed schemes such that the horizontal arrows are elementary étale neighbourhoods and such that \(h^* \text{Coker}(\alpha_1)_s/Y_1'/S'\) has a complete dévissage

\[
(Z_k, Y_k, i_k, \pi_k, G_k, \alpha_k, z_k, y_k)_{k=2,\ldots,n}
\]
at \( y'_1 \). (In particular \( i_2 : Z_2 \to Y'_1 \) is a closed immersion into \( Y'_1 \).) At this point we apply Lemma 4.8 to \( S, X, \mathcal{F}, x, s \), the system \((Z_1, Y_1, i_1, \pi_1, G_1)\) and diagram \((5.7.1)\). We obtain a diagram

\[
\begin{array}{c}
(X'', x'') \leftarrow (Z''_1, z''_1) \\
\downarrow \downarrow \\
(Z_1, z_1) \leftarrow (S'', s'') \\
\downarrow \downarrow \\
(S, s) \leftarrow (Y_1, y_1)
\end{array}
\]

with all the properties as listed in the referenced lemma. In particular \( Y''_1 \subset Y'_1 \times_S S'' \). Set \( X_1 = Y'_1 \times_S S'' \) and let \( \mathcal{F}_1 \) denote the pullback of \( \text{Coker}(\alpha_1) \). By Lemma 5.4 the system

\[
(5.7.2) \quad (Z_k \times_S S'', Y_k \times_S S'', \tau'_k, \pi'_k, G_k, \alpha_k, z_k, y_k)_{k=2,\ldots,n}
\]

is a complete dévissage of \( \mathcal{F}_1 \) to \( X_1 \). Again, the nature of the problem allows us to replace \((X, x) \to (S, s)\) by \((X'', x'') \to (S'', s'')\). In this we see that we may assume:

(a) There exists a one step dévissage \((Z_1, Y_1, i_1, \pi_1, G_1)\) of \( \mathcal{F}/X/S \) at \( x \),

(b) there exists an \( \alpha_1 : \mathcal{O}_{Y_1}^{\tau_1} \to \pi_1, G_1 \) such that \( \alpha \otimes \kappa (\xi_1) \) is an isomorphism,

(c) \( Y_1 \subset X_1 \) is open, \( y_1 = x_1 \), and \( \mathcal{F}_1|_{Y_1} \cong \text{Coker}(\alpha_1) \), and

(d) there exists a complete dévissage \((Z_k, Y_k, i_k, \pi_k, G_k, \alpha_k, z_k, y_k)_{k=2,\ldots,n}\) of \( \mathcal{F}_1/X_1/S \) at \( x_1 \).

To finish the proof all we have to do is shrink the one step dévissage and the complete dévissage such that they fit together to a complete dévissage. (We suggest the reader do this on their own using Lemmas 4.7 and 5.6 instead of reading the proof that follows.) Since \( Y_1 \subset X_1 \) is an open neighbourhood of \( x_1 \) we may apply Lemma 5.6 \((3)\) to find a standard shrinking \( S', X'_1, Z'_2, Y'_2, \ldots, Y'_n \) of the datum \((d)\) so that \( X'_1 \subset Y_1 \). Note that \( X'_1 \) is also a standard open of the affine scheme \( Y_1 \). Next, we shrink the datum \((a)\) as follows: first we shrink the base \( S \) to \( S' \), see Lemma 4.7 \((1)\) and then we shrink the result to \( S'', X'', Z'', Y'' \) using Lemma 4.7 \((2)\) such that eventually \( Y''_1 = X'_1 \times_S S'' \) and \( S'' \subset S' \). Then we see that

\[
Z'_1, Y'_1, Z'_2 \times_S S'', Y'_2 \times_S S'', \ldots, Y'_n \times_S S''
\]

gives the complete dévissage we were looking for. \( \square \)

Some more bookkeeping gives the following consequence.

**Lemma 5.8.** Let \( X \to S \) be a finite type morphism of schemes. Let \( \mathcal{F} \) be a finite type quasi-coherent \( \mathcal{O}_X \)-module. Let \( s \in S \) be a point. There exists an elementary étale neighbourhood \((S', s') \to (S, s)\) and étale morphisms \( h_i : Y_i \to X_{S'} \), \( i = 1, \ldots, n \) such that for each \( i \) there exists a complete dévissage of \( \mathcal{F}/Y_i/S' \) over \( s' \), where \( \mathcal{F}_i \) is the pullback of \( \mathcal{F} \) to \( Y_i \) and such that \( X_s = (X_{S'})_{s'} \cup \bigcup h_i(Y_i) \).

**Proof.** For every point \( x \in X_s \) we can find a diagram

\[
\begin{array}{c}
(X, x) \leftarrow (X', x') \\
\downarrow \downarrow \\
(S, s) \leftarrow (S', s')
\end{array}
\]
of pointed schemes such that the horizontal arrows are elementary étale neighbourhoods and such that \( g^* \mathcal{F} / X' / S' \) has a complete dévissage at \( x' \). As \( X \to S \) is of finite type the fibre \( X_s \) is quasi-compact, and since each \( g : X' \to X \) as above is open we can cover \( X_s \) by a finite union of \( g(X'_{s'}) \). Thus we can find a finite family of such diagrams

\[
\begin{array}{c}
(X, x) \\ \downarrow \downarrow \\
\left( X'_i, x'_i \right) \\
\end{array} \\
\begin{array}{c}
(S, s) \\
\downarrow \downarrow \\
\left( S'_i, s'_i \right) \\
\end{array}
\]

such that \( X_s = \bigcup g_i(X'_{s'_i}) \). Set \( S' = S'_1 \times_S \ldots \times_S S'_n \) and let \( Y_i = X_i \times_{S'_i} S' \) be the base change of \( X'_i \) to \( S' \). By Lemma 5.3 we see that the pullback of \( \mathcal{F} \) to \( Y_i \) has a complete dévissage over \( s \) and we win. \[\square\]

### 6. Translation into algebra

It may be useful to spell out algebraically what it means to have a complete dévissage. We introduce the following notion (which is not that useful so we give it an impossibly long name).

**Definition 6.1.** Let \( R \to S \) be a ring map. Let \( q \) be a prime of \( S \) lying over the prime \( p \) of \( R \). A *elementary étale localization of the ring map \( R \to S \) at \( q \)* is given by a commutative diagram of rings and accompanying primes

\[
\begin{array}{ccc}
S & \rightarrow & S' \\
\downarrow & & \downarrow \\
R & \rightarrow & R' \\
\end{array} \\
\begin{array}{ccc}
q & \rightarrow & q' \\
\downarrow & & \downarrow \\
p & \rightarrow & p' \\
\end{array}
\]

such that \( R \to R' \) and \( S \to S' \) are étale ring maps and \( \kappa(p) = \kappa(p') \) and \( \kappa(q) = \kappa(q') \).

**Definition 6.2.** Let \( R \to S \) be a finite type ring map. Let \( r \) be a prime of \( R \). Let \( N \) be a finite \( S \)-module. A *complete dévissage of \( N / S / R \) over \( r \)* is given by \( R \)-algebra maps

\[
\begin{array}{cccccc}
S & \leftarrow & A_1 & \leftarrow & A_2 & \leftarrow & \ldots & \leftarrow & A_n & \leftarrow & B_n \\
\downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
B_1 & \leftarrow & \ldots & \leftarrow & \ldots & \leftarrow & \ldots & \leftarrow & A_i & \leftarrow & B_i \\
\end{array}
\]

finite \( A_i \)-modules \( M_i \) and \( B_i \)-module maps \( \alpha_i : B_i^\oplus r \to M_i \) such that

1. \( S \to A_1 \) is surjective and of finite presentation,
2. \( B_i \to A_{i+1} \) is surjective and of finite presentation,
3. \( B_i \to A_i \) is finite,
4. \( R \to B_i \) is smooth with geometrically irreducible fibres,
5. \( N \cong M_1 \) as \( S \)-modules,
6. \( \text{Coker}(\alpha_i) \cong M_{i+1} \) as \( B_i \)-modules,
7. \( \alpha_i : \kappa(p_i)^\oplus r \to M_i \otimes_{B_i} \kappa(p_i) \) is an isomorphism where \( p_i = r B_i \), and
8. \( \text{Coker}(\alpha_n) = 0 \).

In this situation we say that \((A_i, B_i, M_i, \alpha_i)_{i=1,\ldots,n}\) is a complete dévissage of \( N / S / R \) over \( r \).
Remark 6.3. Note that the $R$-algebras $B_i$ for all $i$ and $A_i$ for $i \geq 2$ are of finite presentation over $R$. If $S$ is of finite presentation over $R$, then it is also the case that $A_3$ is of finite presentation over $R$. In this case all the ring maps in the complete dévissage are of finite presentation. See Algebra, Lemma 6.2. Still assuming $S$ of finite presentation over $R$ the following are equivalent

1. $M$ is of finite presentation over $S$,
2. $M_1$ is of finite presentation over $A_1$,
3. $M_i$ is of finite presentation over $B_1$,
4. each $M_i$ is of finite presentation both as an $A_i$-module and as a $B_i$-module.

The equivalences (1) $\iff$ (2) and (2) $\iff$ (3) follow from Algebra, Lemma 35.23. If $M_1$ is finitely presented, so is $\text{Coker}(\alpha_1)$ (see Algebra, Lemma 5.3) and hence $M_2$, etc.

Definition 6.4. Let $R \to S$ be a finite type ring map. Let $q$ be a prime of $S$ lying over the prime $r$ of $R$. Let $N$ be a finite $S$-module. A complete dévissage of $N/S/R$ at $q$ is given by a complete dévissage $(A_i, B_i, M_i, \alpha_i)_{i=1,\ldots,n}$ of $N/S/R$ over $r$ and prime ideals $q_i \subset B_i$ lying over $r$ such that

1. $\kappa(r) \subset \kappa(q_i)$ is purely transcendental,
2. there is a unique prime $q_i' \subset A_i$ lying over $q_i \subset B_i$,
3. $q = q_1' \cap S$ and $q_i = q_{i+1}' \cap A_i$,
4. $R \to B_i$ has relative dimension $\text{dim}_{R}(\text{Supp}(M_i \otimes_R \kappa(r)))$.

Remark 6.5. Let $A \to B$ be a finite type ring map and let $N$ be a finite $B$-module. Let $q$ be a prime of $B$ lying over the prime $r$ of $A$. Set $X = \text{Spec}(B)$, $S = \text{Spec}(A)$ and $\mathcal{F} = \overline{N}$ on $X$. Let $x$ be the point corresponding to $q$ and let $s \in S$ be the point corresponding to $p$. Then

1. if there exists a complete dévissage of $\mathcal{F}/X/S$ over $s$ then there exists a complete dévissage of $N/B/A$ over $p$,
2. there exists a complete dévissage of $\mathcal{F}/X/S$ at $x$ if and only if there exists a complete dévissage of $N/B/A$ at $q$.

There is just a small twist in that we omitted the condition on the relative dimension in the formulation of “a complete dévissage of $N/B/A$ over $p$” which is why the implication in (1) only goes in one direction. The notion of a complete dévissage at $q$ does have this condition built in. In any case we will only use that existence for $\mathcal{F}/X/S$ implies the existence for $N/B/A$.

Lemma 6.6. Let $R \to S$ be a finite type ring map. Let $M$ be a finite $S$-module. Let $q$ be a prime ideal of $S$. There exists an elementary étale localization $R' \to S', q', p'$ of the ring map $R \to S$ at $q$ such that there exists a complete dévissage of $(M \otimes_S S')/S'/R'$ at $q'$.

Proof. This is a reformulation of Proposition 5.7 via Remark 6.5.

7. Localization and universally injective maps

Lemma 7.1. Let $R \to S$ be a ring map. Let $N$ be a $S$-module. Assume

1. $R$ is a local ring with maximal ideal $m$,
2. $S = S/mS$ is Noetherian, and
3. $\overline{N} = N/mRN$ is a finite $S$-module.
Let \( \Sigma \subset S \) be the multiplicative subset of elements which are not a zerodivisor on \( N \). Then \( \Sigma^{-1}S \) is a semi-local ring whose spectrum consists of primes \( q \subset S \) contained in an element of \( \text{Ass}_S(N) \). Moreover, any maximal ideal of \( \Sigma^{-1}S \) corresponds to an associated prime of \( N \) over \( S \).

**Proof.** Note that \( \text{Ass}_S(N) = \text{Ass}_S(N) \), see Algebra, Lemma 62.14. This is a finite set by Algebra, Lemma 62.5. Say \( \{ q_1, \ldots, q_r \} = \text{Ass}_S(N) \). We have \( \Sigma = S \setminus (\bigcup q_i) \) by Algebra, Lemma 62.9. By the description of \( \text{Spec}(\Sigma^{-1}S) \) in Algebra, Lemma 16.5 and by Algebra, Lemma 14.2 we see that the primes of \( \Sigma^{-1}S \) correspond to the primes of \( S \) contained in one of the \( q_i \). Hence the maximal ideals of \( \Sigma^{-1}S \) correspond one-to-one with the maximal (w.r.t. inclusion) elements of the set \( \{ q_1, \ldots, q_r \} \). This proves the lemma. \( \square \)

**Lemma 7.2.** Assumption and notation as in Lemma 7.1. Assume moreover that

1. \( S \) is local and \( R \to S \) is a local homomorphism,
2. \( S \) is essentially of finite presentation over \( R \),
3. \( N \) is finitely presented over \( S \), and
4. \( N \) is flat over \( R \).

Then each \( s \in \Sigma \) defines a universally injective \( R \)-module map \( s : N \to N \), and the map \( N \to \Sigma^{-1}N \) is \( R \)-universally injective.

**Proof.** By Algebra, Lemma 127.4 the sequence \( 0 \to N \to N \to N/sN \to 0 \) is exact and \( N/sN \) is flat over \( R \). This implies that \( s : N \to N \) is universally injective, see Algebra, Lemma 38.12. The map \( N \to \Sigma^{-1}N \) is universally injective as the directed colimit of the maps \( s : N \to N \).

**Lemma 7.3.** Let \( R \to S \) be a ring map. Let \( N \) be an \( S \)-module. Let \( S \to S' \) be a ring map. Assume

1. \( R \to S \) is a local homomorphism of local rings
2. \( S \) is essentially of finite presentation over \( R \),
3. \( N \) is of finite presentation over \( S \),
4. \( N \) is flat over \( R \),
5. \( S \to S' \) is flat, and
6. the image of \( \text{Spec}(S') \to \text{Spec}(S) \) contains all primes \( q \) of \( S \) lying over \( m_R \) such that \( q \) is an associated prime of \( N/mRN \).

Then \( N \to N \otimes_S S' \) is \( R \)-universally injective.

**Proof.** Set \( N' = N \otimes_R S' \). Consider the commutative diagram

\[
\begin{array}{ccc}
N & \longrightarrow & N' \\
\downarrow & & \downarrow \\
\Sigma^{-1}N & \longrightarrow & \Sigma^{-1}N'
\end{array}
\]

where \( \Sigma \subset S \) is the set of elements which are not a zerodivisor on \( N/mRN \). If we can show that the map \( N \to \Sigma^{-1}N' \) is universally injective, then \( N \to N' \) is too (see Algebra, Lemma 81.10).

By Lemma 7.1 the ring \( \Sigma^{-1}S \) is a semi-local ring whose maximal ideals correspond to associated primes of \( N/mRN \). Hence the image of \( \text{Spec}(\Sigma^{-1}S') \to \text{Spec}(\Sigma^{-1}S) \) contains all these maximal ideals by assumption. By Algebra, Lemma 38.16 the
ring map $\Sigma^{-1}S \to \Sigma^{-1}S'$ is faithfully flat. Hence $\Sigma^{-1}N \to \Sigma^{-1}N'$, which is the map

$$N \otimes_S \Sigma^{-1}S \longrightarrow N \otimes_S \Sigma^{-1}S'$$

is universally injective, see Algebra, Lemmas 81.11 and 81.8. Finally, we apply Lemma 7.2 to see that $N \to \Sigma^{-1}N$ is universally injective. As the composition of universally injective module maps is universally injective (see Algebra, Lemma 81.9) we conclude that $N \to \Sigma^{-1}N'$ is universally injective and we win. $\square$

**Lemma 7.4.** Let $R \to S$ be a ring map. Let $N$ be an $S$-module. Let $S \to S'$ be a ring map. Assume

1. $R \to S$ is of finite presentation and $N$ is of finite presentation over $S$,
2. $N$ is flat over $R$,
3. $S \to S'$ is flat, and
4. the image of $\text{Spec}(S') \to \text{Spec}(S)$ contains all primes $q$ such that $q$ is an associated prime of $N \otimes_R \kappa(p)$ where $p$ is the inverse image of $q$ in $R$.

Then $N \to N \otimes_S S'$ is $R$-universally injective.

**Proof.** By Algebra, Lemma 81.12 it suffices to show that $N_q \to (N \otimes_R S')_q$ is a $R_p$-universally injective for any prime $q$ of $S$ lying over $p$ in $R$. Thus we may apply Lemma 7.3 to the ring maps $R_p \to S_q \to S'_q$ and the module $N_q$. $\square$

The reader may want to compare the following lemma to Algebra, Lemmas 98.1 and 127.4 and the results of Section 25. In each case the conclusion is that the map $u : M \to N$ is universally injective with flat cokernel.

**Lemma 7.5.** Let $(R, m)$ be a local ring. Let $u : M \to N$ be an $R$-module map. If $M$ is a projective $R$-module, $N$ is a flat $R$-module, and $\bar{u} : M/mM \to N/mN$ is injective then $u$ is universally injective.

**Proof.** By Algebra, Theorem 84.4 the module $M$ is free. If we show the result holds for every finitely generated direct summand of $M$, then the lemma follows. Hence we may assume that $M$ is finite free. Write $N = \colim_i N_i$ as a directed colimit of finite free modules, see Algebra, Theorem 80.4. Note that $u : M \to N$ factors through $N_i$ for some $i$ (as $M$ is finite free). Denote $u_i : M \to N_i$ the corresponding $R$-module map. As $\bar{u}$ is injective we see that $\bar{u}_i : M/mM \to N_i/mN_i$ is injective and remains injective on composing with the maps $N_i/mN_i \to N_{i'}/mN_{i'}$ for all $i' \geq i$. As $M$ and $N_i$ are finite free over the local ring $R$ this implies that $M \to N_i$ is a split injection for all $i' \geq i$. Hence for any $R$-module $Q$ we see that $M \otimes_R Q \to N_i \otimes_R Q$ is injective for all $i' \geq i$. As $- \otimes_R Q$ commutes with colimits we conclude that $M \otimes_R Q \to N_i \otimes_R Q$ is injective as desired. $\square$

**Lemma 7.6.** **Assumption and notation as in Lemma 7.1.** Assume moreover that $N$ is projective as an $R$-module. Then each $s \in \Sigma$ defines a universally injective $R$-module map $s : N \to N$, and the map $N \to \Sigma^{-1}N$ is $R$-universally injective.

**Proof.** Pick $s \in \Sigma$. By Lemma 7.5 the map $s : N \to N$ is universally injective. The map $N \to \Sigma^{-1}N$ is universally injective as the directed colimit of the maps $s : N \to N$. $\square$
8. Completion and Mittag-Leffler modules

Lemma 8.1. Let $R$ be a ring. Let $I \subset R$ be an ideal. Let $A$ be a set. Assume $R$ is Noetherian and complete with respect to $I$. The completion $(\bigoplus_{\alpha \in A} R)^\wedge$ is flat and Mittag-Leffler.

Proof. By More on Algebra, Lemma 27.1 the map $(\bigoplus_{\alpha \in A} R)^\wedge \to \prod_{\alpha \in A} R$ is universally injective. Thus, by Algebra, Lemmas 81.7 and 88.7 it suffices to show that $\prod_{\alpha \in A} R$ is flat and Mittag-Leffler. By Algebra, Proposition 89.6 (and Algebra, Lemma 89.5) we see that $\prod_{\alpha \in A} R$ is flat. Thus we conclude because a product of copies of $R$ is Mittag-Leffler, see Algebra, Lemma 90.3. □

Lemma 8.2. Let $R$ be a ring. Let $I \subset R$ be an ideal. Let $M$ be an $R$-module. Assume

(1) $R$ is Noetherian and $I$-adically complete,
(2) $M$ is flat over $R$, and
(3) $M/IM$ is a projective $R/I$-module.

Then the $I$-adic completion $M^\wedge$ is a flat Mittag-Leffler $R$-module.

Proof. Choose a surjection $F \to M$ where $F$ is a free $R$-module. By Algebra, Lemma 96.9 the module $M^\wedge$ is a direct summand of the module $F^\wedge$. Hence it suffices to prove the lemma for $F$. In this case the lemma follows from Lemma 8.1. □

In Lemmas 8.3 and 8.4 the assumption that $S$ be Noetherian holds if $R \to S$ is of finite type, see Algebra, Lemma 30.1.

Lemma 8.3. Let $R$ be a ring. Let $I \subset R$ be an ideal. Let $R \to S$ be a ring map, and $N$ an $S$-module. Assume

(1) $R$ is a Noetherian ring,
(2) $S$ is a Noetherian ring,
(3) $N$ is a finite $S$-module, and
(4) for any finite $R$-module $Q$, any $q \in \text{Ass}_S(Q \otimes_R N)$ satisfies $IS + q \neq S$.

Then the map $N \to N^\wedge$ of $N$ into the $I$-adic completion of $N$ is universally injective as a map of $R$-modules.

Proof. We have to show that for any finite $R$-module $Q$ the map $Q \otimes_R N \to Q \otimes_R N^\wedge$ is injective, see Algebra, Theorem 81.3. As there is a canonical map $Q \otimes_R N^\wedge \to (Q \otimes_R N)^\wedge$ it suffices to prove that the canonical map $Q \otimes_R N \to (Q \otimes_R N)^\wedge$ is injective. Hence we may replace $N$ by $Q \otimes_R N$ and it suffices to prove the injectivity for the map $N \to N^\wedge$.

Let $K = \ker(N \to N^\wedge)$. It suffices to show that $K_q = 0$ for $q \in \text{Ass}(N)$ as $N$ is a submodule of $\prod_{q \in \text{Ass}(N)} N_q$, see Algebra, Lemma 62.19. Pick $q \in \text{Ass}(N)$. By the last assumption we see that there exists a prime $q' \supset IS + q$. Since $K_q$ is a localization of $K_{q'}$ it suffices to prove the vanishing of $K_{q'}$. Note that $K = \bigcap_I N$, hence $K_{q'} \subset \bigcap_I N_{q'}$. Hence $K_{q'} = 0$ by Algebra, Lemma 50.4. □

Lemma 8.4. Let $R$ be a ring. Let $I \subset R$ be an ideal. Let $R \to S$ be a ring map, and $N$ an $S$-module. Assume

(1) $R$ is a Noetherian ring,
(2) $S$ is a Noetherian ring,
(3) $N$ is a finite $S$-module,
(4) $N$ is flat over $R$, and
(5) for any prime $\mathfrak{q} \subset S$ which is an associated prime of $N \otimes_R \kappa(\mathfrak{p})$ where $\mathfrak{p} = R \cap \mathfrak{q}$ we have $IS + \mathfrak{q} \neq S$.

Then the map $N \to N^\wedge$ of $N$ into the $I$-adic completion of $N$ is universally injective as a map of $R$-modules.

**Proof.** This follows from Lemma 8.3 because Algebra, Lemma 64.5 and Remark 64.6 guarantee that the set of associated primes of tensor products $N \otimes_R Q$ are contained in the set of associated primes of the modules $N \otimes_R \kappa(\mathfrak{p})$. $\square$

9. Projective modules

05DN The following lemma can be used to prove projectivity by Noetherian induction on the base, see Lemma 9.2.

05DP **Lemma 9.1.** Let $R$ be a ring. Let $I \subset R$ be an ideal. Let $R \to S$ be a ring map, and $N$ an $S$-module. Assume

(1) $R$ is Noetherian and $I$-adically complete,
(2) $R \to S$ is of finite type,
(3) $N$ is a finite $S$-module,
(4) $N$ is flat over $R$,
(5) $N/IN$ is projective as a $R/I$-module, and
(6) for any prime $\mathfrak{q} \subset S$ which is an associated prime of $N \otimes_R \kappa(\mathfrak{p})$ where $\mathfrak{p} = R \cap \mathfrak{q}$ we have $IS + \mathfrak{q} \neq S$.

Then $N$ is projective as an $R$-module.

**Proof.** By Lemma 8.4 the map $N \to N^\wedge$ is universally injective. By Lemma 8.2 the module $N^\wedge$ is Mittag-Leffler. By Algebra, Lemma 88.7 we conclude that $N$ is Mittag-Leffler. Hence $N$ is countably generated, flat and Mittag-Leffler as an $R$-module, whence projective by Algebra, Lemma 92.1. $\square$

05FS **Lemma 9.2.** Let $R$ be a ring. Let $R \to S$ be a ring map. Assume

(1) $R$ is Noetherian,
(2) $R \to S$ is of finite type and flat, and
(3) every fibre ring $S \otimes_R \kappa(\mathfrak{p})$ is geometrically integral over $\kappa(\mathfrak{p})$.

Then $S$ is projective as an $R$-module.

**Proof.** Consider the set

$$\{I \subset R \mid S/IS \text{ not projective as } R/I\text{-module}\}$$

We have to show this set is empty. To get a contradiction assume it is nonempty. Then it contains a maximal element $I$. Let $J = \sqrt{I}$ be its radical. If $I \neq J$, then $S/JS$ is projective as a $R/J$-module, and $S/IS$ is flat over $R/I$ and $J/I$ is a nilpotent ideal in $R/I$. Applying Algebra, Lemma 76.6 we see that $S/IS$ is a projective $R/I$-module, which is a contradiction. Hence we may assume that $I$ is a radical ideal. In other words we are reduced to proving the lemma in case $R$ is a reduced ring and $S/IS$ is a projective $R/I$-module for every nonzero ideal $I$ of $R$.

Assume $R$ is a reduced ring and $S/IS$ is a projective $R/I$-module for every nonzero ideal $I$ of $R$. By generic flatness, Algebra, Lemma 117.1 (applied to a localization
MORE ON FLATNESS

Let \( R \) be a ring. Let \( R \to S \) be a ring map. Assume

1. \( R \to S \) is of finite presentation and flat, and
2. every fibre ring \( S \otimes_R \kappa(p) \) is geometrically integral over \( \kappa(p) \).

Then \( S \) is projective as an \( R \)-module.

**Proof.** We can find a cocartesian diagram of rings

\[
\begin{array}{ccc}
S_0 & \longrightarrow & S \\
\uparrow & & \uparrow \\
R_0 & \longrightarrow & R
\end{array}
\]

such that \( R_0 \) is of finite type over \( \mathbb{Z} \), the map \( R_0 \to S_0 \) is of finite type and flat with geometrically integral fibres, see More on Morphisms, Lemmas \[30.4, 30.6, 30.7, \text{ and } 30.11\]. By Lemma \[9.2\] we see that \( S_0 \) is a projective \( R_0 \)-module. Hence \( S = S_0 \otimes_{R_0} R \) is a projective \( R \)-module, see Algebra, Lemma \[93.1\].

**Remark 9.4.** Lemma \[9.3\] is a key step in the development of results in this chapter. The analogue of this lemma in \[GR71\] is \[GR71, I \text{ Proposition 3.3.1}\]: If \( R \to S \) is smooth with geometrically integral fibres, then \( S \) is projective as an \( R \)-module. This is a special case of Lemma \[9.3\], but as we will later improve on this lemma anyway, we do not gain much from having a stronger result at this point. We briefly sketch the proof of this as it is given in \[GR71\].

1. First reduce to the case where \( R \) is Noetherian as above.
2. Since projectivity descends through faithfully flat ring maps, see Algebra, Theorem \[94.5\] we may work locally in the fppf topology on \( R \), hence we may assume that \( R \to S \) has a section \( \sigma : S \to R \). (Just by the usual trick of base changing to \( S \).) Set \( I = \text{Ker}(S \to R) \).
3. Localizing a bit more on \( R \) we may assume that \( I/I^2 \) is a free \( R \)-module and that the completion \( S^\wedge \) of \( S \) with respect to \( I \) is isomorphic to \( R[[t_1, \ldots, t_n]] \) \[32.20\]. Here we are using that \( R \to S \) is smooth.
(4) To prove that $S$ is projective as an $R$-module, it suffices to prove that $S$ is flat, countably generated and Mittag-Leffler as an $R$-module, see Algebra, Lemma \[92.1\]. The first two properties are evident. Thus it suffices to prove that $S$ is Mittag-Leffler as an $R$-module. By Algebra, Lemma \[90.4\], the module $R[[t_1, \ldots, t_n]]$ is Mittag-Leffler over $R$. Hence Algebra, Lemma \[88.7\] shows that it suffices to show that the $S \to S^\wedge$ is universally injective as a map of $R$-modules.

(5) Apply Lemma \[7.4\] to see that $S \to S^\wedge$ is $R$-universally injective. Namely, as $R \to S$ has geometrically integral fibres, any associated point of any fibre ring is just the generic point of the fibre ring which is in the image of $\text{Spec}(S^\wedge) \to \text{Spec}(S)$.

There is an analogy between the proof as sketched just now, and the development of the arguments leading to the proof of Lemma \[9.3\]. In both a completion plays an essential role, and both times the assumption of having geometrically integral fibres assures one that the map from $S$ to the completion of $S$ is $R$-universally injective.

**10. Flat finite type modules, Part I**

In some cases given a ring map $R \to S$ of finite presentation and a finite $S$-module $N$ the flatness of $N$ over $R$ implies that $N$ is of finite presentation. In this section we prove this is true “pointwise”. We remark that the first proof of Proposition \[10.3\] uses the geometric results of Section \[3\] but not the existence of a complete dévissage.

**Lemma 10.1.** Let $(R, m)$ be a local ring. Let $R \to S$ be a finitely presented flat ring map with geometrically integral fibres. Write $\mathfrak{p} = mS$. Let $\mathfrak{q} \subset S$ be a prime ideal lying over $m$. Let $N$ be a finite $S$-module. There exist $r \geq 0$ and an $S$-module map

$$\alpha : S^{\oplus r} \longrightarrow N$$

such that $\alpha : \kappa(\mathfrak{p})^{\oplus r} \to N \otimes_S \kappa(\mathfrak{p})$ is an isomorphism. For any such $\alpha$ the following are equivalent:

1. $N_\mathfrak{q}$ is $R$-flat,
2. $\alpha$ is $R$-universally injective and $\text{Coker}(\alpha)_\mathfrak{q}$ is $R$-flat,
3. $\alpha$ is injective and $\text{Coker}(\alpha)_\mathfrak{q}$ is $R$-flat,
4. $\alpha_\mathfrak{p}$ is an isomorphism and $\text{Coker}(\alpha)_\mathfrak{q}$ is $R$-flat, and
5. $\alpha_\mathfrak{q}$ is injective and $\text{Coker}(\alpha)_\mathfrak{q}$ is $R$-flat.

**Proof.** To obtain $\alpha$ set $r = \dim_{\kappa(\mathfrak{p})} N \otimes_S \kappa(\mathfrak{p})$ and pick $x_1, \ldots, x_r \in N$ which form a basis of $N \otimes_S \kappa(\mathfrak{p})$. Define $\alpha(s_1, \ldots, s_r) = \sum s_ix_i$. This proves the existence.

Fix an $\alpha$. The most interesting implication is (1) $\Rightarrow$ (2) which we prove first. Assume (1). Because $S/mS$ is a domain with fraction field $\kappa(\mathfrak{p})$ we see that $(S/mS)^{\oplus r} \to N_\mathfrak{p}/mN_\mathfrak{p} = N \otimes_S \kappa(\mathfrak{p})$ is injective. Hence by Lemmas \[7.5\] and \[9.3\] the map $S^{\oplus r} \to N_\mathfrak{p}$ is $R$-universally injective. It follows that $S^{\oplus r} \to N$ is $R$-universally injective, see Algebra, Lemma \[81.10\]. Then also the localization $\alpha_\mathfrak{q}$ is $R$-universally injective, see Algebra, Lemma \[81.13\]. We conclude that $\text{Coker}(\alpha)_\mathfrak{q}$ is $R$-flat by Algebra, Lemma \[81.7\].

The implication (2) $\Rightarrow$ (3) is immediate. If (3) holds, then $\alpha_\mathfrak{p}$ is injective as a localization of an injective module map. By Nakayama’s lemma (Algebra, Lemma \[19.1\]) $\alpha_\mathfrak{p}$ is surjective too. Hence (3) $\Rightarrow$ (4). If (4) holds, then $\alpha_\mathfrak{p}$ is an isomorphism,
so $\alpha$ is injective as $S_q \rightarrow S_p$ is injective. Namely, elements of $S \setminus p$ are nonzerodivisors on $S$ by a combination of Lemmas 7.6 and 9.3. Hence (4) $\Rightarrow$ (5). Finally, if (5) holds, then $N_q$ is $R$-flat as an extension of flat modules, see Algebra, Lemma 38.13. Hence (5) $\Rightarrow$ (1) and the proof is finished.

**Lemma 10.2.** Let $(R, m)$ be a local ring. Let $R \rightarrow S$ be a ring map of finite presentation. Let $q$ be a prime of $S$ lying over $m$. Assume that $N_q$ is flat over $R$, and assume there exists a complete dévissage of $N/S/R$ at $q$. Then $N$ is a finitely presented $S$-module, free as an $R$-module, and there exists an isomorphism

$$N \cong B_1^{pr_1} \oplus \cdots \oplus B_n^{pr_n}$$

as $R$-modules where each $B_i$ is a smooth $R$-algebra with geometrically irreducible fibres.

**Proof.** Let $(A_i, B_i, M_i, \alpha_i, q_i)_{i=1, \ldots, n}$ be the given complete dévissage. We prove the lemma by induction on $n$. Note that $N$ is finitely presented as an $S$-module if and only if $M_1$ is finitely presented as an $B_1$-module, see Remark 6.3. Note that $N_q = (M_1)_{q_1}'$ as $R$-modules because (a) $N_q = (M_1)_{q_1}'$ where $q_1'$ is the unique prime in $A_1$ lying over $q_1$ and (b) $(A_1)_{q_1}' = (A_1)_{q_1}$ by Algebra, Lemma 40.11 so (c) $(M_1)_{q_1}' \cong (M_1)_{q_1}$. Hence $(M_1)_{q_1}$ is a flat $R$-module. Thus we may replace $(S, N)$ by $(B_1, M_1)$ in order to prove the lemma. By Lemma 10.1 the map $\alpha_1 : B_1^{pr_1} \rightarrow M_1$ is $R$-universally injective and $\text{Coker}(\alpha_1)_{q_1}$ is $R$-flat. Note that $(A_i, B_i, M_i, \alpha_i, q_i)_{i=2, \ldots, n}$ is a complete dévissage of $\text{Coker}(\alpha_1)/B_1/R$ at $q_1$. Hence the induction hypothesis implies that $\text{Coker}(\alpha_1)$ is finitely presented as a $B_1$-module, free as an $R$-module, and has a decomposition as in the lemma. This implies that $M_1$ is finitely presented as a $B_1$-module, see Algebra, Lemma 5.3. It further implies that $M_1 \cong B_1^{pr_1} \oplus \text{Coker}(\alpha_1)$ as $R$-modules, hence a decomposition as in the lemma. Finally, $B_1$ is projective as an $R$-module by Lemma 9.3 and hence free as an $R$-module by Algebra, Theorem 84.4. This finishes the proof.

**Proposition 10.3.** Let $f : X \rightarrow S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent sheaf on $X$. Let $x \in X$ with image $s \in S$. Assume that

1. $f$ is locally of finite presentation,
2. $\mathcal{F}$ is of finite type, and
3. $\mathcal{F}$ is flat at $x$ over $S$.

Then there exists an elementary étale neighbourhood $(S', s') \rightarrow (S, s)$ and an open subscheme

$$V \subset X \times_S \text{Spec}(O_{S', s'})$$

which contains the unique point of $X \times_S \text{Spec}(O_{S', s'})$ mapping to $x$ such that the pullback of $\mathcal{F}$ to $V$ is an $O_V$-module of finite presentation and flat over $O_{S', s'}$.

**First proof.** This proof is longer but does not use the existence of a complete dévissage. The problem is local around $x$ and $s$, hence we may assume that $X$ and $S$ are affine. During the proof we will finitely many times replace $S$ by an elementary étale neighbourhood of $(S, s)$. The goal is then to find (after such a replacement) an open $V \subset X \times_S \text{Spec}(O_{S, s})$ containing $x$ such that $\mathcal{F}|_V$ is flat over $S$ and finitely presented. Of course we may also replace $S$ by $\text{Spec}(O_{S, s})$ at any point of the proof, i.e., we may assume $S$ is a local scheme. We will prove the proposition by induction on the integer $n = \dim_S(\text{Supp}(\mathcal{F}_s))$.
We can choose

1. elementary étale neighbourhoods \( g : (X', x') \to (X, x) \), \( e : (S', s') \to (S, s) \),
2. a commutative diagram

\[
\begin{array}{ccc}
X & \xleftarrow{g} & X' \\
\downarrow{f} & & \downarrow{\pi} \\
S & \xleftarrow{e} & S'
\end{array}
\]

3. a point \( z' \in Z' \) with \( i(z') = x', y' = \pi(z') \), \( h(y') = s' \),
4. a finite type quasi-coherent \( \mathcal{O}_{Z'} \)-module \( G \),
as in Lemma 3.2. We are going to replace \( S \) by \( \text{Spec}(\mathcal{O}_{S', s'}) \), see remarks in first paragraph of the proof. Consider the diagram

\[
\begin{array}{ccc}
X_{\mathcal{O}_{S', s'}} & \xleftarrow{g} & X'_{\mathcal{O}_{S', s'}} \\
\downarrow{f} & & \downarrow{\pi} \\
\text{Spec}(\mathcal{O}_{S', s'}) & \xleftarrow{i} & Z'_{\mathcal{O}_{S', s'}} \\
\downarrow{h} & & \downarrow{Y'}_{\mathcal{O}_{S', s'}}
\end{array}
\]

Here we have base changed the schemes \( X', Z', Y' \) over \( S' \) via \( \text{Spec}(\mathcal{O}_{S', s'}) \to S' \). It is still the case that \( g \) is étale, see Lemma 2.2. After replacing \( X \) by \( X_{\mathcal{O}_{S', s'}} \), \( X' \) by \( X'_{\mathcal{O}_{S', s'}} \), \( Z' \) by \( Z'_{\mathcal{O}_{S', s'}} \), and \( Y' \) by \( Y'_{\mathcal{O}_{S', s'}} \) we may assume we have a diagram as Lemma 3.2 where in addition \( S = S' \) is a local scheme with closed point \( s \). By Lemmas 3.3 and 3.4 the result for \( Y' \to S \), the sheaf \( \pi_* \mathcal{G} \), and the point \( y' \) implies the result for \( X \to S \), \( \mathcal{F} \) and \( x \).

Hence we may assume that \( S \) is local and \( X \to S \) is a smooth morphism of affines with geometrically irreducible fibres of dimension \( n \).

The base case of the induction: \( n = 0 \). As \( X \to S \) is smooth with geometrically irreducible fibres of dimension 0 we see that \( X \to S \) is an open immersion, see Descent, Lemma 22.2. As \( S \) is local and the closed point is in the image of \( X \to S \) we conclude that \( X = S \). Thus we see that \( \mathcal{F} \) corresponds to a finite flat \( \mathcal{O}_{S, s} \) module. In this case the result follows from Algebra, Lemma 77.5 which tells us that \( \mathcal{F} \) is in fact finite free.

The induction step. Assume the result holds whenever the dimension of the support in the closed fibre is \(< n \). Write \( S = \text{Spec}(A) \), \( X = \text{Spec}(B) \) and \( \mathcal{F} = \mathcal{N} \) for some \( B \)-module \( N \). Note that \( A \) is a local ring; denote its maximal ideal \( m \). Then \( p = mB \) is the unique minimal prime lying over \( m \) as \( X \to S \) has geometrically irreducible fibres. Finally, let \( q \subset B \) be the prime corresponding to \( x \). By Lemma 10.1 we can choose a map

\[ \alpha : B^{\oplus r} \to N \]

such that \( \kappa(p)^{\oplus r} \to N \otimes_B \kappa(p) \) is an isomorphism. Moreover, as \( N_q \) is \( A \)-flat the lemma also shows that \( \alpha \) is injective and that \( \text{Coker}(\alpha)_q \) is \( A \)-flat. Set \( Q = \)
Coker(α). Note that the support of Q/mQ does not contain p. Hence it is certainly the case that dim_q(Supp(Q/mQ)) < n. Combining everything we know about Q we see that the induction hypothesis applies to Q. It follows that there exists an elementary étale morphism (S', s) → (S, s) such that the conclusion holds for $Q \otimes_A A'$ over $B \otimes_A A'$ where $A' = \mathcal{O}_{S', s'}$. After replacing A by $A'$ we have an exact sequence

$$0 \to B^{\oplus r} \to N \to Q \to 0$$

(here we use that α is injective as mentioned above) of finite B-modules and we also get an element $g \in B$, $g \notin q$ such that $Q_g$ is finitely presented over $B_g$ and flat over A. Since localization is exact we see that

$$0 \to B^{\oplus r}_g \to N_g \to Q_g \to 0$$

is still exact. As $B_g$ and $Q_g$ are flat over A we conclude that $N_g$ is flat over A, see Algebra, Lemma [38.13] and as $B_g$ and $Q_g$ are finitely presented over $B_g$ the same holds for $N_g$, see Algebra, Lemma [5.3].

**Second proof.** We apply Proposition 5.7 to find a commutative diagram

$$
\begin{array}{ccc}
(X, x) & \xleftarrow{g} & (X', x') \\
\downarrow & & \downarrow \\
(S, s) & \xleftarrow{g} & (S', s')
\end{array}
$$

of pointed schemes such that the horizontal arrows are elementary étale neighbourhoods and such that $g^* \mathcal{F}/X'/S'$ has a complete dévissage at x. (In particular $S'$ and $X'$ are affine.) By Morphisms, Lemma 24.13 we see that $g^* \mathcal{F}$ is flat at $x'$ over $S$ and by Lemma 2.3 we see that it is flat at $x'$ over $S'$. Via Remark 6.5 we deduce that $\Gamma(X', g^* \mathcal{F})/\Gamma(X', \mathcal{O}_{X'})/\Gamma(S', \mathcal{O}_{S'})$ has a complete dévissage at the prime of $\Gamma(X', \mathcal{O}_{X'})$ corresponding to $x'$. We may base change this complete dévissage to the local ring $\mathcal{O}_{S', s'}$ of $\Gamma(S', \mathcal{O}_{S'})$ at the prime corresponding to $s'$. Thus Lemma 10.2 implies that

$$\Gamma(X', \mathcal{F}')\otimes_{\Gamma(S', \mathcal{O}_{S'})} \mathcal{O}_{S', s'}$$

is flat over $\mathcal{O}_{S', s'}$ and of finite presentation over $\Gamma(X', \mathcal{O}_{X'})\otimes_{\Gamma(S', \mathcal{O}_{S'})} \mathcal{O}_{S', s'}$. In other words, the restriction of $\mathcal{F}$ to $X' \times_S \text{Spec}(\mathcal{O}_{S', s'})$ is of finite presentation and flat over $\mathcal{O}_{S', s'}$. Since the morphism $X' \times_S \text{Spec}(\mathcal{O}_{S', s'}) \to X \times_S \text{Spec}(\mathcal{O}_{S', s'})$ is étale (Lemma 24.13) its image $V \subset X \times_S \text{Spec}(\mathcal{O}_{S', s'})$ is an open subscheme, and by étale descent the restriction of $\mathcal{F}$ to V is of finite presentation and flat over $\mathcal{O}_{S', s'}$. (Results used: Morphisms, Lemma 34.13 Descent, Lemma 7.3 and Morphisms, Lemma 24.13)

**Lemma 10.4.** Let $f : X \to S$ be a morphism of schemes which is locally of finite type. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module of finite type. Let $s \in S$. Then the set

$$\{x \in X_s \mid \mathcal{F} \text{ flat over } S \text{ at } x\}$$

is open in the fibre $X_s$. 

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05KT Lemma 10.5. Let $f : X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent sheaf on $X$. Let $x \in X$ with image $s \in S$. Assume that

1. $f$ is locally of finite type,
2. $\mathcal{F}$ is of finite type, and
3. $\mathcal{F}$ is flat at $x$ over $S$.

Then there exists an elementary étale neighbourhood $(S', s') \to (S, s)$ and an open subscheme

$$V \subset X \times_S \text{Spec}(\mathcal{O}_{S', s'})$$

which contains the unique point of $X \times_S \text{Spec}(\mathcal{O}_{S', s'})$ mapping to $x$ such that the pullback of $\mathcal{F}$ to $V$ is flat over $\mathcal{O}_{S', s'}$.

Proof. (The only difference between this and Proposition 10.3 is that we do not assume $f$ is of finite presentation.) The question is local on $X$ and $S$, hence we may assume $X$ and $S$ are affine. Write $X = \text{Spec}(B)$, $S = \text{Spec}(A)$ and write $B = A[x_1, \ldots, x_n]/I$. In other words we obtain a closed immersion $i : X \to A^n_S$. Denote $t = i(x) \in A^n_S$. We may apply Proposition 10.3 to $A^n_S \to S$, the sheaf $i_*\mathcal{F}$ and the point $t$. We obtain an elementary étale neighbourhood $(S', s') \to (S, s)$ and an open subscheme

$$W \subset \text{Spec}(A^n_{S', s'})$$

such that the pullback of $i_*\mathcal{F}$ to $W$ is flat over $\mathcal{O}_{S', s'}$. This means that $V := W \cap (X \times_S \text{Spec}(\mathcal{O}_{S', s'}))$ is the desired open subscheme.

05KU Lemma 10.6. Let $f : X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent sheaf on $X$. Let $s \in S$. Assume that

1. $f$ is of finite presentation,
2. $\mathcal{F}$ is of finite type, and
3. $\mathcal{F}$ is flat over $S$ at every point of the fibre $X_s$.

Then there exists an elementary étale neighbourhood $(S', s') \to (S, s)$ and an open subscheme

$$V \subset X \times_S \text{Spec}(\mathcal{O}_{S', s'})$$

which contains the fibre $X_s = X \times_S s'$ such that the pullback of $\mathcal{F}$ to $V$ is an $\mathcal{O}_V$-module of finite presentation and flat over $\mathcal{O}_{S', s'}$.

Proof. For every point $x \in X_s$ we can use Proposition 10.3 to find an elementary étale neighbourhood $(S_x, s_x) \to (S, s)$ and an open $V_x \subset X \times_S \text{Spec}(\mathcal{O}_{S_x, s_x})$ such that $x \in X_s = X \times_S s_x$ is contained in $V_x$ and such that the pullback of $\mathcal{F}$ to $V_x$ is an $\mathcal{O}_{V_x}$-module of finite presentation and flat over $\mathcal{O}_{S_x, s_x}$. In particular we may view the fibre $(V_x)_{s_x}$ as an open neighbourhood of $x$ in $X_s$. Because $X_s$ is quasi-compact we can find a finite number of points $x_1, \ldots, x_n \in X_s$ such that $X_s$ is the union of the $(V_i)_{s_i}$. Choose an elementary étale neighbourhood $(S'_s, s'_s) \to (S, s)$ which dominates each of the neighbourhoods $(S_{x_i}, s_{x_i})$, see More on Morphisms,
Lemma \[31.4\] Set \( V = \bigcup \mathcal V_i \) where \( \mathcal V_i \) is the inverse images of the open \( V_x \) via the morphism
\[
X \times_S \text{Spec}(\mathcal O_{S', s'}) \to X \times_S \text{Spec}(\mathcal O_{S_x, s_x})
\]
By construction \( V \) contains \( X \) and by construction the pullback of \( \mathcal F \) to \( V \) is an \( \mathcal O_V \)-module of finite presentation and flat over \( \mathcal O_{S', s'} \).

\[05KV\] \textbf{Lemma 10.7.} Let \( f : X \to S \) be a morphism of schemes. Let \( \mathcal F \) be a quasi-coherent sheaf on \( X \). Let \( s \in S \). Assume that
\[
\begin{enumerate}
  \item \( f \) is of finite type,
  \item \( \mathcal F \) is of finite type, and
  \item \( \mathcal F \) is flat over \( S \) at every point of the fibre \( X_s \).
\end{enumerate}
Then there exists an elementary étale neighbourhood \( (S', s') \to (S, s) \) and an open subscheme
\[
V \subset X \times_S \text{Spec}(\mathcal O_{S', s'})
\]
which contains the fibre \( X_s = X \times_S s' \) such that the pullback of \( \mathcal F \) to \( V \) is flat over \( \mathcal O_{S', s'} \).

\textbf{Proof.} (The only difference between this and Lemma \[10.6\] is that we do not assume \( f \) is of finite presentation.) For every point \( x \in X \) we can use Lemma \[10.5\] to find an elementary étale neighbourhood \( (S_x, s_x) \to (S, s) \) and an open \( V_x \subset X \times_S \text{Spec}(\mathcal O_{S_x, s_x}) \) such that \( x \in X_s = X \times_S s_x \) is contained in \( V_x \) and such that the pullback of \( \mathcal F \) to \( V_x \) is flat over \( \mathcal O_{S_x, s_x} \). In particular we may view the fibre \( (V_x)_s \) as an open neighbourhood of \( x \) in \( X_s \). Because \( X_s \) is quasi-compact we can find a finite number of points \( x_1, \ldots, x_n \in X_s \) such that \( X_s \) is the union of the \( (V_x)_s \). Choose an elementary étale neighbourhood \( (S', s') \to (S, s) \) which dominates each of the neighbourhoods \( (S_x, s_x) \), see More on Morphisms, Lemma \[31.4\] Set \( V = \bigcup V_i \) where \( V_i \) is the inverse images of the open \( V_{x_i} \) via the morphism
\[
X \times_S \text{Spec}(\mathcal O_{S', s'}) \to X \times_S \text{Spec}(\mathcal O_{S_x, s_x})
\]
By construction \( V \) contains \( X \) and by construction the pullback of \( \mathcal F \) to \( V \) is flat over \( \mathcal O_{S', s'} \).

\[05I6\] \textbf{Lemma 10.8.} Let \( S \) be a scheme. Let \( X \) be locally of finite type over \( S \). Let \( x \in X \) with image \( s \in S \). If \( X \) is flat at \( x \) over \( S \), then there exists an elementary étale neighbourhood \( (S', s') \to (S, s) \) and an open subscheme
\[
V \subset X \times_S \text{Spec}(\mathcal O_{S', s'})
\]
which contains the unique point of \( X \times_S \text{Spec}(\mathcal O_{S', s'}) \) mapping to \( x \) such that \( V \to \text{Spec}(\mathcal O_{S', s'}) \) is flat and of finite presentation.

\textbf{Proof.} The question is local on \( X \) and \( S \), hence we may assume \( X \) and \( S \) are affine. Write \( X = \text{Spec}(\mathcal B) \), \( S = \text{Spec}(\mathcal A) \) and write \( \mathcal B = \mathcal A[x_1, \ldots, x_n]/I \). In other words we obtain a closed immersion \( i : X \to \mathbb A^n_S \). Denote \( t = i(x) \in \mathbb A^n_S \). We may apply Proposition \[10.3\] to \( \mathbb A^n_S \to S \), the sheaf \( \mathcal F = i_* \mathcal O_X \) and the point \( t \). We obtain an elementary étale neighbourhood \( (S', s') \to (S, s) \) and an open subscheme
\[
W \subset \mathbb A^n_{S', s'}
\]
such that the pullback of \( i_* \mathcal O_X \) is flat and of finite presentation. This means that \( V := W \cap (X \times_S \text{Spec}(\mathcal O_{S', s'})) \) is the desired open subscheme.
Let $f : X \to S$ be a morphism which is locally of finite presentation. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module of finite type. If $x \in X$ and $\mathcal{F}$ is flat at $x$ over $S$, then $\mathcal{F}_x$ is an $\mathcal{O}_{X,x}$-module of finite presentation.

**Proof.** Let $s = f(x)$. By Proposition [10.3] there exists an elementary étale neighbourhood $(S', s') \to (S, s)$ such that the pullback of $\mathcal{F}$ to $X \times_S \text{Spec}(\mathcal{O}_{S', s'})$ is of finite presentation in a neighbourhood of the point $x' \in X_{s'} = X_s$ corresponding to $x$. The ring map

$$\mathcal{O}_{X,x} \to \mathcal{O}_{X \times_S \text{Spec}(\mathcal{O}_{S', s'}), x'} = \mathcal{O}_{X \times S', x'}$$

is flat and local as a localization of an étale ring map. Hence $\mathcal{F}_x$ is of finite presentation over $\mathcal{O}_{X,x}$ by descent, see Algebra, Lemma [82.2] (and also that a flat local ring map is faithfully flat, see Algebra, Lemma [38.17]).

**Lemma 10.10.** Let $f : X \to S$ be a morphism which is locally of finite type. Let $x \in X$ with image $s \in S$. If $f$ is flat at $x$ over $S$, then $\mathcal{O}_{X,x}$ is essentially of finite presentation over $\mathcal{O}_{S,s}$.

**Proof.** We may assume $X$ and $S$ affine. Write $X = \text{Spec}(B)$, $S = \text{Spec}(A)$ and write $B = A[x_1, \ldots, x_n]/I$. In other words we obtain a closed immersion $i : X \to \mathbb{A}^n_S$. Denote $t = i(x) \in \mathbb{A}^n_S$. We may apply Lemma [10.9] to $\mathbb{A}^n_S \to S$, the sheaf $\mathcal{F} = i_* \mathcal{O}_X$ and the point $t$. We conclude that $\mathcal{O}_{X,x}$ is of finite presentation over $\mathcal{O}_{\mathbb{A}^n_S, t}$ which implies what we want.

11. Extending properties from an open

In this section we collect a number of results of the form: If $f : X \to S$ is a flat morphism of schemes and $f$ satisfies some property over a dense open of $S$, then $f$ satisfies the same property over all of $S$.

**Lemma 11.1.** Let $f : X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module. Let $U \subset S$ be open. Assume

1. $f$ is locally of finite presentation,
2. $\mathcal{F}$ is of finite type and flat over $S$,
3. $U \subset S$ is retrocompact and scheme theoretically dense,
4. $\mathcal{F}|_{f^{-1}U}$ is of finite presentation.

Then $\mathcal{F}$ is of finite presentation.

**Proof.** The problem is local on $X$ and $S$, hence we may assume $X$ and $S$ affine. Write $S = \text{Spec}(A)$ and $X = \text{Spec}(B)$. Let $N$ be a finite $B$-module such that $\mathcal{F}$ is the quasi-coherent sheaf associated to $N$. We have $U = D(f_1) \cup \ldots \cup D(f_n)$ for some $f_i \in A$, see Algebra, Lemma [28.1]. As $U$ is schematically dense the map $A \to \prod A_{f_i}$ is injective. Pick a prime $q \subset B$ lying over $p \subset A$ corresponding to $x \in X$ mapping to $s \in S$. By Lemma [10.9] the module $N_q$ is of finite presentation over $B_q$. Choose a surjection $\varphi : B^{\oplus m} \to N$ of $B$-modules. Choose $k_1, \ldots, k_l \in \text{Ker}(\varphi)$ and set $N' = B^{\oplus m}_{\sum Bk_i}$. There is a canonical surjection $N' \to N$ and $N$ is the filtered colimit of the $B$-modules $N'$ constructed in this manner. Thus we see that we can choose $k_1, \ldots, k_l$ such that (a) $N'_q \cong N_q$, $i = 1, \ldots, n$ and (b) $N'_q \cong N_q$. This in particular implies that $N'_q$ is flat over $A$. 

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By openness of flatness, see Algebra, Theorem 128.4 we conclude that there exists a \( g \in B, g \not\in q \) such that \( N'_g \) is flat over \( A \). Consider the commutative diagram

\[
\begin{array}{ccc}
N'_g & \longrightarrow & N_g \\
\downarrow & & \downarrow \\
\prod N'_{gf_i} & \longrightarrow & \prod N_{gf_i}
\end{array}
\]

The bottom arrow is an isomorphism by choice of \( k_1, \ldots, k_t \). The left vertical arrow is an injective map as \( A \rightarrow \prod A f_i \) is injective and \( N'_g \) is flat over \( A \). Hence the top horizontal arrow is injective, hence an isomorphism. This proves that \( N_g \) is of finite presentation over \( B_g \). We conclude by applying Algebra, Lemma 22.2. □

Lemma 11.2. Let \( f : X \to S \) be a morphism of schemes. Let \( U \subset S \) be open. Assume

1. \( f \) is locally of finite type and flat,
2. \( U \subset S \) is retrocompact and scheme theoretically dense,
3. \( f|_{f^{-1}U} : f^{-1}U \to U \) is locally of finite presentation.

Then \( f \) is of locally of finite presentation.

Proof. The question is local on \( X \) and \( S \), hence we may assume \( X \) and \( S \) affine. Choose a closed immersion \( i : X \to \mathbb{A}^n_S \) and apply Lemma 11.1 to \( i_*\mathcal{O}_X \). Some details omitted. □

Lemma 11.3. Let \( f : X \to S \) be a morphism of schemes which is flat and locally of finite type. Let \( U \subset S \) be a dense open such that \( X_U \to U \) has relative dimension \( \leq e \), see Morphisms, Definition 28.1. If also either

1. \( f \) is locally of finite presentation, or
2. \( U \subset S \) is retrocompact,

then \( f \) has relative dimension \( \leq e \).

Proof. Proof in case (1). Let \( W \subset X \) be the open subscheme constructed and studied in More on Morphisms, Lemmas 20.7 and 20.9. Note that every generic point of every fibre is contained in \( W \), hence it suffices to prove the result for \( W \). Since \( W = \bigcup_{d \geq 0} U_d \), it suffices to prove that \( U_d = \emptyset \) for \( d > e \). Since \( f \) is flat and locally of finite presentation it is open hence \( f(U_d) \) is open (Morphisms, Lemma 24.10). Thus if \( U_d \) is not empty, then \( f(U_d) \cap U \neq \emptyset \) as desired.

Proof in case (2). We may replace \( S \) by its reduction. Then \( U \) is scheme theoretically dense. Hence \( f \) is locally of finite presentation by Lemma 11.2. In this way we reduce to case (1). □

Lemma 11.4. Let \( f : X \to S \) be a morphism of schemes which is flat and proper. Let \( U \subset S \) be a dense open such that \( X_U \to U \) is finite. If also either \( f \) is locally of finite presentation or \( U \subset S \) is retrocompact, then \( f \) is finite.

Proof. By Lemma 11.3 the fibres of \( f \) have dimension zero. Hence \( f \) is quasi-finite (Morphisms, Lemma 28.5) whence has finite fibres (Morphisms, Lemma 19.10). Hence \( f \) is finite by More on Morphisms, Lemma 39.1. □

Lemma 11.5. Let \( f : X \to S \) be a morphism of schemes and \( U \subset S \) an open. If

1. \( f \) is separated, locally of finite type, and flat,
(2) $f^{-1}(U) \to U$ is an isomorphism, and
(3) $U \subset S$ is retrocompact and scheme theoretically dense, then $f$ is an open immersion.

**Proof.** By Lemma 11.2 the morphism $f$ is locally of finite presentation. The image $f(X) \subset S$ is open (Morphisms, Lemma 24.10) hence we may replace $S$ by $f(X)$. Thus we have to prove that $f$ is an isomorphism. We may assume $S$ is affine. We can reduce to the case that $X$ is quasi-compact because it suffices to show that any quasi-compact open $X' \subset X$ whose image is $S$ maps isomorphically to $S$. Thus we may assume $f$ is quasi-compact. All the fibers of $f$ have dimension 0, see Lemma 11.3 Hence $f$ is quasi-finite, see Morphisms, Lemma 28.5. Let $s \in S$. Choose an elementary étale neighbourhood $g: (T, t) \to (S, s)$ such that $X \times_S T = V \amalg W$ with $V \to T$ finite and $W_t = \emptyset$, see More on Morphisms, Lemma 36.6. Denote $\pi : V \amalg W \to T$ the given morphism. Since $\pi$ is flat and locally of finite presentation, we see that $\pi(V)$ is open in $T$ (Morphisms, Lemma 24.10). After shrinking $T$ we may assume that $T = \pi(V)$. Since $f$ is an isomorphism over $U$ we see that $\pi$ is an isomorphism over $g^{-1}U$. Since $\pi(V) = T$ this implies that $\pi^{-1}g^{-1}U$ is contained in $V$. By Morphisms, Lemma 24.15 we see that $\pi^{-1}g^{-1}U \subset V \amalg W$ is scheme theoretically dense. Hence we deduce that $W = \emptyset$. Thus $X \times_S T = V$ is finite over $T$. This implies that $f$ is finite (after replacing $S$ by an open neighbourhood of $s$), for example by Descent, Lemma 20.23. Then $f$ is finite locally free (Morphisms, Lemma 46.2) and after shrinking $S$ to a smaller open neighbourhood of $s$ we see that $f$ is finite locally free of some degree $d$ (Morphisms, Lemma 46.5). But $d = 1$ as is clear from the fact that the degree is 1 over the dense open $U$. Hence $f$ is an isomorphism. \qed

### 12. Flat finitely presented modules

In some cases given a ring map $R \to S$ of finite presentation and a finitely presented $S$-module $N$ the flatness of $N$ over $R$ implies that $N$ is projective as an $R$-module, at least after replacing $S$ by an étale extension. In this section we collect a some results of this nature.

**Lemma 12.1.** Let $R$ be a ring. Let $R \to S$ be a finitely presented flat ring map with geometrically integral fibres. Let $q \subset S$ be a prime ideal lying over the prime $r \subset R$. Set $p = rq$. Let $N$ be a finitely presented $S$-module. There exists $r \geq 0$ and an $S$-module map

$$\alpha : S^\oplus r \longrightarrow N$$

such that $\alpha : \kappa(p)^{\oplus r} \to N \otimes_S \kappa(p)$ is an isomorphism. For any such $\alpha$ the following are equivalent:

1. $N_q$ is $R$-flat,
2. there exists an $f \in R$, $f \notin r$ such that $\alpha_f : S^{\oplus r} \to N_f$ is $R_f$-universally injective and $a \in S$, $a \notin q$ such that $\text{Coker}(\alpha)_a$ is $R$-flat,
3. $\alpha_r$ is $R_r$-universally injective and $\text{Coker}(\alpha)_q$ is $R$-flat
4. $\alpha_r$ is injective and $\text{Coker}(\alpha)_q$ is $R$-flat,
5. $\alpha_p$ is an isomorphism and $\text{Coker}(\alpha)_q$ is $R$-flat, and
6. $\alpha_q$ is injective and $\text{Coker}(\alpha)_q$ is $R$-flat.

**Proof.** To obtain $\alpha$ set $r = \dim_{\kappa(p)} N \otimes_S \kappa(p)$ and pick $x_1, \ldots, x_r \in N$ which form a basis of $N \otimes_S \kappa(p)$. Define $\alpha(s_1, \ldots, s_r) = \sum s_i x_i$. This proves the existence.
Fix a choice of $\alpha$. We may apply Lemma \ref{flatness-lemma} to the map $\alpha_f : S^{\oplus r}_f \rightarrow N_r$. Hence we see that (1), (3), (4), (5), and (6) are all equivalent. Since it is also clear that (2) implies (3) we see that all we have to do is show that (1) implies (2).

Assume (1). By openness of flatness, see Algebra, Theorem \ref{flat-open}, the set

$$U_1 = \{ q' \subset S \mid N_{q'} \text{ is flat over } R \}$$

is open in $\text{Spec}(S)$. It contains $q$ by assumption and hence $p$. Because $S^{\oplus r}$ and $N$ are finitely presented $S$-modules the set

$$U_2 = \{ q' \subset S \mid \alpha_{q'} \text{ is an isomorphism} \}$$

is open in $\text{Spec}(S)$, see Algebra, Lemma \ref{fppf-open}. It contains $p$ by (5). As $R \rightarrow S$ is finitely presented and flat the map $\Phi : \text{Spec}(S) \rightarrow \text{Spec}(R)$ is open, see Algebra, Proposition \ref{fppf-open}. For any prime $q' \in \Phi(U_1 \cap U_2)$ we see that there exists a prime $q'$ lying over $q'$ such that $N_{q'}$ is flat and such that $\alpha_{q'}$ is an isomorphism, which implies that $\alpha \otimes \kappa(q')$ is an isomorphism where $p' = q'S$. Thus $\alpha_{q'}$ is $R_{q'}$-universally injective by the implication (1) $\Rightarrow$ (3). Hence if we pick $f \in R$, $f \notin q$ such that $D(f) \subset \Phi(U_1 \cap U_2)$ then we conclude that $\alpha_f$ is $R_f$-universally injective, see Algebra, Lemma \ref{flat-universally-injective}. The same reasoning also shows that for any $q'' \in U_1 \cap \Phi^{-1}(\Phi(U_1 \cap U_2))$ the module $\text{Coker}(\alpha_{q''})$ is $R$-flat. Note that $q \in U_1 \cap \Phi^{-1}(\Phi(U_1 \cap U_2))$. Hence we can find a $g \in S$, $g \notin q$ such that $D(g) \subset U_1 \cap \Phi^{-1}(\Phi(U_1 \cap U_2))$ and we win. $\square$

**Lemma 12.2.** Let $R \rightarrow S$ be a ring map of finite presentation. Let $N$ be a finitely presented $S$-module flat over $R$. Let $r \subset R$ be a prime ideal. Assume there exists a complete dévissage of $N/S/R$ over $r$. Then there exists an $f \in R$, $f \notin r$ such that

$$N_f \cong B_1^{\oplus r_1} \oplus \cdots \oplus B_n^{\oplus r_n}$$

as $R$-modules where each $B_i$ is a smooth $R_f$-algebra with geometrically irreducible fibres. Moreover, $N_f$ is projective as an $R_f$-module.

**Proof.** Let $(A_i, B_i, M_i, \alpha_i)_{i=1,\ldots,n}$ be the given complete dévissage. We prove the lemma by induction on $n$. Note that the assertions of the lemma are entirely about the structure of $N$ as an $R$-module. Hence we may replace $N$ by $M_1$, and we may think of $M_1$ as a $B_1$-module. See Remark \ref{stable-induction} in order to see why $M_1$ is of finite presentation as a $B_1$-module. By Lemma \ref{flat-universally-injective} we may, after replacing $R$ by $R_f$ for some $f \in R$, $f \notin r$, assume the map $\alpha_1 : B_1^{\oplus r_1} \rightarrow M_1$ is $R$-universally injective. Since $M_1$ and $B_1^{\oplus r_1}$ are $R$-flat and finitely presented as $B_1$-modules we see that $\text{Coker}(\alpha_1)$ is $R$-flat (Algebra, Lemma \ref{flat-universally-injective}) and finitely presented as a $B_1$-module. Note that $(A_i, B_i, M_i, \alpha_i)_{i=2,\ldots,n}$ is a complete dévissage of $\text{Coker}(\alpha_1)$. Hence the induction hypothesis implies that, after replacing $R$ by $R_f$ for some $f \in R$, $f \notin r$, we may assume that $\text{Coker}(\alpha_1)$ has a decomposition as in the lemma and is projective. In particular $M_1 = B_1^{\oplus r_1} \oplus \text{Coker}(\alpha_1)$. This proves the statement regarding the decomposition. The statement on projectivity follows as $B_1$ is projective as an $R$-module by Lemma \ref{projective-lemma}.

**Remark 12.3.** There is a variant of Lemma \ref{flat-universally-injective} where we weaken the flatness condition by assuming only that $N$ is flat at some given prime $q$ lying over $r$ but where we strengthen the dévissage condition by assuming the existence of a complete dévissage at $q$. Compare with Lemma \ref{stable-induction}.

The following is the main result of this section.
Proposition 12.4. Let $f : X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent sheaf on $X$. Let $x \in X$ with image $s \in S$. Assume that

1. $f$ is locally of finite presentation,
2. $\mathcal{F}$ is of finite presentation, and
3. $\mathcal{F}$ is flat at $x$ over $S$.

Then there exists a commutative diagram of pointed schemes

$$
\begin{array}{ccc}
(X, x) & & (X', x') \\
\downarrow & & \downarrow \\
(S, s) & & (S', s')
\end{array}
$$

whose horizontal arrows are elementary étale neighbourhoods such that $X'$, $S'$ are affine and such that $\Gamma(X', g^*\mathcal{F})$ is a projective $\Gamma(S', \mathcal{O}_{S'})$-module.

Proof. By openness of flatness, see More on Morphisms, Theorem 15.1 we may replace $X$ by an open neighbourhood of $x$ and assume that $\mathcal{F}$ is flat over $S$. Next, we apply Proposition 5.7 to find a diagram as in the statement of the proposition such that $g^*\mathcal{F}/X'/S'$ has a complete dévissage over $s'$. (In particular $S'$ and $X'$ are affine.) By Morphisms, Lemma 24.13 we see that $g^*\mathcal{F}$ is flat over $S$ and by Lemma 2.3 we see that it is flat over $S'$. Via Remark 6.5 we deduce that $\Gamma(X', g^*\mathcal{F})/\Gamma(X', \mathcal{O}_{X'})/\Gamma(S', \mathcal{O}_{S'})$ has a complete dévissage over the prime of $\Gamma(S', \mathcal{O}_{S'})$ corresponding to $s'$. Thus Lemma 12.2 implies that the result of the proposition holds after replacing $S'$ by a standard open neighbourhood of $s'$. $\square$

In the rest of this section we prove a number of variants on this result. The first is a “global” version.

Lemma 12.5. Let $f : X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent sheaf on $X$. Let $s \in S$. Assume that

1. $f$ is of finite presentation,
2. $\mathcal{F}$ is of finite presentation, and
3. $\mathcal{F}$ is flat over $S$ at every point of the fibre $X_s$.

Then there exists an elementary étale neighbourhood $(S', s') \to (S, s)$ and a commutative diagram of schemes

$$
\begin{array}{ccc}
X & & X' \\
\downarrow & & \downarrow \\
S & & S'
\end{array}
$$

such that $g$ is étale, $X_s \subset g(X')$, the schemes $X'$, $S'$ are affine, and such that $\Gamma(X', g^*\mathcal{F})$ is a projective $\Gamma(S', \mathcal{O}_{S'})$-module.

Proof. For every point $x \in X_s$ we can use Proposition 12.4 to find a commutative diagram

$$
\begin{array}{ccc}
(X, x) & & (Y_x, y_x) \\
\downarrow & & \downarrow \\
(S, s) & & (S_x, s_x)
\end{array}
$$
whose horizontal arrows are elementary étale neighbourhoods such that $Y_x, S_x$ are
affine and such that $\Gamma(Y_x, g_x^* F)$ is a projective $\Gamma(S_x, \mathcal{O}_{S_x})$-module. In particular
$g_x(Y_x) \cap X_x$ is an open neighbourhood of $x$ in $X_x$. Because $X_x$ is quasi-compact we
can find a finite number of points $x_1, \ldots, x_n \in X_x$ such that $X_x$ is the union of the $g_x(Y_{x_i}) \cap X_x$. Choose an elementary étale neighbourhood $(S', s') \to (S, s)$ which
dominates each of the neighbourhoods $(S_x, s_x)$, see More on Morphisms, Lemma 31.4. We may also assume that $S'$ is affine. Set $X' = \coprod Y_{x_i} \times_{S_x} S'$ and endow it with the obvious morphism $g : X' \to X$. By construction $g(X')$ contains $X_x$ and

$$\Gamma(X', g^* F) = \bigoplus \Gamma(Y_{x_i}, g_{x_i}^* F) \otimes_{\Gamma(S_x, \mathcal{O}_{S_x})} \Gamma(S', \mathcal{O}_{S'}).$$

This is a projective $\Gamma(S', \mathcal{O}_{S'})$-module, see Algebra, Lemma 93.1. □

The following two lemmas are reformulations of the results above in case $F = \mathcal{O}_X$.

**Lemma 12.6.** Let $f : X \to S$ be locally of finite presentation. Let $x \in X$ with image $s \in S$. If $f$ is flat at $x$ over $S$, then there exists a commutative diagram of pointed schemes

$$(X, x) \leftarrow g \rightarrow (X', x')$$

whose horizontal arrows are elementary étale neighbourhoods such that $X', S'$ are affine and such that $\Gamma(X', \mathcal{O}_{X'})$ is a projective $\Gamma(S', \mathcal{O}_{S'})$-module.

**Proof.** This is a special case of Proposition 12.4. □

**Lemma 12.7.** Let $f : X \to S$ be of finite presentation. Let $s \in S$. If $X$ is flat over $S$ at all points of $X_s$, then there exists an elementary étale neighbourhood $(S', s') \to (S, s)$ and a commutative diagram of schemes

$$X \leftarrow g \rightarrow X'$$

$$(S, s) \leftarrow (S', s')$$

with $g$ étale, $X_s \subset g(X')$, such that $X', S'$ are affine, and such that $\Gamma(X', \mathcal{O}_{X'})$ is a projective $\Gamma(S', \mathcal{O}_{S'})$-module.

**Proof.** This is a special case of Lemma 12.5. □

The following lemmas explain consequences of Proposition 12.4 in case we only assume the morphism and the sheaf are of finite type (and not necessarily of finite presentation).

**Lemma 12.8.** Let $f : X \to S$ be a morphism of schemes. Let $F$ be a quasi-coherent sheaf on $X$. Let $x \in X$ with image $s \in S$. Assume that

1. $f$ is locally of finite presentation,
2. $F$ is of finite type, and
3. $F$ is flat at $x$ over $S$. 

05IE **Lemma 12.6.** Let $f : X \to S$ be locally of finite presentation. Let $x \in X$ with image $s \in S$. If $f$ is flat at $x$ over $S$, then there exists a commutative diagram of pointed schemes

$$(X, x) \leftarrow g \rightarrow (X', x')$$

whose horizontal arrows are elementary étale neighbourhoods such that $X', S'$ are affine and such that $\Gamma(X', \mathcal{O}_{X'})$ is a projective $\Gamma(S', \mathcal{O}_{S'})$-module.

**Proof.** This is a special case of Proposition 12.4. □

05KX **Lemma 12.7.** Let $f : X \to S$ be of finite presentation. Let $s \in S$. If $X$ is flat over $S$ at all points of $X_s$, then there exists an elementary étale neighbourhood $(S', s') \to (S, s)$ and a commutative diagram of schemes

$$X \leftarrow g \rightarrow X'$$

$$(S, s) \leftarrow (S', s')$$

with $g$ étale, $X_s \subset g(X')$, such that $X', S'$ are affine, and such that $\Gamma(X', \mathcal{O}_{X'})$ is a projective $\Gamma(S', \mathcal{O}_{S'})$-module.

**Proof.** This is a special case of Lemma 12.5. □

05KY **Lemma 12.8.** Let $f : X \to S$ be a morphism of schemes. Let $F$ be a quasi-coherent sheaf on $X$. Let $x \in X$ with image $s \in S$. Assume that

1. $f$ is locally of finite presentation,
2. $F$ is of finite type, and
3. $F$ is flat at $x$ over $S$. 

The following lemmas explain consequences of Proposition 12.4 in case we only assume the morphism and the sheaf are of finite type (and not necessarily of finite presentation).
Then there exists an elementary étale neighbourhood \((S', s') \to (S, s)\) and a commutative diagram of pointed schemes

\[
\begin{array}{ccc}
(X, x) & \xrightarrow{g} & (X', x') \\
\downarrow & & \downarrow \\
(S, s) & \xleftarrow{(\text{Spec}(\mathcal{O}_{S', s'}), s')} & (S, s)
\end{array}
\]

such that \(X' \to X \times_S \text{Spec}(\mathcal{O}_{S', s'})\) is étale, \(\kappa(x) = \kappa(x')\), the scheme \(X'\) is affine of finite presentation over \(\mathcal{O}_{S', s'}\), the sheaf \(g^*F\) is of finite presentation over \(\mathcal{O}_{X'}\), and such that \(\Gamma(X', g^*F)\) is a free \(\mathcal{O}_{S', s'}\)-module.

**Proof.** To prove the lemma we may replace \((S, s)\) by any elementary étale neighbourhood, and we may also replace \(S\) by \(\text{Spec}(\mathcal{O}_{S, s})\). Hence by Proposition 10.3 we may assume that \(F\) is finitely presented and flat over \(S\) in a neighbourhood of \(x\). In this case the result follows from Proposition 12.4 because Algebra, Theorem 84.4 assures us that projective = free over a local ring. \(\Box\)

**Lemma 12.9.** Let \(f : X \to S\) be a morphism of schemes. Let \(F\) be a quasi-coherent sheaf on \(X\). Let \(x \in X\) with image \(s \in S\). Assume that

1. \(f\) is locally of finite type,
2. \(F\) is of finite type, and
3. \(F\) is flat at \(x\) over \(S\).

Then there exists an elementary étale neighbourhood \((S', s') \to (S, s)\) and a commutative diagram of pointed schemes

\[
\begin{array}{ccc}
(X, x) & \xrightarrow{g} & (X', x') \\
\downarrow & & \downarrow \\
(S, s) & \xleftarrow{(\text{Spec}(\mathcal{O}_{S', s'}), s')} & (S, s)
\end{array}
\]

such that \(X' \to X \times_S \text{Spec}(\mathcal{O}_{S', s'})\) is étale, \(\kappa(x) = \kappa(x')\), the scheme \(X'\) is affine, and such that \(\Gamma(X', g^*F)\) is a free \(\mathcal{O}_{S', s'}\)-module.

**Proof.** (The only difference with Lemma 12.8 is that we do not assume \(f\) is of finite presentation.) The problem is local on \(X\) and \(S\). Hence we may assume \(X\) and \(S\) are affine, say \(X = \text{Spec}(B)\) and \(S = \text{Spec}(A)\). Since \(B\) is a finite type \(A\)-algebra we can find a surjection \(A[x_1, \ldots, x_n] \to B\). In other words, we can choose a closed immersion \(i : X \to \mathbb{A}^n_S\). Set \(t = i(x)\) and \(G = i_*F\). Note that \(G_t \cong F_x\) are \(\mathcal{O}_{S, s}\)-modules. Hence \(G\) is flat over \(S\) at \(t\). We apply Lemma 12.8 to the morphism \(\mathbb{A}^n_S \to S\), the point \(t\), and the sheaf \(G\). Thus we can find an elementary étale neighbourhood \((S', s') \to (S, s)\) and a commutative diagram of pointed schemes

\[
\begin{array}{ccc}
(\mathbb{A}^n_S, t) & \xleftarrow{h} & (Y, y) \\
\downarrow & & \downarrow \\
(S, s) & \xleftarrow{(\text{Spec}(\mathcal{O}_{S', s'}), s')} & (S, s)
\end{array}
\]

such that \(Y \to \mathbb{A}^n_{S', s'}\) is étale, \(\kappa(t) = \kappa(y)\), the scheme \(Y\) is affine, and such that \(\Gamma(Y, h^*G)\) is a projective \(\mathcal{O}_{S', s'}\)-module. Then a solution to the original problem is given by the closed subscheme \(X' = Y \times_{\mathbb{A}^n_S} X\) of \(Y\). \(\Box\)
Lemma 12.10. Let $f : X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent sheaf on $X$. Let $s \in S$. Assume that

1. $f$ is of finite presentation,
2. $\mathcal{F}$ is of finite type, and
3. $\mathcal{F}$ is flat over $S$ at all points of $X_s$.

Then there exists an elementary étale neighbourhood $(S', s') \to (S, s)$ and a commutative diagram of schemes

$$
\begin{array}{ccc}
X & \leftarrow & X' \\
\downarrow & & \downarrow \\
S & \leftarrow & \text{Spec}(O_{S', s'})
\end{array}
$$

such that $X' \to X \times_S \text{Spec}(O_{S', s'})$ is étale, $X_s = g((X')_{s'})$, the scheme $X'$ is affine of finite presentation over $O_{S', s'}$, the sheaf $g^* \mathcal{F}$ is of finite presentation over $O_{X'}$, and such that $\Gamma(X', g^* \mathcal{F})$ is a free $O_{S', s'}$-module.

Proof. For every point $x \in X_s$ we can use Lemma 12.8 to find an elementary étale neighbourhood $(S_x, s_x) \to (S, s)$ and a commutative diagram

$$
\begin{array}{ccc}
(X, x) & \leftarrow & (Y_x, y_x) \\
\downarrow & & \downarrow \\
(S, s) & \leftarrow & \text{Spec}(O_{S_x, s_x}, s_x)
\end{array}
$$

such that $Y_x \to X \times_S \text{Spec}(O_{S_x, s_x})$ is étale, $\kappa(x) = \kappa(y_x)$, the scheme $Y_x$ is affine of finite presentation over $O_{S_x, s_x}$, the sheaf $g_x^* \mathcal{F}$ is of finite presentation over $O_{Y_x}$, and such that $\Gamma(Y_x, g_x^* \mathcal{F})$ is a free $O_{S_x, s_x}$-module. In particular $g_x((Y_x)_{s_x})$ is an open neighbourhood of $x$ in $X_s$. Because $X_s$ is quasi-compact we can find a finite number of points $x_1, \ldots, x_n \in X_s$ such that $X_s$ is the union of the $g_x((Y_x)_{s_x})$. Choose an elementary étale neighbourhood $(S', s') \to (S, s)$ which dominates each of the neighbourhoods $(S_{x_i}, s_{x_i})$, see More on Morphisms, Lemma 31.4.

Set

$$
X' = \coprod Y_{x_i} \times_{\text{Spec}(O_{S_{x_i}, s_{x_i}})} \text{Spec}(O_{S', s'});
$$

and endow it with the obvious morphism $g : X' \to X$. By construction $X_s = g(X'_{s'})$ and

$$
\Gamma(X', g^* \mathcal{F}) = \bigoplus \Gamma(Y_{x_i}, g_{x_i}^* \mathcal{F}) \otimes_{O_{S_{x_i}, s_{x_i}}} O_{S', s'}.
$$

This is a free $O_{S', s'}$-module as a direct sum of base changes of free modules. Some minor details omitted. \qed

Lemma 12.11. Let $f : X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent sheaf on $X$. Let $s \in S$. Assume that

1. $f$ is of finite type,
2. $\mathcal{F}$ is of finite type, and
3. $\mathcal{F}$ is flat over $S$ at all points of $X_s$.
Then there exists an elementary étale neighbourhood \((S', s') \to (S, s)\) and a commutative diagram of schemes

\[
\begin{array}{ccc}
X' & \rightarrow & Y' \\
\downarrow & & \downarrow \\
S & \leftarrow & \text{Spec}(O_{S', s'})
\end{array}
\]

such that \(X' \rightarrow X \times_S \text{Spec}(O_{S', s'})\) is étale, \(X_s = g((X')_{s'})\), the scheme \(X'\) is affine, and such that \(\Gamma(X', g^* F)\) is a free \(O_{S', s'}\)-module.

**Proof.** (The only difference with Lemma \[\ref{12.10}\] is that we do not assume \(f\) is of finite presentation.) For every point \(x \in X_s\) we can use Lemma \[\ref{12.9}\] to find an elementary étale neighbourhood \((S_x, s_x) \to (S, s)\) and a commutative diagram

\[
\begin{array}{ccc}
(X, x) & \rightarrow & (Y, y) \\
\downarrow & & \downarrow \\
(S, s) & \leftarrow & \text{Spec}(O_{S_x, s_x}, s_x)
\end{array}
\]

such that \(Y_x \rightarrow X \times_S \text{Spec}(O_{S_x, s_x})\) is étale, \(\kappa(x) = \kappa(y)\), the scheme \(Y_x\) is affine, and such that \(\Gamma(Y_x, g_x^* F)\) is a free \(O_{S_x, s_x}\)-module. In particular \(g_x((Y_x)_{s_x})\) is an open neighbourhood of \(x\) in \(X_s\). Because \(X_s\) is quasi-compact we can find a finite number of points \(x_1, \ldots, x_n \in X_s\) such that \(X_s\) is the union of the \(g_x, ((Y_x)_{s_x})\). Choose an elementary étale neighbourhood \((S'_i, s'_i) \to (S, s)\) which dominates each of the neighbourhoods \((S_{x_i}, s_{x_i})\), see More on Morphisms, Lemma \[\ref{31.4}\].

Set

\[
X' = \coprod_{x_i} Y_{x_i} \times_{\text{Spec}(O_{S_{x_i}, s_{x_i}})} \text{Spec}(O_{S', s'})
\]

and endow it with the obvious morphism \(g : X' \to X\). By construction \(X_s = g(X'_s)\) and

\[
\Gamma(X', g^* F) = \bigoplus \Gamma(Y_{x_i}, g_x^* F) \otimes_{O_{S_{x_i}, s_{x_i}}} O_{S', s'}.
\]

This is a free \(O_{S', s'}\)-module as a direct sum of base changes of free modules. \qed

### 13. Flat finite type modules, Part II

**Lemma 13.1.** Let \(R \to S\) be a ring map of finite presentation. Let \(N\) be a finitely presented \(S\)-module. Let \(q \subset S\) be a prime ideal lying over \(p \subset R\). Set \(\overline{S} = S \otimes_R \kappa(p), \overline{q} = q \overline{S}, \text{ and } \overline{N} = N \otimes_R \kappa(p)\). Then we can find a \(g \in S\) with \(g \not\in q\) such that \(\overline{g} \in r\) for all \(r \in \overline{N}\) such that \(r \not\in \overline{q}\).

**Proof.** Namely, if \(\text{Ass}_{\overline{S}}(\overline{N}) = \{r_1, \ldots, r_n\}\) (finiteness by Algebra, Lemma \[\ref{62.5}\]), then after renumbering we may assume that

\[
\begin{align*}
&\{r_1, \ldots, r_r\} \subset \overline{q}, \\
&\{r_{r+1}, \ldots, r_n\} \not\subset \overline{q}
\end{align*}
\]

Since \(\overline{q}\) is a prime ideal we see that the product \(r_{r+1} \ldots r_n\) is not contained in \(\overline{q}\) and hence we can pick an element \(a\) of \(\overline{S}\) contained in \(r_{r+1} \ldots r_n\) but not in \(\overline{q}\). If there exists \(g \in S\) mapping to \(a\), then \(g\) works. In general we can find a nonzero element \(\lambda \in \kappa(p)\) such that \(\lambda a\) is the image of a \(g \in S\). \qed

The following lemma has a slightly stronger variant Lemma \[\ref{13.4}\] below.
Lemma 13.2. Let $R \to S$ be a ring map of finite presentation. Let $N$ be a finitely presented $S$-module which is flat as an $R$-module. Let $M$ be an $R$-module. Let $q$ be a prime of $S$ lying over $p \subset R$. Then
\[ q \in \text{WeakAss}_S(M \otimes_R N) \iff (p \in \text{WeakAss}_R(M) \text{ and } \overline{q} \in \text{Ass}_S(N)) \]
Here $\overline{S} = S \otimes_R \kappa(p)$, $\overline{q} = q\overline{S}$, and $\overline{N} = N \otimes_R \kappa(p)$.

Proof. Pick $g \in S$ as in Lemma 13.1. Apply Proposition 12.4 to the morphism of schemes $\text{Spec}(S_g) \to \text{Spec}(R)$, the quasi-coherent module associated to $N_g$, and the points corresponding to the primes $qS_g$ and $p$. Translating into algebra we obtain a commutative diagram of rings
\[
\begin{array}{ccc}
S & \to & S_g \\
\downarrow & & \downarrow \\
R & \to & R'
\end{array}
\begin{array}{ccc}
q & & qS_g \\
\downarrow & & \downarrow \\
p & & p'
\end{array}
\]
edowed with primes as shown, the horizontal arrows are étale, and $N \otimes_S S'$ is projective as an $R'$-module. Set $N' = N \otimes_S S'$, $M' = M \otimes_R R'$, $\overline{S}' = S' \otimes_R \kappa(q')$, $\overline{q}' = q'\overline{S}'$, and $\overline{N}' = N' \otimes_{R'} \kappa(p') = \overline{N} \otimes_{\overline{S}} \overline{S}'$.

By Lemma 2.8 we have
\[
\text{WeakAss}_{S'}(M' \otimes_{R'} N') = (\text{Spec}(S') \to \text{Spec}(S))^{-1}\text{WeakAss}_S(M \otimes_R N) \\
\text{WeakAss}_{R'}(M') = (\text{Spec}(R') \to \text{Spec}(R))^{-1}\text{WeakAss}_R(M) \\
\text{Ass}_{S'}(\overline{N}') = (\text{Spec}(S') \to \text{Spec}(S))^{-1}\text{Ass}_S(\overline{N})
\]
Use Algebra, Lemma 65.9 for $\overline{N}$ and $\overline{N}'$. In particular we have
\[
q \in \text{WeakAss}_S(M \otimes_R N) \iff q' \in \text{WeakAss}_{S'}(M' \otimes_{R'} N') \\
p \in \text{WeakAss}_R(M) \iff p' \in \text{WeakAss}_{R'}(M') \\
\overline{q} \in \text{Ass}_S(\overline{N}) \iff \overline{q}' \in \text{Ass}_{S'}(\overline{N}')
\]
Our careful choice of $g$ and the formula for $\text{Ass}_{S'}(\overline{N}')$ above shows that

if $\overline{r}' \in \text{Ass}_{S'}(\overline{N}')$ lies over $\overline{r} \subset \overline{S}$ then $\overline{r} \subset \overline{q}$

This will be a key observation later in the proof. We will use the characterization of weakly associated primes given in Algebra, Lemma 65.2 without further mention.

Suppose that $\overline{q} \not\in \text{Ass}_S(\overline{N})$. Then $\overline{q}' \not\in \text{Ass}_{S'}(\overline{N}')$. By Algebra, Lemma 62.9, 62.5, and 14.2 there exists an element $\overline{a}' \in \overline{q}'$ which is not a zero divisor on $\overline{N}'$. After replacing $\overline{a}'$ by $\lambda \overline{a}'$ for some nonzero $\lambda \in \kappa(p)$ we can find $a' \in q'$ mapping to $\overline{a}'$. By Lemma 7.6 the map $a' : N'_{p'} \to N'_{p'}$ is $R'_{p'}$-universally injective. In particular we see that $a' : M' \otimes_{R'} N' \to M' \otimes_{R'} N'$ is injective after localizing at $p'$ and hence after localizing at $q'$. Clearly this implies that $q' \not\in \text{WeakAss}_{S'}(M' \otimes_{R'} N')$. We conclude that $q \in \text{WeakAss}_S(M \otimes_R N)$ implies $\overline{q} \in \text{Ass}_S(\overline{N})$.

Assume $q \in \text{WeakAss}_S(M \otimes_R N)$. We want to show $p \in \text{WeakAss}_S(M)$. Let $z \in M \otimes_R N$ be an element such that $q$ is minimal over $J = \text{Ann}_S(z)$. Let $f_i \in p$, $i \in I$ be a set of generators of the ideal $p$. Since $q$ lies over $p$, for every $i$ we
can choose an $n_i \geq 1$ and $g_i \in S$, $g_i \not\in q$ with $g_i f_i^{n_i} \in J$, i.e., $g_i f_i^{n_i} z = 0$. Let $z' \in (M' \otimes_{R'} N')_{p'}$ be the image of $z$. Observe that $z'$ is nonzero because $z$ has nonzero image in $(M \otimes_R N)_q$ and because $S_q \to S'_q$ is faithfully flat. We claim that $f_i^{n_i} z' = 0$.

Proof of the claim: Let $q'_i \in S'$ be the image of $g_i$. By the key observation we find that the image $\tilde{g}_i \in S$ is not contained in $\tilde{r}'$ for any $\tilde{r}' \in \text{Ass}_{\tilde{S}}(N)$. Hence by Lemma 7.6 we see that $q'_i : N'_p \to N'_p$ is $R'_p$-universally injective. In particular we see that $g_i : M' \otimes_{R'} N' \to M' \otimes_{R'} N'$ is injective after localizing at $p'$. The claim follows because $g_i f_i^{n_i} z' = 0$.

Our claim shows that the annihilator of $z'$ in $R'_{p'}$ contains the elements $f_i^{n_i}$. As $R \to R'$ is étale we have $p' R'_{p'} = p R'_{p'}$ by Algebra, Lemma 142.5. Hence the annihilator of $z'$ in $R'_{p'}$ has radical equal to $p' R'_{p'}$ (here we use $z'$ is not zero). On the other hand

$z' \in (M' \otimes_{R'} N')_{p'} = M'_{p'} \otimes_{R'_{p'}} N'_{p'}$

The module $N'_{p'}$ is projective over the local ring $R'_{p'}$ and hence free (Algebra, Theorem 84.4). Thus we can find a finite free direct summand $F' \subset N_{p'}$ such that $z' \in M'_{p'} \otimes_{R'_{p'}} F'$. If $F'$ has rank $n$, then we deduce that $p' R'_p \in \text{WeakAss}_{R'_p}(M'_{p'} \otimes_{R'}^\wedge n)$.

This implies $p' R'_p \in \text{WeakAss}(M'_{p'})$ for example by Algebra, Lemma 85.4. Then $p' \in \text{WeakAss}_{R'_{p'}}(M')$ which in turn gives $p \in \text{WeakAss}_R(M)$. This finishes the proof of the implication “$\Rightarrow$” of the equivalence of the lemma.

Assume that $p \in \text{WeakAss}_R(M)$ and $\overline{q} \in \text{Ass}_{\tilde{S}}(N)$. We want to show that $q$ is weakly associated to $M \otimes_R N$. Note that $\overline{q}$ is a maximal element of $\text{Ass}_{\tilde{S}}(N')$. This is a consequence of (13.2.1) and the fact that there are no inclusions among the primes of $\tilde{S}$ lying over $\overline{q}$ (as fibres of étale morphisms are discrete Morphisms, Lemma 34.7). Thus, after replacing $R, S, p, q, M, N$ by $R', S', p', q', M', N'$ we may assume, in addition to the assumptions of the lemma, that

1. $p \in \text{WeakAss}_R(M)$,
2. $\overline{q} \in \text{Ass}_{\tilde{S}}(N)$,
3. $N$ is projective as an $R$-module, and
4. $\overline{q}$ is maximal in $\text{Ass}_{\tilde{S}}(N)$.

There is one more reduction, namely, we may replace $R, S, M, N$ by their localizations at $p$. This leads to one more condition, namely,

5. $R$ is a local ring with maximal ideal $\mathfrak{p}$.

We will finish by showing that (1) – (5) imply $q \in \text{WeakAss}(M \otimes_R N)$.

Since $R$ is local and $p \in \text{WeakAss}_R(M)$ we can pick a $y \in M$ whose annihilator $I$ has radical equal to $p$. Write $\overline{q} = (\overline{g}_1, \ldots, \overline{g}_n)$ for some $\overline{g}_i \in \overline{S}$. Choose $g_i \in S$ mapping to $\overline{g}_i$. Then $q = p S + g_1 S + \ldots + g_n S$. Consider the map

$\Psi : N/I N \longrightarrow (N/I N)^{\otimes n}, \quad z \longmapsto (g_1 z, \ldots, g_n z)$

This is a homomorphism of projective $R/I$-modules. The local ring $R/I$ is automatically associated (More on Algebra, Definition 15.1) as $p/I$ is locally nilpotent. The map $\Psi \otimes \kappa(p)$ is not injective, because $\overline{q} \in \text{Ass}_{\tilde{S}}(N)$. Hence More on Algebra, Lemma 15.4 implies $\Psi$ is not injective. Pick $z \in N/I N$ nonzero in the kernel of $\Psi$. The annihilator $J = \text{Ann}_S(z)$ contains $IS$ and $g_i$ by construction. Thus $\sqrt{J} \subset S$ contains $q$. Let $s \subset S$ be a prime minimal over $J$. Then $q \subset s$, $s$ lies over $p$, and
Let \( q \in \text{WeakAss}_S(N/IN) \). The last fact by definition of weakly associated primes. Apply the “\( \Rightarrow \)" part of the lemma (which we've already proven) to the ring map \( R \to S \) and the modules \( R/I \) and \( N \) to conclude that \( q \in \text{Ass}_S(N/IN) \). Since \( \overline{q} \subset \overline{r} \) the maximality of \( \overline{q} \), see condition (4) above, implies that \( \overline{q} = \overline{r} \). This shows that \( q = r \) and we conclude what we want. \( \square \)

**Lemma 13.3.** Let \( S \) be a scheme. Let \( f : X \to S \) be locally of finite type. Let \( x \in X \) with image \( s \in S \). Let \( F \) be a finite type quasi-coherent sheaf on \( X \). Let \( G \) be a quasi-coherent sheaf on \( S \). If \( F \) is flat at \( x \) over \( S \), then

\[
\exists \in \text{WeakAss}_X(F \otimes_{\mathcal{O}_X} f^*G) \iff \exists \in \text{WeakAss}_S(G) \text{ and } \exists \in \text{Ass}_X(F_x).
\]

**Proof.** In this paragraph we reduce to \( f \) being of finite presentation. The question is local on \( X \) and \( S \), hence we may assume \( X \) and \( S \) are affine. Write \( X = \text{Spec}(B) \) and \( S = \text{Spec}(A) \) and write \( B = A[x_1, \ldots, x_n]/I \). In other words we obtain a closed immersion \( i : X \to \mathbb{A}^n_S \) over \( S \). Denote \( t = i(x) \in \mathbb{A}^n_S \). Note that \( j_*F \) is a finite type quasi-coherent sheaf on \( \mathbb{A}^n_S \) which is flat at \( t \) over \( S \) and note that

\[
j_*((F \otimes_{\mathcal{O}_X} f^*G)) = j_*F \otimes_{\mathcal{O}_{\mathbb{A}^n_S}} p^*G
\]

where \( p : \mathbb{A}^n_S \to S \) is the projection. Note that \( t \) is a weakly associated point of \( j_*F \otimes_{\mathcal{O}_{\mathbb{A}^n_S}} f^*G \) if and only if \( x \) is a weakly associated point of \( F \otimes_{\mathcal{O}_X} f^*G \), see Divisors, Lemma 6.3. Similarly \( x \in \text{Ass}_X(F_x) \) if and only if \( t \in \text{Ass}_{\mathbb{A}^n_S}((j_*F)_t) \) (see Algebra, Lemma 62.14). Hence it suffices to prove the lemma in case \( X = \mathbb{A}^n_S \). Thus we may assume that \( X \to S \) is of finite presentation.

In this paragraph we reduce to \( F \) being of finite presentation and flat over \( S \). Choose an elementary étale neighbourhood \( e : (S', s') \to (S, s) \) and an open \( V \subset X \times_S \text{Spec}(\mathcal{O}_{S', s'}) \) as in Proposition 10.3. Let \( x' \in X' = X \times_S S' \) be the unique point mapping to \( x \) and \( s' \). Then it suffices to prove the statement for \( X' \to S', \ x', \ s', (X' \to X)^*F, \) and \( e^*G \), see Lemma 2.4. Let \( v \in V \) the unique point mapping to \( x' \) and let \( s' \in \text{Spec}(\mathcal{O}_{S', s'}) \) be the closed point. Then \( \mathcal{O}_{V, v} = \mathcal{O}_{X', x'} \) and \( \mathcal{O}_{\text{Spec}(\mathcal{O}_{S', s'})} \mathcal{O}_{S', s'} = \mathcal{O}_{S', s'} \) and similarly for the stalks of pullbacks of \( F \) and \( G \). Also \( V_s \subset X'_{s'} \) is an open subscheme. Since the condition of being a weakly associated point depend only on the stalk of the sheaf, we may replace \( X' \to S', \ x', \ s', (X' \to X)^*F, \) and \( e^*G \) by \( V \to \text{Spec}(\mathcal{O}_{S', s'}) \), \( v, \ s', (V \to X)^*F, \) and \( (\text{Spec}(\mathcal{O}_{S', s'}) \to S)^*G \). Thus we may assume that \( f \) is of finite presentation and \( F \) of finite presentation and flat over \( S \).

Assume \( f \) is of finite presentation and \( F \) of finite presentation and flat over \( S \). After shrinking \( X \) and \( S \) to affine neighbourhoods of \( x \) and \( s \), this case is handled by Lemma 13.2. \( \square \)

**Lemma 13.4.** Let \( R \to S \) be a ring map which is essentially of finite type. Let \( N \) be a localization of a finite \( S \)-module flat over \( R \). Let \( M \) be an \( R \)-module. Then

\[
\text{WeakAss}_S(M \otimes_R N) = \bigcup_{p \in \text{WeakAss}_R} \text{Ass}_{S \otimes_R \kappa(p)}(N \otimes_R \kappa(p))
\]

**Proof.** This lemma is a translation of Lemma 13.3 into algebra. Details of translation omitted. \( \square \)

**Lemma 13.5.** Let \( f : X \to S \) be a morphism which is locally of finite type. Let \( F \) be a finite type quasi-coherent sheaf on \( X \) which is flat over \( S \). Let \( G \) be a
quasi-coherent sheaf on $S$. Then we have

$$\text{WeakAss}_X(\mathcal{F} \otimes_{\mathcal{O}_X} f^* \mathcal{G}) = \bigcup_{s \in \text{WeakAss}_{\mathcal{O}_S}(\mathcal{G})} \text{Ass}_{X_s}(\mathcal{F}_s)$$

**Proof.** Immediate consequence of Lemma 13.3. □

**Theorem 13.6.** Let $f : X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module. Assume

1. $X \to S$ is locally of finite presentation,
2. $\mathcal{F}$ is an $\mathcal{O}_X$-module of finite type, and
3. the set of weakly associated points of $S$ is locally finite in $S$.

Then $U = \{ x \in X \mid \mathcal{F} \text{ flat at } x \text{ over } S \}$ is open in $X$ and $\mathcal{F}|_U$ is an $\mathcal{O}_U$-module of finite presentation and flat over $S$.

**Proof.** Let $x \in X$ be such that $\mathcal{F}$ is flat at $x$ over $S$. We have to find an open neighbourhood of $x$ such that $\mathcal{F}$ restricts to a $S$-flat finitely presented module on this neighbourhood. The problem is local on $X$ and $S$, hence we may assume that $X$ and $S$ are affine. As $\mathcal{F}_x$ is a finitely presented $\mathcal{O}_{X,x}$-module by Lemma 10.9 we conclude from Algebra, Lemma 125.5 there exists a finitely presented $\mathcal{O}_X$-module $\mathcal{F}'$ and a map $\varphi : \mathcal{F}' \to \mathcal{F}$ which induces an isomorphism $\varphi_x : \mathcal{F}'_x \to \mathcal{F}_x$. In particular we see that $\mathcal{F}'$ is flat over $S$ at $x$, hence by openness of flatness More on Morphisms, Theorem 15.1 we see that after shrinking $X$ we may assume that $\mathcal{F}'$ is flat over $S$. As $\mathcal{F}$ is of finite type after shrinking $X$ we may assume that $\varphi$ is surjective, see Modules, Lemma 9.4 or alternatively use Nakayama’s lemma (Algebra, Lemma 19.1). By Lemma 13.5 we have

$$\text{WeakAss}_X(\mathcal{F}') \subseteq \bigcup_{s \in \text{WeakAss}(S)} \text{Ass}_{X_s}(\mathcal{F}'_s)$$

As $\text{WeakAss}(S)$ is finite by assumption and since $\text{Ass}_{X_s}(\mathcal{F}'_s)$ is finite by Divisors, Lemma 2.5 we conclude that $\text{WeakAss}_X(\mathcal{F}')$ is finite. Using Algebra, Lemma 14.2 we may, after shrinking $X$ once more, assume that $\text{WeakAss}_X(\mathcal{F}')$ is contained in the generalization of $x$. Now consider $K = \text{Ker}(\varphi)$. We have $\text{WeakAss}_X(K) \subseteq \text{WeakAss}_X(\mathcal{F}')$ (by Divisors, Lemma 5.4) but on the other hand, $\varphi_x$ is an isomorphism, also $\varphi_{x'}$ is an isomorphism for all $x' \sim x$. We conclude that $\text{WeakAss}_X(K) = \emptyset$ whence $K = 0$ by Divisors, Lemma 5.5. □

**Lemma 13.7.** Let $R \to S$ be a ring map of finite presentation. Let $M$ be a finite $S$-module. Assume $\text{WeakAss}(S)$ is finite. Then

$$U = \{ q \in S \mid M_q \text{ flat over } R \}$$

is open in $\text{Spec}(S)$ and for every $g \in S$ such that $D(g) \subseteq U$ the localization $M_g$ is a finitely presented $S_q$-module flat over $R$.

**Proof.** Follows immediately from Theorem 13.6. □

**Lemma 13.8.** Let $f : X \to S$ be a morphism of schemes which is locally of finite type. Assume the set of weakly associated points of $S$ is locally finite in $S$. Then the set of points $x \in X$ where $f$ is flat is an open subscheme $U \subseteq X$ and $U \to S$ is flat and locally of finite presentation.

**Proof.** The problem is local on $X$ and $S$, hence we may assume that $X$ and $S$ are affine. Then $X \to S$ corresponds to a finite type ring map $A \to B$. Choose
a surjection $A[x_1, \ldots, x_n] \to B$ and consider $B$ as an $A[x_1, \ldots, x_n]$-module. An application of Lemma 13.7 finishes the proof. □

**Lemma 13.9.** Let $f : X \to S$ be a morphism of schemes which is locally of finite type and flat. If $S$ is integral, then $f$ is locally of finite presentation.

**Proof.** Special case of Lemma 13.8. □

**Proposition 13.10.** Let $R$ be a domain. Let $R \to S$ be a ring map of finite type. Let $M$ be a finite $S$-module.

(1) If $S$ is flat over $R$, then $S$ is a finitely presented $R$-algebra.

(2) If $M$ is flat as an $R$-module, then $M$ is finitely presented as an $S$-module.

**Proof.** Part (1) is a special case of Lemma 13.9. For Part (2) choose a surjection $R[x_1, \ldots, x_n] \to S$. By Lemma 13.7 we find that $M$ is finitely presented as an $R[x_1, \ldots, x_n]$-module. We conclude by Algebra, Lemma 6.4. □

**Remark 13.11 (Finite type version of Theorem 13.6).** Let $f : X \to S$ be a morphism of schemes. Let $F$ be a quasi-coherent $\mathcal{O}_X$-module. Assume

(1) $X \to S$ is locally of finite type,

(2) $F$ is an $\mathcal{O}_X$-module of finite type, and

(3) the set of weakly associated points of $S$ is locally finite in $S$.

Then $U = \{x \in X \mid F$ flat at $x$ over $S\}$ is open in $X$ and $F|_U$ is flat over $S$ and locally finitely presented relative to $S$ (see More on Morphisms, Definition 50.1). If we ever need this result in the Stacks project we will convert this remark into a lemma with a proof.

**Remark 13.12 (Algebra version of Remark 13.11).** Let $R \to S$ be a ring map of finite type. Let $M$ be a finite $S$-module. Assume WeakAss$_R(R)$ is finite. Then $U = \{q \subset S \mid M_q$ flat over $R\}$ is open in Spec($S$) and for every $g \in S$ such that $D(g) \subset U$ the localization $M_q$ is flat over $R$ and an $S_g$-module finitely presented relative to $R$ (see More on Algebra, Definition 74.2). If we ever need this result in the Stacks project we will convert this remark into a lemma with a proof.

14. Examples of relatively pure modules

In the short section we discuss some examples of results that will serve as motivation for the notion of a relatively pure module and the concept of an impurity which we will introduce later. Each of the examples is stated as a lemma. Note the similarity with the condition on associated primes to the conditions appearing in Lemmas 7.4, 8.3, 8.4, and 9.1. See also Algebra, Lemma 64.1 for a discussion.

**Lemma 14.1.** Let $R$ be a local ring with maximal ideal $m$. Let $R \to S$ be a ring map. Let $N$ be an $S$-module. Assume

(1) $N$ is projective as an $R$-module, and

(2) $S/mS$ is Noetherian and $N/mN$ is a finite $S/mS$-module.

Then for any prime $q \subset S$ which is an associated prime of $N \otimes_R \kappa(p)$ where $p = R \cap q$ we have $q + mS \neq S$. 


Proof. Note that the hypotheses of Lemmas 7.1 and 7.6 are satisfied. We will use the conclusions of these lemmas without further mention. Let $\Sigma \subset S$ be the multiplicative set of elements which are not zerodivisors on $N/\mathfrak{m}N$. The map $N \to \Sigma^{-1}N$ is $R$-universally injective. Hence we see that any $q \subset S$ which is an associated prime of $N \otimes_R \kappa(p)$ is also an associated prime of $\Sigma^{-1}N \otimes_R \kappa(p)$. Clearly this implies that $q$ corresponds to a prime of $\Sigma^{-1}S$. Thus $q \subset q'$ where $q'$ corresponds to an associated prime of $N/\mathfrak{m}N$ and we win. □

The following lemma gives another (slightly silly) example of this phenomenon.

**Lemma 14.2.** Let $R$ be a ring. Let $I \subset R$ be an ideal. Let $R \to S$ be a ring map. Let $N$ be an $S$-module. If $N$ is $I$-adically complete, then for any $R$-module $M$ and for any prime $q \subset S$ which is an associated prime of $N \otimes_R M$ we have $q + IS \neq S$.

**Proof.** Let $S^\wedge$ denote the $I$-adic completion of $S$. Note that $N$ is an $S^\wedge$-module, hence also $N \otimes_R M$ is an $S^\wedge$-module. Let $z \in N \otimes_R M$ be an element such that $q = \text{Ann}_S(z)$. Since $z \neq 0$ we see that $\text{Ann}_{S^\wedge}(z) \neq S^\wedge$. Hence $qS^\wedge \neq S^\wedge$. Hence there exists a maximal ideal $m \subset S^\wedge$ with $qS^\wedge \subset m$. Since $IS^\wedge \subset m$ by Algebra, Lemma 95.6 we win. □

Note that the following lemma gives an alternative proof of Lemma 14.1 as a projective module over a local ring is free, see Algebra, Theorem 84.4.

**Lemma 14.3.** Let $R$ be a local ring with maximal ideal $m$. Let $R \to S$ be a ring map. Let $N$ be an $S$-module. Assume $N$ is isomorphic as an $R$-module to a direct sum of finite $R$-modules. Then for any $R$-module $M$ and for any prime $q \subset S$ which is an associated prime of $N \otimes_R M$ we have $q + mS \neq S$.

**Proof.** Write $N = \bigoplus_{i \in I} M_i$ with each $M_i$ a finite $R$-module. Let $M$ be an $R$-module and let $q \subset S$ be an associated prime of $N \otimes_R M$ such that $q + mS = S$. Let $z \in N \otimes_R M$ be an element with $q = \text{Ann}_S(z)$. After modifying the direct sum decomposition a little bit we may assume that $z \in M_1 \otimes_R M$ for some element $1 \in I$. Write $1 = f + \sum x_j g_j$ for some $f \in q, x_j \in m$, and $g_j \in S$. For any $g \in S$ denote $g'$ the $R$-linear map

$$M_1 \to N \xrightarrow{g} N \to M_1$$

where the first arrow is the inclusion map, the second arrow is multiplication by $g$ and the third arrow is the projection map. Because each $x_j \in R$ we obtain the equality

$$f' + \sum x_j g'_j = \text{id}_{M_i} \in \text{End}_R(M_1)$$

By Nakayama’s lemma (Algebra, Lemma 19.1) we see that $f'$ is surjective, hence by Algebra, Lemma 15.4 we see that $f'$ is an isomorphism. In particular the map

$$M_1 \otimes_R M \to N \otimes_R M \xrightarrow{f} N \otimes_R M \to M_1 \otimes_R M$$

is an isomorphism. This contradicts the assumption that $fz = 0$. □

**Lemma 14.4.** Let $R$ be a henselian local ring with maximal ideal $m$. Let $R \to S$ be a ring map. Let $N$ be an $S$-module. Assume $N$ is countably generated and Mittag-Leffler as an $R$-module. Then for any $R$-module $M$ and for any prime $q \subset S$ which is an associated prime of $N \otimes_R M$ we have $q + mS \neq S$.

**Proof.** This lemma reduces to Lemma 14.3 by Algebra, Lemma 149.13. □
Suppose \( f : X \to S \) is a morphism of schemes and \( \mathcal{F} \) is a quasi-coherent module on \( X \). Let \( \xi \in \text{Ass}_{X/S}(\mathcal{F}) \) and let \( Z = \{ \xi \} \). Picture

\[
\begin{array}{ccc}
\xi & \to & X \\
\downarrow & & \downarrow f \\
\{ \xi \} & \to & S
\end{array}
\]

Note that \( f(Z) \subset \{ f(\xi) \} \) and that \( f(Z) \) is closed if and only if equality holds, i.e., \( f(\{ \xi \}) \). It follows from Lemma 14.1 that if \( S, X \) are affine, the fibres \( X_s \) are Noetherian, \( \mathcal{F} \) is of finite type, and \( \Gamma(X, \mathcal{F}) \) is a projective \( \Gamma(S, \mathcal{O}_S) \)-module, then \( f(Z) = \{ f(\xi) \} \) is a closed subset. Slightly different analogous statements holds for the cases described in Lemmas 14.2, 14.3, and 14.4.

15. Impurities

We want to formalize the phenomenon of which we gave examples in Section 14 in terms of specializations of points of \( \text{Ass}_{X/S}(\mathcal{F}) \). We also want to work locally around a point \( s \in S \). In order to do so we make the following definitions.

**Situation 15.1.** Here \( S, X \) are schemes and \( f : X \to S \) is a finite type morphism. Also, \( \mathcal{F} \) is a finite type quasi-coherent \( \mathcal{O}_X \)-module. Finally \( s \) is a point of \( S \).

In this situation consider a morphism \( g : T \to S \), a point \( t \in T \) with \( g(t) = s \), a specialization \( t' \leadsto t \), and a point \( \xi \in X_T \) in the base change of \( X \) lying over \( t' \). Picture

\[
\begin{array}{ccc}
\xi & \to & X_T \\
\downarrow & & \downarrow g \\
t' & \leadsto & s \\
\downarrow & & \downarrow
\end{array}
\]

Moreover, denote \( \mathcal{F}_T \) the pullback of \( \mathcal{F} \) to \( X_T \).

**Definition 15.2.** In Situation 15.1 we say a diagram \((15.1.1)\) defines an impurity of \( \mathcal{F} \) above \( s \) if \( \xi \in \text{Ass}_{X_T/T}(\mathcal{F}_T) \) and \( \{ \xi \} \cap X_t = \emptyset \). We will indicate this by saying “let \( (g : T \to S, t' \leadsto t, \xi) \) be an impurity of \( \mathcal{F} \) above \( s \)”.

**Lemma 15.3.** In Situation 15.1. If there exists an impurity of \( \mathcal{F} \) above \( s \), then there exists an impurity \( (g : T \to S, t' \leadsto t, \xi) \) of \( \mathcal{F} \) above \( s \) such that \( g \) is locally of finite presentation and \( t \) a closed point of the fibre of \( g \) above \( s \).

**Proof.** Let \( (g : T \to S, t' \leadsto t, \xi) \) be any impurity of \( \mathcal{F} \) above \( s \). We apply Limits, Lemma 14.1 to \( t \in T \) and \( Z = \{ \xi \} \) to obtain an open neighbourhood \( V \subset T \) of \( t \), a commutative diagram

\[
\begin{array}{ccc}
V & \to & T' \\
\downarrow & & \downarrow \quad b \\
T & \to & S,
\end{array}
\]

and a closed subscheme \( Z' \subset X_{T'} \) such that

1. the morphism \( b : T' \to S \) is locally of finite presentation,
2. we have \( Z' \cap X_{t'(t)} = \emptyset \), and
(3) $Z \cap X_V$ maps into $Z'$ via the morphism $X_V \to X_{T'}$.

As $t'$ specializes to $t$ we may replace $T$ by the open neighbourhood $V$ of $t$. Thus we have a commutative diagram

$$
\begin{array}{ccc}
X_T & \longrightarrow & X_{T'} \\
\downarrow & & \downarrow \\
T & \underset{a}{\longrightarrow} & T' \underset{b}{\longrightarrow} S
\end{array}
$$

where $b \circ a = g$. Let $\xi' \in X_{T'}$ denote the image of $\xi$. By Divisors, Lemma 7.3 we see that $\xi' \in \text{Ass}_{X_{T'/T'}}(\mathcal{F}_{T'})$. Moreover, by construction the closure of $\{\xi'\}$ is contained in the closed subset $Z'$ which avoids the fibre $X_{a(t)}$. In this way we see that $(T' \to S, a(t') \rightsquigarrow a(t), \xi')$ is an impurity of $\mathcal{F}$ above $s$.

Thus we may assume that $g : T \to S$ is locally of finite presentation. Let $Z = \{\xi\}$. By assumption $Z_t = \emptyset$. By More on Morphisms, Lemma 22.1 this means that $Z_{i''} = \emptyset$ for $t''$ in an open subset of $\{t\}$. Since the fibre of $T \to S$ over $s$ is a Jacobson scheme, see Morphisms, Lemma 15.10 we find that there exist a closed point $t'' \in \{t\}$ such that $Z_{i''} = \emptyset$. Then $(g : T \to S, t'' \rightsquigarrow t', \xi)$ is the desired impurity.

\[05IZ\begin{lemma} \textbf{Lemma 15.4.} In Situation 15.1 \ Let $(g : T \to S, t' \rightsquigarrow t, \xi)$ be an impurity of $\mathcal{F}$ above $s$. Assume $T = \lim_{i \in I} T_i$ is a directed limit of affine schemes over $S$. Then for some $i$ the triple $(T_i \to S, t'_i \rightsquigarrow t_i, \xi_i)$ is an impurity of $\mathcal{F}$ above $s$.
\end{lemma}

\textbf{Proof.} The notation in the statement means this: Let $p_i : T \to T_i$ be the projection morphisms, let $t_i = p_i(t)$ and $t'_i = p_i(t')$. Finally $\xi_i \in X_{T_i}$ is the image of $\xi$. By Divisors, Lemma 7.3 it is true that $\xi_i$ is a point of the relative assassin of $\mathcal{F}_{T_i}$ over $T_i$. Thus the only point is to show that $\{\xi_i\} \cap X_{t_i} = \emptyset$ for some $i$.

First proof. Let $Z_i = \{\xi_i\} \subset X_{T_i}$ and $Z = \{\xi\} \subset X_T$ endowed with the reduced induced scheme structure. Then $Z = \lim Z_i$ by Limits, Lemma 4.4. Choose a field $k$ and a morphism $\text{Spec}(k) \to T$ whose image is $t$. Then

$0 = Z \times_T \text{Spec}(k) = (\lim Z_i) \times_{(\lim T_i)} \text{Spec}(k) = \lim Z_i \times_{T_i} \text{Spec}(k)$

because limits commute with fibred products (limits commute with limits). Each $Z_i \times_{T_i} \text{Spec}(k)$ is quasi-compact because $X_{T_i} \to T_i$ is of finite type and hence $Z_i \to T_i$ is of finite type. Hence $Z_i \times_{T_i} \text{Spec}(k)$ is empty for some $i$ by Limits, Lemma 4.3. Since the image of the composition $\text{Spec}(k) \to T \to T_i$ is $t_i$ we obtain what we want.

Second proof. Set $Z = \{\xi\}$. Apply Limits, Lemma 14.1 to this situation to obtain an open neighbourhood $V \subset T$ of $t$, a commutative diagram

$$
\begin{array}{ccc}
V & \underset{a}{\longrightarrow} & T' \\
\downarrow & & \downarrow \\
T & \underset{b}{\longrightarrow} & S
\end{array}
$$

and a closed subscheme $Z' \subset X_{T'}$ such that

1. the morphism $b : T' \to S$ is locally of finite presentation,
2. we have $Z' \cap X_{a(t)} = \emptyset$, and
3. $Z \cap X_V$ maps into $Z'$ via the morphism $X_V \to X_{T'}$. 

We may assume $V$ is an affine open of $T$, hence by Limits, Lemmas 4.11 and 4.13 we can find an $i$ and an affine open $V_i \subset T_i$ with $V = f_i^{-1}(V_i)$. By Limits, Proposition 6.1 after possibly increasing $i$ a bit we can find a morphism $a_i : V_i \to T'$ such that $a = a_i \circ f_i|_V$. The induced morphism $X_{V_i} \to X_{T'}$ maps $\xi_i$ into $Z'$. As $Z' \cap X_{a(i)} = \emptyset$ we conclude that $(T_i \to S, t'_i \to t_i, \xi_i)$ is an impurity of $\mathcal{F}$ above $s$. □

**Lemma 15.5.** In Situation 15.1. If there exists an impurity $(g : T \to S, t', t, \xi)$ of $\mathcal{F}$ above $s$ with $g$ quasi-finite at $t$, then there exists an impurity $(g : T \to S, t', t, \xi)$ such that $(T, t) \to (S, s)$ is an elementary étale neighbourhood.

**Proof.** Let $(g : T \to S, t', t, \xi)$ be an impurity of $\mathcal{F}$ above $s$ such that $g$ is quasi-finite at $t$. After shrinking $T$ we may assume that $g$ is locally of finite type. Apply More on Morphisms, Lemma 36.1 to $T \to S$ and $t \to s$. This gives us a diagram

$$
\begin{array}{ccc}
T & \leftarrow & T \times_S U \\
\downarrow & & \downarrow \\
S & \leftarrow & U
\end{array}
$$

where $(U, u) \to (S, s)$ is an elementary étale neighbourhood and $V \subset T \times_S U$ is an open neighbourhood of $v = (t, u)$ such that $V \to U$ is finite and such that $v$ is the unique point of $V$ lying over $u$. Since the morphism $V \to T$ is étale hence flat we see that there exists a specialization $v' \to v$ such that $v' \to t'$. Note that $\kappa(t') \subset \kappa(v')$ is finite separable. Pick any point $\zeta \in X_{v'}$ mapping to $\xi \in X_v$. By Divisors, Lemma 7.3 we see that $\zeta \in \text{Ass}_{X_\pi/F_\pi}(\mathcal{F}_\pi)$. Moreover, the closure $\overline{\{\zeta\}}$ does not meet the fibre $X_v$ as by assumption the closure $\overline{\{\xi\}}$ does not meet $X_t$. In other words $(V \to S, v' \to v, \xi)$ is an impurity of $\mathcal{F}$ above $S$.

Next, let $u' \in U'$ be the image of $v'$ and let $\theta \in X_{U'}$ be the image of $\zeta$. Then $\theta \to u'$ and $u' \to u$. By Divisors, Lemma 7.3 we see that $\theta \in \text{Ass}_{X_{U'}/U'}(\mathcal{F})$. Moreover, as $\pi : X_V \to X_U$ is finite we see that $\pi(\overline{\{\zeta\}}) = \overline{\{\pi(\xi)\}}$. Since $v$ is the unique point of $V$ lying over $u$ we see that $X_u \cap \overline{\{\pi(\xi)\}} = \emptyset$ because $X_u \cap \overline{\{\xi\}} = \emptyset$. In this way we conclude that $(U \to S, u' \to u, \theta)$ is an impurity of $\mathcal{F}$ above $s$ and we win. □

**Lemma 15.6.** In Situation 15.1. Assume that $S$ is locally Noetherian. If there exists an impurity of $\mathcal{F}$ above $s$, then there exists an impurity $(g : T \to S, t', t, \xi)$ of $\mathcal{F}$ above $s$ such that $g$ is quasi-finite at $t$.

**Proof.** We may replace $S$ by an affine neighbourhood of $s$. By Lemma 15.3 we may assume that we have an impurity $(g : T \to S, t', t, \xi)$ of such that $g$ is locally of finite type and $t$ a closed point of the fibre of $g$ above $s$. We may replace $T$ by the reduced induced scheme structure on $\{t\}$. Let $Z = \overline{\{\xi\}} \subset X_T$. By assumption $Z_t = \emptyset$ and the image of $Z \to T$ contains $t'$. By More on Morphisms, Lemma 23.1 there exists a nonempty open $V \subset Z$ such that for any $w \in f(V)$ any generic point $\xi'$ of $V_w$ is in $\text{Ass}_{X_{T'/T}}(\mathcal{F}_{T'})$. By More on Morphisms, Lemma 22.2 there exists a nonempty open $W \subset T$ with $W \subset f(V)$. By More on Morphisms, Lemma 47.7 there exists a closed subscheme $T' \subset T$ such that $t \in T'$, $T' \to S$ is quasi-finite at $t$, and there exists a point $z \in T' \cap W$, $z \to t$ which does not map to $s$. Choose any generic point $\xi'$ of the nonempty scheme $V_z$. Then $(T' \to S, z \to t, \xi')$ is the desired impurity. □
In the following we will use the henselization $S^h = \text{Spec}(\mathcal{O}^h_{S,s})$ of $S$ at $s$, see Étale Cohomology, Definition 33.2. Since $S^h \to S$ maps to closed point of $S^h$ to $s$ and induces an isomorphism of residue fields, we will indicate $s \in S^h$ this closed point also. Thus $(S^h, s) \to (S, s)$ is a morphism of pointed schemes.

Lemma 15.7. In Situation 15.1, If there exists an impurity $(S^h \to S, s' \rightsquigarrow s, \xi)$ of $\mathcal{F}$ above $s$ then there exists an impurity $(T \to S, t' \rightsquigarrow t, \xi)$ of $\mathcal{F}$ above $s$ where $(T, t) \to (S, s)$ is an elementary étale neighbourhood.

Proof. We may replace $S$ by an affine neighbourhood of $s$. Say $S = \text{Spec}(A)$ and $s$ corresponds to the prime $p \subset A$. Then $\mathcal{O}^h_{S,s} = \text{colim}_{(T,t)} \Gamma(T, \mathcal{O}_T)$ where the limit is over the opposite of the cofiltered category of affine elementary étale neighbourhoods $(T, t)$ of $(S, s)$, see More on Morphisms, Lemma 31.5 and its proof. Hence $S^h = \lim T$, and we win by Lemma 15.4.

Lemma 15.8. In Situation 15.1 the following are equivalent

1. there exists an impurity $(S^h \to S, s' \rightsquigarrow s, \xi)$ of $\mathcal{F}$ above $s$ where $S^h$ is the henselization of $S$ at $s$,
2. there exists an impurity $(T \to S, t' \rightsquigarrow t, \xi)$ of $\mathcal{F}$ above $s$ such that $(T, t) \to (S, s)$ is an elementary étale neighbourhood, and
3. there exists an impurity $(T \to S, t' \rightsquigarrow t, \xi)$ of $\mathcal{F}$ above $s$ such that $T \to S$ is quasi-finite at $t$.

Proof. As an étale morphism is locally quasi-finite it is clear that (2) implies (3). We have seen that (3) implies (2) in Lemma 15.7. We have seen that (1) implies (2) in Lemma 15.7. Finally, if $(T \to S, t' \rightsquigarrow t, \xi)$ is an impurity of $\mathcal{F}$ above $s$ such that $(T, t) \to (S, s)$ is an elementary étale neighbourhood, then we can choose a factorization $S^h \to T \to S$ of the structure morphism $S^h \to S$. Choose any point $s' \in S^h$ mapping to $t'$ and choose any $\xi' \in X_{s'}$ mapping to $\xi \in X_t$. Then $(S^h \to S, s' \rightsquigarrow s, \xi')$ is an impurity of $\mathcal{F}$ above $s$. We omit the details.

16. Relatively pure modules

Definition 16.1. Let $f : X \to S$ be a morphism of schemes which is of finite type. Let $\mathcal{F}$ be a finite type quasi-coherent $\mathcal{O}_X$-module.

1. Let $s \in S$. We say $\mathcal{F}$ is pure along $X_s$ if there is no impurity $(g : T \to S, t' \rightsquigarrow t, \xi)$ of $\mathcal{F}$ above $s$ with $(T, t) \to (S, s)$ an elementary étale neighbourhood.
2. We say $\mathcal{F}$ is universally pure along $X_s$ if there does not exist any impurity of $\mathcal{F}$ above $s$.
3. We say that $X$ is pure along $X_s$ if $\mathcal{O}_X$ is pure along $X_s$.
4. We say $\mathcal{F}$ is universally $S$-pure, or universally pure relative to $S$ if $\mathcal{F}$ is universally pure along $X_s$ for every $s \in S$.
5. We say $\mathcal{F}$ is $S$-pure, or pure relative to $S$ if $\mathcal{F}$ is pure along $X_s$ for every $s \in S$.
6. We say that $X$ is $S$-pure or pure relative to $S$ if $\mathcal{O}_X$ is pure relative to $S$.

We intentionally restrict ourselves here to morphisms which are of finite type and not just morphisms which are locally of finite type, see Remark 16.2 for a discussion. In the situation of the definition Lemma 15.8 tells us that the following are equivalent.
(1) \( \mathcal{F} \) is pure along \( X_s \),
(2) there is no impurity \((g: T \to S, t' \sim t, \xi)\) with \( g \) quasi-finite at \( t \),
(3) there does not exist any impurity of the form \((S^h \to S, s' \sim s, \xi)\), where \( S^h \) is the henselization of \( S \) at \( s \).

If we denote \( X^h = X \times_S S^h \) and \( \mathcal{F}^h \) the pullback of \( \mathcal{F} \) to \( X^h \), then we can formulate the last condition in the following more positive way:

(4) All points of \( \text{Ass}_{X^h/S^h}(\mathcal{F}^h) \) specialize to points of \( X_s \).

In particular, it is clear that \( \mathcal{F} \) is pure along \( X_s \) if and only if the pullback of \( \mathcal{F} \) to \( X \times_S \text{Spec}(O_{S,s}) \) is pure along \( X_s \).

Remark 16.2. Let \( f: X \to S \) be a morphism which is locally of finite type and \( \mathcal{F} \) a quasi-coherent finite type \( O_X \)-module. In this case it is still true that (1) and (2) above are equivalent because the proof of Lemma 15.5 does not use that \( f \) is quasi-compact. It is also clear that (3) and (4) are equivalent. However, we don’t know if (1) and (3) are equivalent. In this case it may sometimes be more convenient to define purity using the equivalent conditions (3) and (4) as is done in [GR71]. On the other hand, for many applications it seems that the correct notion is really that of being universally pure.

A natural question to ask is if the property of being pure relative to the base is preserved by base change, i.e., if being pure is the same thing as being universally pure. It turns out that this is true over Noetherian base schemes (see Lemma 16.5), or if the sheaf is flat (see Lemmas 18.3 and 18.4). It is not true in general, even if the morphism and the sheaf are of finite presentation, see Examples, Section 34 for a counter example. First we match our usage of “universally” to the usual notion.

Lemma 16.3. Let \( f: X \to S \) be a morphism of schemes which is of finite type. Let \( \mathcal{F} \) be a finite type quasi-coherent \( O_X \)-module. Let \( s \in S \). The following are equivalent

(1) \( \mathcal{F} \) is universally pure along \( X_s \), and
(2) for every morphism of pointed schemes \((S', s') \to (S, s)\) the pullback \( \mathcal{F}_{S'} \) is pure along \( X_{s'} \).

In particular, \( \mathcal{F} \) is universally pure relative to \( S \) if and only if every base change \( \mathcal{F}_{S'} \) of \( \mathcal{F} \) is pure relative to \( S' \).

Proof. This is formal. □

Lemma 16.4. Let \( f: X \to S \) be a morphism of schemes which is of finite type. Let \( \mathcal{F} \) be a finite type quasi-coherent \( O_X \)-module. Let \( s \in S \). Let \((S', s') \to (S, s)\) be a morphism of pointed schemes. If \( S' \to S \) is quasi-finite at \( s \) and \( \mathcal{F} \) is pure along \( X_s \), then \( \mathcal{F}_{S'} \) is pure along \( X_{s'} \).

Proof. It \((T \to S', t' \sim t, \xi)\) is an impurity of \( \mathcal{F}_{S'} \) above \( s' \) with \( T \to S' \) quasi-finite at \( t \), then \((T \to S, t' \sim t, \xi)\) is an impurity of \( \mathcal{F} \) above \( s \) with \( T \to S \) quasi-finite at \( t \), see Morphisms, Lemma 19.12. Hence the lemma follows immediately from the characterization (2) of purity given following Definition 16.1. □

Lemma 16.5. Let \( f: X \to S \) be a morphism of schemes which is of finite type. Let \( \mathcal{F} \) be a finite type quasi-coherent \( O_X \)-module. Let \( s \in S \). If \( O_{S,s} \) is Noetherian then \( \mathcal{F} \) is pure along \( X_s \) if and only if \( \mathcal{F} \) is universally pure along \( X_s \).
Proof. First we may replace $S$ by $\text{Spec}(O_{S,s})$, i.e., we may assume that $S$ is Noetherian. Next, use Lemma 15.6 and characterization (2) of purity given in discussion following Definition 16.1 to conclude. \hfill \square

Purity satisfies flat descent.

Lemma 16.6. Let $f : X \to S$ be a morphism of schemes which is of finite type. Let $F$ be a finite type quasi-coherent $O_X$-module. Let $s \in S$. Let $(S', s') \to (S, s)$ be a morphism of pointed schemes. Assume $S' \to S$ is flat at $s'$.

(1) If $F_{S'}$ is pure along $X_{s'}$, then $F$ is pure along $X_s$.

(2) If $F_{S'}$ is universally pure along $X_{s'}$, then $F$ is universally pure along $X_s$.

Proof. Let $(T \to S, t' \sim t, \xi)$ be an impurity of $F$ above $s$. Set $T_1 = T \times_S S'$, and let $t_1$ be the unique point of $T_1$ mapping to $t$ and $s'$. Since $T_1 \to T$ is flat at $t_1$, see Morphisms, Lemma 24.8, there exists a specialization $t'_1 \sim t_1$ lying over $t' \sim t$, see Algebra, Section 40. Choose a point $\xi_1 \in X_{t'_1}$ which corresponds to a generic point of $\text{Spec}(\kappa(t'_1) \otimes_{\kappa(t_1)} \kappa(\xi))$, see Schemes, Lemma 17.5. By Divisors, Lemma 7.3 we see that $\xi_1 \in \text{Ass}_{X_{T_1/T_1}}(F_{T_1})$. As the Zariski closure of $\{\xi_1\}$ in $X_{T_1}$ maps into the Zariski closure of $\{\xi\}$ in $X_T$ we conclude that this closure is disjoint from $X_{t_1}$. Hence $(T_1 \to S', t'_1 \sim t_1, \xi_1)$ is an impurity of $F_{S'}$ above $s'$. In other words we have proved the contrapositive to part (2) of the lemma. Finally, if $(T, t) \to (S, s)$ is an elementary étale neighbourhood, then $(T_1, t_1) \to (S', s')$ is an elementary étale neighbourhood too, and in this way we see that (1) holds. \hfill \square

Lemma 16.7. Let $i : Z \to X$ be a closed immersion of schemes of finite type over a scheme $S$. Let $s \in S$. Let $F$ be a finite type, quasi-coherent sheaf on $Z$. Then $F$ is (universally) pure along $Z_s$ if and only if $i_* F$ is (universally) pure along $X_s$.

Proof. This follows from Divisors, Lemma 8.3. \hfill \square

17. Examples of relatively pure sheaves

Here are some example cases where it is possible to see what purity means.

Lemma 17.1. Let $f : X \to S$ be a morphism of schemes which is of finite type. Let $F$ be a finite type quasi-coherent $O_X$-module.

(1) If the support of $F$ is proper over $S$, then $F$ is universally pure relative to $S$.

(2) If $f$ is proper, then $F$ is universally pure relative to $S$.

(3) If $f$ is proper, then $X$ is universally pure relative to $S$.

Proof. First we reduce (1) to (2). Namely, let $Z \subset X$ be the scheme theoretic support of $F$. Let $i : Z \to X$ be the corresponding closed immersion and write $F = i_* G$ for some finite type quasi-coherent $O_Z$-module $G$, see Morphisms, Section 5. In case (1) $Z \to S$ is proper by assumption. Thus by Lemma 16.7 case (1) reduces to case (2).

Assume $f$ is proper. Let $(g : T \to S, t' \sim t, \xi)$ be an impurity of $F$ above $s \in S$. Since $f$ is proper, it is universally closed. Hence $f_T : X_T \to T$ is closed. Since $f_T(\xi) = t'$ this implies that $t \in f(\{\xi\})$ which is a contradiction. \hfill \square

Lemma 17.2. Let $f : X \to S$ be a separated, finite type morphism of schemes. Let $F$ be a finite type, quasi-coherent $O_X$-module. Assume that $\text{Supp}(F_s)$ is finite for every $s \in S$. Then the following are equivalent
(1) \( F \) is pure relative to \( S \).
(2) the scheme theoretic support of \( F \) is finite over \( S \), and
(3) \( F \) is universally pure relative to \( S \).

In particular, given a quasi-finite separated morphism \( X \to S \) we see that \( X \) is pure relative to \( S \) if and only if \( X \to S \) is finite.

**Proof.** Let \( Z \subset X \) be the scheme theoretic support of \( F \), see Morphisms, Definition \[5.5\]. Then \( Z \to S \) is a separated, finite type morphism of schemes with finite fibres. Hence it is separated and quasi-finite, see Morphisms, Lemma \[19.10\]. By Lemma \[16.7\] it suffices to prove the lemma for \( Z \to S \) and the sheaf \( F \) viewed as a finite type quasi-coherent module on \( Z \). Hence we may assume that \( X \to S \) is separated and quasi-finite and that \( \text{Supp}(F) = X \).

It follows from Lemma \[17.1\] and Morphisms, Lemma \[42.11\] that (2) implies (3). Trivially (3) implies (1). Assume (1) holds. We will prove that (2) holds. It is clear that we may assume \( S \) is affine. By More on Morphisms, Lemma \[38.3\] we can find a diagram

\[
\begin{array}{ccc}
X & \xrightarrow{f} & T \\
\downarrow{j} & & \downarrow{\pi} \\
S & \xrightarrow{\pi} & \end{array}
\]

with \( \pi \) finite and \( j \) a quasi-compact open immersion. If we show that \( j \) is closed, then \( j \) is a closed immersion and we conclude that \( f = \pi \circ j \) is finite. To show that \( j \) is closed it suffices to show that specializations lift along \( j \), see Schemes, Lemma \[19.8\]. Let \( x \in X \), set \( t' = j(x) \) and let \( t' \leadsto t \) be a specialization. We have to show \( t \in j(X) \). Set \( s' = f(x) \) and \( s = \pi(t) \) so \( s' \leadsto s \). By More on Morphisms, Lemma \[36.4\] we can find an elementary étale neighbourhood \((U, u) \to (S, s)\) and a decomposition

\[
T_U = T \times_S U = V \amalg W
\]

into open and closed subschemes, such that \( V \to U \) is finite and there exists a unique point \( v \) of \( V \) mapping to \( u \), and such that \( v \) maps to \( t \) in \( T \). As \( V \to T \) is étale, we can lift generalizations, see Morphisms, Lemmas \[24.9\] and \[34.12\]. Hence there exists a specialization \( v' \leadsto v \) such that \( v' \) maps to \( t' \in T \). In particular we see that \( v' \in X_U \subset T_U \). Denote \( w' \in U \) the image of \( v' \). Note that \( v' \in \text{Ass}_{X_{w'}/U}(F) \) because \( X_{w'} \) is a finite discrete set and \( X_{w'} = \text{Supp}(F_{w'}) \). As \( F \) is pure relative to \( S \) we see that \( v' \) must specialize to a point in \( X_u \). Since \( v \) is the only point of \( V \) lying over \( u \) (and since no point of \( W \) can be a specialization of \( v' \)) we see that \( v \in X_u \). Hence \( t \in X \). \( \square \)

**Lemma 17.3.** Let \( f : X \to S \) be a finite type, flat morphism of schemes with geometrically integral fibres. Then \( X \) is universally pure over \( S \).

**Proof.** Let \( \xi \in X \) with \( s' = f(\xi) \) and \( s' \leadsto s \) a specialization of \( S \). If \( \xi \) is an associated point of \( X_{s'} \), then \( \xi \) is the unique generic point because \( X_{s'} \) is an integral scheme. Let \( \xi_0 \) be the unique generic point of \( X_s \). As \( X \to S \) is flat we can lift \( s' \leadsto s \) to a specialization \( \xi' \leadsto \xi_0 \) in \( X \), see Morphisms, Lemma \[24.9\]. The \( \xi \leadsto \xi' \) because \( \xi \) is the generic point of \( X_{s'} \) hence \( \xi \leadsto \xi_0 \). This means that \((\text{id}_S, s' \to s, \xi)\) is not an impurity of \( O_X \) above \( s \). Since the assumption that \( f \) is finite type, flat with geometrically integral fibres is preserved under base change,
we see that there doesn’t exist an impurity after any base change. In this way we see that $X$ is universally $S$-pure.

05K6 **Lemma 17.4.** Let $f : X \to S$ be a finite type, affine morphism of schemes. Let $\mathcal{F}$ be a finite type quasi-coherent $\mathcal{O}_X$-module such that $f_*\mathcal{F}$ is locally projective on $S$, see Properties, Definition 21.1. Then $\mathcal{F}$ is universally pure over $S$.

**Proof.** After reducing to the case where $S$ is the spectrum of a henselian local ring this follows from Lemma 14.1.

18. A criterion for purity

05L2 We first prove that given a flat family of finite type quasi-coherent sheaves the points in the relative assassin specialize to points in the relative assassins of nearby fibres (if they specialize at all).

05L3 **Lemma 18.1.** Let $f : X \to S$ be a morphism of schemes of finite type. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module of finite type. Let $s \in S$. Assume that $\mathcal{F}$ is flat over $S$ at all points of $X_s$. Let $x' \in \text{Ass}_{X/S}(\mathcal{F})$ with $f(x') = s'$ such that $s' \rightsquigarrow s$ is a specialization in $S$. If $x'$ specializes to a point of $X_s$, then $x' \rightsquigarrow x$ with $x \in \text{Ass}_{X_s}(\mathcal{F}_s)$.

**Proof.** Let $x' \rightsquigarrow t$ be a specialization with $t \in X_s$. We may replace $X$ by an affine neighbourhood of $t$ and $S$ by an affine neighbourhood of $s$. Choose a closed immersion $i : X \to A^2_S$. Then it suffices to prove the lemma for the module $i_*\mathcal{F}$ on $A^2_S$ and the point $i(x')$. Hence we may assume $X \to S$ is of finite presentation.

Let $x' \rightsquigarrow t$ be a specialization with $t \in X_s$. Set $A = \mathcal{O}_{S,s}$, $B = \mathcal{O}_{X,t}$, and $N = \mathcal{F}_t$. Note that $B$ is essentially of finite presentation over $A$ and that $N$ is a finite $B$-module flat over $A$. Also $N$ is a finitely presented $B$-module by Lemma 10.9. Let $q' \subset B$ be the prime ideal corresponding to $x'$ and let $p' \subset A$ be the prime ideal corresponding to $s'$. The assumption $x' \in \text{Ass}_{X/S}(\mathcal{F})$ means that $q'$ is an associated prime of $N \otimes_A \kappa(p')$. Let $\Sigma \subset B$ be the multiplicative subset of elements which are not zerodivisors on $N/m_A N$. By Lemma 7.2 the map $N \to \Sigma^{-1} N$ is universally injective. In particular, we see that $N \otimes_A \kappa(p') \to \Sigma^{-1} N \otimes_A \kappa(p')$ is injective which implies that $q'$ is an associated prime of $\Sigma^{-1} N \otimes_A \kappa(p')$ and hence $q'$ is in the image of $\text{Spec}(\Sigma^{-1} B) \to \text{Spec}(B)$. Thus Lemma 7.1 implies that $q' \subset q$ for some prime $q \in \text{Ass}_B(N/m_A N)$ (which in particular implies that $m_A = A \cap q$). If $x \in X_s$ denotes the point corresponding to $q$, then $x \in \text{Ass}_{X_s}(\mathcal{F}_s)$ and $x' \rightsquigarrow x$ as desired.

05L4 **Lemma 18.2.** Let $f : X \to S$ be a morphism of schemes of finite type. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module of finite type. Let $s \in S$. Let $(S',s') \to (S,s)$ be an elementary étale neighbourhood and let

$$
\begin{array}{ccc}
X & \xrightarrow{s} & X' \\
\downarrow & & \downarrow \\
S & \xrightarrow{t} & S'
\end{array}
$$

be a commutative diagram of morphisms of schemes. Assume

1. $\mathcal{F}$ is flat over $S$ at all points of $X_s$,
2. $X' \to S'$ is of finite type,
First, assume that \( F \) is of finite type, \( g : X' \to X \) is étale, and \( g(X') \) contains \( \text{Ass}_{X/(S)}(\mathcal{F}) \).

In this situation \( \mathcal{F} \) is pure along \( X\) if and only if the image of \( X' \to X \times_S S' \) specializes to a point of \( \text{Ass}_{X\times_S S'/S}(\mathcal{F} \times_S S') \) lying over points in \( S' \) which specialize to \( s' \).

**Proof.** Since the morphism \( S' \to S \) is étale, we see that if \( \mathcal{F} \) is pure along \( X\), then \( \mathcal{F} \times_S S' \) is pure along \( X\), see Lemma 16.4. Since purity satisfies flat descent, see Lemma 16.6, we see that if \( \mathcal{F} \times_S S' \) is pure along \( X\), then \( \mathcal{F} \) is pure along \( X\). Hence we may replace \( S \) by \( S' \) and assume that \( S = S' \) so that \( g : X' \to X \) is an étale morphism between schemes of finite type over \( S \). Moreover, we may replace \( S \) by \( \text{Spec}(\mathcal{O}_{S,s}) \) and assume that \( S \) is local.

First, assume that \( \mathcal{F} \) is pure along \( X\). In this case every point of \( \text{Ass}_{X/S}(\mathcal{F}) \) specializes to a point of \( X\) by purity. Hence by Lemma 18.1 we see that every point of \( \text{Ass}_{X/S}(\mathcal{F}) \) specializes to a point of \( \text{Ass}_{X_X}(\mathcal{F}) \). Thus every point of \( \text{Ass}_{X/S}(\mathcal{F}) \) is in the image of \( g \) (as the image is open and contains \( \text{Ass}_{X}(\mathcal{F}) \)).

Conversely, assume that \( g(X') \) contains \( \text{Ass}_{X/S}(\mathcal{F}) \). Let \( S^h = \text{Spec}(\mathcal{O}_{S,s}) \) be the henselization of \( S \) at \( s \). Denote \( g^h : (X')^h \to X^h \) the base change of \( g \) by \( S^h \to S \), and denote \( \mathcal{F}^h \) the pullback of \( \mathcal{F} \) to \( X^h \). By Divisors, Lemma 7.3 and Remark 7.4 the relative assassin \( \text{Ass}_{X'/S^h}(\mathcal{F}^h) \) is the inverse image of \( \text{Ass}_{X/S}(\mathcal{F}) \) via the projection \( X^h \to X \). As we have assumed that \( g(X') \) contains \( \text{Ass}_{X/S}(\mathcal{F}) \) we conclude that the base change \( g^h((X')^h) = g(X') \times_S S^h \) contains \( \text{Ass}_{X'/S^h}(\mathcal{F}^h) \).

In this way we reduce to the case where \( S \) is the spectrum of a henselian local ring. Let \( x \in \text{Ass}_{X/S}(\mathcal{F}) \). To finish the proof of the lemma we have to show that \( x \) specializes to a point of \( X\), see criterion (4) for purity in discussion following Definition 16.1. By assumption there exists a \( x' \in X' \) such that \( g(x') = x \). As \( g : X' \to X \) is étale, we see that \( x' \in \text{Ass}_{X'/S}(g^*\mathcal{F}) \), see Lemma 2.8 (applied to the morphism of fibres \( X'_w \to X_w \)) where \( w \in S \) is the image of \( x' \). Since \( g^*\mathcal{F} \) is pure along \( X' \) we see that \( x' \sim y \) for some \( y \in X' \). Hence \( x = g(x') \sim g(y) \) and \( g(y) \in X_s \) as desired. \( \square \)

**Lemma 18.3.** Let \( f : X \to S \) be a morphism of schemes. Let \( \mathcal{F} \) be a quasi-coherent \( \mathcal{O}_X \)-module. Let \( s \in S \). Assume

1. \( f \) is of finite type,
2. \( \mathcal{F} \) is of finite type,
3. \( \mathcal{F} \) is flat over \( S \) at all points of \( X_s \), and
4. \( \mathcal{F} \) is pure along \( X_s \).

Then \( \mathcal{F} \) is universally pure along \( X_s \).

**Proof.** We first make a preliminary remark. Suppose that \( (S',s') \to (S,s) \) is an elementary étale neighbourhood. Denote \( \mathcal{F}' \) the pullback of \( \mathcal{F} \) to \( X' = X \times_S S' \). By the discussion following Definition 16.1 we see that \( \mathcal{F}' \) is pure along \( X'_s \). Moreover, \( \mathcal{F}' \) is flat over \( S' \) along \( X'_s \). Then it suffices to prove that \( \mathcal{F}' \) is universally pure along \( X'_s \). Namely, given any morphism \( (T,t) \to (S,s) \) of pointed schemes the fibre product \( (T',t') = (T \times_S S', (t,s')) \) is flat over \( (T,t) \) and hence if \( \mathcal{F}_T \) is pure along \( X_T \) then \( \mathcal{F}_T \) is pure along \( X_t \) by Lemma 16.6. Thus during the proof we may always replace \( (s,S) \) by an elementary étale neighbourhood. We may also replace \( S \) by \( \text{Spec}(\mathcal{O}_{S,s}) \) due to the local nature of the problem.
Choose an elementary étale neighbourhood \((S', s') \to (S, s)\) and a commutative diagram

\[
\begin{array}{ccc}
X & \xleftarrow{g} & X' \\
\downarrow & & \downarrow \\
S & \to & \text{Spec}(\mathcal{O}_{S', s'})
\end{array}
\]

such that \(X' \to X \times_S \text{Spec}(\mathcal{O}_{S', s'})\) is étale, \(X_s = g((X')_{s'})\), the scheme \(X'\) is affine, and such that \(\Gamma(X', g^* \mathcal{F})\) is a free \(\mathcal{O}_{S', s'}\)-module, see Lemma \[12.11\]. Note that \(X' \to \text{Spec}(\mathcal{O}_{S', s'})\) is of finite type (as a quasi-compact morphism which is the composition of an étale morphism and the base change of a finite type morphism). By our preliminary remarks in the first paragraph of the proof we may replace \(S\) by \(\text{Spec}(\mathcal{O}_{S', s'})\). Hence we may assume there exists a commutative diagram

\[
\begin{array}{ccc}
X & \xleftarrow{g} & X' \\
\downarrow & & \downarrow \\
S & \to & S
\end{array}
\]

of schemes of finite type over \(S\), where \(g\) is étale, \(X_s \subset g(X')\), with \(S\) local with closed point \(s\), with \(X'\) affine, and with \(\Gamma(X', g^* \mathcal{F})\) a free \(\Gamma(S, \mathcal{O}_S)\)-module. Note that in this case \(g^* \mathcal{F}\) is universally pure over \(S\), see Lemma \[17.4\].

In this situation we apply Lemma \[18.2\] to deduce that \(\text{Ass}_{X/S}(\mathcal{F}) \subset g(X')\) from our assumption that \(\mathcal{F}\) is pure along \(X_s\) and flat over \(S\) along \(X_s\). By Divisors, Lemma \[7.3\] and Remark \[7.4\] we see that for any morphism of pointed schemes \((T, t) \to (S, s)\) we have

\[
\text{Ass}_{X_T/T}(\mathcal{F}_T) \subset (X_T \to X)^{-1}(\text{Ass}_{X/S}(\mathcal{F})) \subset g(X') \times_S T = g_T(X'_T).
\]

Hence by Lemma \[18.2\] applied to the base change of our displayed diagram to \((T, t)\) we conclude that \(\mathcal{F}_T\) is pure along \(X_t\) as desired. \(\square\)

\begin{lemma}
Let \(f : X \to S\) be a finite type morphism of schemes. Let \(\mathcal{F}\) be a finite type quasi-coherent \(\mathcal{O}_X\)-module. Assume \(\mathcal{F}\) is flat over \(S\). In this case \(\mathcal{F}\) is pure relative to \(S\) if and only if \(\mathcal{F}\) is universally pure relative to \(S\).
\end{lemma}

\textbf{Proof.} Immediate consequence of Lemma \[18.3\] and the definitions. \(\square\)

\begin{lemma}
Let \(I\) be a directed set. Let \((S_i, g_{i!})\) be an inverse system of affine schemes over \(I\). Set \(S = \lim_i S_i\) and \(s \in S\). Denote \(g_i : S \to S_i\) the projections and set \(s_i = g_i(s)\). Suppose that \(f : X \to S\) is a morphism of finite presentation, \(\mathcal{F}\) a quasi-coherent \(\mathcal{O}_X\)-module of finite presentation which is pure along \(X_s\) and flat over \(S\) at all points of \(X_s\). Then there exists an \(i \in I\), a morphism of finite presentation \(X_i \to S_i\), a quasi-coherent \(\mathcal{O}_{X_i}\)-module \(\mathcal{F}_i\) of finite presentation which is pure along \((X_i)_{s_i}\) and flat over \(S_i\) at all points of \((X_i)_{s_i}\) such that \(X \cong X_i \times_S S\) and such that the pullback of \(\mathcal{F}_i\) to \(X\) is isomorphic to \(\mathcal{F}\).
\end{lemma}

\textbf{Proof.} Let \(U \subset X\) be the set of points where \(\mathcal{F}\) is flat over \(S\). By More on Morphisms, Theorem \[15.1\] this is an open subscheme of \(X\). By assumption \(X_s \subset U\). As \(X_s\) is quasi-compact, we can find a quasi-compact open \(U' \subset U\) with \(X_s \subset U'\). By Limits, Lemma \[10.1\] we can find an \(i \in I\) and a morphism of finite presentation \(f_i : X_i \to S_i\) whose base change to \(S\) is isomorphic to \(f_i\). Fix such a choice and set \(X_i' = X_i \times_{S_i} S_i'\). Then \(X = \lim_i X_i'\) with affine transition morphisms. By Limits,
Lemma 10.2 we can, after possibly increasing \( i \) assume there exists a quasi-coherent \( \mathcal{O}_X \)-module \( \mathcal{F}_i \) of finite presentation whose base change to \( S \) is isomorphic to \( \mathcal{F} \).

By Limits, Lemma 4.11 after possibly increasing \( i \) we may assume there exists an open \( U'_i \subset X_i \) whose inverse image in \( X \) is \( U' \). Note that in particular \((X_i)_s \subset U'_i \).

By Limits, Lemma 10.4 (after increasing \( i \) once more) we may assume that \( \mathcal{F}_i \) is flat on \( U'_i \). In particular we see that \( \mathcal{F}_i \) is flat along \((X_i)_s \).

Next, we use Lemma 12.5 to choose an elementary étale neighbourhood \((S'_i, s'_i) \to (S_i, s_i)\) and a commutative diagram of schemes

\[
\begin{array}{ccc}
X_i & \xleftarrow{g_i} & X'_i \\
\downarrow & & \downarrow \\
S_i & \xleftarrow{g} & S'_i
\end{array}
\]

such that \( g_i \) is étale, \((X_i)_s \subset g_i(X'_i)\), the schemes \( X'_i, S'_i \) are affine, and such that \( \Gamma(X'_i, g_i^*\mathcal{F}_i) \) is a projective \( \Gamma(S'_i, \mathcal{O}_{S'_i}) \)-module. Note that \( g_i^*\mathcal{F}_i \) is universally pure over \( S'_i \), see Lemma 17.4. We may base change the diagram above to a diagram with morphisms \((S'_i, s'_i) \to (S_i, s_i)\) and \( g_i : X'_i \to X_i \) over \( S_i \) for any \( i' \geq i \) and we may base change the diagram to a diagram with morphisms \((S', s') \to (S, s)\) and \( g : X' \to X \) over \( S \).

At this point we can use our criterion for purity. Set \( W'_i \subset X_i \times_{S_i} S'_i \) equal to the image of the étale morphism \( X'_i \to X_i \times_{S_i} S'_i \). For every \( i' \geq i \) we have similarly the image \( W'_i \subset X_i \times_{S_i} S'_i \) and we have the image \( W' \subset X \times_{S} S' \). Taking images commutes with base change, hence \( W'_i = W'_i \times_{S_i} S'_i \) and \( W' = W_i \times_{S_i} S' \). Because \( \mathcal{F} \) is pure along \( X_s \), the Lemma 18.2 implies that

\[
05MB \quad (18.5.1) \quad f^{-1}(\text{Spec}(\mathcal{O}_{S', s'})) \cap \text{Ass}_{X \times_S S'}(\mathcal{F} \times_S S') \subset W'
\]

By More on Morphisms, Lemma 23.5 we see that

\[
E = \{ t \in S' \mid \text{Ass}_{X_i}(\mathcal{F}_i) \subset W' \} \quad \text{and} \quad E_i = \{ t \in S_i' \mid \text{Ass}_{X_s}(\mathcal{F}_i) \subset W_i' \}
\]

are locally constructible subsets of \( S' \) and \( S'_i \). By More on Morphisms, Lemma 23.4 we see that \( E_i \) is the inverse image of \( E \) under the morphism \( S'_i \to S'_s \) and that \( E \) is the inverse image of \( E_i \) under the morphism \( S' \to S'_i \). Thus Equation (18.5.1) is equivalent to the assertion that \( \text{Spec}(\mathcal{O}_{S', s'}) \) maps into \( E_i \). As \( \mathcal{O}_{S', s'} = \text{colim}_{i' \geq i} \mathcal{O}_{S'_i, s'_i} \), we see that \( \text{Spec}(\mathcal{O}_{S'_i, s'_i}) \) maps into \( E_i \) for some \( i' \geq i \), see Limits, Lemma 4.10. Then, applying Lemma 18.2 to the situation over \( S_i \), we conclude that \( \mathcal{F}_i \) is pure along \((X_i)_s \).

\[
05MC \quad \text{Lemma 18.6. Let } f : X \to S \text{ be a morphism of finite presentation. Let } \mathcal{F} \text{ be a quasi-coherent } \mathcal{O}_X \text{-module of finite presentation flat over } S. \text{ Then the set }
\]

\[
U = \{ s \in S \mid \text{F is pure along } X_s \}
\]

is open in \( S \).

**Proof.** Let \( s \in U \). Using Lemma 12.5 we can find an elementary étale neighbourhood \((S', s') \to (S, s)\) and a commutative diagram

\[
\begin{array}{ccc}
X & \xleftarrow{g} & X' \\
\downarrow & & \downarrow \\
S & \xleftarrow{g} & S'
\end{array}
\]


such that \( g \) is étale, \( X_s \subset g(X') \), the schemes \( X' \), \( S' \) are affine, and such that \( \Gamma(X', g^*\mathcal{F}) \) is a projective \( \Gamma(S', \mathcal{O}_{S'}) \)-module. Note that \( g^*\mathcal{F} \) is universally pure over \( S' \), see Lemma [17.4]. Set \( W' \subset X \times_S S' \) equal to the image of the étale morphism \( X' \to X \times_S S' \). Note that \( W \) is open and quasi-compact over \( S' \). Set \( E = \{ t \in S' \mid \text{Ass}_{X_t}(\mathcal{F}_t) \subset W' \} \).

By More on Morphisms, Lemma [23.5] \( E \) is a constructible subset of \( S' \). By Lemma [18.2] we see that \( \text{Spec}(\mathcal{O}_{S', s'}) \subset E \). By Morphisms, Lemma [21.4] we see that \( E \) contains an open neighbourhood \( V' \) of \( s' \). Applying Lemma [18.2] once more we see that for any point \( s_1 \) in the image of \( V' \) in \( S \) the sheaf \( \mathcal{F} \) is pure along \( X_{s_1} \). Since \( S' \to S \) is étale the image of \( V' \) in \( S \) is open and we win. ∎

19. How purity is used

Here are some examples of how purity can be used. The first lemma actually uses a slightly weaker form of purity.

**Lemma 19.1.** Let \( f : X \to S \) be a morphism of finite type. Let \( \mathcal{F} \) be a quasi-coherent sheaf of finite type on \( X \). Assume \( S \) is local with closed point \( s \). Assume \( \mathcal{F} \) is pure along \( X_s \) and that \( \mathcal{F} \) is flat over \( S \). Let \( \varphi : \mathcal{F} \to \mathcal{G} \) of quasi-coherent \( \mathcal{O}_X \)-modules. Then the following are equivalent

1. the map on stalks \( \varphi_x \) is injective for all \( x \in \text{Ass}_{X_s}(\mathcal{F}_s) \), and
2. \( \varphi \) is injective.

**Proof.** Let \( K = \text{Ker}(\varphi) \). Our goal is to prove that \( K = 0 \). In order to do this it suffices to prove that \( \text{WeakAss}_{X_s}(K) = 0 \), see Divisors, Lemma [5.5]. We have \( \text{WeakAss}_{X_s}(K) \subset \text{WeakAss}_{X_s}(\mathcal{F}) \), see Divisors, Lemma [5.4]. As \( \mathcal{F} \) is flat we see from Lemma [13.5] that \( \text{WeakAss}_{X_s}(\mathcal{F}) \subset \text{Ass}_{X_s}(\mathcal{F}) \). By purity any point \( x' \) of \( \text{Ass}_{X_s}(\mathcal{F}) \) is a generalization of a point of \( X_s \), and hence is the specialization of a point \( x \in \text{Ass}_{X_s}(\mathcal{F}_s) \), by Lemma [18.1]. Hence the injectivity of \( \varphi_x \) implies the injectivity of \( \varphi_{x'} \), whence \( K_{x'} = 0 \). ∎

**Proposition 19.2.** Let \( f : X \to S \) be an affine, finitely presented morphism of schemes. Let \( \mathcal{F} \) be a quasi-coherent \( \mathcal{O}_X \)-module of finite presentation, flat over \( S \). Then the following are equivalent

1. \( f_*\mathcal{F} \) is locally projective on \( S \), and
2. \( \mathcal{F} \) is pure relative to \( S \).

In particular, given a ring map \( A \to B \) of finite presentation and a finitely presented \( B \)-module \( N \) flat over \( A \) we have: \( N \) is projective as an \( A \)-module if and only if \( \text{Spec}(B) \) is pure relative to \( \text{Spec}(A) \).

**Proof.** The implication (1) \( \Rightarrow \) (2) is Lemma [17.4]. Assume \( \mathcal{F} \) is pure relative to \( S \). Note that by Lemma [18.3] this implies \( \mathcal{F} \) remains pure after any base change. By Descent, Lemma [7.7] it suffices to prove \( f_*\mathcal{F} \) is fpqc locally projective on \( S \). Pick \( s \in S \). We will prove that the restriction of \( f_*\mathcal{F} \) to an étale neighbourhood of \( s \) is locally projective. Namely, by Lemma [12.5] after replacing \( S \) by an affine elementary étale neighbourhood of \( s \), we may assume there exists a diagram

\[
\begin{array}{ccc}
X & \xymatrix{ \ar[dr] & } & X' \\
\ar[ur] & g & \\
\end{array}
\]

where \( X' \) is étale.
Let $\exists$ a specialization $\xi$ of schemes affine and of finite presentation over $S$, where $g$ is étale, $X_s \subset g(X')$, and with $\Gamma(X', g^*F)$ a projective $\Gamma(S, \mathcal{O}_S)$-module. Note that in this case $g^*F$ is universally pure over $S$, see Lemma \cite{17.4} Hence by Lemma \cite{18.2} we see that the open $g(X')$ contains the points of $\text{Ass}_{X/S}(F)$ lying over $\text{Spec}(\mathcal{O}_{S,s})$. Set

$$E = \{ t \in S \mid \text{Ass}_{X_s}(F_t) \subset g(X') \}.$$ 

By More on Morphisms, Lemma \cite{23.5} $E$ is a constructible subset of $S$. We have seen that $\text{Spec}(\mathcal{O}_{S,s}) \subset E$. By Morphisms, Lemma \cite{21.4} we see that $E$ contains an open neighbourhood of $s$. Hence after replacing $S$ by an affine neighbourhood of $s$ we may assume that $\text{Ass}_{X/S}(F) \subset g(X')$. By Lemma \cite{7.4} this means that

$$\Gamma(X, F) \to \Gamma(X', g^*F)$$

is $\Gamma(S, \mathcal{O}_S)$-universally injective. By Algebra, Lemma \cite{88.7} we conclude that $\Gamma(X, F)$ is Mittag-Leffler as an $\Gamma(S, \mathcal{O}_S)$-module. Since $\Gamma(X, F)$ is countably generated and flat as a $\Gamma(S, \mathcal{O}_S)$-module, we conclude it is projective by Algebra, Lemma \cite{92.1}.

We can use the proposition to improve some of our earlier results. The following lemma is an improvement of Proposition \cite{12.4}.

**Lemma 19.3.** Let $f : X \to S$ be a morphism which is locally of finite presentation. Let $F$ be a quasi-coherent $\mathcal{O}_X$-module which is of finite presentation. Let $x \in X$ with $s = f(x) \in S$. If $F$ is flat at $x$ over $S$ there exists an affine elementary étale neighbourhood $(S', s') \to (S, s)$ and an affine open $U' \subset X \times_S S'$ which contains $x' = (x, s')$ such that $\Gamma(U', F_{|U'})$ is a projective $\Gamma(S', \mathcal{O}_{S'})$-module.

**Proof.** During the proof we may replace $X$ by an open neighbourhood of $x$ and we may replace $S$ by an elementary étale neighbourhood of $s$. Hence, by openness of flatness (see More on Morphisms, Theorem \cite{15.1}) we may assume that $F$ is flat over $S$. We may assume $S$ and $X$ are affine. After shrinking $X$ some more we may assume that any point of $\text{Ass}_{X_s}(F_s)$ is a generalization of $x$. This property is preserved on replacing $(S, s)$ by an elementary étale neighbourhood. Hence we may apply Lemma \cite{12.5} to arrive at the situation where there exists a diagram

$$\begin{array}{ccc}
X & \xrightarrow{g} & X' \\
& \searrow & \\
& S & \\
\end{array}$$

of schemes affine and of finite presentation over $S$, where $g$ is étale, $X_s \subset g(X')$, and with $\Gamma(X', g^*F)$ a projective $\Gamma(S, \mathcal{O}_S)$-module. Note that in this case $g^*F$ is universally pure over $S$, see Lemma \cite{17.4}

Let $U \subset g(X')$ be an affine open neighbourhood of $x$. We claim that $F_{|U}$ is pure along $U_s$. If we prove this, then the lemma follows because $F_{|U}$ will be pure relative to $S$ after shrinking $S$, see Lemma \cite{18.6} whereupon the projectivity follows from Proposition \cite{19.2} To prove the claim we have to show, after replacing $(S, s)$ by an arbitrary elementary étale neighbourhood, that any point $\xi$ of $\text{Ass}_{U_s}(F_{|U})$ lying over some $s' \in S$, $s' \to s$ specializes to a point of $U_s$. Since $U \subset g(X')$ we can find a $\xi' \in X'$ with $g(\xi') = \xi$. Because $g^*F$ is pure over $S$, using Lemma \cite{18.1} we see there exists a specialization $\xi' \to x'$ with $x' \in \text{Ass}_{X'_s}(g^*F_s)$. Then $g(x') \in \text{Ass}_{X_s}(F_s)$ (see for example Lemma \cite{2.8}) applied to the étale morphism $X'_s \to X_s$ of Noetherian
schemes) and hence \( g(x') \sim x \) by our choice of \( X \) above! Since \( x \in U \) we conclude that \( g(x') \in U \). Thus \( \xi = g(\xi') \sim g(x') \in U \), as desired.

The following lemma is an improvement of Lemma 12.9

**Lemma 19.4.** Let \( f : X \to S \) be a morphism which is locally of finite type. Let \( \mathcal{F} \) be a quasi-coherent \( \mathcal{O}_X \)-module which is of finite type. Let \( x \in X \) with \( s = f(x) \in S \). If \( \mathcal{F} \) is flat at \( x \) over \( S \) there exists an affine elementary étale neighbourhood \((S', s') \to (S, s)\) and an affine open \( U' \subset X \times_S \text{Spec}(\mathcal{O}_{S', s'})\) which contains \( x' = (x, s') \) such that \( \Gamma(U', \mathcal{F}|_{U'}) \) is a free \( \mathcal{O}_{S', s'} \)-module.

**Proof.** The question is Zariski local on \( X \) and \( S \). Hence we may assume that \( X \) and \( S \) are affine. Then we can find a closed immersion \( i : X \to \mathbb{A}^d_S \) over \( S \). It is clear that it suffices to prove the lemma for the sheaf \( i_* \mathcal{F} \) on \( \mathbb{A}^d_S \) and the point \( i(x) \). In this way we reduce to the case where \( X \to S \) is of finite presentation. After replacing \( S \) by \( \text{Spec}(\mathcal{O}_{S', s'}) \) and \( X \) by an open of \( X \times_S \text{Spec}(\mathcal{O}_{S', s'}) \) we may assume that \( \mathcal{F} \) is of finite presentation, see Proposition 10.3. In this case we may appeal to Lemma 19.3 and Algebra, Theorem 84.4 to conclude.

**Lemma 19.5.** Let \( A \to B \) be a local ring map of local rings which is essentially of finite type. Let \( N \) be a finite \( B \)-module which is flat as an \( A \)-module. If \( A \) is henselian, then \( N \) is a filtered colimit

\[
N = \text{colim}_i F_i
\]

of free \( A \)-modules \( F_i \) such that all transition maps \( u_i : F_i \to F_{i'} \) of the system induce injective maps \( \pi_i : F_i/\mathfrak{m}_A F_i \to F_{i'}/\mathfrak{m}_A F_{i'} \). Also, \( N \) is a Mittag-Leffler \( A \)-module.

**Proof.** We can find a morphism of finite type \( X \to S = \text{Spec}(A) \) and a point \( x \in X \) lying over the closed point \( s \) of \( S \) and a finite type quasi-coherent \( \mathcal{O}_X \)-module \( \mathcal{F} \) such that \( \mathcal{F}_x \cong N \) as an \( A \)-module. After shrinking \( X \) we may assume that each point of \( \text{Ass}_X(\mathcal{F}_x) \) specializes to \( x \). By Lemma 19.3 we see that there exists a fundamental system of affine open neighbourhoods \( U_i \subset X \) of \( x \) such that \( \Gamma(U_i, \mathcal{F}) \) is a free \( A \)-module \( F_i \). Note that if \( U_{i'} \subset U_i \), then

\[
F_i/\mathfrak{m}_A F_i = \Gamma(U_{i,s}, \mathcal{F}_s) \longrightarrow \Gamma(U_{i',s}, \mathcal{F}_s) = F_{i'}/\mathfrak{m}_A F_{i'}
\]

is injective because a section of the kernel would be supported at a closed subset of \( X_s \) not meeting \( x \) which is a contradiction to our choice of \( X \) above. Since the maps \( F_i \to F_{i'} \) are \( A \)-universally injective (Lemma 7.5) it follows that \( N \) is Mittag-Leffler by Algebra, Lemma 88.9.

The following lemma should be skipped if reading through for the first time.

**Lemma 19.6.** Let \( A \to B \) be a local ring map of local rings which is essentially of finite type. Let \( N \) be a finite \( B \)-module which is flat as an \( A \)-module. If \( A \) is a valuation ring, then any element of \( N \) has a content ideal \( I \subset A \) (More on Algebra, Definition 24.1).

**Proof.** Let \( A/B^h \) be the henselization. Let \( B' \) be the localization of \( B \otimes_A A^h \) at the maximal ideal \( \mathfrak{m}_B \otimes A^h + B \otimes \mathfrak{m}_A^h \). Then \( B \to B' \) is flat, hence faithfully flat. Let \( N' = N \otimes_B B' \). Let \( x \in N \) and let \( x' \in N' \) be the image. We claim that for an ideal \( I \subset A \) we have \( x \in I N \iff x' \in I N' \). Namely, \( N/IN \to N'/IN' \) is the tensor product of \( B \to B' \) with \( N/IN \) and \( B \to B' \) is universally injective by Algebra, Lemma 81.11. By More on Algebra, Lemma 111.5 and Algebra, Lemma 49.17 the
map \( A \to A^b \) defines an inclusion preserving bijection \( I \to IA^b \) on sets of ideals. We conclude that \( x \) has a content ideal in \( A \) if and only if \( x' \) has a content ideal in \( A^b \). The assertion for \( x' \in N' \) follows from Lemma 19.5 and Algebra, Lemma 88.6.

### 20. Flattening functors

**Situation 20.1.** Let \( f : X \to S \) be a morphism of schemes. Let \( u : F \to G \) be a homomorphism of \( \mathcal{O}_X \)-modules. For any scheme \( T \) over \( S \) we will denote \( u_T : F_T \to G_T \) the base change of \( u \) to \( T \), in other words, \( u_T \) is the pullback of \( u \) via the projection morphism \( X_T = X \times_S T \to X \). In this situation we can consider the functor

\[
F_{iso} : (\text{Sch}/S)^{opp} \to \text{Sets}, \quad T \mapsto \begin{cases} \{ \ast \} & \text{if } u_T \text{ is an isomorphism,} \\ \emptyset & \text{else.} \end{cases}
\]

There are variants \( F_{inj}, F_{surj}, F_{zero} \) where we ask that \( u_T \) is injective, surjective, or zero.

**Lemma 20.2.** In **Situation 20.1**

1. Each of the functors \( F_{iso}, F_{inj}, F_{surj}, F_{zero} \) satisfies the sheaf property for the fpqc topology.
2. If \( f \) is quasi-compact and \( G \) is of finite type, then \( F_{surj} \) is limit preserving.
3. If \( f \) is quasi-compact and \( F \) of finite type, then \( F_{zero} \) is limit preserving.
4. If \( f \) is quasi-compact, \( F \) is of finite type, and \( G \) is of finite presentation, then \( F_{iso} \) is limit preserving.

**Proof.** Let \( \{ T_i \to T \}_{i \in I} \) be an fpqc covering of schemes over \( S \). Set \( X_i = X_{T_i} = X \times_S T_i \) and \( u_i = u_{T_i} \). Note that \( \{ X_i \to X_T \}_{i \in I} \) is an fpqc covering of \( X_T \), see Topologies, Lemma 37.7. In particular, for every \( x \in X_T \) there exists an \( i \in I \) and an \( x_i \in X_i \) mapping to \( x \). Since \( \mathcal{O}_{X_T,x} \to \mathcal{O}_{X_i,x_i} \) is flat, hence faithfully flat (see Algebra, Lemma 38.17) we conclude that \( \{ u_i \}_i \) is injective, surjective, bijective, or zero if and only if \( \{ u_T \}_T \) is injective, surjective, bijective, or zero. Whence part (1) of the lemma.

Proof of (2). Assume \( f \) quasi-compact and \( G \) of finite type. Let \( T = \text{lim}_{i \in I} T_i \) be a directed limit of affine \( S \)-schemes and assume that \( u_T \) is surjective. Set \( X_i = X_{T_i} = X \times_S T_i \) and \( u_i = u_{T_i} : F_i = F_{T_i} \to G_i = G_{T_i} \). To prove part (2) we have to show that \( u_i \) is surjective for some \( i \). Pick \( i_0 \in I \) and replace \( I \) by \( \{ i \mid i \geq i_0 \} \). Since \( f \) is quasi-compact the scheme \( X_{i_0} \) is quasi-compact. Hence we may choose affine opens \( W_1, \ldots, W_m \subset X \) and an affine open covering \( X_{i_0} = U_{i_0,1} \cup \ldots \cup U_{i_0,m} \) such that \( U_{j,i_0} \) maps into \( W_j \) under the projection morphism \( X_{i_0} \to X \). For any \( i \in I \) let \( U_{j,i} \) be the inverse image of \( U_{j,i_0} \). Setting \( U_j = \text{lim}_i U_{j,i} \) we see that \( X_T = U_1 \cup \ldots \cup U_m \) is an affine open covering of \( X_T \). Now it suffices to show, for a given \( j \in \{ 1, \ldots, m \} \) that \( u_i |_{U_{j,i}} \) is surjective for some \( i = i(j) \in I \). Using Properties, Lemma 16.1 this translates into the following algebra problem: Let \( A \) be a ring and let \( u : M \to N \) be an \( A \)-module map. Suppose that \( R = \text{colim}_{i \in I} R_i \) is a directed colimit of \( A \)-algebras. If \( N \) is a finite \( A \)-module and if \( u \otimes 1 : M \otimes_A R \to N \otimes_A R \) is surjective,
then for some $i$ the map $u \otimes 1 : M \otimes_A R_i \to N \otimes_A R_i$ is surjective. This is Algebra, Lemma 126.5 part (2).

Proof of (3). Exactly the same arguments as given in the proof of (2) reduces this to the following algebra problem: Let $A$ be a ring and let $u : M \to N$ be an $A$-module map. Suppose that $R = \text{colim}_{i \in I} R_i$ is a directed colimit of $A$-algebras. If $M$ is a finite $A$-module and if $u \otimes 1 : M \otimes_A R \to N \otimes_A R$ is zero, then for some $i$ the map $u \otimes 1 : M \otimes_A R_i \to N \otimes_A R_i$ is zero. This is Algebra, Lemma 126.5 part (1).

Proof of (4). Assume $f$ quasi-compact and $F, G$ of finite presentation. Arguing in exactly the same manner as in the previous paragraph (using in addition also Properties, Lemma 16.2) part (3) translates into the following algebra statement: Let $A$ be a ring and let $u : M \to N$ be an $A$-module map. Suppose that $R = \text{colim}_{i \in I} R_i$ is a directed colimit of $A$-algebras. Assume $M$ is a finite $A$-module, $N$ is a finitely presented $A$-module, and $u \otimes 1 : M \otimes_A R \to N \otimes_A R$ is an isomorphism. Then for some $i$ the map $u \otimes 1 : M \otimes_A R_i \to N \otimes_A R_i$ is an isomorphism. This is Algebra, Lemma 126.5 part (3). $\square$

**Situation 20.3.** Let $(A, \mathfrak{m}_A)$ be a local ring. Denote $C$ the category whose objects are $A$-algebras $A'$ which are local rings such that the algebra structure $A \to A'$ is a local homomorphism of local rings. A morphism between objects $A', A''$ of $C$ is a local homomorphism $A' \to A''$ of $A$-algebras. Let $A \to B$ be a local ring map of local rings and let $M$ be a $B$-module. If $A'$ is an object of $C$ we set $B' = B \otimes_A A'$ and we set $M' = M \otimes_A A'$ as a $B'$-module. Given $A' \in \text{Ob}(C)$, consider the condition

$$\forall q \in V(m_A B'+m_B B') \subset \text{Spec}(B') : M'_q \text{ is flat over } A'.$$

Note the similarity with More on Algebra, Equation (19.1.1). In particular, if $A' \to A''$ is a morphism of $C$ and (20.3.1) holds for $A'$, then it holds for $A''$, see More on Algebra, Lemma 19.2. Hence we obtain a functor

$$F_{lf} : C \to \text{Sets}, \quad A' \mapsto \begin{cases} \{*\} & \text{if (20.3.1) holds,} \\ \emptyset & \text{else.} \end{cases}$$

**Lemma 20.4.** In Situation 20.3

1. If $A' \to A''$ is a flat morphism in $C$ then $F_{lf}(A') = F_{lf}(A'')$.
2. If $A \to B$ is essentially of finite presentation and $M$ is a $B$-module of finite presentation, then $F_{lf}$ is limit preserving: If $\{A_i\}_{i \in I}$ is a directed system of objects of $C$, then $F_{lf}(\text{colim}_i A_i) = \text{colim}_i F_{lf}(A_i)$.

**Proof.** Part (1) is a special case of More on Algebra, Lemma 19.3. Part (2) is a special case of More on Algebra, Lemma 19.4.

**Lemma 20.5.** In Situation 20.3 Let $B \to C$ is a local map of local $A$-algebras and $N$ a $C$-module. Denote $F'_{lf} : C \to \text{Sets}$ the functor associated to the pair $(C, N)$. If $M \cong N$ as $B$-modules and $B \to C$ is finite, then $F'_{lf} = F_{lf}$.

**Proof.** Let $A'$ be an object of $C$. Set $C' = C \otimes_A A'$ and $N' = N \otimes_A A'$ similarly to the definitions of $B'$, $M'$ in Situation 20.3. Note that $M' \cong N'$ as $B'$-modules. The assumption that $B \to C$ is finite has two consequences: (a) $m_C = \sqrt{m_B C}$ and (b) $B' \to C'$ is finite. Consequence (a) implies that

$$V(m_A C' + m_C C') = (\text{Spec}(C') \to \text{Spec}(B'))^{-1} V(m_A B' + m_B B').$$
Suppose \( q \subseteq V(m_A'B' + m_BB') \). Then \( M'_q \) is flat over \( A' \) if and only if the \( C'_q \)-module \( N'_q \) is flat over \( A' \) (because these are isomorphic as \( A' \)-modules) if and only if for every maximal ideal \( r \) of \( C'_q \) the module \( N'_q \) is flat over \( A' \) (see Algebra, Lemma \( 38.18 \)). As \( B'_q \to C'_q \) is finite by (b), the maximal ideals of \( C'_q \) correspond exactly to the primes of \( C' \) lying over \( q \) (see Algebra, Lemma \( 35.22 \)) and these primes are all contained in \( V(m_A'C' + m_CC') \) by the displayed equation above. Thus the result of the lemma holds. \( \square \)

**Lemma 20.6.** In Situation \( 20.3 \) suppose that \( B \to C \) is a flat local homomorphism of local rings. Set \( N = M \otimes_B C \). Denote \( F'_{ij} : C \to \text{Sets} \) the functor associated to the pair \( (C, N) \). Then \( F'_{ij} = F'_{ij} \).

**Proof.** Let \( A' \) be an object of \( C \). Set \( C' = C \otimes_A A' \) and \( N' = N \otimes_A A' = M' \otimes_B C' \) similarly to the definitions of \( B' \), \( M' \) in Situation \( 20.3 \). Note that \( V(m_A'B' + m_BB') = \text{Spec}(\kappa(\kappa(m_B) \otimes_A \kappa(m_A))) \)

and similarly for \( V(m_A'C' + m_CC') \). The ring map \( \kappa(\kappa(m_B) \otimes_A \kappa(m_A)) \to \kappa(m_C) \otimes_A \kappa(m_A) \)

is faithfully flat, hence \( V(m_A'B' + m_BB') \to V(m_A'C' + m_CC') \) is surjective. Finally, if \( r \in V(m_A'C' + m_CC') \) maps to \( q \in V(m_A'B' + m_BB') \), then \( M'_q \) is flat over \( A' \) if and only if \( N'_q \) is flat over \( A' \) because \( B' \to C' \) is flat, see Algebra, Lemma \( 38.9 \).

The lemma follows formally from these remarks. \( \square \)

**Situation 20.7.** Let \( f : X \to S \) be a smooth morphism with geometrically irreducible fibres. Let \( \mathcal{F} \) be a quasi-coherent \( \mathcal{O}_X \)-module of finite type. For any scheme \( T \) over \( S \) we will denote \( \mathcal{F}_T \) the base change of \( \mathcal{F} \) to \( T \), in other words, \( \mathcal{F}_T \) is the pullback of \( \mathcal{F} \) via the projection morphism \( X_T = X \times_S T \to X \). Note that \( X_T \to T \) is smooth with geometrically irreducible fibres, see Morphisms, Definition \( 32.5 \) and More on Morphisms, Lemma \( 25.2 \). Let \( p \geq 0 \) be an integer. Given a point \( t \in T \) consider the condition

\( \tag{20.7.1} \mathcal{F}_T \) is free of rank \( p \) in a neighbourhood of \( \xi_t \)

where \( \xi_t \) is the generic point of the fibre \( X_t \). This condition for all \( t \in T \) is stable under base change, and hence we obtain a functor

\( \tag{20.7.2} H_p : (\text{Sch}/S)^{opp} \to \text{Sets}, \quad T \to \begin{cases} \{ \ast \} & \text{if } \mathcal{F}_T \text{ satisfies } (20.7.1) \forall t \in T, \\ \emptyset & \text{else}. \end{cases} \)

**Lemma 20.8.** In Situation \( 20.7 \)

1. The functor \( H_p \) satisfies the sheaf property for the fpqc topology.
2. If \( \mathcal{F} \) is of finite presentation, then functor \( H_p \) is limit preserving.

**Proof.** Let \( \{ T_i \to T \}_{i \in I} \) be an fpqc\(^1\) covering of schemes over \( S \). Set \( X_i = X_{T_i} = X \times_S T_i \) and denote \( \mathcal{F}_i \) the pullback of \( \mathcal{F} \) to \( X_i \). Assume that \( \mathcal{F}_i \) satisfies \( (20.7.1) \) for all \( i \). Pick \( t \in T \) and let \( \xi_t \in X_T \) denote the generic point of \( X_t \). We have to show that \( \mathcal{F} \) is free in a neighbourhood of \( \xi_t \). For some \( i \in I \) we can find a \( t_i \in T_i \) mapping to \( t \). Let \( \xi_i \in X_i \) denote the generic point of \( X_{t_i} \), so that \( \xi_i \) maps to \( \xi_t \). The fact that \( \mathcal{F}_i \) is free of rank \( p \) in a neighbourhood of \( \xi_i \) implies that

\(^1\)It is quite easy to show that \( H_p \) is a sheaf for the fppf topology using that flat morphisms of finite presentation are open. This is all we really need later on. But it is kind of fun to prove directly that it also satisfies the sheaf condition for the fpqc topology.
Let $f : X \to S$ be a morphism of schemes which is locally of finite type. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module of finite type. Let $n \geq 0$. The following are equivalent

1. for $s \in S$ the closed subset $Z \subset X_s$ of points where $\mathcal{F}$ is not flat over $S$ (see Lemma 10.4) satisfies $\dim(Z) < n$, and
2. for $x \in X$ such that $\mathcal{F}$ is not flat at $x$ over $S$ we have $\text{trdeg}_{\kappa(f(x))}(\kappa(x)) < n$.

If this is true, then it remains true after any base change.

**Proof.** Let $x \in X$ be a point over $s \in S$. Then the dimension of the closure of $\{x\}$ in $X_s$ is $\text{trdeg}_{\kappa(s)}(\kappa(x))$ by Varieties, Lemma 20.3 Conversely, if $Z \subset X_s$ is a closed subset of dimension $d$, then there exists a point $x \in Z$ with $\text{trdeg}_{\kappa(s)}(\kappa(x)) = d$ (same reference). Therefore the equivalence of (1) and (2) holds (even fibre by fibre). The statement on base change follows from Morphisms, Lemmas 24.7 and 27.3. □

**Definition 20.10.** Let $f : X \to S$ be a morphism of schemes which is locally of finite type. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module of finite type. Let $n \geq 0$. We say $\mathcal{F}$ is flat over $S$ in dimensions $\geq n$ if the equivalent conditions of Lemma 20.9 are satisfied.
05MT **Situation** 20.11. Let \( f : X \to S \) be a morphism of schemes which is locally of finite type. Let \( \mathcal{F} \) be a quasi-coherent \( \mathcal{O}_X \)-module of finite type. For any scheme \( T \) over \( S \) we will denote \( \mathcal{F}_T \) the base change of \( \mathcal{F} \) to \( T \), in other words, \( \mathcal{F}_T \) is the pullback of \( \mathcal{F} \) via the projection morphism \( X_T = X \times_S T \to X \). Note that \( X_T \to T \) is of finite type and that \( \mathcal{F}_T \) is an \( \mathcal{O}_{X_T} \)-module of finite type (Morphisms, Lemma 14.4) and Modules, Lemma 9.2. Let \( n \geq 0 \). By Definition 20.10 and Lemma 20.9 we obtain a functor
\[
(20.11.1)
\]
\[
\mathcal{F}_n : (\text{Sch}/S)^{\text{opp}} \to \text{Sets}, \quad T \to \begin{cases} \{ \ast \} & \text{if } \mathcal{F}_T \text{ is flat over } T \text{ in } \dim \geq n, \\ \emptyset & \text{else.} \end{cases}
\]

05MV **Lemma** 20.12. In Situation 20.11

1. The functor \( \mathcal{F}_n \) satisfies the sheaf property for the fpqc topology.
2. If \( f \) is quasi-compact and locally of finite presentation and \( \mathcal{F} \) is of finite presentation, then the functor \( \mathcal{F}_n \) is limit preserving.

**Proof.** Let \( \{ T_i \to T \}_{i \in I} \) be an fpqc covering of schemes over \( S \). Set \( X_i = X_{T_i} = X \times_S T_i \) and denote \( \mathcal{F}_i \) the pullback of \( \mathcal{F} \) to \( X_i \). Assume that \( \mathcal{F}_i \) is flat over \( T_i \) in dimensions \( \geq n \) for all \( i \). Let \( t \in T \). Choose an index \( i \) and a point \( t_i \in T_i \) mapping to \( t \). Consider the cartesian diagram
\[
\begin{array}{ccc}
X_{\text{Spec}(\mathcal{O}_{T,i})} & \longrightarrow & X_{\text{Spec}(\mathcal{O}_{T_i,t_i})} \\
\downarrow & & \downarrow \\
\text{Spec}(\mathcal{O}_{T,i}) & \longrightarrow & \text{Spec}(\mathcal{O}_{T_i,t_i})
\end{array}
\]
As the lower horizontal morphism is flat we see from More on Morphisms, Lemma 15.2 that the set \( Z_i \subset X_i \), where \( \mathcal{F}_i \) is not flat over \( T_i \) and the set \( Z \subset X_i \) where \( \mathcal{F}_T \) is not flat over \( T \) are related by the rule \( Z_i = Z_n(t) \). Hence we see that \( \mathcal{F}_T \) is flat over \( T \) in dimensions \( \geq n \) by Morphisms, Lemma 27.3.

Assume that \( f \) is quasi-compact and locally of finite presentation and that \( \mathcal{F} \) is of finite presentation. In this paragraph we first reduce the proof of (2) to the case where \( f \) is of finite presentation. Let \( T = \lim_{i \in I} T_i \) be a directed limit of affine \( S \)-schemes and assume that \( \mathcal{F}_T \) is flat in dimensions \( \geq n \). Set \( X_j = X_{T_j} = X \times_S T_j \) and denote \( \mathcal{F}_j \) the pullback of \( \mathcal{F} \) to \( X_j \). We have to show that \( \mathcal{F}_j \) is flat in dimensions \( \geq n \) for some \( i \). Pick \( i_0 \in I \) and replace \( I \) by \( \{ i \mid i \geq i_0 \} \). Since \( T_{i_0} \) is affine (hence quasi-compact) there exist finitely many affine opens \( W_j \subset S \), \( j = 1, \ldots, m \) and an affine open overing \( T_{i_0} = \bigcup_{j=1,\ldots,m} V_{j,i_0} \) such that \( T_{i_0} \to S \) maps \( V_{j,i_0} \) into \( W_j \). For \( i \geq i_0 \) denote \( V_{j,i} \) the inverse image of \( V_{j,i_0} \) in \( T_i \). If we can show, for each \( j \), that there exists an \( i \) such that \( \mathcal{F}_{V_{j,i_0}} \) is flat in dimensions \( \geq n \), then we win. In this way we reduce to the case that \( S \) is affine. In this case \( X \) is quasi-compact and we can choose a finite affine open covering \( X = W_1 \cup \ldots \cup W_m \). In this case the result for \( (X \to S, \mathcal{F}) \) is equivalent to the result for \( (\coprod W_j, \coprod \mathcal{F}|_{W_j}) \). Hence we may assume that \( f \) is of finite presentation.

Assume \( f \) is of finite presentation and \( \mathcal{F} \) is of finite presentation. Let \( U \subset X_T \) denote the open subscheme of points where \( \mathcal{F}_T \) is flat over \( T \), see More on Morphisms, Theorem 15.1. By assumption the dimension of every fibre of \( Z = X_T \setminus U \) over \( T \) has dimension \( < n \). By Limits, Lemma 16.4 we can find a closed subscheme \( Z \subset Z' \subset X_T \) such that \( \dim(Z'_i) < n \) for all \( i \in T \) and such that \( Z' \to X_T \) is of
finite presentation. By Limits, Lemmas \[10.1\] and \[5.5\] there exists an \(i \in I\) and a closed subscheme \(Z'_i \subset X_i\) of finite presentation whose base change to \(T\) is \(Z'\). By Limits, Lemma \[10.4\] we may assume all fibres of \(Z'_i \rightarrow T_i\) have dimension \(< n\). By Limits, Lemma \[10.4\] we may assume that \(\mathcal{F}_{i|X_i \times T_i}\) is flat over \(T_i\). This implies that \(\mathcal{F}_i\) is flat in dimensions \(\geq n\); here we use that \(Z' \rightarrow X_T\) is of finite presentation, and hence the complement \(X_T \setminus Z'\) is quasi-compact! Thus part (2) is proved and the proof of the lemma is complete. \(\square\)

**Situation 20.13.** Let \(f : X \rightarrow S\) be a morphism of schemes. Let \(\mathcal{F}\) be a quasi-coherent \(\mathcal{O}_X\)-module. For any scheme \(T\) over \(S\) we will denote \(\mathcal{F}_T\) the base change of \(\mathcal{F}\) to \(T\), in other words, \(\mathcal{F}_T\) is the pullback of \(\mathcal{F}\) via the projection morphism \(X_T = X \times_S T \rightarrow X\). Since the base change of a flat module is flat we obtain a functor

\[
F_{flat} : (\text{Sch}/S)^{opp} \rightarrow \text{Sets}, \quad T \rightarrow \begin{cases} \{\ast\} & \text{if } \mathcal{F}_T \text{ is flat over } T, \\ \emptyset & \text{else.} \end{cases}
\]

**Lemma 20.14.** In Situation 20.13

1. The functor \(F_{\text{flat}}\) satisfies the sheaf property for the fppf topology.
2. If \(f\) is quasi-compact and locally of finite presentation and \(\mathcal{F}\) is of finite presentation, then the functor \(F_{\text{flat}}\) is limit preserving.

**Proof.** Part (1) follows from the following statement: If \(T' \rightarrow T\) is a surjective flat morphism of schemes over \(S\), then \(\mathcal{F}_{T'}\) is flat over \(T'\) if and only if \(\mathcal{F}_T\) is flat over \(T\), see More on Morphisms, Lemma \[15.2\] Part (2) follows from Limits, Lemma \[10.4\] after reducing to the case where \(X\) and \(S\) are affine (compare with the proof of Lemma \[20.12\]). \(\square\)

## 21. Flattening stratifications

**Definition 21.1.** Let \(X \rightarrow S\) be a morphism of schemes. Let \(\mathcal{F}\) be a quasi-coherent \(\mathcal{O}_X\)-module. We say that the *universal flattening of \(\mathcal{F}\) exists* if the functor \(F_{\text{flat}}\) defined in Situation 20.13 is representable by a scheme \(S'\) over \(S\). We say that the *universal flattening of \(X\) exists* if the universal flattening of \(\mathcal{O}_X\) exists.

Note that if the universal flattening \(\tilde{S}'\) of \(\mathcal{F}\) exists, then the morphism \(S' \rightarrow S\) is a monomorphism of schemes such that \(\mathcal{F}_{S'}\) is flat over \(S'\) and such that a morphism \(T \rightarrow S\) factors through \(S'\) if and only if \(\mathcal{F}_T\) is flat over \(T\).

**Example 21.2.** Let \(X = S = \text{Spec}(k[x, y])\) where \(k\) is a field. Let \(\mathcal{F} = \widehat{M}\) where \(\widehat{M} = k[x, x^{-1}, y]/(y)\). For a \(k[x, y]\)-algebra \(A\) set \(F_{\text{flat}}(A) = F_{\text{flat}}(\text{Spec}(A))\). Then \(F_{\text{flat}}(k[x, y]/(x, y)^n) = \{\ast\}\) for all \(n\), while \(F_{\text{flat}}(k[[x, y]]) = \emptyset\). This means that \(F_{\text{flat}}\) isn’t representable (even by an algebraic space, see Formal Spaces, Lemma \[26.3\]). Thus the universal flattening does not exist in this case.

We define (compare with Topology, Remark \[28.5\]) a (locally finite, scheme theoretic) *stratification* of a scheme \(S\) to be given by closed subschemes \(Z_i \subset S\) indexed by a

---

2The scheme \(S'\) is sometimes called the *universal flatification*. In [GR71] it is called the *platificateur universel*. Existence of the universal flattening should not be confused with the type of results discussed in More on Algebra, Section \[26\].
partially ordered set $I$ such that $S = \bigcup Z_i$ (set theoretically), such that every point of $S$ has a neighbourhood meeting only a finite number of $Z_i$, and such that

$$Z_i \cap Z_j = \bigcup_{k \leq i,j} Z_k.$$  

Setting $S_i = Z_i \setminus \bigcup_{j<i} Z_j$, the actual stratification is the decomposition $S = \coprod S_i$ into locally closed subschemes. We often only indicate the strata $S_i$ and leave the construction of the closed subschemes $Z_i$ to the reader. Given a stratification we obtain a monomorphism

$$S' = \coprod_{i \in I} S_i \rightarrow S.$$  

We will call this the monomorphism associated to the stratification. With this terminology we can define what it means to have a flattening stratification.

**Definition 21.3.** Let $X \rightarrow S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module. We say that $\mathcal{F}$ has a flattening stratification if the functor $\mathcal{F}_{\text{flat}}$ defined in Situation [20.13] is representable by a monomorphism $S' \rightarrow S$ associated to a stratification of $S$ by locally closed subschemes. We say that $X$ has a flattening stratification if $\mathcal{O}_X$ has a flattening stratification.

When a flattening stratification exists, it is often important to understand the index set labeling the strata and its partial ordering. This often has to do with ranks of modules. For example if $X = S$ and $\mathcal{F}$ is a finitely presented $\mathcal{O}_S$-module, then the flattening stratification exists and is given by the Fitting ideals of $\mathcal{F}$, see Divisors, Lemma [9.7].

We end this section showing that if we do not insist on a canonical stratification, then we can use generic flatness to construct some stratification such that our sheaf is flat over the strata.

**Lemma 21.4** (Generic flatness stratification). Let $f : X \rightarrow S$ be a morphism of finite presentation between quasi-compact and quasi-separated schemes. Let $\mathcal{F}$ be an $\mathcal{O}_X$-module of finite presentation. Then there exists a $t \geq 0$ and closed subschemes

$$S \supset S_0 \supset S_1 \supset \ldots \supset S_t = \emptyset$$  

such that $S_i \rightarrow S$ is defined by a finite type ideal sheaf, $S_0 \subset S$ is a thickening, and $\mathcal{F}$ pulled back to $X \times_S (S_i \setminus S_{i+1})$ is flat over $S_i \setminus S_{i+1}$.

**Proof.** We can find a cartesian diagram

$$
\begin{array}{ccc}
X & \longrightarrow & X_0 \\
\downarrow & & \downarrow \\
S & \longrightarrow & S_0
\end{array}
$$

and a finitely presented $\mathcal{O}_{X_0}$-module $\mathcal{F}_0$ which pulls back to $\mathcal{F}$ such that $X_0$ and $S_0$ are of finite type over $\mathbf{Z}$. See Limits, Proposition [5.4] and Lemmas [10.1] and [10.2]. Thus we may assume $X$ and $S$ are of finite type over $\mathbf{Z}$ and $\mathcal{F}$ is a coherent $\mathcal{O}_X$-module.

Assume $X$ and $S$ are of finite type over $\mathbf{Z}$ and $\mathcal{F}$ is a coherent $\mathcal{O}_X$-module. In this case every quasi-coherent ideal is of finite type, hence we do not have to check the condition that $S_i$ is cut out by a finite type ideal. Set $S_0 = S_{\text{red}}$ equal to the reduction of $S$. By generic flatness as stated in Morphisms, Proposition [26.2]
there is a dense open \( U_0 \subset S_0 \) such that \( F \) pulled back to \( X \times_S U_0 \) is flat over \( U_0 \). Let \( S_1 \subset S_0 \) be the reduced closed subscheme whose underlying closed subset is \( S \setminus U_0 \). We continue in this way, provided \( S_1 \neq \emptyset \), to find \( S_0 \supset S_1 \supset \ldots \). Because \( S \) is Noetherian any descending chain of closed subsets stabilizes hence we see that \( S_t = \emptyset \) for some \( t \geq 0 \).

\[ 22. \text{ Flattening stratification over an Artinian ring} \]

\[ 05 \text{PA A flattening stratification exists when the base scheme is the spectrum of an Artinian ring.} \]

\[ 05 \text{PB Lemma 22.1. Let} \ S \text{ be the spectrum of an Artinian ring. For any scheme} \ X \text{ over} \ S, \text{ and any quasi-coherent} \ O_X \text{-module there exists a universal flattening. In fact the universal flattening is given by a closed immersion} \ S' \rightarrow S, \text{ and hence is a flattening stratification for} \ F \text{ as well.} \]

\[ \textbf{Proof.} \text{ Choose an affine open covering} \ X = \bigcup U_i. \text{ Then} \ F_{\text{flat}} \text{ is the product of the functors associated to each of the pairs} (U_i, F|_{U_i}). \text{ Hence it suffices to prove the result for each} (U_i, F|_{U_i}). \text{ In the affine case the lemma follows immediately from} \text{ More on Algebra, Lemma 17.2.} \]

\[ 23. \text{ Flattening a map} \]

\[ 05 \text{PC Theorem 23.3 is the key to further flattening statements.} \]

\[ 05 \text{PD Lemma 23.1. Let} \ S \text{ be a scheme. Let} \ g : X' \rightarrow X \text{ be a flat morphism of schemes over} \ S, \text{ with} X \text{ locally of finite type over} \ S. \text{ Let} \ F \text{ be a finite type quasi-coherent} \ O_X \text{-module which is flat over} \ S. \text{ If} \ Ass_{X/S}(F) \subset g(X') \text{ then the canonical map} \]

\[ F \rightarrow g_*g^*F \]

\[ \text{is injective, and remains injective after any base change.} \]

\[ \textbf{Proof.} \text{ The final assertion means that} F_T \rightarrow (g_T)_*g_T^*F_T \text{ is injective for any morphism} T \rightarrow S. \text{ The assumption} Ass_{X/g}(F) \subset g(X') \text{ is preserved by base change, see Divisors, Lemma 7.3 and Remark 7.4. The same holds for the assumption of flatness and finite type. Hence it suffices to prove the injectivity of the displayed arrow. Let} \ K = \text{Ker}(F \rightarrow g_*g^*F). \text{ Our goal is to prove that} K = 0. \text{ In order to do this it suffices to prove that WeakAss}_X(K) = 0, \text{ see Divisors, Lemma 5.5. We have WeakAss}_X(K) \subset \text{WeakAss}_X(F), \text{ see Divisors, Lemma 5.4. As} F \text{ is flat we see from Lemma 13.5 that} WeakAss_X(F) \subset Ass_{X/S}(F). \text{ By assumption any point} x \text{ of} Ass_{X/S}(F) \text{ is the image of some} x' \in X'. \text{ Since} g \text{ is flat the local ring map} O_{X,x} \rightarrow O_{X',x'} \text{ is faithfully flat, hence the map} \]

\[ F_x \rightarrow g^*F_{x'} = F_x \otimes_{O_{X,x}} O_{X',x'} \]

\[ \text{is injective (see Algebra, Lemma 81.11). This implies that} K_x = 0 \text{ as desired.} \]

\[ 05 \text{PE Lemma 23.2. Let} \ A \text{ be a ring. Let} u : M \rightarrow N \text{ be a surjective map of} A \text{-modules. If} M \text{ is projective as an} A \text{-module, then there exists an ideal} I \subset A \text{ such that for any ring map} \varphi : A \rightarrow B \text{ the following are equivalent} \]

\[ (1) \ u \otimes 1 : M \otimes_A B \rightarrow N \otimes_A B \text{ is an isomorphism, and} \]

\[ (2) \ \varphi(I) = 0. \]
Proof. As $M$ is projective we can find a projective $A$-module $C$ such that $F = M \oplus C$ is a free $R$-module. By replacing $u$ by $u \oplus 1 : F = M \oplus C \to N \oplus C$ we see that we may assume $M$ is free. In this case let $I$ be the ideal of $A$ generated by coefficients of all the elements of $\text{Ker}(u)$ with respect to some (fixed) basis of $M$. The reason this works is that, since $u$ is surjective and $\otimes A B$ is right exact, $\text{Ker}(u \otimes 1)$ is the image of $\text{Ker}(u) \otimes_A B$ in $M \otimes_A B$. □

**Theorem 23.3.** In Situation 20.1 assume

1. $f$ is of finite presentation,
2. $\mathcal{F}$ is of finite presentation, flat over $S$, and pure relative to $S$, and
3. $u$ is surjective.

Then $F_{\text{iso}}$ is representable by a closed immersion $Z \to S$. Moreover $Z \to S$ is of finite presentation if $G$ is of finite presentation.

Proof. We will use without further mention that $\mathcal{F}$ is universally pure over $S$, see Lemma [18.3]. By Lemma [20.2] and Descent, Lemmas [34.2] and [36.1] the question is local for the étale topology on $S$. Hence it suffices to prove, given $s \in S$, that there exists an étale neighbourhood of $(S, s)$ so that the theorem holds.

Using Lemma [12.5] and after replacing $S$ by an elementary étale neighbourhood of $s$ we may assume there exists a commutative diagram

$$
\begin{array}{ccc}
X & \xleftarrow{g} & X' \\
\downarrow & & \downarrow \\
S & \xleftarrow{g} & g(X')
\end{array}
$$

of schemes of finite presentation over $S$, where $g$ is étale, $X_s \subset g(X')$, the schemes $X'$ and $S$ are affine, $\Gamma(X', g^* \mathcal{F})$ a projective $\Gamma(S, \mathcal{O}_S)$-module. Note that $g^* \mathcal{F}$ is universally pure over $S$, see Lemma [17.4]. Hence by Lemma [18.2] we see that the open $g(X')$ contains the points of $\text{Ass}_{X/S}(\mathcal{F})$ lying over $\text{Spec}(\mathcal{O}_{S,s})$. Set

$$
E = \{ t \in S \mid \text{Ass}_{X_t}(\mathcal{F}_t) \subset g(X') \}.
$$

By More on Morphisms, Lemma [23.3] $E$ is a constructible subset of $S$. We have seen that $\text{Spec}(\mathcal{O}_{S,s}) \subset E$. By More on Morphisms, Lemma [21.4] we see that $E$ contains an open neighbourhood of $s$. Hence after replacing $S$ by a smaller affine neighbourhood of $s$ we may assume that $\text{Ass}_{X/S}(\mathcal{F}) \subset g(X')$.

Since we have assumed that $u$ is surjective we have $F_{\text{iso}} = F_{\text{inj}}$. From Lemma [23.1] it follows that $u : \mathcal{F} \to \mathcal{G}$ is injective if and only if $g^* u : g^* \mathcal{F} \to g^* \mathcal{G}$ is injective, and the same remains true after any base change. Hence we have reduced to the case where, in addition to the assumptions in the theorem, $X \to S$ is a morphism of affine schemes and $\Gamma(X, \mathcal{F})$ is a projective $\Gamma(S, \mathcal{O}_S)$-module. This case follows immediately from Lemma [23.2].

To see that $Z$ is of finite presentation if $\mathcal{G}$ is of finite presentation, combine Lemma [20.2] part (4) with Limits, Remark [6.2]. □

**Lemma 23.4.** Let $f : X \to S$ be a morphism of schemes which is of finite presentation, flat, and pure. Let $Y$ be a closed subscheme of $X$. Let $F = f_* Y$ be the Weil restriction functor of $Y$ along $f$, defined by

$$
F : (\text{Sch}/S)^{\text{op}} \to \text{Sets}, \quad T \mapsto \begin{cases} 
\{ * \} & \text{if } Y_T \to X_T \text{ is an isomorphism}, \\
\emptyset & \text{else}.
\end{cases}
$$
Then $F$ is representable by a closed immersion $Z \to S$. Moreover $Z \to S$ is of finite presentation if $Y \to S$ is.

**Proof.** Let $I$ be the ideal sheaf defining $Y$ in $X$ and let $u : \mathcal{O}_X \to \mathcal{O}_X/I$ be the surjection. Then for an $S$-scheme $T$, the closed immersion $Y_T \to X_T$ is an isomorphism if and only if $u_T$ is an isomorphism. Hence the result follows from Theorem 23.3.

### 24. Flattening in the local case

05MZ In this section we start applying the earlier material to obtain a shadow of the flattening stratification.

05PG **Theorem 24.1.** In Situation 20.3 assume $A$ is henselian, $B$ is essentially of finite type over $A$, and $M$ is a finite $B$-module. Then there exists an ideal $I \subset A$ such that $A/I$ corepresents the functor $F_{lf}$ on the category $\mathcal{C}$. In other words given a local homomorphism of local rings $\varphi : A \to A'$ with $B' = B \otimes_A A'$ and $M' = M \otimes_A A'$ the following are equivalent:

1. $\varphi(I) = 0$.
2. $\varphi(I) = 0$.

If $B$ is essentially of finite presentation over $A$ and $M$ of finite presentation over $B$, then $I$ is a finitely generated ideal.

**Proof.** Choose a finite type ring map $A \to C$ and a finite $C$-module $N$ and a prime $q$ of $C$ such that $B = C_q$ and $M = N_q$. In the following, when we say “the theorem holds for $(N/C/A, q)$ we mean that it holds for $(A \to B, M)$ where $B = C_q$ and $M = N_q$. By Lemma 20.6 the functor $F_{lf}$ is unchanged if we replace $B$ by a local ring flat over $B$. Hence, since $A$ is henselian, we may apply Lemma 6.6 and assume that there exists a complete dévissage of $N/C/A$ at $q$.

Let $(A_i, B_i, M_i, \alpha_i, q_i)_{i=1,...,n}$ be such a complete dévissage of $N/C/A$ at $q$. Let $q'_i \subset A_i$ be the unique prime lying over $q_i \subset B_i$ as in Definition 6.4. Since $C \to A_1$ is surjective and $N \cong M_1$ as $C$-modules, we see by Lemma 20.5 it suffices to prove the theorem holds for $(M_1/A_1, q'_1)$. Since $B_1 \to A_1$ is finite and $q_1$ is the only prime of $B_1$ over $q'_1$ we see that $(A_1, A_1, q'_1)$ is finite (see Algebra, Lemma 40.11 or More on Morphisms, Lemma 22.4). Hence by Lemma 20.5 it suffices to prove the theorem holds for $(M_1/B_1/A_1, q_1)$.

At this point we may assume, by induction on the length $n$ of the dévissage, that the theorem holds for $(M_2/B_2/A, q_2)$. (If $n = 1$, then $M_2 = 0$ which is flat over $A$.) Reversing the last couple of steps of the previous paragraph, using that $M_2 \cong \text{Coker}(\alpha_2)$ as $B_1$-modules, we see that the theorem holds for $(\text{Coker}(\alpha_1)/B_1/A, q_1)$.

Let $A'$ be an object of $\mathcal{C}$. At this point we use Lemma 10.1 to see that if $(M_1 \otimes_A A')_{q'}$ is flat over $A'$ for a prime $q'$ of $B_1 \otimes_A A'$ lying over $\mathfrak{m}_A'$, then $(\text{Coker}(\alpha_1) \otimes_A A')_{q'}$ is flat over $A'$. Hence we conclude that $F_{lf}$ is a subfunctor of the functor $F_{lf}'$ associated to the module $\text{Coker}(\alpha_1)_{q_1}$ over $(B_1)_{q_1}$. By the previous paragraph we know $F_{lf}'$ is corepresented by $A/J$ for some ideal $J \subset A$. Hence we may replace $A$ by $A/J$ and assume that $\text{Coker}(\alpha_1)_{q_1}$ is flat over $A$.

Since $\text{Coker}(\alpha_1)$ is a $B_1$-module for which there exist a complete dévissage of $N_1/B_1/A$ at $q_1$ and since $\text{Coker}(\alpha_1)_{q_1}$ is flat over $A$ by Lemma 10.2 we see that $\text{Coker}(\alpha_1)$ is free as an $A$-module, in particular flat as an $A$-module. Hence
Here is a scheme theoretic reformulation of Theorem 24.1. Let $N = \text{Im}(\alpha_1) \subset M$ so that we have exact sequences

$$0 \to N \to M \to \text{Coker}(\alpha_1) \to 0 \quad \text{and} \quad B^{0r_1}_i \to N_1 \to 0$$

The flatness of $\text{Coker}(\alpha_1)$ implies the first sequence is universally exact (see Algebra, Lemma 24.3). Hence $\alpha \otimes 1_{A'}$ is injective if and only if $B^{0r_1}_i \otimes_{A'} A' \to N_1 \otimes_{A'} A'$ is an isomorphism. Finally, Theorem 25.3 applies to show this functor is corepresentable by $A/I$ for some ideal $I$ and we conclude $F_{ij}$ is corepresentable by $A/I$ also.

To prove the final statement, suppose that $A \to B$ is essentially of finite presentation and $M$ of finite presentation over $B$. Let $I \subset A$ be the ideal such that $F_{ij}$ is corepresented by $A/I$. Write $I = \bigcup I_\lambda$ where $I_\lambda$ ranges over the finitely generated ideals contained in $I$. Then, since $F_{ij}(A/I) = \{\ast\}$ we see that $F_{ij}(A/I_\lambda) = \{\ast\}$ for some $\lambda$, see Lemma 20.4 part (2). Clearly this implies that $I = I_\lambda$. 

**Remark 24.2.** Here is a scheme theoretic reformulation of Theorem 24.1. Let $(X, x) \to (S, s)$ be a morphism of pointed schemes which is locally of finite type. Let $\mathcal{F}$ be a finite type quasi-coherent $O_X$-module. Assume $S$ henselian local with closed point $s$. There exists a closed subscheme $Z \subset S$ with the following property: for any morphism of pointed schemes $(T, t) \to (S, s)$ the following are equivalent

1. $\mathcal{F}_T$ is flat over $T$ at all points of the fibre $X_t$ which map to $x \in X_s$, and
2. $\text{Spec}(\mathcal{O}_{T, t}) \to S$ factors through $Z$.

Moreover, if $X \to S$ is of finite presentation at $x$ and $\mathcal{F}_x$ of finite presentation over $O_{X, x}$, then $Z \to S$ is of finite presentation.

At this point we can obtain some very general results completely for free from the result above. Note that perhaps the most interesting case is when $E = X_s$!

**Lemma 24.3.** Let $S$ be the spectrum of a henselian local ring with closed point $s$. Let $X \to S$ be a morphism of schemes which is locally of finite type. Let $\mathcal{F}$ be a finite type quasi-coherent $O_X$-module. Let $E \subset X_s$ be a subset. There exists a closed subscheme $Z \subset S$ with the following property: for any morphism of pointed schemes $(T, t) \to (S, s)$ the following are equivalent

1. $\mathcal{F}_T$ is flat over $T$ at all points of the fibre $X_t$ which map to a point of $E \subset X_s$, and
2. $\text{Spec}(\mathcal{O}_{T, t}) \to S$ factors through $Z$.

Moreover, if $X \to S$ is locally of finite presentation, $\mathcal{F}$ is of finite presentation, and $E \subset X_s$ is closed and quasi-compact, then $Z \to S$ is of finite presentation.

**Proof.** For $x \in X_s$ denote $Z_x \subset S$ the closed subscheme we found in Remark 24.2 Then it is clear that $Z = \bigcap_{x \in E} Z_x$ works!

To prove the final statement assume $X$ locally of finite presentation, $\mathcal{F}$ of finite presentation and $Z$ closed and quasi-compact. First, choose finitely many affine opens $W_j \subset X$ such that $E \subset \bigcup W_j$. It clearly suffices to prove the result for each morphism $W_j \to S$ with sheaf $\mathcal{F}|_{X_j}$ and closed subset $E \cap W_j$. Hence we may assume $X$ is affine. In this case, More on Algebra, Lemma 19.4 shows that the functor defined by (1) is “limit preserving”. Hence we can show that $Z \to S$ is of finite presentation exactly as in the last part of the proof of Theorem 24.1. 

**Remark 24.4.** Tracing the proof of Lemma 24.3 to its origins we find a long and winding road. But if we assume that
(1) f is of finite type,
(2) F is a finite type $O_X$-module,
(3) $E = X_s$, and
(4) $S$ is the spectrum of a Noetherian complete local ring.

then there is a proof relying completely on more elementary algebra as follows: first we reduce to the case where $X$ is affine by taking a finite affine open cover. In this case $Z$ exists by More on Algebra, Lemma 20.3. The key step in this proof is constructing the closed subscheme $Z$ step by step inside the truncations $\text{Spec}(O_{S,s}/m^n_s)$. This relies on the fact that flattening stratifications always exist when the base is Artinian, and the fact that $O_{S,s} = \lim O_{S,s}/m^n_s$.

25. Variants of a lemma

In this section we discuss variants of Algebra, Lemmas 127.4 and 98.1. The most general version is Proposition 25.13; this was stated as [GR71, Lemma 4.2.2] but the proof in loc.cit. only gives the weaker result as stated in Lemma 25.5. The intricate proof of Proposition 25.13 is due to Ofer Gabber. As we currently have no application for the proposition we encourage the reader to skip to the next section after reading the proof of Lemma 25.5; this lemma will be used in the next section to prove Theorem 26.1.

25.1. Let $\varphi : A \to B$ be a local ring homomorphism of local rings which is essentially of finite type. Let $M$ be a flat $A$-module, $N$ a finite $B$-module and $u : N \to M$ an $A$-module map such that $\pi : N/m_A N \to M/m_A M$ is injective.

In this situation it is our goal to show that $u$ is $A$-universally injective, $N$ is of finite presentation over $B$, and $N$ is flat as an $A$-module. If this is true, we will say the lemma holds in the given situation.

Lemma 25.2. If in Situation 25.1 the ring $A$ is Noetherian then the lemma holds.

Proof. Applying Algebra, Lemma 98.1 we see that $u$ is injective and that $N/u(M)$ is flat over $A$. Then $u$ is $A$-universally injective (Algebra, Lemma 38.12) and $N$ is $A$-flat (Algebra, Lemma 38.13). Since $B$ is Noetherian in this case we see that $N$ is of finite presentation. □

Lemma 25.3. Let $A_0$ be a local ring. If the lemma holds for every Situation 25.1 with $A = A_0$, with $B$ a localization of a polynomial algebra over $A$, and $N$ of finite presentation over $B$, then the lemma holds for every Situation 25.1 with $A = A_0$.

Proof. Let $A \to B$, $u : N \to M$ be as in Situation 25.1. Write $B = C/I$ where $C$ is the localization of a polynomial algebra over $A$ at a prime. If we can show that $N$ is finitely presented as a $C$-module, then a fortiori this shows that $N$ is finitely presented as a $B$-module (see Algebra, Lemma 6.4). Hence we may assume that $B$ is the localization of a polynomial algebra. Next, write $N = B^{\oplus n}/K$ for some submodule $K \subset B^{\oplus n}$. Since $B/m_A B$ is Noetherian (as it is essentially of finite type over a field), there exist finitely many elements $k_1, \ldots, k_s \in K$ such that for $K' = \sum Bk_i$ and $N' = B^{\oplus n}/K'$ the canonical surjection $N' \to N$ induces an isomorphism $N'/m_A N' \cong N/m_A N$. Now, if the lemma holds for the composition $u' : N' \to M$, then $u'$ is injective, hence $N' = N$ and $u' = u$. Thus the lemma holds for the original situation. □

Lemma 25.4. If in Situation 25.1 the ring $A$ is henselian then the lemma holds.
Proof. It suffices to prove this when $B$ is essentially of finite presentation over $A$ and $N$ is of finite presentation over $B$, see Lemma 25.3. Let us temporarily make the additional assumption that $N$ is flat over $A$. Then $N$ is a filtered colimit $N = \text{colim}_i F_i$ of free $A$-modules $F_i$ such that the transition maps $u_{ii'} : F_i \to F_{i'}$ are injective modulo $\mathfrak{m}_A$, see Lemma 19.5. Each of the compositions $u_i : F_i \to M$ is $A$-universally injective by Lemma 25.5 wherefore $u = \text{colim}_i u_i$ is $A$-universally injective as desired.

Assume $A$ is a henselian local ring, $B$ is essentially of finite presentation over $A$, $N$ of finite presentation over $B$. By Theorem 24.1, there exists a finitely generated ideal $I \subset A$ such that $N/IN$ is flat over $A/I$ and such that $N/I^2N$ is not flat over $A/I^2$ unless $I = 0$. The result of the previous paragraph shows that the lemma holds for $u \mod I : N/IN \to M/IM$ over $A/I$. Consider the commutative diagram

$$
\begin{array}{cccc}
0 & \longrightarrow & M \otimes_A I/I^2 & \longrightarrow & M/I^2M & \longrightarrow & M/IM & \longrightarrow & 0 \\
& & \uparrow u & & \uparrow u & & \uparrow u & & \\
0 & \longrightarrow & N \otimes_A I/I^2 & \longrightarrow & N/I^2N & \longrightarrow & N/IN & \longrightarrow & 0
\end{array}
$$

whose rows are exact by right exactness of $\otimes$ and the fact that $M$ is flat over $A$. Note that the left vertical arrow is the map $N/IN \otimes_{A/I} I/I^2 \to M/IM \otimes_{A/I} I/I^2$, hence is injective. A diagram chase shows that the lower left arrow is injective, i.e., $\text{Tor}^1_{A/I}(I/I^2, M/I^2) = 0$ see Algebra, Remark 74.9. Hence $N/I^2N$ is flat over $A/I^2$ by Algebra, Lemma 98.8 a contradiction unless $I = 0$.

The following lemma discusses the special case of Situation 25.1 where $M$ has a $B$-module structure and $u$ is $B$-linear. This is the case most often used in practice and it is significantly easier to prove than the general case.

Lemma 25.5. Let $A \to B$ be a local ring homomorphism of local rings which is essentially of finite type. Let $u : N \to M$ be a $B$-module map. If $N$ is a finite $B$-module, $M$ is flat over $A$, and $\pi : N/\mathfrak{m}_AN \to M/\mathfrak{m}_AM$ is injective, then $u$ is $A$-universally injective, $N$ is of finite presentation over $B$, and $N$ is flat over $A$.

Proof. Let $A \to A^h$ be the henselization of $A$. Let $B'$ be the localization of $B \otimes_A A^h$ at the maximal ideal $\mathfrak{m}_B \otimes A^h + B \otimes \mathfrak{m}_{A^h}$. Since $B \to B'$ is flat (hence faithfully flat, see Algebra, Lemma 38.17), we may replace $A \to B$ with $A^h \to B'$, the module $M$ by $M \otimes_B B'$, the module $N$ by $N \otimes_B B'$, and $u$ by $u \otimes \text{id}_{B'}$, see Algebra, Lemmas 82.2 and 38.9. Thus we may assume that $A$ is a henselian local ring. In this case our lemma follows from the more general Lemma 25.4.

Lemma 25.6. If in Situation 25.1 the ring $A$ is a valuation ring then the lemma holds.

Proof. Recall that an $A$-module is flat if and only if it is torsion free, see More on Algebra, Lemma 22.10. Let $T \subset N$ be the $A$-torsion. Then $u(T) = 0$ and $N/T$ is $A$-flat. Hence $N/T$ is finitely presented over $B$, see More on Algebra, Lemma 25.6. Thus $T$ is a finite $B$-module, see Algebra, Lemma 5.3. Since $N/T$ is $A$-flat we see that $T/\mathfrak{m}_AN \subset N/\mathfrak{m}_AN$, see Algebra, Lemma 38.12. As $\pi$ is injective but $u(T) = 0$, we conclude that $T/\mathfrak{m}_AN = 0$. Hence $T = 0$ by Nakayama’s lemma, see Algebra, Lemma 19.1. At this point we have proved two out of the three assertions.
(N is A-flat and of finite presentation over B) and what is left is to show that u is universally injective.

By Algebra, Theorem 81.3 it suffices to show that \( N \otimes_A Q \to M \otimes_A Q \) is injective for every finitely presented A-module Q. By More on Algebra, Lemma 112.3 we may assume \( Q = A/(a) \) with \( a \in \mathfrak{m}_A \) nonzero. Thus it suffices to show that \( N/aN \to M/aM \) is injective. Let \( x \in N \) with \( u(x) \in aM \). By Lemma 19.6 we know that \( x \) has a content ideal \( I \subset A \). Since \( I \) is finitely generated (More on Algebra, Lemma 24.2) and \( A \) is a valuation ring, we have \( I = (b) \) for some \( b \) (by Algebra, Lemma 49.13). By More on Algebra, Lemma 24.3 the element \( u(x) \) has content ideal \( I \) as well. Since \( u(x) \in aM \) we see that \( (b) \subset (a) \) by More on Algebra, Definition 24.1. Since \( x \in bN \) we conclude \( x \in aN \) as desired. \( \square \)

Consider the following situation

(25.6.1) \[ A \to B \] of finite presentation, \( S \subset B \) a multiplicative subset, and \( N \) a finitely presented \( S^{-1}B \)-module

In this situation a pure spreadout is an affine open \( U \subset \text{Spec}(B) \) with \( \text{Spec}(S^{-1}B) \subset U \) and a finitely presented \( \mathcal{O}(U) \)-module \( N' \) extending \( N \) such that \( N' \) is \( A \)-projective and \( N' \to N = S^{-1}N' \) is \( A \)-universally injective.

In (25.6.1) if \( A \to A_1 \) is a ring map, then we can base change: take \( B_1 = B \otimes_A A_1 \), let \( S_1 \subset B_1 \) be the image of \( S \), and let \( N_1 = N \otimes_A A_1 \). This works because \( S_1^{-1}B_1 = S^{-1}B \otimes_A A_1 \). We will use this without further mention in the following.

**Lemma 25.7.** In (25.6.1) if there exists a pure spreadout, then

1. elements of \( N \) have content ideals in \( A \), and
2. if \( u : N \to M \) is a morphism to a flat \( A \) module \( M \) such that \( N/mN \to M/mM \) is injective for all maximal ideals \( m \) of \( A \), then \( u \) is \( A \)-universally injective.

**Proof.** Choose \( U, N' \) as in the definition of a pure spreadout. Any element \( x' \in N' \) has a content ideal in \( A \) because \( N' \) is \( A \)-projective (this can easily be seen directly, but it also follows from More on Algebra, Lemma 24.4 and Algebra, Example 90.1). Since \( N' \to N \) is \( A \)-universally injective, we see that the image \( x \in N \) of any \( x' \in N' \) has a content ideal in \( A \) (it is the same as the content ideal of \( x' \)). For a general \( x \in N \) we choose \( s \in S \) such that \( sx \) is in the image of \( N' \to N \) and we use that \( x \) and \( sx \) have the same content ideal.

Let \( u : N \to M \) be as in (2). To show that \( u \) is \( A \)-universally injective, we may replace \( A \) by a localization at a maximal ideal (small detail omitted). Assume \( A \) is local with maximal ideal \( m \). Pick \( s \in S \) and consider the composition

\[ N' \to N \xrightarrow{1/s} N \xrightarrow{u} M \]

Each of these maps is injective modulo \( m \), hence the composition is \( A \)-universally injective by Lemma 7.5. Since \( N = \text{colim}_{s \in S}(1/s)N' \) we conclude that \( u \) is \( A \)-universally injective as a colimit of universally injective maps. \( \square \)

**Lemma 25.8.** In (25.6.1) for every \( p \in \text{Spec}(A) \) there is a finitely generated ideal \( I \subset pA_p \) such that over \( A_p/I \) we have a pure spreadout.
Proof. We may replace $A$ by $A_p$. Thus we may assume $A$ is local and $p$ is the maximal ideal $m$ of $A$. We may write $N = S^{-1}N'$ for some finitely presented $B$-module $N'$ by clearing denominators in a presentation of $N$ over $S^{-1}B$. Since $B/mB$ is Noetherian, the kernel $K$ of $N'/mN' \to N/mN$ is finitely generated. Thus we can pick $s \in S$ such that $K$ is annihilated by $s$. After replacing $B$ by $B_s$ which is allowed as it just means passing to an affine open subscheme of $\text{Spec}(B)$, we find that the elements of $S$ are injective on $N'/mN'$. At this point we choose a local subring $A_0 \subset A$ essentially of finite type over $\mathbf{Z}$, a finite type ring map $A_0 \to B_0$ such that $B = A \otimes_{A_0} B_0$, and a finite $B_0$-module $N_0'$ such that $N' = B \otimes_{B_0} N_0' = A \otimes_{A_0} N_0'$. We claim that $I = m_{A_0} A$ works. Namely, we have

$$N'/IN' = N_0'/m_{A_0} N_0' \otimes_{A_0} A/I$$

which is free over $A/I$. Multiplication by the elements of $S$ is injective after dividing out by the maximal ideal, hence $N'/IN' \to N/IN$ is universally injective for example by Lemma 7.6. □

Lemma 25.9. In (25.6.1) assume $N$ is $A$-flat, $M$ is a flat $A$-module, and $u : N \to M$ is an $A$-module map such that $u \otimes \text{id}_{\kappa(p)}$ is injective for all $p \in \text{Spec}(A)$. Then $u$ is $A$-universally injective.

Proof. By Algebra, Lemma 81.14 it suffices to check that $N/IN \to M/IM$ is injective for every ideal $I \subset A$. After replacing $A$ by $A/I$ we see that it suffices to prove that $u$ is injective.

Proof that $u$ is injective. Let $x \in N$ be a nonzero element of the kernel of $u$. Then there exists a weakly associated prime $p$ of the module $Ax$, see Algebra, Lemma 65.5. Replacing $A$ by $A_p$ we may assume $A$ is local and we find a nonzero element $y \in Ax$ whose annihilator has radical equal to $m_A$, see Algebra, Lemma 65.2. Thus $\text{Supp}(y) \subset \text{Spec}(S^{-1}B)$ is nonempty and contained in the closed fibre of $\text{Spec}(S^{-1}B) \to \text{Spec}(A)$. Let $I \subset m_A$ be a finitely generated ideal so that we have a pure spreadout over $A/I$, see Lemma 25.8. Then $I^n y = 0$ for some $n$. Now $y \in \text{Ann}_A(I^n) = \text{Ann}_A(I^n) \otimes_R N$ by flatness. Thus, to get the desired contradiction, it suffices to show that

$$\text{Ann}_A(I^n) \otimes_R N \longrightarrow \text{Ann}_A(I^n) \otimes_R M$$

is injective. Since $N$ and $M$ are flat and since $\text{Ann}_A(I^n)$ is annihilated by $I^n$, it suffices to show that $Q \otimes_A N \to Q \otimes_A M$ is injective for every $A$-module $Q$ annihilated by $I$. This holds by our choice of $I$ and Lemma 25.7 part (2). □

Lemma 25.10. Let $A$ be a local domain which is not a field. Let $S$ be a set of finitely generated ideals of $A$. Assume that $S$ is closed under products and such that $\bigcup_{I \in S} V(I)$ is the complement of the generic point of $\text{Spec}(A)$. Then $\bigcap_{I \in S} I = (0)$.

Proof. Since $m_A \subset A$ is not the generic point of $\text{Spec}(A)$ we see that $I \subset m_A$ for at least one $I \in S$. Hence $\bigcap_{I \in S} I \subset m_A$. Let $f \in m_A$ be nonzero. Then $V(f) \subset \bigcup_{I \in S} V(I)$. Since the constructible topology on $V(f)$ is quasi-compact (Topology, Lemma 23.2 and Algebra, Lemma 25.2) we find that $V(f) \subset V(I_1) \cup \ldots \cup V(I_n)$ for some $I_1 \in S$. Because $I_1 \ldots I_n \in S$ we see that $V(f) \subset V(I)$ for some $I$. As $I$ is finitely generated this implies that $I^n \subset (f)$ for some $m$ and since $S$ is closed under products we see that $I \subset (f^2)$ for some $I \in S$. Then it is not possible to have $f \in I$. □
**Lemma 25.11.** Let \( A \) be a local ring. Let \( I, J \subset A \) be ideals. If \( J \) is finitely generated and \( I \subset J^n \) for all \( n \geq 1 \), then \( V(I) \) contains the closed points of \( \text{Spec}(A) \setminus V(J) \).

**Proof.** Let \( p \subset A \) be a closed point of \( \text{Spec}(A) \setminus V(J) \). We want to show that \( I \subset p \). If not, then some \( f \in I \) maps to a nonzero element of \( A/p \). Note that \( V(J) \cap \text{Spec}(A/p) \) is the set of non-generic points. Hence by Lemma 25.10 applied to the collection of ideals \( J^nA/p \) we conclude that the image of \( f \) is zero in \( A/p \).

**Lemma 25.12.** Let \( A \) be a local ring. Let \( I \subset A \) be an ideal. Let \( U \subset \text{Spec}(A) \) be quasi-compact open. Let \( M \) be an \( A \)-module. Assume that

1. \( M/IM \) is flat over \( A/I \),
2. \( M \) is flat over \( U \),

Then \( M/I_2M \) is flat over \( A/I_2 \) where \( I_2 = \text{Ker}(I \to \Gamma(U, I/I^2)) \).

**Proof.** It suffices to show that \( M \otimes_A I/I_2 \to IM/I_2M \) is injective, see Algebra, Lemma 98.9. This is true over \( U \) by assumption (2). Thus it suffices to show that \( M \otimes_A I/I_2 \) injects into its sections over \( U \). We have \( M \otimes_A I/I_2 = M/IM \otimes_A I/I_2 \) and \( M/IM \) is a filtered colimit of finite free \( A/I \)-modules (Algebra, Theorem 80.4). Hence it suffices to show that \( I/I_2 \) injects into its sections over \( U \), which follows from the construction of \( I_2 \).

**Proposition 25.13.** Let \( A \to B \) be a local ring homomorphism of local rings which is essentially of finite type. Let \( M \) be a flat \( A \)-module, \( N \) a finite \( B \)-module and \( u : N \to M \) an \( A \)-module map such that \( \pi : N/m_AN \to M/m_AM \) is injective. Then \( u \) is \( A \)-universally injective, \( N \) is of finite presentation over \( B \), and \( N \) is flat over \( A \).

**Proof.** We may assume that \( B \) is the localization of a finitely presented \( A \)-algebra \( B_0 \) and that \( N \) is the localization of a finitely presented \( B_0 \)-module \( M_0 \), see Lemma 25.3. By Lemma 21.4 there exists a “generic flatness stratification” for \( \tilde{M}_0 \) on \( \text{Spec}(B_0) \) over \( \text{Spec}(A) \). Translating back to \( N \) we find a sequence of closed subschemes

\[ S = \text{Spec}(A) \supset S_0 \supset S_1 \supset \ldots \supset S_t = \emptyset \]

with \( S_i \subset S \) cut out by a finitely generated ideal of \( A \) such that the pullback of \( \tilde{N} \) to \( \text{Spec}(B) \times_S (S_i \setminus S_{i+1}) \) is flat over \( S_i \setminus S_{i+1} \). We will prove the proposition by induction on \( t \) (the base case \( t = 1 \) will be proved in parallel with the other steps). Let \( \text{Spec}(A/J_i) \) be the scheme theoretic closure of \( S_i \setminus S_{i+1} \).

**Claim 1.** \( N/J_iN \) is flat over \( A/J_i \). This is immediate for \( i = t - 1 \) and follows from the induction hypothesis for \( i > 0 \). Thus we may assume \( t > 1, S_{t-1} \neq \emptyset \), and \( J_0 = 0 \) and we have to prove that \( N \) is flat. Let \( J \subset A \) be the ideal defining \( S_1 \).

By induction on \( t \) again, we also have flatness modulo powers of \( J \). Let \( A^h \) be the henselization of \( A \) and let \( B^h \) be the localization of \( B \otimes_A A^h \) at the maximal ideal \( m_B \otimes A^h + B \otimes m_A \). Then \( B \to B^h \) is faithfully flat. Set \( N' = N \otimes_B B' \). Note that \( N' \) is \( A^h \)-flat if and only if \( N \) is \( A \)-flat. By Theorem 24.1 there is a smallest ideal \( I \subset A^h \) such that \( N'/IN' \) is flat over \( A^h/I \), and \( I \) is finitely generated. By the above \( I \subset J^nA^h \) for all \( n \geq 1 \). Let \( S^h \subset \text{Spec}(A^h) \) be the inverse image of \( S_0 \subset \text{Spec}(A) \). By Lemma 25.11 we see that \( V(I) \) contains the closed points of \( U = \text{Spec}(A^h) \setminus S^h \). By construction \( N' \) is \( A^h \)-flat over \( U \). By Lemma 25.12 we see that \( N'/I_2N' \) is flat over \( A/I_2 \), where \( I_2 = \text{Ker}(I \to \Gamma(U, I/I^2)) \). Hence \( I = I_2 \) by
minimality of \( I \). This implies that \( I = I^2 \) locally on \( U \), i.e., we have \( IO_{U,u} = (0) \) or \( IO_{U,u} = (1) \) for all \( u \in U \). Since \( V(I) \) contains the closed points of \( U \) we see that \( I = 0 \) on \( U \). Since \( U \subset \text{Spec}(A^h) \) is scheme theoretically dense (because replaced \( A \) by \( A/J_0 \) in the beginning of this paragraph), we see that \( I = 0 \). Thus \( N' \) is \( A^h \)-flat and hence Claim 1 holds.

We return to the situation as laid out before Claim 1. With \( A^h \) the henselization of \( A \), with \( B' \) the localization of \( B \otimes_A A^h \) at the maximal ideal \( m_B \otimes A^h + B \otimes m_{A^h} \), and with \( N' = N \otimes_B B' \) we now see that the flattening ideal \( I \subset A^h \) of Theorem 24.1 is nilpotent. If \( \text{nil}(A^h) \) denotes the ideal of nilpotent elements, then \( \text{nil}(A^h) = \text{nil}(A)A^h \) (More on Algebra, Lemma 44.5). Hence there exists a finitely generated nilpotent ideal \( I_0 \subset A \) such that \( N/I_0N \) is flat over \( A/I_0 \).

**Claim 2.** For every prime ideal \( p \subset A \) the map \( \kappa(p) \otimes_A N \to \kappa(p) \otimes_A M \) is injective. We say \( p \) is bad if this is false. Suppose that \( C \) is a nonempty chain of bad primes and set \( p^* = \bigcup_{p \in C} p \). By Lemma 25.8 there is a finitely generated ideal \( a \subset p^*A_{p^*} \) such that there is a pure spread out over \( V(a) \). If \( p^* \) were good, then it would follow from Lemma 25.7 that the points of \( V(a) \) are good. However, since \( a \) is finitely generated and since \( p^*A_{p^*} = \bigcup_{p \in C} A_p \), we see that \( V(a) \) contains a \( p \in C \), contradiction. Hence \( p^* \) is bad. By Zorn’s lemma, if there exists a bad prime, there exists a maximal one, say \( p \). In other words, we may assume every \( p^* \supset p \), \( p \neq p' \) is good. In this case we see that for every \( f \in A \), \( f \not\in p \) the map \( u \otimes id_{A/(p+f)} \) is universally injective, see Lemma 25.9. Thus it suffices to show that \( N/pN \) is separated for the topology defined by the submodules \( f(N/pN) \). Since \( B \to B' \) is faithfully flat, it is enough to prove the same for the module \( N'/pN' \). By Lemma 19.5 and More on Algebra, Lemma 24.4 elements of \( N'/pN' \) have content ideals in \( A^h/pA^h \). Thus it suffices to show that \( \bigcap_{f \in A, f \not\in p} f(A^h/pA^h) = 0 \). Then it suffices to show the same for \( A^h/qA^h \) for every prime \( q \subset A^h \) minimal over \( pA^h \). Because \( A \to A^h \) is the henselization, every \( q \) contracts to \( p \) and every \( q' \supset q \), \( q' \neq q \) contracts to a prime \( p' \) which strictly contains \( p \). Thus we get the vanishing of the intersections from Lemma 25.10.

At this point we can put everything together. Namely, using Claim 1 and Claim 2 we see that \( N/I_0N \to M/I_0M \) is \( A/I_0 \)-universally injective by Lemma 25.9. Then the diagrams

\[
\begin{align*}
N \otimes_A (I_0^n/I_0^{n+1}) &\longrightarrow M \otimes_A (I_0^n/I_0^{n+1}) \\
I_0^n N/I_0^{n+1} N &\longrightarrow I_0^n M/I_0^{n+1} M
\end{align*}
\]

show that the left vertical arrows are injective. Hence by Algebra, Lemma 98.9 we see that \( N \) is flat. In a similar way the universal injectivity of \( u \) can be reduced (even without proving flatness of \( N \) first) to the one modulo \( I_0 \). This finishes the proof.

26. Flat finite type modules, Part III

**Theorem 26.1.** Let \( f : X \to S \) be locally of finite type. Let \( F \) be a quasi-coherent \( O_X \)-module of finite type. Let \( x \in X \) with image \( s \in S \). The following are equivalent
In Situation 20.7. For each $s \in \text{Ass}_{X/(F_s)}$ which specializes to $x$ we have that $F$ is flat at $x'$ over $S$.

**Proof.** It is clear that (1) implies (2) as $F_{x'}$ is a localization of $F_x$ for every point which specializes to $x$. Set $A = \mathcal{O}_{S,s}$, $B = \mathcal{O}_{X,x}$ and $N = F_x$. Let $\Sigma < B$ be the multiplicative subset of $B$ of elements which act as nonzerodivisors on $N/\mathfrak{m}_A N$. Assumption (2) implies that $\Sigma^{-1} N$ is $A$-flat by the description of $\text{Spec}(\Sigma^{-1} N)$ in Lemma 7.1. On the other hand, the map $N \to \Sigma^{-1} N$ is injective modulo $\mathfrak{m}_A$ by construction. Hence applying Lemma 25.5 we win. \qed

Now we apply this directly to obtain the following useful results.

**Lemma 26.2.** Let $S$ be a local scheme with closed point $s$. Let $f : X \to S$ be locally of finite type. Let $F$ be a finite type quasi-coherent $\mathcal{O}_X$-module. Assume that

1. every point of $\text{Ass}_{X/S}(F)$ specializes to a point of the closed fibre $X_s$,
2. $F$ is flat over $S$ at every point of $X_s$.

Then $F$ is flat over $S$.

**Proof.** This is immediate from the fact that it suffices to check for flatness at points of the relative assassin of $F$ over $S$ by Theorem 26.1 \qed

### 27. Universal flatting

If $f : X \to S$ is a proper, finitely presented morphism of schemes then one can find a universal flattening of $f$. In this section we discuss this and some of its variants.

**Lemma 27.1.** In Situation 20.7. For each $p \geq 0$ the functor $H_p$ (20.7.2) is representable by a locally closed immersion $S_p \to S$. If $F$ is of finite presentation, then $S_p \to S$ is of finite presentation.

**Proof.** For each $S$ we will prove the statement for all $p \geq 0$ concurrently. The functor $H_p$ is a sheaf for the fppf topology by Lemma 20.8. Hence combining Descent, Lemma 36.1, More on Morphisms, Lemma 49.1, and Descent, Lemma 21.1 we see that the question is local for the étale topology on $S$. In particular, the question is Zariski local on $S$.

For $s \in S$ denote $\xi_s$ the unique generic point of the fibre $X_s$. Note that for every $s \in S$ the restriction $F_s$ of $F$ is locally free of some rank $p(s) \geq 0$ in some neighbourhood of $\xi_s$. (As $X_s$ is irreducible and smooth this follows from generic flatness for $F_s$ over $X_s$, see Algebra, Lemma 17.1 although this is overkill.) For future reference we note that

$$p(s) = \dim_{\kappa(\xi_s)}(F_{\xi_s} \otimes_{\mathcal{O}_{X,\xi_s}} \kappa(\xi_s)).$$

In particular $H_{p(s)}(s)$ is nonempty and $H_q(s)$ is empty if $q \neq p(s)$.

Let $U \subset X$ be an open subscheme. As $f : X \to S$ is smooth, it is open. It is immediate from (20.7.2) that the functor $H_p$ for the pair $(f|_U : U \to f(U), F|_U)$ and the functor $H_p$ for the pair $(f|_{f^{-1}(U)}), F|_{f^{-1}(f(U))})$ are the same. Hence to prove the existence of $S_p$ over $f(U)$ we may always replace $X$ by $U$.

Pick $s \in S$. There exists an affine open neighbourhood $U$ of $\xi_s$ such that $F|_U$ can be generated by at most $p(s)$ elements. By the arguments above we see that

\footnote{For example this holds if $f$ is finite type and $F$ is pure along $X_s$, or if $f$ is proper.}
order to prove the statement for $H_p(s)$ in an neighbourhood of $s$ we may assume that $\mathcal{F}$ is generated by $p(s)$ elements, i.e., that there exists a surjection

$$u : \mathcal{O}_X^{\oplus p(s)} \longrightarrow \mathcal{F}$$

In this case it is clear that $H_p(s)$ is equal to $F_{iso}$ (20.1.1) for the map $u$ (this follows immediately from Lemma 19.1 but also from Lemma 12.1 after shrinking a bit more so that both $S$ and $X$ are affine.) Thus we may apply Theorem 23.3 to see that $H_p(s)$ is representable by a closed immersion in a neighbourhood of $s$.

The result follows formally from the above. Namely, the arguments above show that locally on $S$ the function $s \mapsto p(s)$ is bounded. Hence we may use induction on $p = \max_{x \in S} p(s)$. The functor $H_p$ is representable by a closed immersion $S_p \to S$ by the above. Replace $S$ by $S \setminus S_p$ which drops the maximum by at least one and we win by induction hypothesis.

Assume $\mathcal{F}$ is of finite presentation. Then $S_p \to S$ is locally of finite presentation by Lemma 20.8 part (2) combined with Limits, Remark 6.2. Then we redo the induction argument in the paragraph to see that each $S_p$ is quasi-compact when $S$ is affine: first if $p = \max_{x \in S} p(s)$, then $S_p \subset S$ is closed (see above) hence quasi-compact. Then $U = S \setminus S_p$ is quasi-compact open in $S$ because $S_p \to S$ is a closed immersion of finite presentation (see discussion in Morphisms, Section 21 for example). Then $S_{p-1} \to U$ is a closed immersion of finite presentation, and so $S_{p-1}$ is quasi-compact and $U' = S \setminus (S_p \cup S_{p-1})$ is quasi-compact. And so on.

05UD Lemma 27.2. In Situation 20.11. Let $h : X' \to X$ be an étale morphism. Set $\mathcal{F}' = h^*\mathcal{F}$ and $f' = f \circ h$. Let $F'_n$ be (20.11.1) associated to $(f' : X' \to S, \mathcal{F}')$. Then $F_n$ is a subfunctor of $F'_n$ and if $h(X') \supset \text{Ass}_{X/S}(\mathcal{F})$, then $F_n = F'_n$.

Proof. Let $T \to S$ be any morphism. Then $h_T : X'_T \to X_T$ is étale as a base change of the étale morphism $g$. For $t \in T$ denote $Z \subset X_t$ the set of points where $\mathcal{F}_T$ is not flat over $T$, and similarly denote $Z' \subset X'_t$ the set of points where $\mathcal{F}'_T$ is not flat over $T$. As $\mathcal{F}'_T = h_T^*\mathcal{F}_T$ we see that $Z' = h_T^{-1}(Z)$, see Morphisms, Lemma 24.13. Hence $Z' \to Z$ is an étale morphism, so $\dim(Z') \leq \dim(Z)$ (for example by Descent, Lemma 18.2 or just because an étale morphism is smooth of relative dimension 0). This implies that $F_n \subset F'_n$.

Finally, suppose that $h(X') \supset \text{Ass}_{X/S}(\mathcal{F})$ and that $T \to S$ is a morphism such that $F'_n(T)$ is nonempty, i.e., such that $\mathcal{F}'_T$ is flat in dimensions $\geq n$ over $T$. Pick a point $z \in Z$ and let $Z' \subset X'_t$ be as above. To get a contradiction assume that $\dim(Z) \geq n$. Pick a generic point $\xi \in Z$ corresponding to a component of dimension $\geq n$. Let $x \in \text{Ass}_{X_t}(\mathcal{F}_t)$ be a generalization of $\xi$. Then $x$ maps to a point of $\text{Ass}_{X/S}(\mathcal{F})$ by Divisors, Lemma 7.3 and Remark 7.4. Thus we see that $x$ is in the image of $h_T$, say $z = h_T(x')$ for some $x' \in X'_t$. But $x' \notin Z'$ as $x \sim \xi$ and $\dim(Z') < n$. Hence $\mathcal{F}'_T$ is flat over $T$ at $x'$ which implies that $\mathcal{F}_T$ is flat at $x$ over $T$ (by Morphisms, Lemma 24.13). Since this holds for every such $x$ we conclude that $\mathcal{F}_T$ is flat over $T$ at $\xi$ by Theorem 26.1 which is the desired contradiction.

05UE Lemma 27.3. Assume that $X \to S$ is a smooth morphism of affine schemes with geometrically irreducible fibres of dimension $d$ and that $\mathcal{F}$ is a quasi-coherent $\mathcal{O}_X$-module of finite presentation. Then $F_d = \coprod_{p=0, \ldots, d} H_p$ for some $c \geq 0$ with $F_d$ as in (20.11.1) and $H_p$ as in (20.7.2).
**Proof.** As $X$ is affine and $\mathcal{F}$ is quasi-coherent of finite presentation we know that $\mathcal{F}$ can be generated by $c \geq 0$ elements. Then $\dim_{x(x)}(\mathcal{F}_x \otimes \kappa(x))$ in any point $x \in X$ never exceeds $c$. In particular $H_p = \emptyset$ for $p > c$. Moreover, note that there certainly is an inclusion $\coprod H_p \to F_d$. Having said this the content of the lemma is that, if a base change $\mathcal{F}_T$ is flat in dimensions $\geq d$ over $T$ and if $t \in T$, then $\mathcal{F}_T$ is free of some rank $r$ in an open neighbourhood $U \subset X_T$ of the unique generic point $\xi$ of $X_t$. Namely, then $H_r$ contains the image of $U$ which is an open neighbourhood of $t$. The existence of $U$ follows from More on Morphisms, Lemma 16.7. 

**Lemma 27.4.** In Situation 20.11. Let $s \in S$ let $d \geq 0$. Assume

1. there exists a complete dévissage of $\mathcal{F}/X/S$ over some point $s \in S$,
2. $X$ is of finite presentation over $S$,
3. $\mathcal{F}$ is an $\mathcal{O}_X$-module of finite presentation, and
4. $\mathcal{F}$ is flat in dimensions $\geq d + 1$ over $S$.

Then after possibly replacing $S$ by an open neighbourhood of $s$ the functor $F_d$ (20.11.1) is representable by a monomorphism $Z_d \to S$ of finite presentation.

**Proof.** A preliminary remark is that $X, S$ are affine schemes and that it suffices to prove $F_d$ is representable by a monomorphism of finite presentation $Z_d \to S$ on the category of affine schemes over $S$. (Of course we do not require $Z_d$ to be affine.) Hence throughout the proof of the lemma we work in the category of affine schemes over $S$.

Let $(Z_k, Y_k, i_k, \pi_k, G_k, \alpha_k)_{k=1,\ldots,n}$ be a complete dévissage of $\mathcal{F}/X/S$ over $s$, see Definition 5.1. We will use induction on the length $n$ of the dévissage. Recall that $Y_k \to S$ is smooth with geometrically irreducible fibres, see Definition 4.1. Let $d_k$ be the relative dimension of $Y_k$ over $S$. Recall that $i_k, s \mathcal{G}_k = \text{Coker}(\alpha_k)$ and that $i_k$ is a closed immersion. By the definitions referenced above we have $d_1 = \dim(\text{Supp}(\mathcal{F}_s))$ and

$$d_k = \dim(\text{Supp}(\text{Coker}(\alpha_{k-1}))) = \dim(\text{Supp}(\mathcal{G}_{k,s}))$$

for $k = 2, \ldots, n$. It follows that $d_1 > d_2 > \ldots > d_n \geq 0$ because $\alpha_k$ is an isomorphism in the generic point of $(Y_k)_s$.

Note that $i_1$ is a closed immersion and $\mathcal{F} = i_{1,*}\mathcal{G}_1$. Hence for any morphism of schemes $T \to S$ with $T$ affine, we have $\mathcal{F}_T = i_{1,T,*}\mathcal{G}_{1,T}$ and $i_{1,T}$ is still a closed immersion of schemes over $T$. Thus $\mathcal{F}_T$ is flat in dimensions $\geq d$ over $T$ if and only if $\mathcal{G}_{1,T}$ is flat in dimensions $\geq d$ over $T$. Because $\pi_1 : Z_1 \to Y_1$ is finite we see in the same manner that $\mathcal{G}_{1,T}$ is flat in dimensions $\geq d$ over $T$ if and only if $\pi_{1,T,*}\mathcal{G}_{1,T}$ is flat in dimensions $\geq d$ over $T$. The same arguments work for “flat in dimensions $\geq d + 1”$ and we conclude in particular that $\pi_{1,*}\mathcal{G}_1$ is flat over $S$ in dimensions $\geq d + 1$ by our assumption on $\mathcal{F}$.

Suppose that $d_1 > d$. It follows from the discussion above that in particular $\pi_{1,*}\mathcal{G}_1$ is flat over $S$ at the generic point of $(Y_1)_s$. By Lemma 12.1 we may replace $S$ by an affine neighbourhood of $s$ and assume that $\alpha_1$ is $S$-universally injective. Because $\alpha_1$ is $S$-universally injective, for any morphism $T \to S$ with $T$ affine, we have a short exact sequence

$$0 \to \mathcal{O}_{Y_1,T}^{\oplus r_{1,T}} \to \pi_{1,T,*}\mathcal{G}_{1,T} \to \text{Coker}(\alpha_{1,T}) \to 0$$

and still the first arrow is $T$-universally injective. Hence the set of points of $(Y_1)_T$ where $\pi_{1,T,*}\mathcal{G}_{1,T}$ is flat over $T$ is the same as the set of points of $(Y_1)_T$ where
Coker(\(\alpha_1\))\(_T\) is flat over \(S\). In this way the question reduces to the sheaf Coker(\(\alpha_1\)) which has a complete dévissage of length \(n - 1\) and we win by induction.

If \(d_1 < d\) then \(F_d\) is represented by \(S\) and we win.

The last case is the case \(d_1 = d\). This case follows from a combination of Lemma 27.3 and Lemma 27.1.

\[\square\]

**Theorem 27.5.** In Situation 20.11 Assume moreover that \(f\) is of finite presentation, that \(\mathcal{F}\) is an \(\mathcal{O}_X\)-module of finite presentation, and that \(\mathcal{F}\) is pure relative to \(S\). Then \(F_n\) is representable by a monomorphism \(Z_n \to S\) of finite presentation.

**Proof.** The functor \(F_n\) is a sheaf for the fppf topology by Lemma 20.12. Observe that a monomorphism of finite presentation is separated and quasi-finite (Morphisms, Lemma 19.15). Hence combining Descent, Lemma 36.1, More on Morphisms, Lemma 49.1, and Descent, Lemmas 20.31 and 20.13 we see that the question is local for the étale topology on \(S\).

In particular the situation is local for the Zariski topology on \(S\) and we may assume that \(S\) is affine. In this case the dimension of the fibres of \(f\) is bounded above, hence we see that \(F_n\) is representable for \(n\) large enough. Thus we may use descending induction on \(n\). Suppose that we know \(F_{n+1}\) is representable by a monomorphism \(Z_{n+1} \to S\) of finite presentation. Consider the base change \(X_{n+1} = Z_{n+1} \times_S X\) and the pullback \(\mathcal{F}_{n+1}\) of \(\mathcal{F}\) to \(X_{n+1}\). The morphism \(Z_{n+1} \to S\) is quasi-finite as it is a monomorphism of finite presentation, hence Lemma 16.4 implies that \(\mathcal{F}_{n+1}\) is pure relative to \(Z_{n+1}\). Since \(F_n\) is a subfunctor of \(F_{n+1}\) we conclude that in order to prove the result for \(F_n\) it suffices to prove the result for the corresponding functor for the situation \(F_{n+1}/X_{n+1}/Z_{n+1}\). In this way we reduce to proving the result for \(F_n\) in case \(S_{n+1} = S\), i.e., we may assume that \(\mathcal{F}\) is flat in dimensions \(\geq n + 1\) over \(S\).

Fix \(n\) and assume \(\mathcal{F}\) is flat in dimensions \(\geq n + 1\) over \(S\). To finish the proof we have to show that \(F_n\) is representable by a monomorphism \(Z_n \to S\) of finite presentation. Since the question is local in the étale topology on \(S\) it suffices to show that for every \(s \in S\) there exists an elementary étale neighbourhood \((S', s') \to (S, s)\) such that the result holds after base change to \(S'\). Thus by Lemma 5.8 we may assume there exist étale morphisms \(h_j : Y_j \to X\), \(j = 1, \ldots, m\) such that for each \(j\) there exists a complete dévissage of \(\mathcal{F}_j/Y_j/S\) over \(s\), where \(\mathcal{F}_j\) is the pullback of \(\mathcal{F}\) to \(Y_j\) and such that \(X_s \subset \bigcup h_j(Y_j)\). Note that by Lemma 27.2 the sheaves \(\mathcal{F}_j\) are still flat over in dimensions \(\geq n + 1\) over \(S\). Set \(W = \bigcup h_j(Y_j)\), which is a quasi-compact open of \(X\). As \(\mathcal{F}\) is pure along \(X_s\) we see that

\[E = \{ t \in S \mid \text{Ass}_{X_t}(\mathcal{F}_t) \subset W \}\]

contains all generalizations of \(s\). By More on Morphisms, Lemma 23.5 \(E\) is a constructible subset of \(S\). We have seen that \(\text{Spec}(\mathcal{O}_{S, s}) \subset E\). By Morphisms, Lemma 21.4 we see that \(E\) contains an open neighbourhood of \(s\). Hence after shrinking \(S\) we may assume that \(E = S\). It follows from Lemma 27.2 that it suffices to prove the lemma for the functor \(F_n\) associated to \(X = \bigsqcup Y_j\) and \(\mathcal{F} = \bigsqcup \mathcal{F}_j\). If \(F_{j,n}\) denotes the functor for \(Y_j \to S\) and the sheaf \(\mathcal{F}_j\) we see that \(F_n = \bigsqcup F_{j,n}\). Hence it suffices to prove each \(F_{j,n}\) is representable by some monomorphism \(Z_{j,n} \to S\) of finite presentation, since then

\[Z_n = Z_{1,n} \times_S \cdots \times_S Z_{m,n}\]
Thus we have reduced the theorem to the special case handled in Lemma 27.4.

We make explicit what the theorem means in terms of universal flattenings in the following lemma.

Lemma 27.6. Let $f : X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent $\mathcal{O}_X$-module.

1. If $f$ is of finite presentation, $\mathcal{F}$ is an $\mathcal{O}_X$-module of finite presentation, and $\mathcal{F}$ is pure relative to $S$, then there exists a universal flattening $S' \to S$ of $\mathcal{F}$. Moreover $S' \to S$ is a monomorphism of finite presentation.

2. If $f$ is of finite presentation and $X$ is pure relative to $S$, then there exists a universal flattening $S' \to S$ of $X$. Moreover $S' \to S$ is a monomorphism of finite presentation.

3. If $f$ is proper and of finite presentation and $\mathcal{F}$ is an $\mathcal{O}_X$-module of finite presentation, then there exists a universal flattening $S' \to S$ of $\mathcal{F}$. Moreover $S' \to S$ is a monomorphism of finite presentation.

4. If $f$ is proper and of finite presentation then there exists a universal flattening $S' \to S$ of $X$.

Proof. These statements follow immediately from Theorem 27.5 applied to $\mathcal{F}$ flat and the fact that if $f$ is proper then $\mathcal{F}$ is automatically pure over the base, see Lemma 17.1. □

28. Grothendieck’s Existence Theorem, IV

This section continues the discussion in Cohomology of Schemes, Sections 24, 25, and 27. We will work in the following situation.

Situation 28.1. Here we have an inverse system of rings $(A_n)$ with surjective transition maps whose kernels are locally nilpotent. Set $A = \lim A_n$. We have a scheme $X$ separated and of finite presentation over $A$. We set $X_n = X \times_{\text{Spec}(A)} \text{Spec}(A_n)$ and we view it as a closed subscheme of $X$. We assume further given a system $(\mathcal{F}_n, \varphi_n)$ where $\mathcal{F}_n$ is a finitely presented $\mathcal{O}_{X_n}$-module, flat over $A_n$, with support proper over $A_n$, and

$$\varphi_n : \mathcal{F}_n \otimes_{\mathcal{O}_{X_n}} \mathcal{O}_{X_n-1} \to \mathcal{F}_{n-1}$$

is an isomorphism (notation using the equivalence of Morphisms, Lemma 4.1).

Our goal is to see if we can find a quasi-coherent sheaf $\mathcal{F}$ on $X$ such that $\mathcal{F}_n = \mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{O}_{X_n}$ for all $n$.

Lemma 28.2. In Situation 28.1 consider

$$K = R\lim_{DQ\text{Coh}(\mathcal{O}_X)}(\mathcal{F}_n) = DQ_X(R\lim_{D(\mathcal{O}_X)} \mathcal{F}_n)$$

Then $K$ is in $D^b_{Q\text{Coh}}(\mathcal{O}_X)$ and in fact $K$ has nonzero cohomology sheaves only in degrees $\geq 0$.

Proof. Special case of Derived Categories of Schemes, Example 20.3. □

Lemma 28.3. In Situation 28.1 let $K$ be as in Lemma 28.2. For any perfect object $E$ of $D(\mathcal{O}_X)$ we have

1. $M = R\Gamma(X, K \otimes^L E)$ is a perfect object of $D(A)$ and there is a canonical isomorphism $R\Gamma(X_n, \mathcal{F}_n \otimes^L E|_{X_n}) = M \otimes^L A_n$ in $D(A_n)$,
(2) \( N = R\text{Hom}_X(E, K) \) is a perfect object of \( D(A) \) and there is a canonical isomorphism \( R\text{Hom}_{X_n}(E|_{X_n}, F_n) = N \otimes_A^L A_n \) in \( D(A_n) \).

In both statements \( E|_{X_n} = \text{derived pullback of } E \) to \( X_n \).

**Proof.** Proof of (2). Write \( E_n = E|_{X_n} \) and \( N_n = R\text{Hom}_{X_n}(E_n, F_n) \). Recall that \( R\text{Hom}_{X_n}(\cdot, \cdot) \) is equal to \( R\Gamma(X_n, R\text{Hom}(\cdot, \cdot)) \), see Cohomology, Section 40. Hence by Derived Categories of Schemes, Lemma 27.7 we see that \( N_n \) is a perfect object of \( D(A_n) \) whose formation commutes with base change. Thus the maps \( N_n \otimes_{A_n} A_{n-1} \to N_{n-1} \) coming from \( \varphi_n \) are isomorphisms. By More on Algebra, Lemma 89.3 we find that \( R\lim N_n \) is perfect and that its base change back to \( A_n \) recovers \( N_n \). On the other hand, the exact functor \( R\text{Hom}_X(E, \cdot) : D\text{QCoh}(\mathcal{O}_X) \to D(A) \) of triangulated categories commutes with products and hence with derived limits, whence

\[
R\text{Hom}_X(E, K) = R\lim N_n = R\lim R\text{Hom}_X(E_n, F_n) = R\lim R\text{Hom}_X(E_n, F_n) = R\lim N_n
\]

This proves (2). To see that (1) holds, translate it into (2) using Cohomology, Lemma 46.4. \( \square \)

0CTF **Lemma 28.4.** In Situation 28.1 let \( K \) be as in Lemma 28.2. Then \( K \) is pseudo-coherent relative to \( A \).

**Proof.** Combining Lemma 28.3 and Derived Categories of Schemes, Lemma 31.3 we see that \( R\Gamma(X, K \otimes^L E) \) is pseudo-coherent in \( D(A) \) for all pseudo-coherent \( E \) in \( D(\mathcal{O}_X) \). Thus the lemma follows from More on Morphisms, Lemma 61.4. \( \square \)

0CTG **Lemma 28.5.** In Situation 28.1 let \( K \) be as in Lemma 28.2. For any quasi-compact open \( U \subset X \) we have

\[
R\Gamma(U, K) \otimes_A^L A_n = R\Gamma(U_n, F_n)
\]

in \( D(A_n) \) where \( U_n = U \cap X_n \).

**Proof.** Fix \( n \). By Derived Categories of Schemes, Lemma 30.4 there exists a system of perfect complexes \( E_m \) on \( X \) such that \( R\Gamma(U, K) = \text{hocolim} R\Gamma(X, K \otimes^L E_m) \). In fact, this formula holds not just for \( K \) but for every object of \( D\text{QCoh}(\mathcal{O}_X) \). Applying this to \( F_n \) we obtain

\[
R\Gamma(U_n, F_n) = R\Gamma(U, F_n)
\]

\[
= \text{hocolim}_m R\Gamma(X, F_n \otimes^L E_m)
\]

\[
= \text{hocolim}_m R\Gamma(X_n, F_n \otimes^L E_m|_{X_n})
\]

Using Lemma 28.3 and the fact that \( - \otimes_A^L A_n \) commutes with homotopy colimits we obtain the result. \( \square \)

0CTH **Lemma 28.6.** In Situation 28.1 let \( K \) be as in Lemma 28.2. Denote \( X_0 \subset X \) the closed subset consisting of points lying over the closed subset \( \text{Spec}(A_1) = \text{Spec}(A_2) = \ldots = \text{Spec}(A) \). There exists an open \( W \subset X \) containing \( X_0 \) such that

1. \( H^i(K)|_W = 0 \) unless \( i = 0 \),
2. \( \mathcal{F} = H^0(K)|_W \) is of finite presentation, and
3. \( \mathcal{F}_n = \mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{O}_{X_n} \).
**Proof.** Fix \( n \geq 1 \). By construction there is a canonical map \( K \to F_n \) in \( D_{QCoh}(\mathcal{O}_X) \) and hence a canonical map \( H^0(K) \to F_n \) of quasi-coherent sheaves. This explains the meaning of part (3).

Let \( x \in X_0 \) be a point. We will find an open neighbourhood \( W \) of \( x \) such that (1), (2), and (3) are true. Since \( X_0 \) is quasi-compact this will prove the lemma. Let \( U \subset X \) be an affine open neighbourhood of \( x \). Say \( U = \text{Spec}(B) \). Choose a surjection \( P \to B \) with \( P \) smooth over \( A \). By Lemma \( 28.4 \) and the definition of relative pseudo-coherence there exists a bounded above complex \( F^* \) of finite free \( P \)-modules representing \( Ri_*K \) where \( i : U \to \text{Spec}(P) \) is the closed immersion induced by the presentation. Let \( M_n \) be the \( B \)-module corresponding to \( F_n|_U \). By Lemma \( 28.5 \)

\[
H^i(F^* \otimes_A A_n) = \begin{cases} 0 & \text{if } i \neq 0 \\ M_n & \text{if } i = 0 \end{cases}
\]

Let \( i \) be the maximal index such that \( F^i \) is nonzero. If \( i \leq 0 \), then (1), (2), and (3) are true. If not, then \( i > 0 \) and we see that the rank of the map

\[
F^{i-1} \to F^i
\]

in the point \( x \) is maximal. Hence in an open neighbourhood of \( x \) inside \( \text{Spec}(P) \) the rank is maximal. Thus after replacing \( P \) by a principal localization we may assume that the displayed map is surjective. Since \( F^i \) is finite free we may choose a splitting \( F^{i-1} = F' \oplus F^i \). Then we may replace \( F^* \) by the complex

\[
\ldots \to F^{i-2} \to F' \to 0 \to \ldots
\]

and we win by induction on \( i \). \( \square \)

---

**Lemma 28.7.** In Situation 28.1 let \( K \) be as in Lemma 28.2. Let \( W \subset X \) be as in Lemma 28.6. Set \( F = H^0(K)|_W \). Then, after possibly shrinking the open \( W \), the support of \( F \) is proper over \( A \).

**Proof.** Fix \( n \geq 1 \). Let \( I_n = \text{Ker}(A \to A_n) \). By More on Algebra, Lemma 11.3 the pair \((A, I_n)\) is henselian. Let \( Z \subset W \) be the support of \( F \). This is a closed subset as \( F \) is of finite presentation. By part (3) of Lemma 28.6 we see that \( Z \times_{\text{Spec}(A)} \text{Spec}(A_n) \) is equal to the support of \( F_n \) and hence proper over \( \text{Spec}(A/I) \).

By More on Morphisms, Lemma 48.9 we can write \( Z = Z_1 \amalg Z_2 \) with \( Z_1, Z_2 \) open and closed in \( Z \), with \( Z_1 \) proper over \( A \), and with \( Z_1 \times_{\text{Spec}(A)} \text{Spec}(A/I_n) \) equal to the support of \( F_n \). In other words, \( Z_2 \) does not meet \( X_0 \). Hence after replacing \( W \) by \( W \setminus Z_2 \) we obtain the lemma. \( \square \)

---

**Lemma 28.8.** Let \( A = \text{lim} A_n \) be a limit of a system of rings whose transition maps are surjective and with locally nilpotent kernels. Let \( S = \text{Spec}(A) \). Let \( T \to S \) be a monomorphism which is locally of finite type. If \( \text{Spec}(A_n) \to S \) factors through \( T \) for all \( n \), then \( T = S \).

**Proof.** Set \( S_n = \text{Spec}(A_n) \). Let \( T_0 \subset T \) be the common image of the factorizations \( S_n \to T \). Then \( T_0 \) is quasi-compact. Let \( T' \subset T \) be a quasi-compact open containing \( T_0 \). Then \( S_n \to T \) factors through \( T' \). If we can show that \( T' = S \), then \( T' = T = S \). Hence we may assume \( T \) is quasi-compact.

Assume \( T \) is quasi-compact. In this case \( T \to S \) is separated and quasi-finite (Morphisms, Lemma 19.15). Using Zariski’s Main Theorem (in the form of More on Morphisms, Lemma 48.3) we choose a factorization \( T \to W \to S \) with \( W \to S \) finite
and $T \to W$ an open immersion. Write $W = \text{Spec}(B)$. The (unique) factorizations $S_n \to T$ may be viewed as morphisms into $W$ and we obtain

$$A \to B \to \lim A_n = A$$

Consider the morphism $h : S = \text{Spec}(A) \to \text{Spec}(B) = W$ coming from the arrow on the right. Then

$$T \times_{W, h} S$$

is an open subscheme of $S$ containing the image of $S_n \to S$ for all $n$. To finish the proof it suffices to show that any open $U \subset S$ containing the image of $S_n \to S$ for some $n \geq 1$ is equal to $S$. This is true because $(A, \text{Ker}(A \to A_n))$ is a henselian pair (More on Algebra, Lemma 11.3) and hence every closed point of $S$ is contained in the image of $S_n \to S$. \qed

**Theorem 28.9** (Grothendieck Existence Theorem). In Situation 28.1 there exists a finitely presented $O_X$-module $F$, flat over $A$, with support proper over $A$, such that $F_n = F \otimes_{O_X} O_{X, n}$ for all $n$ compatibly with the maps $\varphi_n$.

**Proof.** Apply Lemmas 28.2, 28.3, 28.4, 28.5, 28.6, and 28.7 to get an open subscheme $W \subset X$ containing all points lying over Spec($A_n$) and a finitely presented $O_W$-module $F$ whose support is proper over $A$ with $F_n = F \otimes_{O_W} O_{X, n}$ for all $n \geq 1$. (This makes sense as $X_n \subset W$.) By Lemma 17.1 we see that $F$ is universally pure relative to Spec($A$). By Theorem 27.5 (for explanation, see Lemma 27.6) there exists a universal flattening $S' \to \text{Spec}(A)$ of $F$ and moreover the morphism $S' \to \text{Spec}(A)$ is a monomorphism of finite presentation. Since the base change of $F$ to Spec($A_n$) is $F_n$ we find that Spec($A_n$) $\to$ Spec($A$) factors (uniquely) through $S'$ for each $n$. By Lemma 28.8 we see that $S' = \text{Spec}(A)$. This means that $F$ is flat over $A$. Finally, since the scheme theoretic support $Z$ of $F$ is proper over Spec($A$), the morphism $Z \to X$ is closed. Hence the pushforward $(W \to X)_* F$ is supported on $W$ and has all the desired properties. \qed

**29. Grothendieck’s Existence Theorem, V**

In this section we prove an analogue for Grothendieck’s existence theorem in the derived category, following the method used in Section 28 for quasi-coherent modules. The classical case is discussed in Cohomology of Schemes, Sections 24, 25, and 27. We will work in the following situation.

**Situation 29.1.** Here we have an inverse system of rings $(A_n)$ with surjective transition maps whose kernels are locally nilpotent. Set $A = \lim A_n$. We have a scheme $X$ proper, flat, and of finite presentation over $A$. We set $X_n = X \times_{\text{Spec}(A)} \text{Spec}(A_n)$ and we view it as a closed subscheme of $X$. We assume further given a system $(K_n, \varphi_n)$ where $K_n$ is a pseudo-coherent object of $D(O_{X_n})$ and

$$\varphi_n : K_n \to K_{n-1}$$

is a map in $D(O_{X_n})$ which induces an isomorphism $K_n \otimes_{O_{X_n}} O_{X_{n-1}} \to K_{n-1}$ in $D(O_{X_{n-1}})$.

More precisely, we should write $\varphi_n : K_n \to R\text{im}_{n-1, n} K_{n-1}$ where $i_{n-1} : X_{n-1} \to X_n$ is the inclusion morphism and in this notation the condition is that the adjoint map $Li_{n-1, n}^* K_n \to K_{n-1}$ is an isomorphism. Our goal is to find a pseudo-coherent $K \in D(O_X)$ such that $K_n = K \otimes_{O_X} O_{X_n}$ for all $n$ (with the same abuse of notation).
Let $K$ be as in Lemma \ref{lemma:cohomological-dimension}. For any perfect object $E$ of $D(O_X)$ the cohomology 

$$M = R\Gamma(X, K \otimes^L E)$$

is a pseudo-coherent object of $D(A)$ and there is a canonical isomorphism 

$$R\Gamma(X_n, K_n \otimes^L E|_{X_n}) = M \otimes^L_{A_n} A_n$$

in $D(A_n)$. Here $E|_{X_n}$ denotes the derived pullback of $E$ to $X_n$.

**Proof.** Write $E_n = E|_{X_n}$ and $M_n = R\Gamma(X_n, K_n \otimes^L E|_{X_n})$. By Derived Categories of Schemes, Lemma \ref{lemma:derived-cohomology-pseudo-coherent} we see that $M_n$ is a pseudo-coherent object of $D(A_n)$ whose formation commutes with base change. Thus the maps $M_n \otimes^L_{A_n} A_{n-1} \to M_{n-1}$ coming from $\phi_n$ are isomorphisms. By More on Algebra, Lemma \ref{lemma:derived-cohomology-base-change} we find that $R\lim M_n$ is pseudo-coherent and that its base change back to $A_n$ recovers $M_n$. On the other hand, the exact functor $R\Gamma(X, -) : D_{QCoh}(O_X) \to D(A)$ of triangulated categories commutes with products and hence with derived limits, whence 

$$R\Gamma(X, E \otimes^L K) = R\lim R\Gamma(X, E \otimes^L K_n) = R\lim R\Gamma(X_n, E_n \otimes^L K_n) = R\lim M_n$$

as desired. \hfill $\Box$

**Lemma 29.4.** In Situation \ref{situation:flatness} let $K$ be as in Lemma \ref{lemma:cohomological-dimension} Then $K$ is pseudo-coherent on $X$. \hfill $\Box$
Proof. Combining Lemma \[29.3\] and Derived Categories of Schemes, Lemma \[31.3\] we see that $R\Gamma(X, K \otimes^L E)$ is pseudo-coherent in $D(A)$ for all pseudo-coherent $E$ in $D(O_X)$. Thus it follows from More on Morphisms, Lemma \[61.4\] that $K$ is pseudo-coherent relative to $A$. Since $X$ is of flat and of finite presentation over $A$, this is the same as being pseudo-coherent on $X$, see More on Morphisms, Lemma \[51.18\]. □

Lemma 29.5. In Situation \[29.4\] let $K$ be as in Lemma \[29.2\]. For any quasi-compact open $U \subset X$ we have

$$R\Gamma(U, K) \otimes^L_A A_n = R\Gamma(U_n, K_n)$$

in $D(A_n)$ where $U_n = U \cap X_n$.

Proof. Fix $n$. By Derived Categories of Schemes, Lemma \[30.4\] there exists a system of perfect complexes $E_m$ on $X$ such that $R\Gamma(U, K) = \hocolim R\Gamma(X, K \otimes^L E_m)$. In fact, this formula holds not just for $K$ but for every object of $D_{QCoh}(O_X)$. Applying this to $K_n$ we obtain

$$R\Gamma(U_n, K_n) = \hocolim R\Gamma(X_n, K_n \otimes^L E_m|_{X_n})$$

Using Lemma \[29.3\] and the fact that $- \otimes^L_A A_n$ commutes with homotopy colimits we obtain the result. □

Theorem 29.6 (Derived Grothendieck Existence Theorem). In Situation \[29.4\] there exists a pseudo-coherent $K$ in $D(O_X)$ such that $K_n = K \otimes^L_{O_X} O_{X_n}$ for all $n$ compatibly with the maps $\varphi_n$.

Proof. Apply Lemmas \[29.2\], \[29.3\], \[29.4\] to get a pseudo-coherent object $K$ of $D(O_X)$. Choosing affine opens in Lemma \[29.5\] it follows immediately that $K$ restricts to $K_n$ over $X_n$. □

Remark 29.7. The result in this section can be generalized. It is probably correct if we only assume $X \to \Spec(A)$ to be separated, of finite presentation, and $K_n$ pseudo-coherent relative to $A_n$ supported on a closed subset of $X_n$ proper over $A_n$. The outcome will be a $K$ which is pseudo-coherent relative to $A$ supported on a closed subset proper over $A$. If we ever need this, we will formulate a precise statement and prove it here.

30. Blowing up and flatness

In this section we continue our discussion of results of the form: “After a blowup the strict transform becomes flat”, see More on Algebra, Section \[26\] and Divisors, Section \[35\]. We will use the following (more or less standard) notation in this section. If $X \to S$ is a morphism of schemes, $F$ is a quasi-coherent module on $X$, and $T \to S$ is a morphism of schemes, then we denote $F_T$ the pullback of $F$ to the base change $X_T = X \times_S T$.

Remark 30.1. Let $S$ be a quasi-compact and quasi-separated scheme. Let $f : X \to S$ be a morphism of schemes. Let $F$ be a quasi-coherent module on $X$. Let $U \subset S$ be a quasi-compact open subscheme. Given a $U$-admissible blowup $S' \to S$ we denote $X'$ the strict transform of $X$ and $F'$ the strict transform of $F$ which
we think of as a quasi-coherent module on $X'$ (via Divisors, Lemma \[33.2\]). Let $P$ be a property of $\mathcal{F}/X/S$ which is stable under strict transform (as above) for $U$-admissible blowups. The general problem in this section is: Show (under auxiliary conditions on $\mathcal{F}/X/S$) there exists a $U$-admissible blowup $S' \to S$ such that the strict transform $\mathcal{F}'/X'/S'$ has $P$.

The general strategy will be to use that a composition of $U$-admissible blowups is a $U$-admissible blowup, see Divisors, Lemma \[34.2\]. In fact, we will make use of the more precise Divisors, Lemma \[32.14\] and combine it with Divisors, Lemma \[33.6\]. The result is that it suffices to find a sequence of $U$-admissible blowups

$$S = S_0 \leftarrow S_1 \leftarrow \ldots \leftarrow S_n$$

such that, setting $\mathcal{F}_0 = \mathcal{F}$ and $X_0 = X$ and setting $\mathcal{F}_i/X_i$ equal to the strict transform of $\mathcal{F}_{i-1}/X_{i-1}$, we arrive at $\mathcal{F}_n/X_n/S_n$ with property $P$.

In particular, choose a finite type quasi-coherent sheaf of ideals $\mathcal{I} \subset \mathcal{O}_S$ such that $V(\mathcal{I}) = S \setminus U$, see Properties, Lemma \[24.1\]. Let $S' \to S$ be the blowup in $\mathcal{I}$ and let $E \subset S'$ be the exceptional divisor (Divisors, Lemma \[32.4\]). Then we see that we’ve reduced the problem to the case where there exists an effective Cartier divisor $D \subset S$ whose support is $X \setminus U$. In particular we may assume $U$ is scheme theoretically dense in $S$ (Divisors, Lemma \[34.3\]).

Suppose that $P$ is local on $S$: If $S = \bigcup S_i$ is a finite open covering by quasi-compact opens and $P$ holds for $\mathcal{F}_{S_i}/X_{S_i}/S_i$ then $P$ holds for $\mathcal{F}/X/S$. In this case the general problem above is local on $S$ as well, i.e., if given $s \in S$ we can find a quasi-compact open neighbourhood $W$ of $s$ such that the problem for $\mathcal{F}_W/X_W/S$ is solvable, then the problem is solvable for $\mathcal{F}/X/S$. This follows from Divisors, Lemmas \[34.3\] and \[34.4\].

**Lemma 30.2.** Let $R$ be a ring and let $f \in R$. Let $r \geq 0$ be an integer. Let $R \to S$ be a ring map and let $M$ be an $S$-module. Assume

1. $R \to S$ is of finite presentation and flat,
2. every fibre ring $S \otimes_R \kappa(p)$ is geometrically integral over $R$,
3. $M$ is a finite $S$-module,
4. $M_f$ is a finitely presented $S_f$-module,
5. for all $p \in R$, $f \notin p$ with $q = pS$ the module $M_q$ is free of rank $r$ over $S_q$.

Then there exists a finitely generated ideal $I \subset R$ with $V(f) = V(I)$ such that for all $a \in I$ with $R' = R[f^{-1}]$ the quotient

$$M' = (M \otimes_R R')/a\text{-power torsion}$$

over $S' = S \otimes_R R'$ satisfies the following: for every prime $p' \subset R'$ there exists a $g \in S'$, $g \notin p'S'$ such that $M'_g$ is a free $S'_g$-module of rank $r$.

**Proof.** This lemma is a generalization of More on Algebra, Lemma \[26.5\] we urge the reader to read that proof first. Choose a surjection $S^{\oplus n} \to M$, which is possible by (1). Choose a finite submodule $K \subset \text{Ker}(S^{\oplus n} \to M)$ such that $S^{\oplus n}/K \to M$ becomes an isomorphism after inverting $f$. This is possible by (4). Set $M_1 = S^{\oplus n}/K$ and suppose we can prove the lemma for $M_1$. Say $I \subset R$ is the corresponding ideal. Then for $a \in I$ the map

$$M'_1 = (M_1 \otimes_R R')/a\text{-power torsion} \to M' = (M \otimes_R R')/a\text{-power torsion}$$
is surjective. It is also an isomorphism after inverting $a$ in $R'$ as $R'_a = R_f$, see Algebra, Lemma 69.4. But $a$ is a nonzerodivisor on $M'_1$, whence the displayed map is an isomorphism. Thus it suffices to prove the lemma in case $M$ is a finitely presented $S$-module.

Assume $M$ is a finitely presented $S$-module satisfying (3). Then $J = \text{Fit}_r(M) \subset S$ is a finitely generated ideal. By Lemma 69.3 we can write $S$ as a direct summand of a free $R$-module: $\bigoplus_{a \in A} R_S = S \oplus C$. For any element $h \in S$ writing $h = \sum a_\alpha$ in the decomposition above, we say that the $a_\alpha$ are the coefficients of $h$. Let $I' \subset R$ be the ideal of coefficients of elements of $J$. Multiplication by an element of $S$ defines an $R$-linear map $S \to S$, hence $I'$ is generated by the coefficients of the generators of $J$, i.e., $I'$ is a finitely generated ideal. We claim that $I = fI'$ works.

We first check that $V(f) = V(I)$. The inclusion $V(f) \subset V(I)$ is clear. Conversely, if $f \notin p$, then $q = pS$ is not an element of $V(J)$ by property (5) and More on Algebra, Lemma 8.6. Hence there is an element of $J$ which does not map to zero in $S \otimes_R \kappa(p)$. Thus there exists an element of $I'$ which is not contained in $p$, so $p \notin V(fI') = V(I)$.

Let $a \in I$ and set $R' = R[\frac{1}{a_i}]$. We may write $a = fa'$ for some $a' \in I'$. By Algebra, Lemmas 69.2 and 69.5 we see that $I'R' = a'R'$ and $a'$ is a nonzerodivisor in $R'$. Set $S' = S \otimes_S R'$. Every element $g$ of $JS' = \text{Fit}_r(M \otimes_S S')$ can be written as $g = \sum c_\alpha$ for some $c_\alpha \in I'R'$. Since $I'R' = a'R'$ we can write $c_\alpha = a'c'_\alpha$ for some $c'_\alpha \in R'$ and $g = (\sum c'_\alpha)a' = g'a'$ in $S'$. Moreover, there is an $g_0 \in J$ such that $a' = c_\alpha$ for some $\alpha$. For this element we have $g_0 = g_0a' \in S'$ where $g_0$ is a unit in $S'$. Let $p' \subset R'$ be a prime ideal and $q' = p'S'$. By the above we see that $JS_{q'}$ is the principal ideal generated by the nonzerodivisor $a'$. It follows from More on Algebra, Lemma 8.8 that $M_{q'}$ can be generated by $r$ elements. Since $M'$ is finite, there exist $m_1, \ldots, m_r \in M'$ and $g \in S'$, $g \notin q'$ such that the corresponding map $(S')^{\oplus r} \to M'$ becomes surjective after inverting $g$.

Finally, consider the ideal $J' = \text{Fit}_{k-1}(M')$. Note that $J'S_{q''}$ is generated by the coefficients of relations between $m_1, \ldots, m_r$ (compatibility of Fitting ideal with base change). Thus it suffices to show that $J' = 0$, see More on Algebra, Lemma 8.7. Since $R'_a = R_f$ (Algebra, Lemma 69.4) and $M'_a = M_f$ we see from (5) that $J'_a$ maps to zero in $S_{q''}$ for any prime $q'' \subset \text{Spec } S$ of the form $q'' = p''S'$ where $p'' \subset R'_a$. Since $S'_a \subset \prod_{q''}$ as above $S_{q''}$ (as $(S'_a)_{p''} \subset S_{q''}$ by Lemma 7.4) we see that $J'R'_a = 0$. Since $a$ is a nonzerodivisor in $R'$ we conclude that $J' = 0$ and we win. 

0811 Lemma 30.3. Let $S$ be a quasi-compact and quasi-separated scheme. Let $X \to S$ be a morphism of schemes. Let $F$ be a quasi-coherent module on $X$. Let $U \subset S$ be a quasi-compact open. Assume

(1) $X \to S$ is affine, of finite presentation, flat, geometrically integral fibres,
(2) $F$ is a module of finite type,
(3) $F_U$ is of finite presentation,
(4) $F$ is flat over $S$ at all generic points of fibres lying over points of $U$.

Then there exists a $U$-admissible blowup $S' \to S$ and an open subscheme $V \subset X_{S'}$ such that (a) the strict transform $F'$ of $F$ restricts to a finitely locally free $O_{V'}$-module and (b) $V \to S'$ is surjective.

Proof. Given $F/X/S$ and $U \subset S$ with hypotheses as in the lemma, denote $P$ the property “$F$ is flat over $S$ at all generic points of fibres”. It is clear that $P$ is
preserved under strict transform, see Divisors, Lemma \[33.3\] and Morphisms, Lemma \[30.1\] apply to the problem posed by the lemma.

Consider the function \( r : U \to \mathbb{Z}_{\geq 0} \) which assigns to \( u \in U \) the integer

\[
r(u) = \dim_{\kappa(\xi_u)}(\mathcal{F}_{\xi_u} \otimes \kappa(\xi_u))
\]

where \( \xi_u \) is the generic point of the fibre \( X_u \). By More on Morphisms, Lemma \[16.7\] and the fact that the image of an open in \( X_S \) in \( S \) is open, we see that \( r(u) \) is locally constant. Accordingly \( U = U_0 \amalg U_1 \amalg \ldots \amalg U_c \) is a finite disjoint union of open and closed subschemes where \( r \) is constant with value \( i \) on \( U_i \). By Divisors, Lemma \[34.5\] we can find a \( U \)-admissible blowup to decompose \( S \) into the disjoint union of two schemes, the first containing \( U_0 \) and the second \( U_1 \cup \ldots \cup U_c \). Repeating this \( c - 1 \) more times we may assume that \( S \) is a disjoint union \( S = S_0 \amalg S_1 \amalg \ldots \amalg S_c \) with \( U_i \subset S_i \). Thus we may assume the function \( r \) defined above is constant, say with value \( r \).

By Remark \[30.1\] we see that we may assume that we have an effective Cartier divisor \( D \subset S \) whose support is \( S \setminus U \). Another application of Remark \[30.1\] combined with Divisors, Lemma \[13.2\] tells us we may assume that \( S = \text{Spec}(R) \) and \( D = \text{Spec}(R/(f)) \) for some nonzerodivisor \( f \in R \). This case is handled by Lemma \[30.2\].

**Lemma 30.4.** Let \( A \to C \) be a finite locally free ring map of rank \( d \). Let \( h \in C \) be an element such that \( C_h \) is étale over \( A \). Let \( J \subset C \) be an ideal. Set \( I = \text{Fit}_0(C/J) \) where we think of \( C/J \) as a finite \( A \)-module. Then \( IC_h = J'J' \) for some ideal \( J' \subset C_h \). If \( J' \) is finitely generated so are \( I \) and \( J' \).

**Proof.** We will use basic properties of Fitting ideals, see More on Algebra, Lemma \[8.4\]. Then \( IC \) is the Fitting ideal of \( C/J \otimes_A C \). Note that \( C \to C \otimes_A C, c \mapsto 1 \otimes c \) has a section (the multiplication map). By assumption \( C \to C \otimes_A C \) is étale at every prime in the image of \( \text{Spec}(C_h) \) under this section. Hence the multiplication map \( C \otimes_A C_h \to C_h \) is étale in particular flat, see Algebra, Lemma \[142.8\]. Hence there exists a \( C_h \)-algebra such that \( C \otimes_A C_h \cong C_h \oplus C' \) as \( C_h \)-algebras, see Algebra, Lemma \[142.9\]. Thus \( (C/J) \otimes_A C_h \cong (C_h/J_h) \oplus C'/J' \) as \( C_h \)-modules for some ideal \( J' \subset C' \). Hence \( IC_h = J' \) with \( J' = \text{Fit}_0(C'/I') \) where we view \( C'/J' \) as a \( C_h \)-module.

**Lemma 30.5.** Let \( A \to B \) be an étale ring map. Let \( a \in A \) be a nonzerodivisor. Let \( J \subset B \) be a finite type ideal with \( V(J) \subset V(aB) \). For every \( q \subset B \) there exists a finite type ideal \( I \subset A \) with \( V(I) \subset V(a) \) and \( g \in B, g \notin q \) such that \( IB_g = J' \) for some finite type ideal \( J' \subset B_g \).

**Proof.** We may replace \( B \) by a principal localization at an element \( g \in B, g \notin q \). Thus we may assume that \( B \) is standard étale, see Algebra, Proposition \[142.16\]. Thus we may assume \( B \) is a localization of \( C = A[x]/(f) \) for some monic \( f \in A[x] \) of some degree \( d \). Say \( B = C_h \) for some \( h \in C \). Choose elements \( h_1, \ldots, h_n \in C \) which generate \( J \) over \( B \). The condition \( V(J) \subset V(aB) \) signifies that \( a^m = \sum b_i h_i \) in \( B \) for some large \( m \). Set \( h_{n+1} = a^m \). As in Lemma \[30.4\] we take \( I = \text{Fit}_0(C/(h_1, \ldots, h_{r+1})) \). Since the module \( C/(h_1, \ldots, h_{r+1}) \) is annihilated by \( a^m \) we see that \( a^{dm} \in I \) which implies that \( V(I) \subset V(a) \).
Lemma 30.6. Let $S$ be a quasi-compact and quasi-separated scheme. Let $X \to S$ be a morphism of schemes. Let $\mathcal{F}$ be a quasi-coherent module on $X$. Let $U \subset S$ be a quasi-compact open. Assume there exist finitely many commutative diagrams

$$
x_i \xrightarrow{j_i} X
$$

where

1. $e_i : S_i \to S$ are quasi-compact étale morphisms and $S = \bigcup e_i(S_i)$,
2. $j_i : X_i \to X$ are étale morphisms and $X = \bigcup j_i(X_i)$,
3. $S_i^* \to S_i$ is an $e_i^{-1}(U)$-admissible blowup such that the strict transform $\mathcal{F}_i^*$ of $j_i^* \mathcal{F}$ is flat over $S_i^*$.

Then there exists a $U$-admissible blowup $S' \to S$ such that the strict transform of $\mathcal{F}$ is flat over $S'$.

Proof. We claim that the hypotheses of the lemma are preserved under $U$-admissible blowups. Namely, suppose $b : S' \to S$ is a $U$-admissible blowup in the quasi-coherent sheaf of ideals $\mathcal{I}$. Moreover, let $S'_i \to S_i$ be the blowup in the quasi-coherent sheaf of ideals $\mathcal{J}_i$. Then the collection of morphisms $e'_i : S'_i = S_i \times_S S' \to S'$ and $j'_i : X'_i = X_i \times_S S' \to X \times_S S'$ satisfy conditions (1), (2), (3) for the strict transform $\mathcal{F}'$ of $\mathcal{F}$ relative to the blowup $S' \to S$. First, observe that $S'_i$ is the blowup of $S_i$ in the pullback of $\mathcal{I}$, see Divisors, Lemma 32.3. Second, consider the blowup $S_i^* \to S'_i$ in the pullback of the ideal $\mathcal{J}_i$. By Divisors, Lemma 32.12, we get a commutative diagram

$$
S_i^* \xrightarrow{e_i} S_i \xrightarrow{j_i} X
$$

and all the morphisms in the diagram above are blowups. Hence by Divisors, Lemmas 33.3 and 33.6, we see

- the strict transform of $(j'_i)^* \mathcal{F}'$ under $S_i^* \to S_i$
- the strict transform of $j_i^* \mathcal{F}$ under $S_i^* \to S_i$
- the strict transform of $\mathcal{F}'$ under $S_i^* \to S_i$
- the pullback of $\mathcal{F}'$ via $X_i \times_S S_i^* \to X_i$

which is therefore flat over $S_i^*$ (Morphisms, Lemma 24.7). Having said this, we see that all observations of Remark 30.1 apply to the problem of finding a $U$-admissible blowup such that the strict transform of $\mathcal{F}$ becomes flat over the base under assumptions as in the lemma. In particular, we may assume that $S \setminus U$ is the support of an effective Cartier divisor $D \subset S$. Another application of Remark 30.1 combined with Divisors, Lemma 13.2, shows we may assume that $S = \text{Spec}(A)$ and $D = \text{Spec}(A/(a))$ for some nonzero divisor $a \in A$.

Pick an $i$ and $s \in S_i$. Lemma 30.3 implies we can find an open neighbourhood $s \in W_i \subset S_i$ and a finite type quasi-coherent ideal $\mathcal{I} \subset \mathcal{O}_S$ such that $\mathcal{I} \cdot \mathcal{O}_{W_i} = \mathcal{J}_i \mathcal{J}_i'$ for some finite type quasi-coherent ideal $\mathcal{J}_i' \subset \mathcal{O}_{W_i}$, and such that $V(\mathcal{I}) \subset V(a) = S \setminus U$. 
Since $S_i$ is quasi-compact we can replace $S_i$ by a finite collection $W_1, \ldots, W_n$ of these opens and assume that for each $i$ there exists a quasi-coherent sheaf of ideals $I_i \subset O_S$ such that $I_i \cdot O_{S_i} = J_i J'_i$ for some finite type quasi-coherent ideal $J'_i \subset O_{S_i}$. As in the discussion of the first paragraph of the proof, consider the blowup $S'$ of $S$ in the product $I_1 \ldots I_n$ (this blowup is $U$-admissible by construction). The base change of $S' \to S$ to $S_1$ is the blowup in

$$J_i \cdot J'_i \cdot I_1 \ldots I_n$$

which factors through the given blowup $S'_i \to S_i$ (Divisors, Lemma 32.12). In the notation of the diagram above this means that $S'_i = S'_i$. Hence after replacing $S$ by $S'$ we arrive in the situation that $j'_i \mathcal{F}$ is flat over $S_i$. Hence $j'_i \mathcal{F}$ is flat over $S_i$, see Lemma 2.3. By Morphisms, Lemma 24.13 we see that $\mathcal{F}$ is flat over $S$. □

**Theorem 30.7.** Let $S$ be a quasi-compact and quasi-separated scheme. Let $X$ be a scheme over $S$. Let $\mathcal{F}$ be a quasi-coherent module on $X$. Let $U \subset S$ be a quasi-compact open. Assume

1. $X$ is quasi-compact,
2. $X$ is locally of finite presentation over $S$,
3. $\mathcal{F}$ is a module of finite type,
4. $\mathcal{F}_U$ is of finite presentation, and
5. $\mathcal{F}_U$ is flat over $U$.

Then there exists a $U$-admissible blowup $S' \to S$ such that the strict transform $\mathcal{F}'$ of $\mathcal{F}$ is an $O_{X \times_S S'}$-module of finite presentation and flat over $S'$.

**Proof.** We first prove that we can find a $U$-admissible blowup such that the strict transform is flat. The question is étale local on the source and the target, see Lemma 30.6 for a precise statement. In particular, we may assume that $S = \text{Spec}(R)$ and $X = \text{Spec}(A)$ are affine. For $s \in S$ write $\mathcal{F}_s = \mathcal{F}|_{X_s}$ (pullback of $\mathcal{F}$ to the fibre). As $X \to S$ is of finite type $d = \max_{s \in S} \dim(\text{Supp}(\mathcal{F}_s))$ is an integer. We will do induction on $d$.

Let $x \in X$ be a point of $X$ lying over $s \in S$ with $\dim_x(\text{Supp}(\mathcal{F}_s)) = d$. Apply Lemma 3.2 to get $g : X' \to X$, $e : S' \to S$, $i : Z' \to X'$, and $\pi : Z' \to Y'$. Observe that $Y' \to S'$ is a smooth morphism of affines with geometrically irreducible fibres of dimension $d$. Because the problem is étale local it suffices to prove the theorem for $g^* \mathcal{F}/X'/S'$. Because $i : Z' \to X'$ is a closed immersion of finite presentation (and since strict transform commutes with affine pushforward, see Divisors, Lemma 33.4) it suffices to prove the flattening result for $G$. Since $\pi$ is finite (hence also affine) it suffices to prove the flattening result for $\pi_* G/Y'/S'$. Thus we may assume that $X \to S$ is a smooth morphism of affines with geometrically irreducible fibres of dimension $d$.

Next, we apply a blowup as in Lemma 30.3. Doing so we reach the situation where there exists an open $V \subset X$ surjecting onto $S$ such that $\mathcal{F}|_V$ is locally free. Let $\xi \in X$ be the generic point of $X_s$. Let $r = \dim_{k(\xi)} \mathcal{F}_{\xi} \otimes k(\xi)$. Choose a map $\alpha : O_X^{\oplus r} \to \mathcal{F}$ which induces an isomorphism $\kappa(\xi)^{\oplus r} \to \mathcal{F}_{\xi} \otimes k(\xi)$. Because $\mathcal{F}$ is locally free over $V$ we find an open neighbourhood $W$ of $\xi$ where $\alpha$ is an isomorphism. Shrink $S$ to an affine open neighbourhood of $s$ such that $W \to S$ is surjective. Say $\mathcal{F}$ is the quasi-coherent module associated to the $A$-module $N$. 

Since $\mathcal{F}$ is flat over $S$ at all generic points of fibres (in fact at all points of $W$), we see that $\alpha_p : A_p^{\oplus r} \to N_p$ is universally injective for all primes $p$ of $R$, see Lemma 10.1. Hence $\alpha$ is universally injective, see Algebra, Lemma 81.12. Set $\mathcal{H} = \text{Coker}(\alpha)$. By Divisors, Lemma 33.7 we see that, given a $U$-admissible blowup $S' \to S$ the strict transforms of $\mathcal{F}'$ and $\mathcal{H}'$ fit into an exact sequence

$$0 \to \mathcal{O}_{X \times_S S'}^{\oplus r} \to \mathcal{F}' \to \mathcal{H}' \to 0$$

Hence Lemma 10.1 also shows that $\mathcal{F}'$ is flat at a point $x'$ if and only if $\mathcal{H}'$ is flat at that point. In particular $\mathcal{H}_U$ is flat over $U$ and $\mathcal{H}_U$ is a module of finite presentation. We may apply the induction hypothesis to $\mathcal{H}$ to see that there exists a $U$-admissible blowup such that the strict transform $\mathcal{H}'$ is flat as desired.

To finish the proof of the theorem we still have to show that $\mathcal{F}'$ is a module of finite presentation (after possibly another $U$-admissible blowup). This follows from Lemma 11.1 as we can assume $U \subset S$ is scheme theoretically dense (see third paragraph of Remark 30.1). This finishes the proof of the theorem. □

### 31. Applications

In this section we apply some of the results above.

**Lemma 31.1.** Let $S$ be a quasi-compact and quasi-separated scheme. Let $X$ be a scheme over $S$. Let $U \subset S$ be a quasi-compact open. Assume

1. $X \to S$ is of finite type and quasi-separated, and
2. $X_U \to U$ is flat and locally of finite presentation.

Then there exists a $U$-admissible blowup $S' \to S$ such that the strict transform of $X$ is flat and of finite presentation over $S'$.

**Proof.** Since $X \to S$ is quasi-compact and quasi-separated by assumption, the strict transform of $X$ with respect to a blowing up $S' \to S$ is also quasi-compact and quasi-separated. Hence to prove the lemma it suffices to find a $U$-admissible blowup such that the strict transform is flat and locally of finite presentation. Let $X = W_1 \cup \ldots \cup W_n$ be a finite affine open covering. If we can find a $U$-admissible blowup $S_i \to S$ such that the strict transform of $W_i$ is flat and locally of finite presentation, then there exists a $U$-admissible blowing up $S' \to S$ dominating all $S_i \to S$ which does the job (see Divisors, Lemma 34.4 see also Remark 30.1). Hence we may assume $X$ is affine.

Assume $X$ is affine. By Morphisms, Lemma 37.2 we can choose an immersion $j : X \to \mathbb{A}^d_S$ over $S$. Let $V \subset \mathbb{A}^d_S$ be a quasi-compact open subscheme such that $j$ induces a closed immersion $i : X \to V$ over $S$. Apply Theorem 30.7 to $V \to S$ and the quasi-coherent module $i_* \mathcal{O}_X$ to obtain a $U$-admissible blowup $S' \to S$ such that the strict transform of $i_* \mathcal{O}_X$ is flat over $S'$ and of finite presentation over $\mathcal{O}_{V \times_S S'}$. Let $X'$ be the strict transform of $X$ with respect to $S' \to S$. Let $i' : X' \to V \times_S S'$ be the induced morphism. Since taking strict transform commutes with pushforward along affine morphisms (Divisors, Lemma 33.4), we see that $i'_* \mathcal{O}_{X'}$ is flat over $S$ and of finite presentation as a $\mathcal{O}_{V \times_S S'}$-module. This implies the lemma. □

**Lemma 31.2.** Let $S$ be a quasi-compact and quasi-separated scheme. Let $X$ be a scheme over $S$. Let $U \subset S$ be a quasi-compact open. Assume
(1) $X \to S$ is proper, and
(2) $X_U \to U$ is finite locally free.

Then there exists a $U$-admissible blowup $S' \to S$ such that the strict transform of $X$ is finite locally free over $S'$.

**Proof.** By Lemma 31.1 we may assume that $X \to S$ is flat and of finite presentation. After replacing $S$ by a $U$-admissible blowup if necessary, we may assume that $U \subset S$ is scheme theoretically dense. Then $f$ is finite by Lemma 11.4. Hence $f$ is finite locally free by Morphisms, Lemma 46.2. □

**Lemma 31.3.** Let $\varphi : X \to S$ be a separated morphism of finite type with $S$ quasi-compact and quasi-separated. Let $U \subset S$ be a quasi-compact open such that $\varphi^{-1}U \to U$ is an isomorphism. Then there exists a $U$-admissible blowup $S' \to S$ such that the strict transform $X'$ of $X$ is isomorphic to an open subscheme of $S'$.

**Proof.** The discussion in Remark 30.1 applies. Thus we may do a first $U$-admissible blowup and assume the complement $S \setminus U$ is the support of an effective Cartier divisor $D$. In particular $U$ is scheme theoretically dense in $S$. Next, we do another $U$-admissible blowup to get to the situation where $X \to S$ is flat and of finite presentation, see Lemma 31.1. □

The following lemma says that a proper modification can be dominated by a blowup.

**Lemma 31.4.** Let $\varphi : X \to S$ be a proper morphism with $S$ quasi-compact and quasi-separated. Let $U \subset S$ be a quasi-compact open such that $\varphi^{-1}U \to U$ is an isomorphism. Then there exists a $U$-admissible blowup $S' \to S$ which dominates $X$, i.e., such that there exists a factorization $S' \to X \to S$ of the blowup morphism.

**Proof.** The discussion in Remark 30.1 applies. Thus we may do a first $U$-admissible blowup and assume the complement $S \setminus U$ is the support of an effective Cartier divisor $D$. In particular $U$ is scheme theoretically dense in $S$. Choose another $U$-admissible blowup $S' \to S$ such that the strict transform $X'$ of $X$ is an open subscheme of $S'$, see Lemma 31.3. Since $X' \to S'$ is proper, and $U \subset S'$ is dense, we see that $X' = S'$. Some details omitted. □

**Lemma 31.5.** Let $S$ be a scheme. Let $U \subset W \subset S$ be open subschemes. Let $f : X \to W$ be a morphism and let $s : U \to X$ be a morphism such that $f \circ s = id_U$. Assume

(1) $f$ is proper,
(2) $S$ is quasi-compact and quasi-separated, and
(3) $U$ and $W$ are quasi-compact.

Then there exists a $U$-admissible blowup $b : S' \to S$ and a morphism $s' : b^{-1}(W) \to X$ extending $s$ with $f \circ s' = b|_{b^{-1}(W)}$.

**Proof.** We may and do replace $X$ by the scheme theoretic image of $s$. Then $X \to W$ is an isomorphism over $U$, see Morphisms, Lemma 6.8. By Lemma 31.4 there exists a $U$-admissible blowup $W' \to W$ and an extension $W' \to X$ of $s$. We finish the proof by applying Divisors, Lemma 31.3 to extend $W' \to W$ to a $U$-admissible blowup of $S$. □
32. Compactifications

Let $S$ be a quasi-compact and quasi-separated scheme. We will say a scheme $X$ over $S$ has a **compactification over $S$** if there exists a quasi-compact open immersion $X \to \overline{X}$ into a scheme $\overline{X}$ proper over $S$. If $X$ has a compactification over $S$, then $X \to S$ is separated and of finite type. It is a theorem of Nagata, see [Laü93], [Cho07], [Nag50], [Nag57], [Nag62], and [Nag63], that the converse is true as well. We will prove this theorem in the next section, see Theorem 33.8.

Let $S$ be a quasi-compact and quasi-separated scheme. Let $X \to S$ be a separated finite type morphism of schemes. The category of **compactifications of $X$ over $S$** is the category defined as follows:

1. Objects are open immersions $j : X \to \overline{X}$ over $S$ with $\overline{X} \to S$ proper.
2. Morphisms $(j' : X \to \overline{X}') \to (j : X \to \overline{X})$ are morphisms $f : \overline{X}' \to \overline{X}$ of schemes over $S$ such that $f \circ j = j$.

If $j : X \to \overline{X}$ is a compactification, then $j$ is a quasi-compact open immersion, see Schemes, Remark 21.18.

**Warning.** We do not assume compactifications $j : X \to \overline{X}$ to have dense image. Consequently, if $f : \overline{X}' \to \overline{X}$ is a morphism of compactifications, it may not be the case that $f^{-1}(j(X)) = j'(X)$.

**Lemma 32.1.** Let $S$ be a quasi-compact and quasi-separated scheme. Let $X$ be a compactifyable scheme over $S$.

(a) The category of compactifications of $X$ over $S$ is cofiltered.
(b) The full subcategory consisting of compactifications $j : X \to \overline{X}$ such that $j(X)$ is dense and scheme theoretically dense in $\overline{X}$ is initial (Categories, Definition 17.3).
(c) If $f : \overline{X}' \to \overline{X}$ is a morphism of compactifications of $X$ such that $j'(X)$ is dense in $\overline{X}'$, then $f^{-1}(j(X)) = j'(X)$.

**Proof.** To prove part (a) we have to check conditions (1), (2), (3) of Categories, Definition 20.4. Condition (1) holds exactly because we assumed that $X$ is compactifyable. Let $j_i : X \to \overline{X}_i$, $i = 1, 2$ be two compactifications. Then we can consider the scheme theoretic image $\overline{X}$ of $(j_1, j_2) : X \to \overline{X}_1 \times_S \overline{X}_2$. This determines a third compactification $j : X \to \overline{X}$ which dominates both $j_i$:

$$(X, \overline{X}_1) \leftarrow (X, \overline{X}) \rightarrow (X, \overline{X}_2)$$

Thus (2) holds. Let $f_1, f_2 : \overline{X}_1 \to \overline{X}_2$ be two morphisms between compactifications $j_i : X \to \overline{X}_i$, $i = 1, 2$. Let $\overline{X} \subset \overline{X}_1$ be the equalizer of $f_1$ and $f_2$. As $\overline{X}_2 \to S$ is separated, we see that $\overline{X}$ is a closed subscheme of $\overline{X}_1$ and hence proper over $S$. Moreover, we obtain an open immersion $X \to \overline{X}$ because $f_1|_X = f_2|_X = \text{id}_X$. The morphism $(X \to \overline{X}) \to (j_1 : X \to \overline{X}_1)$ given by the closed immersion $X \to \overline{X}$ equalizes $f_1$ and $f_2$ which proves condition (3).

Proof of (b). Let $j : X \to \overline{X}$ be a compactification. If $\overline{X}'$ denotes the scheme theoretic closure of $X$ in $\overline{X}$, then $X$ is dense and scheme theoretically dense in $\overline{X}'$ by Morphisms, Lemma 7.7. This proves the first condition of Categories, Definition 17.3. Since we have already shown the category of compactifications of $X$ is...
cofiltered, the second condition of Categories, Definition 17.3 follows from the first (we omit the solution to this categorical exercise).

Proof of (c). After replacing $X'$ with the scheme theoretic closure of $j'(X)$ (which doesn’t change the underlying topological space) this follows from Morphisms, Lemma 6.8.

□

We can also consider the category of all compactifications (for varying $X$). It turns out that this category, localized at the set of morphisms which induce an isomorphism on the interior is equivalent to the category of compactifyable schemes over $S$.

Lemma 32.2. Let $S$ be a quasi-compact and quasi-separated scheme. Let $f : X \to Y$ be a morphism of schemes over $S$ with $Y$ separated and of finite type over $S$ and $X$ compactifiable over $S$. Then $X$ has a compactification over $Y$.

Proof. Let $j : X \to \overline{X}$ be a compactification of $X$ over $S$. Then we let $X'$ be the scheme theoretic image of $(j, f) : X \to \overline{X} \times_S Y$. The morphism $X' \to Y$ is proper because $\overline{X} \times_S Y \to Y$ is proper as a base change of $\overline{X} \to S$. On the other hand, since $Y$ is separated over $S$, the morphism $(1, f) : X \to X \times_S Y$ is a closed immersion (Schemes, Lemma 21.10) and hence $X \to X'$ is an open immersion. □

Let $S$ be a quasi-compact and quasi-separated scheme. We define the category of compactifications to be the category whose objects are pairs $(X, \overline{X})$ where $\overline{X}$ is a scheme proper over $S$ and $X \subset \overline{X}$ is a quasi-compact open and whose morphisms are commutative diagrams

\[
\begin{array}{ccc}
X & \xrightarrow{f} & Y \\
\downarrow & & \downarrow \\
\overline{X} & \xrightarrow{f} & Y
\end{array}
\]

of morphisms of schemes over $S$.

Lemma 32.3. Let $S$ be a quasi-compact and quasi-separated scheme. The collection of morphisms $(u, \pi) : (X', \overline{X}') \to (X, \overline{X})$ such that $u$ is an isomorphism forms a right multiplicative system (Categories, Definition 26.1) of arrows in the category of compactifications.

Proof. Axiom RMS1 is trivial to verify. Let us check RMS2 holds. Suppose given a diagram

\[
\begin{array}{ccc}
(X', \overline{X}') & \xrightarrow{(u, \pi)} & (Y, \overline{Y}) \\
\downarrow & & \downarrow \xrightarrow{(j, \overline{j})} \\
(Y', \overline{X}) & \xrightarrow{(f, \overline{f})} & (X, \overline{X})
\end{array}
\]

with $u : X' \to X$ an isomorphism. Then we let $Y' = Y \times_X X'$ with the projection map $v : Y' \to Y$ (an isomorphism). We also set $\overline{Y}' = \overline{Y} \times_{\overline{X}} \overline{X}'$ with the projection
map \( \tau : Y' \to Y \) It is clear that \( Y' \to Y \) is an open immersion. The diagram

\[
\begin{array}{ccc}
(Y', Y') & \xrightarrow{(g, \bar{f})} & (X', X') \\
(v, \tau) & \downarrow & \downarrow (u, \bar{\tau}) \\
(Y, Y) & \xrightarrow{(f, \bar{f})} & (X, X)
\end{array}
\]

shows that axiom RMS3 holds.

Let us check RMS3 holds. Suppose given a pair of morphisms \((f, \bar{f}), (g, \bar{g}) : (X, X) \to (Y, Y)\) of compactifications and a morphism \((v, \tau) : (Y, Y) \to (Y', Y')\) such that \(v\) is an isomorphism and such that \((v, \tau) \circ (f, \bar{f}) = (v, \tau) \circ (g, \bar{g})\). Then \(f = g\). Hence if we let \(X' \subset X\) be the equalizer of \(\bar{f}\) and \(\bar{g}\), then \((u, \bar{\tau}) : (X, X') \to (X, X)\) will be a morphism of the category of compactifications such that \((f, \bar{f}) \circ (u, \bar{\tau}) = (g, \bar{g}) \circ (u, \bar{\tau})\) as desired. \(\square\)

**Lemma 32.4.** Let \(S\) be a quasi-compact and quasi-separated scheme. The functor \((X, X) \to X\) defines an equivalence from the category of compactifications localized \((Categories, Lemma \[26.11]\) at the right multiplicative system of Lemma \[32.3\] to the category of compactifyable schemes over \(S\).

**Proof.** Denote \(C\) the category of compactifications and denote \(Q : C \to C'\) the localization functor of Categories, Lemma \[26.16\]. Denote \(D\) the category of compactifyable schemes over \(S\). It is clear from the lemma just cited and our choice of multiplicative system that we obtain a functor \(C' \to D\). This functor is clearly essentially surjective. If \(f : X \to Y\) is a morphism of compactifyable schemes, then we choose an open immersion \(Y \to Y'\) into a scheme proper over \(S\), and then we choose an embedding \(X \to X\) into a scheme \(X\) proper over \(Y\) (possible by Lemma \[32.2\] applied to \(X \to Y\)). This gives a morphism \((X, X) \to (Y, Y)\) of compactifications which produces our given morphism \(X \to Y\). Finally, suppose given a pair of morphisms in the localized category with the same source and target: say

\[a = ((f, \bar{f}) : (X', X') \to (Y, Y), (u, \bar{\tau}) : (X', X') \to (X, X))\]

and

\[b = ((g, \bar{g}) : (X'', X'') \to (Y, Y), (v, \bar{\tau}) : (X'', X'') \to (X, X))\]

which produce the same morphism \(X \to Y\) over \(S\), in other words \(f \circ \tau^{-1} = g \circ \tau^{-1}\). By Categories, Lemma \[26.13\] we may assume that \((X', X') = (X'', X'')\) and \((u, \bar{\tau}) = (v, \bar{\tau})\). In this case we can consider the equalizer \(X^{'''} \subset X'\) of \(\bar{f}\) and \(\bar{g}\). The morphism \((w, \bar{w}) : (X', X^{''''}) \to (X', X')\) is in the multiplicative subset and we see that \(a = b\) in the localized category by precomposing with \((w, \bar{w})\). \(\square\)

### 33. Nagata compactification

**Lemma 33.1.** Let \(X \to S\) be a morphism of schemes. If \(X = U \cup V\) is an open cover such that \(U \to S\) and \(V \to S\) are separated and \(U \cap V \to U \times_S V\) is closed, then \(X \to S\) is separated.

**Proof.** Omitted. Hint: check that \(\Delta : X \to X \times_S X\) is closed by using the open covering of \(X \times_S X\) given by \(U \times_S U, U \times_S V, V \times_S U,\) and \(V \times_S V\). \(\square\)
Lemma 33.2. Let $X$ be a quasi-compact and quasi-separated scheme. Let $U \subset X$ be a quasi-compact open.

1. If $Z_1, Z_2 \subset X$ are closed subschemes of finite presentation such that $Z_1 \cap Z_2 \cap U = \emptyset$, then there exists a $U$-admissible blowing up $X' \to X$ such that the strict transforms of $Z_1$ and $Z_2$ are disjoint.

2. If $T_1, T_2 \subset U$ are disjoint constructible closed subsets, then there is a $U$-admissible blowing up $X' \to X$ such that the closures of $T_1$ and $T_2$ are disjoint.

Proof. Proof of (1). The assumption that $Z_i \to X$ is of finite presentation signifies that the quasi-coherent ideal sheaf $I_i$ of $Z_i$ is of finite type, see Morphisms, Lemma 20.7. Denote $Z \subset X$ the closed subscheme cut out by the product $I_1I_2$. Observe that $Z \cap U$ is the disjoint union of $Z_1 \cap U$ and $Z_2 \cap U$. By Divisors, Lemma 34.5 there is a $U \cap Z$-admissible blowup $Z' \to Z$ such that the strict transforms of $Z_1$ and $Z_2$ are disjoint. Denote $Y \subset Z$ the center of this blowing up. Then $Y \to X$ is a closed immersion of finite presentation as the composition of $Y \to Z$ and $Z \to X$ (Divisors, Definition 34.1 and Morphisms, Lemma 20.3). Thus the blowing up $X' \to X$ of $Y$ is a $U$-admissible blowing up. By general properties of strict transforms, the strict transform of $Z_1, Z_2$ with respect to $X' \to X$ is the same as the strict transform of $Z_1, Z_2$ with respect to $Z' \to Z$, see Divisors, Lemma 33.2. Thus (1) is proved.

Proof of (2). By Properties, Lemma 24.1 there exists a finite type quasi-coherent sheaf of ideals $J_i \subset O_V$ such that $T_i = V(J_i)$ (set theoretically). By Properties, Lemma 22.2 there exists a finite type quasi-coherent sheaf of ideals $I_i \subset O_X$ whose restriction to $U$ is $J_i$. Apply the result of part (1) to the closed subschemes $Z_i = V(I_i)$ to conclude. □

Lemma 33.3. Let $f : X \to Y$ be a proper morphism of quasi-compact and quasi-separated schemes. Let $V \subset Y$ be a quasi-compact open and $U = f^{-1}(V)$. Let $T \subset V$ be a closed subset such that $f|_T : U \to V$ is an isomorphism over an open neighbourhood of $T$ in $V$. Then there exists a $V$-admissible blowing up $Y' \to Y$ such that the strict transform $f' : X' \to Y'$ of $f$ is an isomorphism over an open neighbourhood of the closure of $T$ in $Y'$.

Proof. Let $T' \subset V$ be the complement of the maximal open over which $f|_{T'}$ is an isomorphism. Then $T', T$ are closed in $V$ and $T \cap T' = \emptyset$. Since $V$ is a spectral topological space, we can find constructible closed subsets $T_c, T'_c$ with $T \subset T_c$, $T' \subset T'_c$ such that $T_c \cap T'_c = \emptyset$ (choose a quasi-compact open $W$ of $V$ containing $T'$ not meeting $T$ and set $T_c = V \setminus W$, then choose a quasi-compact open $W'$ of $V$ containing $T_c$ not meeting $T'$ and set $T'_c = V \setminus W'$). By Lemma 33.2 we may, after replacing $Y$ by a $V$-admissible blowing up, assume that $T_c$ and $T'_c$ have disjoint closures in $Y$. Set $Y_0 = Y \setminus T'_c$, $V_0 = V \setminus T'_c$, $U_0 = U \times_Y V_0$, and $X_0 = X \times_Y Y_0$. Since $U_0 \to V_0$ is an isomorphism, we can find a $V_0$-admissible blowing up $Y_0' \to Y_0$ such that the strict transform $X_0'$ of $X_0$ maps isomorphically to $Y_0'$, see Lemma 31.3. By Divisors, Lemma 34.3 there exists a $V$-admissible blow up $Y' \to Y$ whose restriction to $Y_0$ is $Y_0' \to Y_0$. If $f' : X' \to Y'$ denotes the strict transform of $f$, then we see what we want is true because $f'$ restricts to an isomorphism over $Y_0'$. □

Lemma 33.4. Let $S$ be a quasi-compact and quasi-separated scheme. Let $U \to X_1$ and $U \to X_2$ be open immersions of schemes over $S$ and assume $U, X_1, X_2$ of finite
type and separated over $S$. Then there exists a commutative diagram

$$
\begin{array}{ccc}
X'_1 & \rightarrow & X_1 \\
\downarrow & & \downarrow \\
U & \rightarrow & X_2 \\
\downarrow & & \downarrow \\
X_1 & \leftarrow & X'_2
\end{array}
$$

of schemes over $S$ where $X'_i \rightarrow X_i$ is a $U$-admissible blowup, $X'_i \rightarrow X$ is an open immersion, and $X$ is separated and finite type over $S$.

**Proof.** Throughout the proof all schemes will be separated of finite type over $S$. This in particular implies these schemes are quasi-compact and quasi-separated and the morphisms between them are quasi-compact and separated. See Schemes, Sections 19 and 21. We will use that if $U \rightarrow W$ is an immersion of such schemes over $S$, then the scheme theoretic image $Z$ of $U$ in $W$ is a closed subscheme of $W$ and $U \rightarrow Z$ is an open immersion, $U \subset Z$ is scheme theoretically dense, and $U \subset Z$ is dense topologically. See Morphisms, Lemma 7.7.

Let $X_{12} \subset X_1 \times_S X_2$ be the scheme theoretic image of $U \rightarrow X_1 \times_S X_2$. The projections $p_i : X_{12} \rightarrow X_i$ induce isomorphisms $p_i^{-1}(U) \rightarrow U$ by Morphisms, Lemma 6.8. Choose a $U$-admissible blowup $X_1' \rightarrow X_1$ such that the strict transform $X_{12}'$ of $X_{12}$ is isomorphic to an open subscheme of $X_1'$, see Lemma 31.3. Let $I_i \subset \mathcal{O}_{X_i}$ be the corresponding finite type quasi-coherent sheaf of ideals. Recall that $X_{12}' \rightarrow X_{12}$ is the blowup in $p_1^{-1}I_1 \mathcal{O}_{X_{12}}$, see Divisors, Lemma 33.2. Let $X_{12}'$ be the blowup of $X_{12}$ in $p_1^{-1}I_1 p_2^{-1}I_2 \mathcal{O}_{X_{12}}$, see Divisors, Lemma 32.12 for what this entails. We obtain in particular a commutative diagram

$$
\begin{array}{ccc}
X_{12}' & \rightarrow & X_{12}' \\
\downarrow & & \downarrow \\
X_{12}' & \rightarrow & X_{12}
\end{array}
$$

where all the morphisms are $U$-admissible blowing ups. Since $X_{12}' \subset X_1'$ is an open we may choose a $U$-admissible blowup $X_i' \rightarrow X_i'$ restricting to $X_{12}' \rightarrow X_{12}'$, see Divisors, Lemma 34.3. Then $X_{12}' \subset X_i'$ is an open subscheme and the diagram

$$
\begin{array}{ccc}
X_{12}' & \rightarrow & X_i' \\
\downarrow & & \downarrow \\
X_{12}' & \rightarrow & X_i
\end{array}
$$

is commutative with vertical arrows blowing ups and horizontal arrows open immersions. Note that $X_{12}' \rightarrow X_i' \times_S X_i'$ is an immersion and proper (use that $X_{12}' \rightarrow X_{12}$ is proper and $X_{12} \rightarrow X_1 \times_S X_2$ is closed and $X_1' \times_S X_2' \rightarrow X_1 \times_S X_2$ is separated and apply Morphisms, Lemma 39.7). Thus $X_{12}' \rightarrow X_1' \times_S X_2'$ is a closed immersion. It follows that if we define $X$ by gluing $X_1'$ and $X_2'$ along the common open subscheme $X_{12}'$, then $X \rightarrow S$ is of finite type and separated (Lemma 33.1). As compositions of $U$-admissible blowups are $U$-admissible blowups (Divisors, Lemma 34.2) the lemma is proved. \hfill \Box

**0F3Y Lemma 33.5.** Let $X \rightarrow S$ and $Y \rightarrow S$ be morphisms of schemes. Let $U \subset X$ be an open subscheme. Let $V \rightarrow X \times_S Y$ be a quasi-compact morphism whose
composition with the first projection maps into $U$. Let $Z \subset X \times_S Y$ be the scheme theoretic image of $V \to X \times_S Y$. Let $X' \to X$ be a $U$-admissible blowup. Then the scheme theoretic image of $V \to X' \times_S Y$ is the strict transform of $Z$ with respect to the blowing up.

**Proof.** Denote $Z' \to Z$ the strict transform. The morphism $Z' \to X'$ induces a morphism $Z' \to X' \times_S Y$ which is a closed immersion (as $Z'$ is a closed subscheme of $X' \times_X Z$ by definition). Thus to finish the proof it suffices to show that the scheme theoretic image $Z''$ of $V \to Z'$ is $Z'$. Observe that $Z'' \subset Z'$ is a closed subscheme such that $V \to Z''$ factors through $Z''$. Since both $V \to X \times_S Y$ and $V \to X' \times_S Y$ are quasi-compact (for the latter this follows from Schemes, Lemma \cite{21.14} and the fact that $X' \times_S Y \to X \times_S Y$ is separated as a base change of a proper morphism), by Morphisms, Lemma \cite{6.3} we see that $Z \cap (U \times_S Y) = Z'' \cap (U \times_S Y)$. Thus the inclusion morphism $Z'' \to Z'$ is an isomorphism away from the exceptional divisor $E$ of $Z' \to Z$. However, the structure sheaf of $Z'$ does not have any nonzero sections supported on $E$ (by definition of strict transforms) and we conclude that the surjection $\mathcal{O}_{Z'} \to \mathcal{O}_{Z''}$ must be an isomorphism. \hfill \Box

**Lemma 33.6.** Let $S$ be a quasi-compact and quasi-separated scheme. Let $U$ be a scheme of finite type and separated over $S$. Let $V \subset U$ be a quasi-compact open. If $V$ has a compactification $V \subset Y$ over $S$, then there exists a $V$-admissible blowing up $Y' \to Y$ and an open $V \subset V' \subset Y'$ such that $V \to U$ extends to a proper morphism $V' \to U$.

**Proof.** Consider the scheme theoretic image $Z \subset Y \times_S U$ of the “diagonal” morphism $V \to Y \times_S U$. If we replace $Y$ by a $V$-admissible blowing up, then $Z$ is replaced by the strict transform with respect to this blowing up, see Lemma \cite{33.5}. Hence by Lemma \cite{31.3} we may assume $Z \to Y$ is an open immersion. If $V' \subset Y$ denotes the image, then we see that the induced morphism $V' \to U$ is proper because the projection $Y \times_S U \to U$ is proper and $V' \cong Z$ is a closed subscheme of $Y \times_S U$.

The following lemma is formulated in the Noetherian case only. The version for quasi-compact and quasi-separated schemes is true as well, but will be trivially implied by the main theorem in this section.

**Lemma 33.7.** Let $S$ be a Noetherian scheme. Let $U$ be a scheme of finite type and separated over $S$. Let $U = U_1 \cup U_2$ be opens such that $U_1$ and $U_2$ have compactifications over $S$ and such that $U_1 \cap U_2$ is dense in $U$. Then $U$ has a compactification over $S$.

**Proof.** Choose a compactification $U_i \subset X_i$ for $i = 1, 2$. We may assume $U_i$ is scheme theoretically dense in $X_i$. We may assume there is an open $V_i \subset X_i$ and a proper morphism $\psi_i : V_i \to U$ extending $\text{id} : U_i \to U_i$, see Lemma \cite{33.6}. Picture

$$
\begin{array}{ccc}
U_i & \longrightarrow & V_i \\
\downarrow & & \downarrow \\
U & \longrightarrow & X_i
\end{array}
$$

If $\{i, j\} = \{1, 2\}$ denote $Z_i = U \setminus U_j = U_i \setminus (U_1 \cap U_2)$ and $Z_j = U \setminus U_i = U_j \setminus (U_1 \cap U_2)$. Thus we have

$$U = U_1 \amalg Z_2 = Z_1 \amalg U_2 = Z_1 \amalg (U_1 \cap U_2) \amalg Z_2.$$
Denote $Z_{i,i} \subset V_i$ the inverse image of $Z_i$ under $\psi_i$. Observe that $\psi_i$ is an isomorphism over an open neighbourhood of $Z_i$. Denote $Z_{i,j} \subset V_i$ the inverse image of $Z_j$ under $\psi_i$. Observe that $\psi_i : Z_{i,j} \to Z_j$ is a proper morphism. Since $Z_i$ and $Z_j$ are disjoint closed subsets of $U$, we see that $Z_{i,i}$ and $Z_{i,j}$ are disjoint closed subsets of $V_i$.

Denote $\overline{Z}_{i,i}$ and $\overline{Z}_{i,j}$ the closures of $Z_{i,i}$ and $Z_{i,j}$ in $X_i$. After replacing $X_i$ by a $V_i$-admissible blowup we may assume that $\overline{Z}_{i,i}$ and $\overline{Z}_{i,j}$ are disjoint, see Lemma \[33.2\]. We assume this holds for both $X_1$ and $X_2$. Observe that this property is preserved if we replace $X_i$ by a further $V_i$-admissible blowup.

Consider the scheme theoretic image $X_{12} \subset X_1 \times_S X_2$ of the immersion $(U_1 \cap U_2) \to X_1 \times_S X_2$ given by $(U_1 \cap U_2) \to U_1 \to X_1$ and $(U_1 \cap U_2) \to U_2 \to X_2$. The projection morphisms

$$p_1 : X_{12} \to X_1 \quad \text{and} \quad p_2 : X_{12} \to X_2$$

are proper as $X_1$ and $X_2$ are proper over $S$. If we replace $X_1$ by a $V_1$-admissible blowing up, then $X_{12}$ is replaced by the strict transform with respect to this blowing up, see Lemma \[33.5\].

Denote $V_{12} \subset X_{12}$ the open subscheme $V_{12} = p_1^{-1}(V_1) = p_2^{-1}(V_2)$ and denote $\psi : V_{12} \to U$ the compositions $\psi = \psi_1 \circ p_1|_{V_{12}} = \psi_2 \circ p_2|_{V_{12}}$. Consider the closed subscheme

$$Z_{12,2} = p_1^{-1}(Z_{1,2}) = p_2^{-1}(Z_{2,2}) = \psi^{-1}(Z_2) \subset V_{12}$$

The morphism $p_1|_{V_{12}} : V_{12} \to V_1$ is an isomorphism over an open neighbourhood of $Z_{1,2}$ because $\psi_2 : V_2 \to U$ is an isomorphism over an open neighbourhood of $Z_2$, see Morphisms, Lemma \[6.8\]. By Lemma \[33.3\] there exists a $V_1$-admissible blowing up $X'_1 \to X_1$ such that the strict tranform $p'_1 : X'_{12} \to X'_1$ of $p_1$ is an isomorphism over an open neighbourhood of the closure of $Z_{1,2}$ in $X'_1$. After replacing $X_1$ by $X'_1$ and $X_{12}$ by $X'_{12}$ we may assume that $p_1$ is an isomorphism over an open neighbourhood of $Z_{1,2}$.

The reduction of the previous paragraph tells us that

$$X_{12} \cap (Z_{1,2} \times_S Z_{2,1}) = \emptyset$$

where the intersection taken in $X_1 \times_S X_2$. Namely, the inverse image $p_1^{-1}(Z_{1,2})$ in $X_{12}$ maps isomorphically to $Z_{1,2}$. In particular, we see that $Z_{12,2}$ is dense in $p_1^{-1}(Z_{1,2})$. Thus $p_2$ maps $p_1^{-1}(Z_{1,2})$ into $Z_{2,2}$. Since $Z_{2,2} \cap Z_{2,1} = \emptyset$ we conclude.

Consider the schemes

$$W_i = U \coprod_{U_i} (X_i \setminus Z_{i,j}), \quad i = 1, 2$$

obtained by glueing. Let us apply Lemma \[33.1\] to see that $W_i \to S$ is separated. First, $U \to S$ and $X_i \to S$ are separated. The immersion $U_i \to U \times_S (X_i \setminus Z_{i,j})$ is closed because any specialization $u_i \leadsto u$ with $u_i \in U_i$ and $u \in U \setminus U_i$ can be lifted uniquely to a specialization $u_i \leadsto v_i$ in $V_i$ along the proper morphism $\psi_i : V_i \to U$ and then $v_i$ must be in $Z_{i,j}$. Thus the image of the immersion is closed, whence the immersion is a closed immersion.

On the other hand, for any valuation ring $A$ over $S$ with fraction field $K$ and any morphism $\gamma : \text{Spec}(K) \to (U_1 \cap U_2)$ over $S$, there is an $i$ and an extension of $\gamma$ to a morphism $b_i : \text{Spec}(A) \to W_i$. Namely, for both $i = 1, 2$ there is a morphism $g_i : \text{Spec}(A) \to X_i$ extending $\gamma$ by the valuative criterion of properness for $X_i$. 
over $S$, see Morphisms, Lemma\(^{40.1}\) Thus we only are in trouble if $g_i(m_A) \in Z_{i,j}$ for $i = 1, 2$. This is impossible by the emptyness of the intersection of $X_{12}$ and $Z_{1,2} \times S Z_{2,1}$ we proved above.

Consider a diagram

$$
\begin{array}{ccc}
W'_1 & \rightarrow & W \\
\downarrow & & \downarrow \\
W'_2 & \leftarrow & W \\
\downarrow & \swarrow & \downarrow \\
W_1 & \leftarrow & U \\
\downarrow & \searrow & \downarrow \\
W_2 & \leftarrow & W
\end{array}
$$

as in Lemma\(^{33.4}\). By the previous paragraph for every solid diagram

$$
\begin{array}{ccc}
\text{Spec}(K) & \rightarrow & W \\
\downarrow & & \downarrow \\
\text{Spec}(A) & \rightarrow & S
\end{array}
$$

where $\text{Im}(\gamma) \subset U_1 \cap U_2$ there is an $i$ and an extension $h_i : \text{Spec}(A) \rightarrow W_i$ of $\gamma$. Using the valuative criterion of properness for $W'_i \rightarrow W_i$, we can then lift $h_i$ to $h'_i : \text{Spec}(A) \rightarrow W'_i$. Hence the dotted arrow in the diagram exists. Since $W$ is separated over $S$, we see that the arrow is unique as well. This implies that $W \rightarrow S$ is universally closed by Morphisms, Lemma\(^{40.2}\). As $W \rightarrow S$ is already of finite type and separated, we win. □

**Theorem 33.8.** Let $S$ be a quasi-compact and quasi-separated scheme. Let $X \rightarrow S$ be a separated, finite type morphism. Then $X$ has a compactification over $S$.

**Proof.** We first reduce to the Noetherian case. We strongly urge the reader to skip this paragraph. There exists a closed immersion $X \rightarrow X'$ with $X' \rightarrow S$ of finite presentation and separated. See Limits, Proposition\(^{9.6}\). If we find a compactification of $X'$ over $S$, then taking the scheme theoretic image of $X$ in this will give a compactification of $X$ over $S$. Thus we may assume $X \rightarrow S$ is separated and of finite presentation. We may write $S = \lim S_i$ as a directed limit of a system of Noetherian schemes with affine transition morphisms. See Limits, Proposition\(^{5.4}\). We can choose an $i$ and a morphism $X_i \rightarrow S_i$ of finite presentation whose base change to $S$ is $X \rightarrow S$, see Limits, Lemma\(^{10.1}\). After increasing $i$ we may assume $X_i \rightarrow S_i$ is separated, see Limits, Lemma\(^{8.6}\). If we can find a compactification of $X_i$ over $S_i$, then the base change of this to $S$ will be a compactification of $X$ over $S$. This reduces us to the case discussed in the next paragraph.

Assume $S$ is Noetherian. We can choose a finite affine open covering $X = \bigcup_{i=1}^n U_i$ such that $U_1 \cap \ldots \cap U_n$ is dense in $X$. This follows from Properties, Lemma\(^{29.4}\) and the fact that $X$ is quasi-compact with finitely many irreducible components. For each $i$ we can choose an $n_i \geq 0$ and an immersion $U_i \rightarrow A^n_S$ by Morphisms, Lemma\(^{37.2}\). Hence $U_i$ has a compactification over $S$ for $i = 1, \ldots, n$ by taking the scheme theoretic image in $\mathbb{P}_S^n$. Applying Lemma\(^{33.7}\) $(n - 1)$ times we conclude that the theorem is true. □

**34. The h topology**

For us, loosely speaking, an h sheaf is a sheaf for the Zariski topology which satisfies the sheaf property for surjective proper morphisms of finite presentation, see Lemma...
However, it may be worth pointing out that the definition of the h topology on the category of schemes depends on the reference. Voevodsky initially defined an h covering to be a finite collection of finite type morphisms which are jointly universally submersive (Morphisms, Definition 23.1). See [Voe96, Definition 3.1.2]. This definition works best if the underlying category of schemes is restricted to all schemes of finite type over a fixed Noetherian base scheme. In this setting, Voevodsky relates h coverings to ph coverings. The ph topology is generated by Zariski coverings and proper surjective morphisms. See Topologies, Section 8 for more information.

In Topologies, Section 10 we study the V topology. A quasi-compact morphism $X \to Y$ defines a V covering, if any specialization of points of $Y$ is the image of a specialization of points in $X$ and the same is true after any base change (Topologies, Lemma 10.13). In this case $X \to Y$ is universally submersive (Topologies, Lemma 10.14). It turns out the notion of a V covering is a good replacement for “families of morphisms with fixed target which are jointly universally submersive” when working with non-Noetherian schemes.

Our approach will be to first prove the equivalence between ph covers and V coverings for (possibly infinite) families of morphisms which are locally of finite presentation. We will then use these families as our notion of h coverings in the Stacks project. For Noetherian schemes and finite families these coverings match those in Voevodsky’s definition, see Lemma 34.3. On the category of schemes of finite presentation over a fixed quasi-compact and quasi-separated scheme $S$ these coverings determine the same topology as the one in [BS17, Definition 2.7].

**Lemma 34.1.** Let $\{f_i : X_i \to X\}_{i \in I}$ be a family of morphisms of schemes with fixed target with $f_i$ locally of finite presentation for all $i$. The following are equivalent

1. $\{X_i \to X\}$ is a ph covering, and
2. $\{X_i \to X\}$ is a V covering.

**Proof.** Let $U \subset X$ be affine open. Looking at Topologies, Definitions 8.4 and 10.7 it suffices to show that the base change $\{X_i \times_X U \to U\}$ can be refined by a standard ph covering if and only if it can be refined by a standard V covering. Thus we may assume $X$ is affine and we have to show $\{X_i \to X\}$ can be refined by a standard ph covering if and only if it can be refined by a standard V covering. Since a standard ph covering is a standard V covering, see Topologies, Lemma 10.3 it suffices to prove the other implication.

Assume $X$ is affine and assume $\{f_i : X_i \to X\}_{i \in I}$ can be refined by a standard V covering $\{g_j : Y_j \to X\}_{j=1,\ldots,m}$. For each $j$ choose an $i_j$ and a morphism $h_j : Y_j \to X_{i_j}$ such that $g_j = f_{i_j} \circ h_j$. Since $Y_j$ is affine hence quasi-compact, for each $j$ we can find (possibly many) affine opens $U_{j,k} \subset X_{i_j}$ such that $\text{Im}(h_j) \subset \bigcup U_{j,k}$. Then $\{U_{j,k} \to X\}_{j,k}$ refines $\{X_j \to X\}$ and is a standard V covering (as it is a finite family of morphisms of affines and it inherits the lifting property for valuation rings from the corresponding property of $\{Y_j \to X\}$). Thus we reduce to the case discussed in the next paragraph.

Assume $\{f_i : X_i \to X\}_{i=1,\ldots,n}$ is a standard V covering with $f_i$ of finite presentation. We have to show that $\{X_i \to X\}$ can be refined by a standard ph covering. Choose
a generic flatness stratification
\[ X = S \supset S_0 \supset S_1 \supset \ldots \supset S_i = \emptyset \]
as in Lemma \[21.4\] for the finitely presented morphism
\[ \prod_{i=1,\ldots,n} f_i : \prod_{i=1,\ldots,n} X_i \to X \]
of affines. We are going to use all the properties of the stratification without further mention. By construction the base change of each \( f_i \) to \( U_k = S_k \setminus S_{k+1} \) is flat. Denote \( Y_k \) the scheme theoretic closure of \( U_k \) in \( S_k \). Since \( U_k \to S_k \) is a quasi-compact open immersion (see Properties, Lemma \[24.1\]), we see that \( U_k \subset Y_k \) is a quasi-compact dense (and scheme theoretically dense) open immersion, see Morphisms, Lemma \[6.3\]. The morphism \( \coprod_{k=0,\ldots,i-1} Y_k \to X \) is finite surjective, hence \( \{Y_k \to X\} \) is a standard ph covering and hence a standard V covering (see above). By the transitivity property of standard V coverings (Topologies, Lemma \[10.5\]) it suffices to show that the pullback of the covering \( \{X_i \to X\} \) to each \( Y_k \) can be refined by a standard V covering. This reduces us to the case described in the next paragraph.

Assume \( \{f_i : X_i \to X\}_{i=1,\ldots,n} \) is a standard V covering with \( f_i \) of finite presentation and there is a dense quasi-compact open \( U \subset X \) such that \( X_i \times_X U \to U \) is flat. By Theorem \[30.7\] there is a \( U \)-admissible blowup \( X' \to X \) such that the strict transform \( f'_i : X'_i \to X' \) of \( f_i \) is flat. Observe that the projective (hence closed) morphism \( X' \to X \) is surjective as \( U \subset X \) is dense and as \( U \) is identified with an open of \( X' \). After replacing \( X' \) by a further \( U \)-admissible blowup if necessary, we may also assume \( U \subset X' \) is scheme theoretically dense (see Remark \[30.1\]). Hence for every point \( x \in X' \) there is a valuation ring \( V \) and a morphism \( g : \text{Spec}(V) \to X' \) such that the generic point of \( \text{Spec}(V) \) maps into \( U \) and the closed point of \( \text{Spec}(V) \) maps to \( x \), see Morphisms, Lemma \[6.3\]. Since \( \{X_i \to X\} \) is a standard V covering, we can choose an extension of valuation rings \( V \subset W \), an index \( i \), and a morphism \( \text{Spec}(W) \to X_i \) such that the diagram

\[
\begin{array}{ccc}
\text{Spec}(W) & \longrightarrow & X_i \\
\downarrow & & \downarrow \\
\text{Spec}(V) & \longrightarrow & X'
\end{array}
\]
is commutative. Since \( X'_i \subset X' \times_X X_i \) is a closed subscheme containing the open \( U \times_X X_i \), since \( \text{Spec}(W) \) is an integral scheme, and since the induced morphism \( h : \text{Spec}(W) \to X' \times_X X_i \) maps the generic point of \( \text{Spec}(W) \) into \( U \times_X X_i \), we conclude that \( h \) factors through the closed subscheme \( X'_i \subset X' \times_X X_i \). We conclude that \( \{f'_i : X'_i \to X'\} \) is a V covering. In particular, \( \coprod f'_i \) is surjective. In particular \( \{X'_i \to X'\} \) is an fpf covering. Since an fpf covering is a ph covering (More on Morphisms, Lemma \[43.7\]), we can find a standard ph covering \( \{Y_j \to X'\} \) refining \( \{X'_i \to X'\} \). Say this covering is given by a proper surjective morphism \( Y \to X' \) and a finite affine open covering \( Y = \bigcup Y_j \). Then the composition \( Y \to X \) is proper surjective and we conclude that \( \{Y_j \to X\} \) is a standard ph covering. This finishes the proof. \( \square \)

Here is our definition.
0ETS \textbf{Definition 34.2.} Let $T$ be a scheme. A \textit{$h$ covering of $T$} is a family of morphisms \{$f_i : T_i \to T\}_{i \in I}$ such that each $f_i$ is locally of finite presentation and one of the equivalent conditions of \textbf{Lemma 34.1} is satisfied.

For Noetherian schemes we recover Voevodsky’s notion.

0ETT \textbf{Lemma 34.3.} Let $X$ be a Noetherian scheme. Let \{$X_i \to X\}_{i \in I}$ be a finite family of finite type morphisms. The following are equivalent

1. $\coprod_{i \in I} X_i \to X$ is universally submersive (\textit{Morphisms, Definition 23.1}), and
2. \{$X_i \to X\}_{i \in I}$ is an $h$ covering.

\textbf{Proof.} The implication (2) $\implies$ (1) follows from the more general \textit{Topologies, Lemma 10.14} and our definition of $h$ covers. Assume \coprod_{i \in I} X_i \to X$ is universally submersive. We will show that \{$X_i \to X\}$ can be refined by a ph covering: this will suffice by \textit{Topologies, Lemma 8.7} and our definition of $h$ coverings. The argument will be the same as the one used in the proof of \textbf{Lemma 34.1}.

Choose a generic flatness stratification

$X = S \supset S_0 \supset S_1 \supset \ldots \supset S_t = \emptyset$

as in \textbf{Lemma 21.4} for the finitely presented morphism

$\coprod_{i=1}^{t} f_i : \coprod_{i=1}^{t} X_i \to X$

We are going to use all the properties of the stratification without further mention. By construction the base change of each $f_i$ to $U_k = S_k \setminus S_{k+1}$ is flat. Denote $Y_k$ the scheme theoretic closure of $U_k$ in $S_k$. Since $U_k \to S_k$ is a quasi-compact open immersion (all schemes in this paragraph are Noetherian), we see that $U_k \subset Y_k$ is a quasi-compact dense (and scheme theoretically dense) open immersion, see \textit{Morphisms, Lemma 6.3}. The morphism $\coprod_{k=0}^{t} Y_k \to X$ is finite surjective, hence \{$Y_k \to X\}$ is a ph covering. By the transitivity property of ph coverings (\textit{Topologies, Lemma 8.8}) it suffices to show that the pullback of the covering \{$X_i \to X\}$ to each $Y_k$ can be refined by a ph covering. This reduces us to the case described in the next paragraph.

Assume \coprod_{i \in I} X_i \to X$ is universally submersive and there is a dense open $U \subset X$ such that $X_i \times_X U \to U$ is flat for all $i$. By \textbf{Theorem 30.7} there is a $U$-admissible blowup $X' \to X$ such that the strict transform $f'_i : X'_i \to X'$ of $f_i$ is flat for all $i$. Observe that the projective (hence closed) morphism $X' \to X$ is surjective as $U \subset X$ is dense and as $U$ is identified with an open of $X'$. After replacing $X'$ by a further $U$-admissible blowup if necessary, we may also assume $U \subset X'$ is dense (see \textbf{Remark 30.1}). Hence for every point $x \in X'$ there is a discrete valuation ring $A$ and a morphism $g : \text{Spec}(A) \to X'$ such that the generic point of $\text{Spec}(A)$ maps into $U$ and the closed point of $\text{Spec}(A)$ maps to $x$, see \textit{Limits, Lemma 15.1}.

Set

$W = \text{Spec}(A) \times_X \coprod X_i = \coprod \text{Spec}(A) \times_X X_i$

Since \coprod X_i \to X$ is universally submersive, there is a specialization $w' \rightsquigarrow w$ in $W$ such that $w'$ maps to the generic point of $\text{Spec}(A)$ and $w$ maps to the closed point of $\text{Spec}(A)$. (If not, then the closed fibre of $W \to \text{Spec}(A)$ is stable under generalizations, hence open, which contradicts the fact that $W \to \text{Spec}(A)$ is submersive.) Say $w' \in \text{Spec}(A) \times_X X_i$ so of course $w \in \text{Spec}(A) \times_X X_i$ as well. Let $x'_i \rightsquigarrow x_i$ be the image of $w' \rightsquigarrow w$ in $X' \times_X X_i$. Since $x'_i \in X'_i$ and since $X'_i \subset X' \times_X X_i$...
is a closed subscheme we see that \( x_i \in X' \). Since \( x_i \) maps to \( x \in X' \) we conclude that \( \prod X'_i \to X' \) is surjective! In particular \( \{ X'_i \to X' \} \) is an fppf covering. But an fppf covering is a ph covering (More on Morphisms, Lemma 43.7). Since \( X' \to X \) is proper surjective, we conclude that \( \{ X'_i \to X \} \) is a ph covering and the proof is complete.

The following lemma and [Ryd07, Theorem 8.4] shows our definition agrees with (or at least is closely related to) the definition in the paper [Ryd07] by David Rydh. We restrict to affine base for simplicity.

**Lemma 34.4.** Let \( X \) be an affine scheme. Let \( \{ X_i \to X \}_{i \in I} \) be an h covering. Then there exists a surjective proper morphism \( Y \to X \) of finite presentation (!) and a finite affine open covering \( Y = \bigcup_{j=1}^m Y_j \) such that \( \{ Y_j \to X \}_{j=1}^m \) refines \( \{ X_i \to X \}_{i \in I} \).

**Proof.** By assumption there exists a proper surjective morphism \( Y \to X \) and a finite affine open covering \( Y = \bigcup_{j=1}^m Y_j \) such that \( \{ Y_j \to X \}_{j=1}^m \) refines \( \{ X_i \to X \}_{i \in I} \). This means that for each \( j \) there is an index \( i_j \in I \) and a morphism \( h_j : Y_j \to X_{i_j} \) over \( X \). See Definition 34.2 and Topologies, Definition 8.4. The problem is that we don’t know that \( Y \to X \) is of finite presentation. By Limits, Lemma 13.2 we can write

\[
Y = \lim_{\lambda} Y_\lambda
\]

as a directed limit of schemes \( Y_\lambda \) proper and of finite presentation over \( X \) such that the morphisms \( Y \to Y_\lambda \) and the the transition morphisms are closed immersions. Observe that each \( Y_\lambda \to X \) is surjective. By Limits, Lemma 4.11 we can find a \( \lambda \) and quasi-compact opens \( Y_{\lambda,j} \subset Y_\lambda \), \( j = 1, \ldots, m \) covering \( Y_\lambda \) and restricting to \( Y_j \) in \( Y \). Then \( Y_j = \lim_{\lambda} Y_{\lambda,j} \). After increasing \( \lambda \) we may assume \( Y_{\lambda,j} \) is affine for all \( j \), see Limits, Lemma 4.13. Finally, since \( X_i \to X \) is locally of finite presentation we can use the functorial characterization of morphisms which are locally of finite presentation (Limits, Proposition 6.1) to find a \( \lambda \) such that for each \( j \) there is a morphism \( h_{\lambda,j} : Y_{\lambda,j} \to X_{i_j} \) whose restriction to \( Y_j \) is the morphism \( h_j \) chosen above. Thus \( \{ Y_{\lambda,j} \to X \} \) refines \( \{ X_i \to X \} \) and the proof is complete.

We return to the development of the general theory of h coverings.

**Lemma 34.5.** An fppf covering is a h covering. Hence syntomic, smooth, étale, and Zariski coverings are h coverings as well.

**Proof.** This is true because in an fppf covering the morphisms are required to be locally of finite presentation and because fppf coverings are ph covering, see More on Morphisms, Lemma 43.7. The second statement follows from the first and Topologies, Lemma 7.2.

**Lemma 34.6.** Let \( f : Y \to X \) be a surjective proper morphism of schemes which is of finite presentation. Then \( \{ Y \to X \} \) is an h covering.

**Proof.** Combine Topologies, Lemmas 10.10 and 8.6.

**Lemma 34.7.** Let \( T \) be a scheme. Let \( \{ f_i : T_i \to T \}_{i \in I} \) be a family of morphisms such that \( f_i \) is locally of finite presentation for all \( i \). The following are equivalent

1. \( \{ T_i \to T \}_{i \in I} \) is an h covering.
There is an h covering which refines $\{T_i \to T\}_{i \in I}$, and $\prod_{i \in I} T_i \to T$ is an h covering.

**Proof.** This follows from the analogous statement for ph coverings (Topologies, Lemma 8.7) or from the analogous statement for V coverings (Topologies, Lemma 10.8). □

Next, we show that our notion of an h covering satisfies the conditions of Sites, Definition 6.2.

**Lemma 34.8.** Let $T$ be a scheme.

1. If $T' \to T$ is an isomorphism then $\{T' \to T\}$ is an h covering of $T$.
2. If $\{T_i \to T\}_{i \in I}$ is an h covering and for each $i$ we have an h covering $\{T_{ij} \to T_i\}_{j \in J_i}$, then $\{T_{ij} \to T\}_{i \in I, j \in J_i}$ is an h covering.
3. If $\{T_i \to T\}_{i \in I}$ is an h covering and $T' \to T$ is a morphism of schemes then $\{T' \times_T T_i \to T\}_{i \in I}$ is an h covering.

**Proof.** Follows immediately from the corresponding statement for either ph or V coverings (Topologies, Lemma 8.8 or 10.9) and the fact that the class of morphisms which are locally of finite presentation is preserved under base change and composition. □

Next, we define the big h sites we will work with in the Stacks project. It makes sense to read the general discussion in Topologies, Section 2 before proceeding.

**Definition 34.9.** A big h site is any site $\mathcal{S}_{h}$ as in Sites, Definition 6.2 constructed as follows:

1. Choose any set of schemes $S_0$, and any set of h coverings Cov$_{0}$ among these schemes.
2. As underlying category take any category $\mathcal{S}_{\alpha}$ constructed as in Sets, Lemma 9.2 starting with the set $S_0$.
3. Choose any set of coverings as in Sets, Lemma 11.1 starting with the category $\mathcal{S}_{\alpha}$ and the class of h coverings, and the set Cov$_{0}$ chosen above.

See the remarks following Topologies, Definition 3.5 for motivation and explanation regarding the definition of big sites.

**Definition 34.10.** Let $T$ be an affine scheme. A standard h covering of $T$ is a family $\{f_i : T_i \to T\}_{i=1,\ldots,n}$ with each $T_i$ affine, with $f_i$ of finite presentation satisfying either of the following equivalent conditions: (1) $\{U_i \to U\}$ can be refined by a standard ph covering or (2) $\{U_i \to U\}$ is a V covering.

The equivalence of the conditions follows from Lemma 34.1, Topologies, Definition 8.4 and Lemma 8.7.

Before we continue with the introduction of the big h site of a scheme $S$, let us point out that the topology on a big h site $\mathcal{S}_{h}$ is in some sense induced from the h topology on the category of all schemes.

**Lemma 34.11.** Let $\mathcal{S}_{h}$ be a big h site as in Definition 34.9. Let $T \in \text{Ob}(\mathcal{S}_{h})$.

Let $\{T_i \to T\}_{i \in I}$ be an arbitrary h covering of $T$.

1. There exists a covering $\{U_j \to T\}_{j \in J}$ of $T$ in the site $\mathcal{S}_{h}$ which refines $\{T_i \to T\}_{i \in I}$. 


Let $S$ be a scheme. Let $\text{Sch}_h$ be a big $h$ site containing $S$.

1. The big $h$ site of $S$, denoted $(\text{Sch}/S)_h$, is the site $\text{Sch}_h/S$ introduced in Sites, Section 25.

2. The big affine $h$ site of $S$, denoted $(\text{Aff}/S)_h$, is the full subcategory of $(\text{Sch}/S)_h$ whose objects are affine $U/S$. A covering of $(\text{Aff}/S)_h$ is any covering $\{U_i \to U\}$ of $(\text{Sch}/S)_h$ which is a standard $h$ covering.

We explicitly state that the big affine $h$ site is a site.

**Lemma 34.13.** Let $S$ be a scheme. Let $\text{Sch}_h$ be a big $h$ site containing $S$. Then $(\text{Aff}/S)_h$ is a site.

**Proof.** Reasoning as in the proof of Topologies, Lemma 4.9 it suffices to show that the collection of standard $h$ coverings satisfies properties (1), (2) and (3) of Sites, Definition 6.2. This is clear since for example, given a standard $h$ covering $\{T_i \to T\}_{i \in I}$ and for each $i$ a standard $h$ covering $\{T_{ij} \to T_i\}_{j \in J_i}$, then $\{T_{ij} \to T\}_{i \in I, j \in J_i}$ is a $h$ covering (Lemma 34.8). $\bigcup_{i \in I} J_i$ is finite and each $T_{ij}$ is affine. Thus $\{T_{ij} \to T\}_{i \in I, j \in J_i}$ is a standard $h$ covering.

**Lemma 34.14.** Let $S$ be a scheme. Let $\text{Sch}_h$ be a big $h$ site containing $S$. The underlying categories of the sites $\text{Sch}_h$, $(\text{Sch}/S)_h$, and $(\text{Aff}/S)_h$ have fibre products. In each case the obvious functor into the category $\text{Sch}$ of all schemes commutes with taking fibre products. The category $(\text{Sch}/S)_h$ has a final object, namely $S/S$.

**Proof.** For $\text{Sch}_h$ it is true by construction, see Sets, Lemma 9.9. Suppose we have $U \to S$, $V \to U$, $W \to S$ morphisms of schemes with $U, V, W \in \text{Ob}(\text{Sch}_h)$. The fibre product $V \times_U W$ in $\text{Sch}_h$ is a fibre product in $\text{Sch}$ and is the fibre product of $V/S$ with $W/S$ over $U/S$ in the category of all schemes over $S$, and hence also a fibre product in $(\text{Sch}/S)_h$. This proves the result for $(\text{Sch}/S)_h$. If $U, V, W$ are affine, so is $V \times_U W$ and hence the result for $(\text{Aff}/S)_h$.

Next, we check that the big affine site defines the same topos as the big site.

**Lemma 34.15.** Let $S$ be a scheme. Let $\text{Sch}_h$ be a big $h$ site containing $S$. The functor $(\text{Aff}/S)_h \to (\text{Sch}/S)_h$ is cocontinuous and induces an equivalence of topoi from $\text{Sh}((\text{Aff}/S)_h)$ to $\text{Sh}((\text{Sch}/S)_h)$.

**Proof.** The notion of a special cocontinuous functor is introduced in Sites, Definition 29.2. Thus we have to verify assumptions (1) – (5) of Sites, Lemma 29.1. Denote the inclusion functor $u: (\text{Aff}/S)_h \to (\text{Sch}/S)_h$. Being cocontinuous follows because any $h$ covering of $T/S$, $T$ affine, can be refined by a standard $h$ covering for example by Lemma 34.4. Hence (1) holds. We see $u$ is continuous simply because a standard $h$ covering is a $h$ covering. Hence (2) holds. Parts (3) and (4) follow immediately from the fact that $u$ is fully faithful. And finally condition (5) follows from the fact that every scheme has an affine open covering (which is a $h$ covering).
Lemma 34.16. Let $\mathcal{F}$ be a presheaf on $(\text{Sch}/S)_h$. Then $\mathcal{F}$ is a sheaf if and only if

1. $\mathcal{F}$ satisfies the sheaf condition for Zariski coverings, and
2. if $f : V \to U$ is proper, surjective, and of finite presentation, then $\mathcal{F}(U)$ maps bijectively to the equalizer of the two maps $\mathcal{F}(V) \to \mathcal{F}(V \times_U V)$.

Moreover, in the presence of (1) property (2) is equivalent to property

(2') the sheaf property for $\{V \to U\}$ as in (2) with $U$ affine.

Proof. We will show that if (1) and (2) hold, then $\mathcal{F}$ is sheaf. Let $\{T_i \to T\}$ be a covering in $(\text{Sch}/S)_h$. We will verify the sheaf condition for this covering. Let $s_i \in \mathcal{F}(T_i)$ be sections which restrict to the same section over $T_i \times_T T_j$. We will show that there exists a unique section $s \in \mathcal{F}(T)$ restricting to $s_i$ over $T_i$. Let $T = \bigcup T_i$ be an affine open covering. By property (1) it suffices to produce sections $s_j \in \mathcal{F}(U_j)$ which agree on $U_j \cap U_j'$ in order to produce $s$. Consider the coverings $\{T_i \times_T U_j \to U_j\}$. Then $s_{ji} = s_i|_{T_i \times_T U_j}$ are sections agreeing over $(T_i \times_T U_j) \times_{U_j'} (T_j \times_T U_j')$. Choose a proper surjective morphism $V_j \to U_j$ of finite presentation and a finite affine open covering $V_j = \bigcup V_{jk}$ such that $V_{jk} \to U_j$ refines $\{T_i \times_T U_j \to U_j\}$. See Lemma 34.4 If $s_{jk} \in \mathcal{F}(V_{jk})$ denotes the pullback of $s_{ji}$ to $V_{jk}$ by the implied morphisms, then we find that $s_{jk}$ glue to a section $s'_j \in \mathcal{F}(V_j)$. Using the agreement on overlaps once more, we find that $s'_j$ is in the equalizer of the two maps $\mathcal{F}(V_j) \to \mathcal{F}(V_j \times_U V_j)$. Hence by (2) we find that $s'_j$ comes from a unique section $s_j \in \mathcal{F}(U_j)$. We omit the verification that these sections $s_j$ have all the desired properties.

Proof of the equivalence of (2) and (2') in the presence of (1). Suppose $V \to U$ is a morphism of $(\text{Sch}/S)_h$ which is proper, surjective, and of finite presentation. Choose an affine open covering $U = \bigcup U_i$ and set $V_i = V \times_U U_i$. Then we see that $\mathcal{F}(U) \to \mathcal{F}(V)$ is injective because we know $\mathcal{F}(U_i) \to \mathcal{F}(V_i)$ is injective by (2') and we know $\mathcal{F}(U) \to \prod \mathcal{F}(U_i)$ is injective by (1). Finally, suppose that we are given an $t \in \mathcal{F}(V)$ in the equalizer of the two maps $\mathcal{F}(V) \to \mathcal{F}(V \times_U V)$. Then $t|_{V_i}$ is in the equalizer of the two maps $\mathcal{F}(V_i) \to \mathcal{F}(V_i \times_U V_i)$ for all $i$. Hence we obtain a unique section $s_i \in \mathcal{F}(U_i)$ mapping to $t|_{V_i}$ for all $i$ by (2'). We omit the verification that $s_i|_{U_i \cap U_j} = s_j|_{U_i \cap U_j}$ for all $i, j$; this uses the uniqueness property just shown. By the sheaf property for the covering $U = \bigcup U_i$ we obtain a section $s \in \mathcal{F}(U)$. We omit the proof that $s$ maps to $t$ in $\mathcal{F}(V)$. □

Next, we establish some relationships between the topoi associated to these sites.

Lemma 34.17. Let $Sh_{h}$ be a big $h$ site. Let $f : T \to S$ be a morphism in $Sh_{h}$. The functor $u : (\text{Sch}/T)_h \to (\text{Sch}/S)_h$, $V/T \mapsto V/S$ is cocontinuous, and has a continuous right adjoint $v : (\text{Sch}/S)_h \to (\text{Sch}/T)_h$, $(U \to S) \mapsto (U \times_S T \to T)$. They induce the same morphism of topoi $f_{big} : Sh((\text{Sch}/T)_h) \to Sh((\text{Sch}/S)_h)$ We have $f^{-1}_{big}(G)(U/T) = G(U/S)$. We have $f_{big,*}(\mathcal{F})(U/S) = \mathcal{F}(U \times_S T/T)$. Also, $f_{big}^{-1}$ has a left adjoint $f_{big!}$ which commutes with fibre products and equalizers.
In this section we prove a few more results on the h topology. First, some non-examples.

Lemma 34.18. Given schemes $X$, $Y$, $Z$ in $(\text{Sch}/S)_{h}$ and morphisms $f : X \to Y$, $g : Y \to Z$ we have $g_{\big} \circ f_{\big} = (g \circ f)_{\big}$.

Proof. This follows from the simple description of pushforward and pullback for the functors on the big sites from Lemma 34.17.

35. More on the h topology

In this section we prove a few more results on the h topology. First, some non-examples.

Example 35.1. The "structure sheaf" $\mathcal{O}$ is not a sheaf in the h topology. For example, consider a surjective closed immersion of finite presentation $X \to Y$. Then $\{X \to Y\}$ is an h covering by Example 34.6. Moreover, note that $X \times Y \to X$. Thus if $\mathcal{O}$ is a sheaf in the h topology, then $\mathcal{O}(Y) \to \mathcal{O}(X)$ would be bijective. This is not the case as soon as $X$, $Y$ are affine and the morphism $X \to Y$ is not an isomorphism.

Example 35.2. On any of the sites $(\text{Sch}/S)_{h}$ the topology is not subcanonical, in other words, representable sheaves are not sheaves. Namely, the "structure sheaf" $\mathcal{O}$ is representable because $\mathcal{O}(X) = \text{Mor}_{S}(X, A^{1}_{S})$ in $(\text{Sch}/S)_{h}$ and we saw in Example 35.1 that $\mathcal{O}$ is not a sheaf.

Lemma 35.3. Let $T$ be an affine scheme which is written as a limit $T = \lim_{i \in I} T_{i}$ of a directed inverse system of affine schemes.

1. Let $\mathcal{V} = \{V_{j} \to T\}_{j = 1, \ldots, m}$ be a standard h covering of $T$, see Definition 34.10. Then there exists an index $i$ and a standard h covering $\mathcal{V}_{i} = \{V_{i,j} \to T\}_{j = 1, \ldots, m}$ whose base change $T \times_{T_{i}} V_{i}$ to $T_{i}$ is isomorphic to $\mathcal{V}$.

2. Let $\mathcal{V}_{i}, \mathcal{V}'_{i}$ be a pair of standard h coverings of $T_{i}$. If $f : T \times_{T_{i}} V_{i} \to T \times_{T_{i}} V'_{i}$ is a morphism of coverings of $T$, then there exists an index $i' \geq i$ and a morphism $f' : T'_{i'} \times_{T'} V'_{i'} \to T \times_{T_{i}} V_{i}$ whose base change to $T_{i}$ is $f$.

3. If $f, g : \mathcal{V} \to \mathcal{V}'_{i}$ are morphisms of standard h coverings of $T_{i}$ whose base changes $f_{T'}, g_{T'}$ to $T$ are equal then there exists an index $i' \geq i$ such that $f_{T'} = g_{T'}$.

In other words, the category of standard h coverings of $T$ is the colimit over $I$ of the categories of standard h coverings of $T_{i}$.

Proof. By Limits, Lemma 10.1 the category of schemes of finite presentation over $T$ is the colimit over $I$ of the categories of finite presentation over $T_{i}$. By Limits, Lemma 8.2 the same is true for category of schemes which are affine and of finite presentation over $T$. To finish the proof of the lemma it suffices to show that if $\{V_{j,i} \to T_{i}\}_{j = 1, \ldots, m}$ is a finite family of finitely presented morphisms with $V_{j,i}$ affine, and the base change family $\{T \times_{T_{i}} V_{j,i} \to T\}$ is an h covering, then for some $i' \geq i$ the family $\{T'_{i'} \times_{T_{i'}} V_{j,i} \to T'_{i'}\}$ is an h covering. To see this we use Lemma 34.4 to choose a finitely presented, proper, surjective morphism $Y \to T$ and...
a finite affine open covering \( Y = \bigcup_{k=1,...,n} Y_k \) such that \( \{Y_k \to T\}_{k=1,...,n} \) refines \( \{T \times_{T_i} V_{j,i} \to T\} \). Using the arguments above and Limits, Lemmas 13.1, 8.14 and 4.11 we can find an \( i' \geq i \) and a finitely presented, surjective, proper morphism \( Y_{i'} \to T_{i'} \) and an affine open covering \( Y_{i'} = \bigcup_{k=1,...,n} Y_{i',k} \) such that moreover \( \{Y_{i',k} \to Y_{i'}\} \) refines \( \{T_{i'} \times_{T_i} V_{j,i} \to T_{i'}\} \). It follows that this last mentioned family is a h covering and the proof is complete.

\[\begin{align*}
\text{Lemma 35.4.} & \quad \text{Let } S \text{ be a scheme contained in a big site } \text{Sch}_h. \text{ Let } F \text{ be a sheaf on } (\text{Sch}_h/S)_h \text{ satisfying property (b) of Topologies, Lemma 13.1. Then the extension } F \text{ of } F \text{ to the category of all schemes over } S \text{ satisfies the sheaf condition for all h coverings and is limit preserving (Limits, Remark 6.2).} \\
\text{Proof.} & \quad \text{The proof is exactly the same as the proof of Topologies, Lemma 13.3 except that it uses Lemmas 35.3 and 34.11.} \\
\end{align*}\]

36. Blow up squares and the ph topology

Let X be a scheme. Let \( Z \subset X \) be a closed subscheme such that the inclusion morphism is of finite presentation, i.e., the quasi-coherent sheaf of ideals corresponding to \( Z \) is of finite type. Let \( b : X' \to X \) be the blowup of \( X \) in \( Z \) and let \( E = b^{-1}(Z) \) be the exceptional divisor. See Divisors, Section 32. In this situation and in this section, let us say (36.0.1)

0EW1 \[\begin{align*}
E & \longrightarrow X' \\
\downarrow & \\
Z & \longrightarrow X
\end{align*}\]

is a blow up square.

\[\begin{align*}
\text{Lemma 36.1.} & \quad \text{Let } F \text{ be a sheaf on a site } (\text{Sch}/S)_{ph}, \text{ see Topologies, Definition 8.11. Then for any blow up square (36.0.1) in the category } (\text{Sch}/S)_{ph} \text{ the diagram} \\
& \quad \\
& \quad \text{is cartesian in the category of sets.} \\
\text{Proof.} & \quad \text{Since } Z \amalg X' \to X \text{ is a surjective proper morphism we see that } \{Z \amalg X' \to X\} \text{ is a ph covering (Topologies, Lemma 8.6). We have} \\
& \quad (Z \amalg X') \times_X (Z \amalg X') = Z \amalg E \amalg E \amalg E \amalg X' \times_X X' \\
& \quad \text{Since } F \text{ is a Zariski sheaf we see that } F \text{ sends disjoint unions to products. Thus the sheaf condition for the covering } \{Z \amalg X' \to X\} \text{ says that } F(X) \to F(Z) \times F(X') \text{ is injective with image the set of pairs } (t,s') \text{ such that (a) } t|_E = s'|_E \text{ and (b) } s' \text{ is in the equalizer of the two maps } F(X') \to F(X' \times_X X'). \\
& \quad \text{Next, observe that the obvious morphism} \\
& \quad E \times_Z E \amalg X' \longrightarrow X' \times_X X' \\
& \quad \text{is a surjective proper morphism as } b \text{ induces an isomorphism } X' \setminus Z \to X \setminus Z. \text{ We conclude that } F(X' \times_X X') \to F(E \times_Z E) \times F(X') \text{ is injective. It follows that (a) } \Rightarrow (b) \text{ which means that the lemma is true.} \]
Lemma 36.2. Let $\mathcal{F}$ be a sheaf on a site $(\text{Sch}/S)_{ph}$ as in Topologies, Definition 8.11. Let $X \to X'$ be a morphism of $(\text{Sch}/S)_{ph}$ which is a thickening. Then $\mathcal{F}(X') \to \mathcal{F}(X)$ is bijective.

Proof. Observe that $X \to X'$ is a proper surjective morphism of and $X \times_{X'} X = X$. By the sheaf property for the $\text{ph}$ covering $\{X \to X'\}$ (Topologies, Lemma 8.6) we conclude. \qed

37. Almost blow up squares and the $\mathcal{H}$ topology

Consider a blow up square (36.0.1). Although the morphism $b : X' \to X$ is projective (Divisors, Lemma 32.13) in general there is no simple way to guarantee that $b$ is of finite presentation. Since $\mathcal{H}$ coverings are constructed using morphisms of finite presentation, we need a variant. Namely, we will say a commutative diagram

$$
\begin{array}{ccc}
E & \to & X' \\
\downarrow & & \downarrow b \\
Z & \to & X
\end{array}
$$

of schemes is an almost blow up square if the following conditions are satisfied

1. $Z \to X$ is a closed immersion of finite presentation,
2. $E = b^{-1}(Z)$ is a locally principal closed subscheme of $X'$,
3. $b$ is proper and of finite presentation,
4. the closed subscheme $X'' \subset X'$ cut out by the quasi-coherent ideal of sections of $\mathcal{O}_{X'}$ supported on $E$ (Properties, Lemma 24.5) is the blow up of $X$ in $Z$. 

It follows that the morphism $b$ induces an isomorphism $X' \setminus E \to X \setminus Z$. For some very simple examples of almost blow up squares, see Examples 37.10 and 37.11.

The base change of a blow up usually isn’t a blow up, but almost blow ups are compatible with base change.

Lemma 37.1. Consider an almost blow up square (37.0.1). Let $Y \to X$ be any morphism. Then the base change

$$
\begin{array}{ccc}
Y \times_X E & \to & Y \times_X X' \\
\downarrow & & \downarrow \\
Y \times_X Z & \to & Y
\end{array}
$$

is an almost blow up square too.

Proof. The morphism $Y \times_X X' \to Y$ is proper and of finite presentation by Morphisms, Lemmas 39.5 and 20.4. The morphism $Y \times_X Z \to Y$ is a closed immersion (Morphisms, Lemma 2.4) of finite presentation. The inverse image of $Y \times_X Z$ in $Y \times_X X'$ is equal to the inverse image of $E$ in $Y \times_X X'$ and hence is locally principal (Divisors, Lemma 13.11). Let $X'' \subset X'$, resp. $Y'' \subset Y \times_X X'$ be the closed subscheme corresponding to the quasi-coherent ideal of sections of $\mathcal{O}_{X'}$, resp. $\mathcal{O}_{Y \times_X X'}$ supported on $E$, resp. $Y \times_X E$. Clearly, $Y'' \subset Y \times_X X'$ is the closed subscheme corresponding to the quasi-coherent ideal of sections of $\mathcal{O}_{Y \times_X X''}$ supported on $Y \times_X (E \cap X'')$. Thus $Y''$ is the strict transform of $Y$ relative to the blowing up $X'' \to X$, see Divisors, Definition 33.1. Thus by Divisors, Lemma 33.2 we see that $Y''$ is the blow up of $Y \times_X Z$ on $Y$. \qed
One can shrink almost blow up squares.

Lemma 37.2. Consider an almost blow up square (37.0.1). Let $W \to X'$ be a closed immersion of finite presentation. The following are equivalent

1. $X' \setminus E$ is scheme theoretically contained in $W$,
2. the blowup $X''$ of $X$ in $Z$ is scheme theoretically contained in $W$,
3. the diagram

\[
\begin{CD}
E \cap W @>>> W \\
@VVV @VVV \\
Z @>>> X
\end{CD}
\]

is an almost blow up square. Here $E \cap W$ is the scheme theoretic intersection.

Proof. Assume (1). Then the surjection $\mathcal{O}_{X'} \to \mathcal{O}_W$ is an isomorphism over the open $X' \subset E$. Since the ideal sheaf of $X'' \subset X'$ is the sections of $\mathcal{O}_{X'}$ supported on $E$ (by our definition of almost blow up squares) we conclude (2) is true. If (2) is true, then (3) holds. If (3) holds, then (1) holds because $X'' \cap (X' \setminus E)$ is isomorphic to $X \setminus Z$ which in turn is isomorphic to $X' \setminus E$. □

The actual blowup is the limit of shrinkings of any given almost blowup.

Lemma 37.3. Consider an almost blow up square (37.0.1) with $X$ quasi-compact and quasi-separated. Then the blowup $X''$ of $X$ in $Z$ can be written as

\[X'' = \operatorname{lim} X'_i\]

where the limit is over the directed system of closed subschemes $X'_i \subset X'$ of finite presentation satisfying the equivalent conditions of Lemma 37.2.

Proof. Let $\mathcal{I} \subset \mathcal{O}_X$ be the quasi-coherent sheaf of ideals corresponding to $X''$. By Properties, Lemma 22.3 we can write $\mathcal{I}$ as the filtered colimit $\mathcal{I} = \operatorname{colim} \mathcal{I}_i$ of its quasi-coherent submodules of finite type. Since these modules correspond 1-to-1 to the closed subschemes $X'_i$ the proof is complete. □

Almost blow up squares exist.

Lemma 37.4. Let $X$ be a quasi-compact and quasi-separated scheme. Let $Z \subset X$ be a closed subscheme cut out by a finite type quasi-coherent sheaf of ideals. Then there exists an almost blow up square as in (37.0.1).

Proof. We may write $X = \operatorname{lim} X_i$ as a directed limit of an inverse system of Noetherian schemes with affine transition morphisms, see Limits, Proposition 5.4. We can find an index $i$ and a closed immersion $Z_i \to X_i$ whose base change to $X$ is the closed immersion $Z \to X$. See Limits, Lemmas 10.1 and 8.5. Let $b_i : X'_i \to X_i$ be the blowing up with center $Z_i$. This produces a blow up square

\[
\begin{CD}
E_i @>>> X'_i \\
@VVV @VV{b_i}V \\
Z_i @>>> X_i
\end{CD}
\]

where all the morphisms are finite type morphisms of Noetherian schemes and hence of finite presentation. Thus this is an almost blow up square. By Lemma 37.1 the base change of this diagram to $X$ produces the desired almost blow up square. □
Almost blow up squares are unique up to shrinking as in Lemma 37.2.

**Lemma 37.5.** Let $X$ be a quasi-compact and quasi-separated scheme and let $Z \subset X$ be a closed subscheme cut out by a finite type quasi-coherent sheaf of ideals. Suppose given almost blow up squares (37.0.1)

\[
\begin{array}{ccc}
E_k & \rightarrow & X'_k \\
\downarrow & & \downarrow \\
Z & \rightarrow & X
\end{array}
\]

for $k = 1, 2$, then there exists an almost blow up square

\[
\begin{array}{ccc}
E & \rightarrow & X' \\
\downarrow & & \downarrow \\
Z & \rightarrow & X
\end{array}
\]

and closed immersions $i_k : X' \rightarrow X'_k$ over $X$ with $E = i_k^{-1}(E_k)$.

**Proof.** Denote $X'' \rightarrow X$ the blowing up of $Z$ in $X$. We view $X''$ as a closed subscheme of both $X'_1$ and $X'_2$. Write $X'' = \lim X'_{1,i}$ as in Lemma 37.3. By Limits, Proposition 6.1 there exists an $i$ and a morphism $h : X'_{1,i} \rightarrow X'_2$ agreeing with the inclusions $X' \subset X'_{1,i}$ and $X'' \subset X'_2$. By Limits, Lemma 4.20 the restriction of $h$ to $X'_{1,i'}$ is a closed immersion for some $i' \geq i$. This finishes the proof. \qed

Our flattening techniques for blowing up are inherited by almost blowups in favorable situations.

**Lemma 37.6.** Let $Y$ be a quasi-compact and quasi-separated scheme. Let $X$ be a scheme of finite presentation over $Y$. Let $V \subset Y$ be a quasi-compact open such that $X_V \rightarrow V$ is flat. Then there exist a commutative diagram

\[
\begin{array}{ccc}
E & \rightarrow & D \\
\downarrow & & \downarrow \\
Y' & \leftarrow & X' \\
\downarrow & & \downarrow \\
Y & \leftarrow & X \\
\downarrow & & \downarrow \\
Z & \rightarrow & T
\end{array}
\]

whose right and left hand squares are almost blow up squares, whose lower and top squares are cartesian, such that $Z \cap V = \emptyset$, and such that $X' \rightarrow Y'$ is flat (and of finite presentation).

**Proof.** If $Y$ is a Noetherian scheme, then this lemma follows immediately from Lemma 31.1 because in this case blow up squares are almost blow up squares (we also use that strict transforms are blow ups). The general case is reduced to the Noetherian case by absolute Noetherian approximation.

We may write $Y = \lim Y_i$ as a directed limit of an inverse system of Noetherian schemes with affine transition morphisms, see Limits, Proposition 5.4. We can find
an index $i$ and a morphism $X_i \to Y_i$ of finite presentation whose base change to $Y$ is $X \to Y$. See Limits, Lemmas 10.1. After increasing $i$ we may assume $V$ is the inverse image of an open subscheme $V_i \subset Y_i$, see Limits, Lemma 10.1. Finally, after increasing $i$ we may assume that $X_{i,V} \to V_i$ is flat, see Limits, Lemma 8.7. By the Noetherian case, we may construct a diagram as in the lemma for $X_i \to Y_i \supset V_i$. The base change of this diagram by $Y \to Y_i$ provides the solution. Use that base change preserves properties of morphisms, see Morphisms, Lemmas 39.5, 20.4, 2.4, and 24.8 and that base change of an almost blow up square is an almost blow up square, see Lemma 37.1.

\[ \text{Lemma 37.7.} \]

Let $\mathcal{F}$ be a sheaf on one of the sites $(\text{Sch}/S)_h$ constructed in Definition 34.12. Then for any almost blow up square in the category $(\text{Sch}/S)_h$ the diagram

\[
\begin{array}{ccc}
\mathcal{F}(E) & \leftarrow & \mathcal{F}(X') \\
\uparrow & & \uparrow \\
\mathcal{F}(Z) & \leftarrow & \mathcal{F}(X)
\end{array}
\]

is cartesian in the category of sets.

\textbf{Proof.} Since $Z \amalg X' \to X$ is a surjective proper morphism of finite presentation we see that $\{Z \amalg X' \to X\}$ is an h covering (Lemma 34.6). We have

\[(Z \amalg X') \times_X (Z \amalg X') = Z \amalg (E \amalg (X' \times_X X))\]

Since $\mathcal{F}$ is a Zariski sheaf we see that $\mathcal{F}$ sends disjoint unions to products. Thus the sheaf condition for the covering $\{Z \amalg X' \to X\}$ says that $\mathcal{F}(X) \to \mathcal{F}(Z) \times \mathcal{F}(X')$ is injective with image the set of pairs $(t,s')$ such that (a) $t|_E = s'|_E$ and (b) $s'$ is in the equalizer of the two maps $\mathcal{F}(X') \to \mathcal{F}(X' \times_X X')$. Next, observe that the obvious morphism

\[ E \times_Z E \amalg X' \longrightarrow X' \times_X X' \]

is a surjective proper morphism of finite presentation as $b$ induces an isomorphism $X' \setminus E = X \setminus Z$. We conclude that $\mathcal{F}(X' \times_X X') \to \mathcal{F}(X' \times_Z E) \times \mathcal{F}(X')$ is injective. It follows that (a) $\Rightarrow$ (b) which means that the lemma is true. \hfill $\square$

\[ \text{Lemma 37.8.} \]

Let $\mathcal{F}$ be a sheaf on one of the sites $(\text{Sch}/S)_h$ constructed in Definition 34.12. Let $X \to X'$ be a morphism of $(\text{Sch}/S)_h$ which is a thickening and of finite presentation. Then $\mathcal{F}(X') \to \mathcal{F}(X)$ is bijective.

\textbf{Proof.} First proof. Observe that $X \to X'$ is a proper surjective morphism of finite presentation and $X \times_{X'} X = X$. By the sheaf property for the h covering $\{X \to X'\}$ (Lemma 34.6) we conclude.

Second proof (silly). The blow up of $X'$ in $X$ is the empty scheme. The reason is that the affine blowup algebra $A[\mathcal{I}]/(a)$ (Algebra, Section 69) is zero if $a$ is a nilpotent element of $A$. Details omitted. Hence we get an almost blow up square of the form

\[
\begin{array}{ccc}
\emptyset & \longrightarrow & \emptyset \\
\downarrow & & \downarrow \\
X & \longrightarrow & X'
\end{array}
\]

Since $\mathcal{F}$ is a sheaf we have that $\mathcal{F}(\emptyset)$ is a singleton. Applying Lemma 37.7 we get the conclusion. \hfill $\square$
Proposition 37.9. Let $\mathcal{F}$ be a presheaf on one of the sites $(\mathcal{S}ch/S)_h$ constructed in Definition 34.12. Then $\mathcal{F}$ is a sheaf if and only if the following conditions are satisfied

1. $\mathcal{F}$ is a sheaf for the Zariski topology,
2. given a morphism $f : X \to Y$ of $(\mathcal{S}ch/S)_h$ with $Y$ affine and $f$ surjective, flat, proper, and of finite presentation, then $\mathcal{F}(Y)$ is the equalizer of the two maps $\mathcal{F}(X) \to \mathcal{F}(X \times_Y X)$,
3. given an almost blow up square (37.0.1) with $X$ affine in the category $(\mathcal{S}ch/S)_h$ the diagram

$$
\begin{array}{c}
\mathcal{F}(E) \\ \uparrow \\
\mathcal{F}(Z) \\ \uparrow \\
\mathcal{F}(X') \\
\end{array}
\leftarrow
\begin{array}{c}
\mathcal{F}(X) \\
\end{array}
$$

is cartesian in the category of sets.

Proof. Assume $\mathcal{F}$ is a sheaf. Condition (1) holds because a Zariski covering is a h covering, see Lemma 34.5. Condition (2) holds because for $f$ as in (2) we have that $\{X \to Y\}$ is an fppf covering (this is clear) and hence an h covering, see Lemma 34.5. Condition (3) holds by Lemma 37.7.

Conversely, assume $\mathcal{F}$ satisfies (1), (2), and (3). We will prove $\mathcal{F}$ is a sheaf by applying Lemma 34.16. Consider a surjective, finitely presented, proper morphism $f : X \to Y$ in $(\mathcal{S}ch/S)_h$ with $Y$ affine. It suffices to show that $\mathcal{F}(Y)$ is the equalizer of the two maps $\mathcal{F}(X) \to \mathcal{F}(X \times_Y X)$.

First, assume that $f : X \to Y$ is in addition a closed immersion (in other words, $f$ is a thickening). Then the blow up of $Y$ in $X$ is the empty scheme and this produces an almost blow up square consisting with $\emptyset, \emptyset, X, Y$ at the vertices (compare with the second proof of Lemma 37.8). Hence we see that condition (3) tells us that

$$
\begin{array}{c}
\mathcal{F}(\emptyset) \\ \uparrow \\
\mathcal{F}(X) \\
\end{array}
\leftarrow
\begin{array}{c}
\mathcal{F}(Y) \\
\end{array}
$$

is cartesian in the category of sets. Since $\mathcal{F}$ is a sheaf for the Zariski topology, we see that $\mathcal{F}(\emptyset)$ is a singleton. Hence we see that $\mathcal{F}(X) = \mathcal{F}(Y)$.

Interlude A: let $T \to T'$ be a morphism of $(\mathcal{S}ch/S)_h$ which is a thickening and of finite presentation. Then $\mathcal{F}(T') \to \mathcal{F}(T)$ is bijective. Namely, choose an affine open covering $T' = \bigcup T'_i$ and let $T_i = T \times_{T'} T'_i$ be the corresponding affine opens of $T$. Then we have $\mathcal{F}(T'_i) \to \mathcal{F}(T_i)$ is bijective for all $i$ by the result of the previous paragraph. Using the Zariski sheaf property we see that $\mathcal{F}(T') \to \mathcal{F}(T)$ is injective. Repeating the argument we find that it is bijective. Minor details omitted.
Interlude B: consider an almost blow up square \((37.0.1)\) in the category \((\text{Sch}/S)_h\). Then we claim the diagram

\[
\begin{array}{c}
\mathcal{F}(E) & \xleftarrow{=} & \mathcal{F}(X') \\
\uparrow & & \uparrow \\
\mathcal{F}(Z) & \xleftarrow{=} & \mathcal{F}(X)
\end{array}
\]

is cartesian in the category of sets. This is a consequence of condition (3) as follows by choosing an affine open covering of \(X\) and arguing as in Interlude A. We omit the details.

Next, let \(f : X \to Y\) be a surjective, finitely presented, proper morphism in \((\text{Sch}/S)_h\) with \(Y\) affine. Choose a generic flatness stratification \(Y \supset Y_0 \supset Y_1 \supset \ldots \supset Y_t = \emptyset\) as in Lemma 21.4 for \(f : X \to Y\). We are going to use all the properties of the stratification without further mention. Set \(X_0 = X \times_Y Y_0\). By the Interlude B we have \(\mathcal{F}(Y_0) = \mathcal{F}(Y)\), \(\mathcal{F}(X_0) = \mathcal{F}(X)\), and \(\mathcal{F}(X_0 \times_{Y_0} X_0) = \mathcal{F}(X \times_Y X)\).

We are going to prove the result by induction on \(t\). If \(t = 1\) then \(X_0 \to Y_0\) is surjective, proper, flat, and of finite presentation and we see that the result holds by property (2). For \(t > 1\) we may replace \(Y\) by \(Y_0\) and \(X\) by \(X_0\) (see above) and assume \(Y = Y_0\).

Consider the quasi-compact open subscheme \(V = Y \setminus Y_1 = Y_0 \setminus Y_1\). Choose a diagram

\[
\begin{array}{c}
E & \xleftarrow{=} & X' \\
\downarrow & & \downarrow \\
D & \xleftarrow{=} & X' \\
\downarrow & & \downarrow \\
Y & \xleftarrow{=} & Z \\
\downarrow & & \downarrow \\
Y & \xleftarrow{=} & T
\end{array}
\]

as in Lemma \([37.6]\) for \(f : X \to Y \supset V\). Then \(f' : X' \to Y'\) is flat and of finite presentation. Also \(f'\) is proper (use Morphisms, Lemmas \([39.4]\) and \([39.7]\) to see this). Thus the image \(W = f'(X') \subset Y'\) is an open (Morphisms, Lemma \([24.10]\)) and closed subscheme of \(Y'\). Observe that \(Y' \setminus E\) is contained in \(W\). By Lemma \([37.2]\) this means we may replace \(Y'\) by \(W\) in the above diagram. In other words, we may and do assume \(f'\) is surjective. At this point we know that

\[
\begin{array}{c}
\mathcal{F}(E) & \xleftarrow{=} & \mathcal{F}(Y') \\
\uparrow & & \uparrow \\
\mathcal{F}(Z) & \xleftarrow{=} & \mathcal{F}(Y) \\
\uparrow & & \uparrow \\
\mathcal{F}(T) & \xleftarrow{=} & \mathcal{F}(X)
\end{array}
\]

are cartesian by Interlude B. Note that \(Z \cap Y_1 \to Z\) is a thickening of finite presentation (as \(Z\) is set theoretically contained in \(Y_1\) as a closed subscheme of \(Y\) disjoint
from $V$). Thus we obtain a filtration
\[ Z \supset Z \cap Y_1 \supset Z \cap Y_2 \subset \ldots \subset Z \cap Y_t = \emptyset \]
as above for the restriction $T = Z \times_Y X \to Z$ of $f$ to $T$. Thus by induction hypothesis we find that $F(Z) \to F(T)$ is an injective map of sets whose image is the equalizer of the two maps $F(T) \to F(T \times_Z T)$.

Let $s \in F(X)$ be in the equalizer of the two maps $F(X) \to F(X \times_Y X)$. By the above we see that the restriction $s|_T$ comes from a unique element $t \in F(Z)$ and similarly that the restriction $s|_{X'}$ comes from a unique element $t' \in F(Y')$. Chasing sections using the restriction maps for $F$ corresponding to the arrows in the huge commutative diagram above the reader finds that $t$ and $t'$ restrict to the same element of $F(E)$ because they restrict to the same element of $F(D)$ and we have (2); here we use that $D \to E$ is surjective, flat, proper, and of finite presentation as the restriction of $X' \to Y'$. Thus by the first of the two cartesian squares displayed above we get a unique section $u \in F(Y)$ restricting to $t$ and $t'$ on $Z$ and $Y'$. To see that $u$ restrict to $s$ on $X$ use the second diagram. \[\square\]

**Example 37.10.** Let $A$ be a ring. Let $f \in A$ be an element. Let $J \subset A$ be a finitely generated ideal annihilated by a power of $f$. Then

\[
\begin{array}{ccc}
\text{Spec}(A/fA + J) & \longrightarrow & \text{Spec}(A/J) \\
\downarrow & & \downarrow \\
\text{Spec}(A/fA) & \longrightarrow & \text{Spec}(A)
\end{array}
\]
is an almost blowup square.

**Example 37.11.** Let $A$ be a ring. Let $f_1, f_2 \in A$ be elements.

\[
\begin{array}{ccc}
\text{Proj}(A/(f_1, f_2)[T_0, T_1]) & \longrightarrow & \text{Proj}(A[T_0, T_1]/(f_2T_0 - f_1T_1)) \\
\downarrow & & \downarrow \\
\text{Spec}(A/(f_1, f_2)) & \longrightarrow & \text{Spec}(A)
\end{array}
\]
is an almost blowup square.

**Lemma 37.12.** Let $F$ be a presheaf on one of the sites $(\text{Sch}/S)_h$ constructed in Definition 34.12. Then $F$ is a sheaf if and only if the following conditions are satisfied

1. $F$ is a sheaf for the Zariski topology,
2. given a morphism $f : X \to Y$ of $(\text{Sch}/S)_h$ with $Y$ affine and $f$ surjective, flat, proper, and of finite presentation, then $F(Y)$ is the equalizer of the two maps $F(X) \to F(X \times_Y X),$
3. $F$ turns an almost blow up square as in Example 37.10 in the category $(\text{Sch}/S)_h$ into a cartesian diagram of sets, and
4. $F$ turns an almost blow up square as in Example 37.11 in the category $(\text{Sch}/S)_h$ into a cartesian diagram of sets.
**Proof.** By Proposition 37.9 it suffices to show that given an almost blow up square (37.0.1) with $X$ affine in the category $(\text{Sch}/S)_h$ the diagram

$$
\begin{array}{ccc}
F(E) & \rightarrow & F(X') \\
\uparrow & & \uparrow \\
F(Z) & \rightarrow & F(X)
\end{array}
$$

is cartesian in the category of sets. The rough idea of the proof is to dominate the morphism by other almost blowup squares to which we can apply assumptions (3) and (4) locally.

Suppose we have an almost blow up square (37.0.1) in the category $(\text{Sch}/S)_h$, an open covering $X = \bigcup U_i$, and open coverings $U_i \cap U_j = \bigcup U_{ijk}$ such that the diagrams

$$
\begin{array}{ccc}
F(E \cap b^{-1}(U_i)) & \rightarrow & F(b^{-1}(U_i)) \\
\uparrow & & \uparrow \\
F(Z \cap U_i) & \rightarrow & F(U_i)
\end{array}
\quad \text{and} \quad
\begin{array}{ccc}
F(E \cap b^{-1}(U_{ijk})) & \rightarrow & F(b^{-1}(U_{ijk})) \\
\uparrow & & \uparrow \\
F(Z \cap U_{ijk}) & \rightarrow & F(U_{ijk})
\end{array}
$$

are cartesian, then the same is true for

$$
\begin{array}{ccc}
F(E) & \rightarrow & F(X') \\
\uparrow & & \uparrow \\
F(Z) & \rightarrow & F(X)
\end{array}
$$

This follows as $F$ is a sheaf in the Zariski topology.

In particular, if we have a blow up square (37.0.1) such that $b : X' \rightarrow X$ is a closed immersion and $Z$ is a locally principal closed subscheme, then we see that $F(X) = F(X') \times_{F(E)} F(Z)$. Namely, affine locally on $X$ we obtain an almost blow up square as in (3).

Let $Z \subset X$, $E_k \subset X'_k \rightarrow X$, $E \subset X' \rightarrow X$, and $i_k : X' \rightarrow X'_k$ be as in the statement of Lemma 37.5. Then

$$
\begin{array}{ccc}
E & \rightarrow & X' \\
\downarrow & & \downarrow \\
E_k & \rightarrow & X'_k
\end{array}
$$

is an almost blow up square of the kind discussed in the previous paragraph. Thus

$$
F(X'_k) = F(X') \times_{F(E)} F(E_k)
$$

for $k = 1, 2$ by the result of the previous paragraph. It follows that

$$
F(X) \rightarrow F(X'_k) \times_{F(E_k)} F(Z)
$$

is bijective for $k = 1$ if and only if it is bijective for $k = 2$. Thus given a closed immersion $Z \rightarrow X$ of finite presentation with $X$ quasi-compact and quasi-separated, whether or not $F(X) = F(X') \times_{F(E)} F(Z)$ is independent of the choice of the almost blow up square (37.0.1) one chooses. (Moreover, by Lemma 37.4 there does indeed exist an almost blow up square for $Z \subset X$.)
Finally, consider an affine object $X$ of $(\text{Sch}/S)_h$ and a closed immersion $Z \to X$ of finite presentation. We will prove the desired property for the pair $(X, Z)$ by induction on the number of generators $r$ for the ideal defining $Z$ in $X$. If the number of generators is $\leq 2$, then we can choose our almost blow up square as in Example 37.11 and we conclude by assumption (4).

Induction step. Suppose $X = \text{Spec}(A)$ and $Z = \text{Spec}(A/(f_1, \ldots, f_r))$ with $r > 2$. Choose a blow up square $\text{37.0.1}$ for the pair $(X, Z)$. Set $Z_1 = \text{Spec}(A/(f_1, f_2))$ and let

$$
\begin{array}{ccc}
E_1 & \longrightarrow & Y \\
\downarrow & & \downarrow \\
Z_1 & \longrightarrow & X
\end{array}
$$

be the almost blow up square constructed in Example 37.11 By Lemma 37.1 the base changes

$$
\begin{array}{ccc}
Y \times_X E & \longrightarrow & Y \times_X X' \\
\downarrow & & \downarrow \\
Y \times_X Z & \longrightarrow & Y
\end{array}
$$

and

$$
\begin{array}{ccc}
E & \longrightarrow & Z_1 \times_X X' \\
\downarrow & & \downarrow \\
Z & \longrightarrow & Z_1
\end{array}
$$

are almost blow up squares. The ideal of $Z$ in $Z_1$ is generated by $r - 2$ elements. The ideal of $Y \times_X Z$ is generated by the pullbacks of $f_1, \ldots, f_r$ to $Y$. Locally on $Y$ the ideal generated by $f_1, f_2$ can be generated by one element, thus $Y \times_X Z$ is affine locally on $Y$ cut out by at most $r - 1$ elements. By induction hypotheses and the discussion above

$$
\mathcal{F}(Y) = \mathcal{F}(Y \times_X X') \times_{\mathcal{F}(Y \times_X E)} \mathcal{F}(Y \times_X Z)
$$

and

$$
\mathcal{F}(Z_1) = \mathcal{F}(Z_1 \times_X X') \times_{\mathcal{F}(E)} \mathcal{F}(Z)
$$

By assumption (4) we have

$$
\mathcal{F}(X) = \mathcal{F}(Y) \times_{\mathcal{F}(E_1)} \mathcal{F}(Z_1)
$$

Now suppose we have a pair $(s', t)$ with $s' \in \mathcal{F}(X')$ and $t \in \mathcal{F}(Z)$ with same restriction in $\mathcal{F}(E)$. Then $(s'|_{Z_1 \times_X X'}, t|_{Y \times_X Z})$ are the image of a unique element $t_1 \in \mathcal{F}(Z_1)$. Similarly, $(s'|_{Y \times_X X'}, t|_{Y \times_X Z})$ are the image of a unique element $s_Y \in \mathcal{F}(Y)$. We claim that $s_Y$ and $t_1$ restrict to the same element of $\mathcal{F}(E_1)$. This is true because the almost blow up square

$$
\begin{array}{ccc}
E_1 \times_X E & \longrightarrow & E_1 \times_X X' \\
\downarrow & & \downarrow \\
E_1 \times_X Z & \longrightarrow & E_1
\end{array}
$$

is the base change of almost blow up square (I) via $E_1 \to Y$ and the base change of almost blow up square (II) via $E_1 \to Z_1$ and because the pairs of sections used to construct $s_Y$ and $t_1$ match. Thus by the third fibre product equality we see that there is a unique $s \in \mathcal{F}(X)$ mapping to $s_Y$ in $\mathcal{F}(Y)$ and to $t_1$ in $\mathcal{F}(Z)$. We omit the verification that $s$ maps to $s'$ in $\mathcal{F}(X')$ and to $t$ in $\mathcal{F}(Z)$; hint: use uniqueness of $s$ just constructed and work affine locally. □
Lemma 37.13. Let \( p : S \to (\text{Sch}/S)_h \) be a category fibred in groupoids. Then \( S \) is a stack in groupoids if and only if the following conditions are satisfied

1. \( S \) is a stack in groupoids for the Zariski topology,
2. given a morphism \( f : X \to Y \) of \((\text{Sch}/S)_h\) with \( Y \) affine and \( f \) surjective, flat, proper, and of finite presentation, then \( \mathcal{S}_Y \to \mathcal{S}_X \times \mathcal{S}_{X \times_Y X} \) is an equivalence of categories,
3. for an almost blow up square as in Example 37.10 or 37.11 in the category \((\text{Sch}/S)_h\) the functor \( \mathcal{S}_X \to \mathcal{S}_Z \times \mathcal{S}_{E \times X} \) is an equivalence of categories.

Proof. This lemma is a formal consequence of Lemma 37.12 and our definition of stacks in groupoids. For example, assume (1), (2), (3). To show that \( S \) is a stack, we have to prove descent for morphisms and objects, see Stacks, Definition 5.1. If \( x, y \) are objects of \( S \) over an object \( U \) of \((\text{Sch}/S)_h\), then our assumptions imply \( \text{Isom}(x, y) \) is a presheaf on \( (\text{Sch}/U)_h \) which satisfies (1), (2), (3), and (4) of Lemma 37.12 and therefore is a sheaf. Some details omitted.

Let \( \{ U_i \to U \}_{i \in I} \) be a covering of \((\text{Sch}/S)_h\). Let \( (x_i, \varphi_{ij}) \) be a descent datum in \( S \) relative to the family \( \{ U_i \to U \}_{i \in I} \), see Stacks, Definition 3.1. Consider the rule \( F \) which to \( V/U \) in \((\text{Sch}/U)_h \) associates the set of pairs \( (y, \psi_i) \) where \( y \) is an object of \( \mathcal{S}_V \) and \( \psi_i : y|_{U_i \times_U V} \to x_i|_{U_i \times_U V} \) is a morphism of \( S \) over \( U_i \times_U V \) such that

\[
\varphi_{ij}|_{U_i \times_U U_j \times_U V} \circ \psi_i|_{U_i \times_U U_j \times_U V} = \psi_j|_{U_i \times_U U_j \times_U V}
\]

up to isomorphism. Since we already have descent for morphisms, it is clear that \( F(V/U) \) is either empty or a singleton set. On the other hand, we have \( F(U_{i_0}/U) \) is nonempty because it contains \( (x_{i_0}, \varphi_{i_0}) \). Since our goal is to prove that \( F(U/U) \) is nonempty, it suffices to show that \( F \) is a sheaf on \((\text{Sch}/U)_h\). To do this we may use the criterion of Lemma 37.12. However, our assumptions (1), (2), (3) imply (by drawing some commutative diagrams which we omit), that properties (1), (2), (3), and (4) of Lemma 37.12 hold for \( F \).

We omit the verification that if \( S \) is a stack in groupoids, then (1), (2), and (3) are satisfied. \( \square \)

38. Absolute weak normalization and \( h \) coverings

In this section we use the criteria found in Section 37 to exhibit some \( h \) sheaves and we relate \( h \) sheafification of the structure sheaf to absolute weak normalization. We will need the following elementary lemma to do this.

Lemma 38.1. Let \( Z, X, X', E \) be an almost blow up square as in Example 37.11. Then \( H^p(X', \mathcal{O}_{X'}) = 0 \) for \( p > 0 \) and \( \Gamma(X, \mathcal{O}_X) \to \Gamma(X', \mathcal{O}_{X'}) \) is a surjective map of rings whose kernel is an ideal of square zero.

Proof. First assume that \( A = \mathbb{Z}[f_1, f_2] \) is the polynomial ring. In this case our almost blow up square is the blowing up of \( X = \text{Spec}(A) \) in the closed subscheme.
Let $Z$ and in fact $X' \subset \mathbf{P}_X^1$ is an effective Cartier divisor cut out by the global section $f_2 T_0 - f_1 T_1$ of $\mathcal{O}_{\mathbf{P}_X^1}(1)$. Thus we have a resolution

$$0 \to \mathcal{O}_{\mathbf{P}_X^1}(-1) \to \mathcal{O}_{\mathbf{P}_X^1} \to \mathcal{O}_{X'} \to 0$$

Using the description of the cohomology given in Cohomology of Schemes, Section 8 it follows that in this case $\Gamma(X, \mathcal{O}_X) \to \Gamma(X', \mathcal{O}_{X'})$ is an isomorphism and $H^1(X', \mathcal{O}_{X'}) = 0$.

Next, we observe that any diagram as in Example 37.11 is the base change of the diagram in the previous paragraph by the ring map $\mathbf{Z}[f_1, f_2] \to A$. Hence by More on Morphisms, Lemmas 64.1, 64.2, and 64.4 we conclude that $H^1(X', \mathcal{O}_{X'})$ is zero in general and the surjectivity of the map $H^0(X, \mathcal{O}_X) \to H^0(X', \mathcal{O}_{X'})$ in general.

Next, in the general case, let us study the kernel. If $a \in A$ maps to zero, then looking on affine charts we see that

$$a = (f_1 x - f_2)(a_0 + a_1 x + \ldots + a_r x^r) \text{ in } A[x]$$

for some $r \geq 0$ and $a_0, \ldots, a_r \in A$ and similarly

$$a = (f_1 - f_2 y)(b_0 + b_1 y + \ldots + b_s y^s) \text{ in } A[y]$$

for some $s \geq 0$ and $b_0, \ldots, b_s \in A$. This means we have

$$a = f_2 a_0, \ f_1 a_0 = f_2 a_1, \ldots, \ f_1 a_r = 0, \ a = f_1 b_0, \ f_2 b_0 = f_1 b_1, \ldots, \ f_2 b_s = 0$$

If $(a', r', a'_1, s', b'_1)$ is a second such system, then we have

$$a a' = f_1 f_2 a_0 b'_0 = f_1 f_2 a_1 b'_1 = f_1 f_2 a_2 b'_2 = \ldots = 0$$

as desired. \(\square\)

For an $\mathbf{F}_p$-algebra $A$ we set $\text{colim}_F A$ equal to the colimit of the system

$$A \xrightarrow{F} A \xrightarrow{F} A \xrightarrow{F} \ldots$$

where $F : A \to A$, $a \mapsto a^p$ is the Frobenius endomorphism.

**Lemma 38.2.** Let $p$ be a prime number. Let $S$ be a scheme over $\mathbf{F}_p$. Let $(\text{Sch}/S)_h$ be a site as in Definition 34.12. There is a unique sheaf $\mathcal{F}$ on $(\text{Sch}/S)_h$ such that

$$\mathcal{F}(X) = \text{colim}_F \Gamma(X, \mathcal{O}_X)$$

for any quasi-compact and quasi-separated object $X$ of $(\text{Sch}/S)_h$.

**Proof.** Denote $\mathcal{F}$ the Zariski sheafification of the functor

$$X \mapsto \text{colim}_F \Gamma(X, \mathcal{O}_X)$$

For quasi-compact and quasi-separated schemes $X$ we have $\mathcal{F}(X) = \text{colim}_F \Gamma(X, \mathcal{O}_X)$.

by Sheaves, Lemma 29.1 and the fact that $\mathcal{O}$ is a sheaf for the Zariski topology. Thus it suffices to show that $\mathcal{F}$ is a $h$ sheaf. To prove this we check conditions (1), (2), (3), and (4) of Lemma 37.12. Condition (1) holds because we performed an (almost unnecessary) Zariski sheafification. Condition (2) holds because $\mathcal{O}$ is an fppf sheaf (Descent, Lemma 8.1) and if $A$ is the equalizer of two maps $B \to C$ of $\mathbf{F}_p$-algebras, then $\text{colim}_F A$ is the equalizer of the two maps $\text{colim}_F B \to \text{colim}_F C$.

We check condition (3). Let $A, f, J$ be as in Example 37.10. We have to show that

$$\text{colim}_F A = \text{colim}_F A/J \times_{\text{colim}_F A/fA} \text{colim}_F A/fA$$
This reduces to the following algebra question: suppose $a', a'' \in A$ are such that $F^n(a' - a'') \in fA + J$. Find $a \in A$ and $m \geq 0$ such that $a - F^m(a') \in J$ and $a - F^m(a'') \in fA$ and show that the pair $(a, m)$ is uniquely determined up to a replacement of the form $(a, m) \mapsto (F(a), m + 1)$. To do this just write $F^n(a' - a'') = fh + g$ with $h \in A$ and $g \in J$ and set $a = F^n(a') - g = F^n(a'') + fh$ and set $m = n$. To see uniqueness, suppose $(a_1, m_1)$ is a second solution. By a replacement of the form given above we may assume $m = m_1$. Then we see that $a - a_1 \in J$ and $a - a_1 \in fA$. Since $J$ is annihilated by a power of $f$ we see that $a - a_1$ is a nilpotent element. Hence $F^k(a - a_1)$ is zero for some large $k$. Thus after doing more replacements we get $a = a_1$.

We check condition (4). Let $X, X', Z, E$ be as in Example 37.11 By Lemma 38.1 we see that

$$F(X) = \text{colim}_F \Gamma(X, O_X) \longrightarrow \text{colim}_F \Gamma(X', O_{X'}) = F(X')$$

is bijective. Since $E = \mathbf{P}^1_\mathbb{Z}$ in this case we also see that $F(Z) \to F(E)$ is bijective. Thus the conclusion holds in this case as well. \qed

Let $p$ be a prime number. For an $\mathbf{F}_p$-algebra $A$ we set $\text{lim}_F A$ equal to the limit of the inverse system

$$\ldots \xrightarrow{F} A \xrightarrow{E} A \xrightarrow{F} A$$

where $F: A \to A, a \mapsto a^p$ is the Frobenius endomorphism.

**Lemma 38.3.** Let $p$ be a prime number. Let $S$ be a scheme over $\mathbf{F}_p$. Let $(\text{Sch}/S)_h$ be a site as in Definition 34.12. The rule

$$F(X) = \text{lim}_F \Gamma(X, O_X)$$

defines a sheaf on $(\text{Sch}/S)_h$.

**Proof.** To prove $F$ is a sheaf, let’s check conditions (1), (2), (3), and (4) of Lemma 37.12. Condition (1) holds because limits of sheaves are sheaves and $O$ is a Zariski sheaf. Condition (2) holds because $O$ is an fppf sheaf (Descent, Lemma 8.1) and if $A$ is the equalizer of two maps $B \to C$ of $\mathbf{F}_p$-algebras, then $\text{lim}_F A$ is the equalizer of the two maps $\text{lim}_F B \to \text{lim}_F C$.

We check condition (3). Let $A, f, J$ be as in Example 37.10 We have to show that

$$\text{lim}_F A \to \text{lim}_F A/J \times_{\text{lim}_F A/fA + J} \text{lim}_F A/fA$$

$$= \text{lim}_F (A/J \times_{A/fA + J} A/fA)$$

$$= \text{lim}_F A/(fA \cap J)$$

is bijective. Since $J$ is annihilated by a power of $f$ we see that $a = fA \cap J$ is a nilpotent ideal, i.e., there exists an $n$ such that $a^n = 0$. It is straightforward to verify that in this case $\text{lim}_F A \to \text{lim}_F A/a$ is bijective.

We check condition (4). Let $X, X', Z, E$ be as in Example 37.11 By Lemma 38.1 and the same argument as above we see that

$$F(X) = \text{lim}_F \Gamma(X, O_X) \longrightarrow \text{lim}_F \Gamma(X', O_{X'}) = F(X')$$

is bijective. Since $E = \mathbf{P}^1_\mathbb{Z}$ in this case we also see that $F(Z) \to F(E)$ is bijective. Thus the conclusion holds in this case as well. \qed

In the following lemma we use the absolute weak normalization $X^{an}$ of a scheme $X$, see Morphisms, Section 45.
**Lemma 38.4.** Let \((\text{Sch}/S)_{ph}\) be a site as in Topologies, Definition 8.11. The rule \(X \mapsto \Gamma(X^{\text{\acute{e}t}}, \mathcal{O}_{X^{\text{\acute{e}t}}})\) is a sheaf on \((\text{Sch}/S)_{ph}\).

**Proof.** To prove \(\mathcal{F}\) is a sheaf, let’s check conditions (1) and (2) of Topologies, Lemma 8.15. Condition (1) holds because formation of \(X^{\text{\acute{e}t}}\) commutes with open coverings, see Morphisms, Lemma 45.7 and its proof.

Let \(\pi : Y \rightarrow X\) be a surjective proper morphism. We have to show that the equalizer of the two maps

\[\Gamma(Y^{\text{\acute{e}t}}, \mathcal{O}_{Y^{\text{\acute{e}t}}}) \rightarrow \Gamma((Y \times_X Y)^{\text{\acute{e}t}}, \mathcal{O}_{(Y \times_X Y)^{\text{\acute{e}t}}})\]

is equal to \(\Gamma(X^{\text{\acute{e}t}}, \mathcal{O}_{X^{\text{\acute{e}t}}})\). Let \(f\) be an element of this equalizer. Then we consider the morphism

\[f : Y^{\text{\acute{e}t}} \rightarrow A^1_X\]

Since \(Y^{\text{\acute{e}t}} \rightarrow X\) is universally closed, the scheme theoretic image \(Z\) of \(f\) is a closed subscheme of \(A^1_X\) proper over \(X\) and \(f : Y^{\text{\acute{e}t}} \rightarrow Z\) is surjective. See Morphisms, Lemma 39.10. Thus \(Z \rightarrow X\) is finite (Morphisms, Lemma 42.11) and surjective.

Let \(k\) be a field and let \(z_1, z_2 : \text{Spec}(k) \rightarrow Z\) be two morphisms equalized by \(Z \rightarrow X\). We claim that \(z_1 = z_2\). It suffices to show the images \(\lambda_1 = z_1^* f \in k\) agree (as the structure sheaf of \(Z\) is generated by \(f\) over the structure sheaf of \(X\)). To see this we choose a field extension \(K/k\) and morphisms \(y_1, y_2 : \text{Spec}(K) \rightarrow Y^{\text{\acute{e}t}}\) such that \(z_i \circ (\text{Spec}(K) \rightarrow \text{Spec}(k)) = f \circ y_i\). This is possible by the surjectivity of the map \(Y^{\text{\acute{e}t}} \rightarrow Z\). Choose an algebraically closed extension \(\Omega/k\) of very large cardinality. For any \(k\)-algebra maps \(\sigma_i : K \rightarrow \Omega\) we obtain

\[\text{Spec}(\Omega) \xrightarrow{\sigma_1, \sigma_2} \text{Spec}(K \otimes_k K) \xrightarrow{y_1, y_2} Y^{\text{\acute{e}t}} \times_X Y^{\text{\acute{e}t}}\]

Since the canonical morphism \((Y \times_X Y)^{\text{\acute{e}t}} \rightarrow Y^{\text{\acute{e}t}} \times_X Y^{\text{\acute{e}t}}\) is a universal homeomorphism and since \(\Omega\) is algebraically closed, we can lift the composition above uniquely to a morphism \(\text{Spec}(\Omega) \rightarrow (Y \times_X Y)^{\text{\acute{e}t}}\). Since \(f\) is in the equalizer above, this proves that \(\sigma_1(\lambda_1) = \sigma_2(\lambda_2)\). An easy lemma about field extensions shows that this implies \(\lambda_1 = \lambda_2\); details omitted.

We conclude that \(Z \rightarrow X\) is universally injective, i.e., \(Z \rightarrow X\) is injective on points and induces purely inseparated residue field extensions (Morphisms, Lemma 10.2). All in all we conclude that \(Z \rightarrow X\) is a universal homeomorphism, see Morphisms, Lemma 33.5.

Let \(g : X^{\text{\acute{e}t}} \rightarrow Z\) be the map obtained from the universal property of \(X^{\text{\acute{e}t}}\). Then \(Y^{\text{\acute{e}t}} \rightarrow X^{\text{\acute{e}t}} \rightarrow Z\) and \(f : Y^{\text{\acute{e}t}} \rightarrow Z\) are two morphisms over \(X\). By the universal property of \(Y^{\text{\acute{e}t}} \rightarrow Y\) the two corresponding morphisms \(Y^{\text{\acute{e}t}} \rightarrow Y \times_X Z\) over \(Y\) have to be equal. This implies that \(g \circ \pi^{\text{\acute{e}t}} = f\) as morphisms into \(A^1_X\) and we conclude that \(g \in \Gamma(X^{\text{\acute{e}t}}, \mathcal{O}_{X^{\text{\acute{e}t}}})\) is the element we were looking for.

---

**Lemma 38.5.** Let \(S\) be a scheme. Choose a site \((\text{Sch}/S)_{ph}\) as in Definition 34.11. The rule

\[X \mapsto \Gamma(X^{\text{\acute{e}t}}, \mathcal{O}_{X^{\text{\acute{e}t}}})\]

is the sheafification of the “structure sheaf” \(\mathcal{O}\) on \((\text{Sch}/S)_{ph}\). Similarly for the ph topology.
Proof. In Lemma \textbf{38.4} we have seen that the rule $\mathcal{F}$ of the lemma defines a sheaf in the $\mathfrak{ph}$ topology and hence a fortiori a sheaf for the $\mathfrak{h}$ topology. Clearly, there is a canonical map of presheaves of rings $\mathcal{O} \to \mathcal{F}$. To finish the proof, it suffices to show

1. if $f \in \mathcal{O}(X)$ maps to zero in $\mathcal{F}(X)$, then there is a $h$ covering $\{X_i \to X\}$ such that $f|_{X_i} = 0$, and
2. given $f \in \mathcal{F}(X)$ there is a $h$ covering $\{X_i \to X\}$ such that $f|_{X_i}$ is the image of $f_i \in \mathcal{O}(X_i)$.

Let $f$ be as in (1). Then $f|_{X_{\text{unw}}} = 0$. This means that $f$ is locally nilpotent. Thus if $X' \subset X$ is the closed subscheme cut out by $f$, then $X' \to X$ is a surjective closed immersion of finite presentation. Hence $\{X' \to X\}$ is the desired $h$ covering. Let $f$ be as in (2). After replacing $X$ by the members of an affine open covering we may assume $X = \text{Spec}(A)$ is affine. Then $f \in A^{\text{unw}}$, see Morphisms, Lemma \textbf{45.6}

By Morphisms, Lemma \textbf{44.11} we can find a ring map $A \to B$ of finite presentation such that $\text{Spec}(B) \to \text{Spec}(A)$ is a universal homeomorphism and such that $f$ is the image of an element $b \in B$ under the canonical map $B \to A^{\text{unw}}$. Then $\{\text{Spec}(B) \to \text{Spec}(A)\}$ is an $h$ covering and we conclude. The statement about the $\mathfrak{ph}$ topology follows in the same manner (or it can be deduced from the statement for the $\mathfrak{h}$ topology).

Let $p$ be a prime number. An $\mathbf{F}_p$-algebra $A$ is called perfect if the map $F : A \to A$, $x \mapsto x^p$ is an automorphism of $A$.

\textbf{Lemma 38.6}. Let $p$ be a prime number. An $\mathbf{F}_p$-algebra $A$ is absolutely weakly normal if and only if it is perfect.

Proof. It is immediate from condition (2)(b) in Morphisms, Definition \textbf{45.1} that if $A$ is absolutely weakly normal, then it is perfect.

Assume $A$ is perfect. Suppose $x, y \in A$ with $x^3 = y^2$. If $p > 3$ then we can write $p = 2n + 3m$ for some $n, m > 0$. Choose $a, b \in A$ with $a^p = x$ and $b^p = y$. Setting $c = a^n b^m$ we have

$c^{2p} = x^{2n} y^{2m} = x^{2n+3m} = x^p$

and hence $c^2 = x$. Similarly $c^3 = y$. If $p = 2$, then write $x = a^2$ to get $a^6 = y^2$ which implies $a^3 = y$. If $p = 3$, then write $y = a^3$ to get $x^3 = a^6$ which implies $x = a^2$.

Suppose $x, y \in A$ with $\ell \cdot x = y^\ell$ for some prime number $\ell$. If $\ell \neq p$, then $a = y/\ell$ satisfies $a^\ell = x$ and $\ell a = y$. If $\ell = p$, then $y = 0$ and $x = a^p$ for some $a$.

\textbf{Lemma 38.7}. Let $p$ be a prime number.

1. If $A$ is an $\mathbf{F}_p$-algebra, then $\text{colim}_F A = A^{\text{unw}}$.
2. If $S$ is a scheme over $\mathbf{F}_p$, then the $h$ sheafification of $\mathcal{O}$ sends a quasi-compact and quasi-separated $X$ to $\text{colim}_F \Gamma(X, \mathcal{O}_X)$.

Proof. Proof of (1). Observe that $A \to \text{colim}_F A$ induces a universal homeomorphism on spectra by Algebra, Lemma \textbf{45.7}. Thus it suffices to show that $B = \text{colim}_F A$ is absolutely weakly normal, see Morphisms, Lemma \textbf{45.6}. Note that the ring map $F : B \to B$ is an automorphism, in other words, $B$ is a perfect ring. Hence Lemma \textbf{38.6} applies.

Proof of (2). This follows from (1) and Lemmas \textbf{38.2} and \textbf{38.5} by looking affine locally.
39. Descent vector bundles in positive characteristic

For a scheme $S$ let us denote $\text{Vect}(S)$ the category of finitely locally free $\mathcal{O}_S$-modules. Let $p$ be a prime number. Let $S$ be a quasi-compact and quasi-separated scheme over $\mathbf{F}_p$. In this section we will work with the category

$$\text{colim}_F \text{Vect}(S) = \text{colim} \left( \text{Vect}(S) \overset{F^*}{\to} \text{Vect}(S) \overset{F^*}{\to} \text{Vect}(S) \overset{F^*}{\to} \ldots \right)$$

where $F : S \to S$ is the absolute Frobenius morphism. In down to earth terms an object of this category is a pair $(\mathcal{E}, n)$ where $\mathcal{E}$ is a finite locally free $\mathcal{O}_S$-module and $n \geq 0$ is an integer. For morphisms we take

$$\text{Hom}_{\text{colim}_F \text{Vect}(S)}((\mathcal{E}, n), (\mathcal{G}, m)) = \text{colim}_N \text{Hom}_S(F^{N-n} \cdot \mathcal{E}, F^{N-m} \cdot \mathcal{G})$$

where $F : S \to S$ is the absolute Frobenius morphism of $S$. Thus the object $(\mathcal{E}, n)$ is isomorphic to the object $(F^n \mathcal{E}, n + 1)$.

\textbf{Lemma 39.1.} Let $p$ be a prime number. Let $S$ be a quasi-compact and quasi-separated scheme over $\mathbf{F}_p$. The category $\text{colim}_F \text{Vect}(S)$ is equivalent to the category of finite locally free modules over the sheaf of rings $\text{colim}_F \mathcal{O}_S$ on $S$.

\textbf{Proof.} Omitted. \hfill \Box

\textbf{Lemma 39.2.} Let $p$ be a prime number. Consider an almost blowup square $X, X', Z, E$ in characteristic $p$ as in Example \textbf{37.10} Then the functor

$$\text{colim}_F \text{Vect}(X) \rightarrow \text{colim}_F \text{Vect}(Z) \times_{\text{colim}_F \text{Vect}(E)} \text{colim}_F \text{Vect}(X')$$

is an equivalence.

\textbf{Proof.} Let $A, f, J$ be as in Example \textbf{37.10}. Since all our schemes are affine and since we have internal Hom in the category of vector bundles, the fully faithfulness of the functor follows if we can show that

$$\text{colim} P \otimes_{A, F \cdot N} A = \text{colim} P \otimes_{A, F \cdot N} A/J \times_{\text{colim} P \otimes_{A, F \cdot N} A/fA} \text{colim} P \otimes_{A, F \cdot N} A/fA$$

for a finite projective $A$-module $P$. After writing $P$ as a summand of a finite free module, this follows from the case where $P$ is finite free. This case immediately reduces to the case $P = A$. The case $P = A$ follows from Lemma \textbf{38.2} (in fact we proved this case directly in the proof of this lemma).

Essential surjectivity. Here we obtain the following algebra problem. Suppose $P_1$ is a finite projective $A/J$-module, $P_2$ is a finite projective $A/fA$-module, and

$$\varphi : P_1 \otimes_{A/J} A/fA + J \rightarrow P_2 \otimes_{A/fA} A/fA + J$$

is an isomorphism. Goal: show that there exists an $N$, a finite projective $A$-module $P$, an isomorphism $\varphi_1 : P \otimes A/J \rightarrow P_1 \otimes_{A/J, F \cdot N} A/J$, and an isomorphism $\varphi_2 : P \otimes A/fA \rightarrow P_2 \otimes_{A/fA, F \cdot N} A/fA$ compatible with $\varphi$ in an obvious manner. This can be seen as follows. First, observe that

$$A/(J \cap fA) = A/J \times_{A/fA + J} A/fA$$

Hence by More on Algebra, Lemma \textbf{6.9} there is a finite projective module $P'$ over $A/(J \cap fA)$ which comes with isomorphisms $\varphi'_1 : P' \otimes A/J \rightarrow P_1$ and $\varphi'_2 : P' \otimes A/fA \rightarrow P_2$ compatible with $\varphi$. Since $J$ is a finitely generated ideal and
of $F^N$. Setting $P = P^r \otimes_{A/(J \cap fA)} A$ we conclude. \hfill \Box

**Lemma 39.3.** Let $p$ be a prime number. Consider an almost blow up square $X , X', Z , E$ in characteristic $p$ as in Example 37.11. Then the functor
\[ G : \text{colim}_F \text{Vect}(X) \longrightarrow \text{colim}_F \text{Vect}(Z) \times_{\text{colim}_F \text{Vect}(E)} \text{colim}_F \text{Vect}(X') \]
is an equivalence.

**Proof.** Fully faithfulness. Suppose that $(E, n)$ and $(F, m)$ are objects of $\text{colim}_F \text{Vect}(X)$. Let $(a, b) : G(E, n) \to G(F, m)$ be a morphism in the RHS. We may choose $N > 0$ and think of $a$ as a map $a : F^{N-n} \cdot E[Z] \to F^{N-m} \cdot F[Z]$ and $b$ as a map $b : F^{N-n} \cdot E[X'] \to F^{N-m} \cdot F[X']$ agreeing over $E$. Choose a finite affine open covering $X = X_1 \cup \ldots \cup X_n$ such that $E|_{X_i}$ and $F|_{X_i}$ are finite free $O_{X_i}$-modules. For each $i$ the base change
\[
\begin{array}{ccc}
E_i & \longrightarrow & X_i' \\
\downarrow & & \downarrow \\
Z_i & \longrightarrow & X_i \\
\end{array}
\]
is another almost blow up square as in Example 37.11. For these squares we know that
\[
\text{colim}_F H^0(X_i, O_{X_i}) = \text{colim}_F H^0(Z_i, O_{Z_i}) \times_{\text{colim}_F H^0(E_i, O_{E_i})} \text{colim}_F H^0(X'_i, O_{X'_i})
\]
by Lemma 38.2 (see proof of the lemma). Hence after increasing $N$ we may assume the maps $a|_{Z_i}$ and $b|_{X'_i}$ come from maps $c_i : F^{N-n} \cdot E[X_i] \to F^{N-m} \cdot F[X_i]$. After possibly increasing $N$ we may assume $c_i$ and $c_j$ agree on $X_i \cap X_j$. Thus these maps glue to give the desired morphism $(E, n) \to (F, m)$ in the LHS.

Essential surjectivity. Let $(F, G, \varphi)$ be a triple consisting of a finite locally free $O_Z$-module $F$, a finite locally free $O_{X'}$-module $G$, and an isomorphism $\varphi : F|_E \to G|_E$. We have to show that after replacing this triple by a Frobenius power pullback, it comes from a finite locally free $O_X$-module.

Noetherian reduction; we urge the reader to skip this paragraph. Recall that $X = \text{Spec}(A)$ and $Z = \text{Spec}(A/(f_1, f_2))$, $X' = \text{Proj}(A[T_0, T_1]/(f_2T_0 - f_1T_1))$, and $E = \mathbf{P}^1_Z$. By Limits, Lemma 10.3 we can find a finitely generated $F_p$-subalgebra $A_0 \subset A$ containing $f_1$ and $f_2$ such that the triple $(F, G, \varphi)$ descends to $X_0 = \text{Spec}(A_0)$ and $Z_0 = \text{Spec}(A_0/(f_1, f_2))$, $X'_0 = \text{Proj}(A_0[T_0, T_1]/(f_2T_0 - f_1T_1))$, and $E_0 = \mathbf{P}^1_{Z_0}$. Thus we may assume our schemes are Noetherian.

Assume $X$ is Noetherian. We may choose a finite affine open covering $X = X_1 \cup \ldots \cup X_n$ such that $F|_{Z \cap X_i}$ is free. Since we can glue objects of $\text{colim}_F \text{Vect}(X)$ in the Zariski topology (Lemma 39.1), and since we already know fully faithfulness over $X_i$ and $X_i \cap X_j$ (see first paragraph of the proof), it suffices to prove the existence over each $X_i$. This reduces us to the case discussed in the next paragraph.

Assume $X$ is Noetherian and $F = O_{\mathbf{Z}'}^{\oplus r}$. Using $\varphi$ we get an isomorphism $O_{\mathbf{Z}'}^{\oplus r} \to G|_E$. Let $I = (f_1, f_2) \subset A$. Let $\mathcal{I} \subset O_{X'}$ be the ideal sheaf of $E$; it is globally
generated by \( f_1 \) and \( f_2 \). For any \( n \) there is a surjection
\[
(T^n / T^{n+1})^\oplus = T^n / T^{n+1} \otimes_{OE} \mathcal{G} \longrightarrow T^n \mathcal{G} / T^{n+1} \mathcal{G}
\]
Hence the first cohomology group of this module is zero. Here we use that \( E = \mathbb{P}_E^1 \) and hence its structure sheaf and in fact any globally generated quasi-coherent module has vanishing \( H^1 \). Compare with More on Morphisms, Lemma\cite{64.3}. Then using the short exact sequences
\[
0 \to T^n \mathcal{G} / T^{n+1} \mathcal{G} \to \mathcal{G} / T^{n+1} \mathcal{G} \to \mathcal{G} / T^n \mathcal{G} \to 0
\]
and induction, we see that
\[
\lim H^0(X', \mathcal{G} / T^n \mathcal{G}) \to H^0(E, \mathcal{G}|_E) = H^0(E, \mathcal{O}_E^\oplus) = A / I^\oplus
\]
is surjective. By the theorem on formal functions (Cohomology of Schemes, Theorem\cite{20.5}) this implies that
\[
H^0(X', \mathcal{G}) \to H^0(E, \mathcal{G}|_E) = H^0(E, \mathcal{O}_E^\oplus) = A / I^\oplus
\]
is surjective. Thus we can choose a map \( \alpha : \mathcal{O}_X^\oplus \to \mathcal{G} \) which is compatible with the given trivialization of \( \mathcal{G}|_E \). Thus \( \alpha \) is an isomorphism over an open neighbourhood of \( E \) in \( X' \). Thus every point of \( Z \) has an affine open neighbourhood where we can solve the problem. Since \( X' \setminus E \to X \setminus Z \) is an isomorphism, the same holds for points of \( X \) not in \( Z \). Thus another Zariski glueing argument finishes the proof. \( \square \)

**Proposition 39.4.** Let \( p \) be a prime number. Let \( S \) be a scheme in characteristic \( p \). Then the category fibred in groupoids
\[
p : S \longrightarrow (\text{Sch}/S)_h
\]
whose fibre category over \( U \) is the category of finite locally free \( \mathcal{O}_U \)-modules over \( U \) is a stack in groupoids. Moreover, if \( U \) is quasi-compact and quasi-separated, then \( S_U \) is \( \text{colim}_F \operatorname{Vect}(U) \).

**Proof.** The final assertion is the content of Lemma\cite{39.1}. To prove the proposition we will check conditions (1), (2), and (3) of Lemma\cite{37.13}.

Condition (1) holds because by definition we have glueing for the Zariski topology.

To see condition (2), suppose that \( f : X \to Y \) is a surjective, flat, proper morphism of finite presentation over \( S \) with \( Y \) affine. Since \( Y, X, X \times_Y X \) are quasi-compact and quasi-separated, we can use the description of fibre categories given in the statement of the proposition. Then it is clearly enough to show that
\[
\operatorname{Vect}(Y) \longrightarrow \operatorname{Vect}(X) \times_{\operatorname{Vect}(X \times_Y X)} \operatorname{Vect}(X)
\]
is an equivalence (as this will imply the same for the colimits). This follows immediately from fppf descent of finite locally free modules, see Descent, Proposition\cite{5.2} and Lemma\cite{7.0}.

Condition (3) is the content of Lemmas\cite{39.2} and \cite{39.3}. \( \square \)

**Lemma 39.5.** Let \( f : X \to S \) be a proper morphism with geometrically connected fibres where \( S \) is the spectrum of a discrete valuation ring. Denote \( \eta \in S \) the generic point and denote \( X_n \subset X \) the closed subscheme cutout by the \( n \)th power of a uniformizer on \( S \). Then there exists an integer \( n \) such that the following is true: any finite locally free \( \mathcal{O}_X \)-module \( \mathcal{E} \) such that \( \mathcal{E}|_{X_\eta} \) and \( \mathcal{E}|_{X_n} \) are free, is free.
Proof. We first reduce to the case where \( X \to S \) has a section. Say \( S = \text{Spec}(A) \). Choose a closed point \( \xi \) of \( X_n \). Choose an extension of discrete valuation rings \( A \subset B \) such that the fraction field of \( B \) is \( \kappa(\xi) \). This is possible by Krull-Akizuki (Algebra, Lemma 119.18) and the fact that \( \kappa(\xi) \) is a finite extension of the fraction field of \( A \). By the valuative criterion of properness (Morphisms, Lemma 40.1) we get a \( B \)-valued point \( \tau : \text{Spec}(B) \to X \) which induces a section \( \sigma : \text{Spec}(B) \to X_B \). For a finite locally free \( \mathcal{O}_X \)-module \( \mathcal{E} \) let \( \mathcal{E}_B \) be the pullback to the base change \( X_B \). By flat base change (Cohomology of Schemes, Lemma 5.2) we see that \( H^0(X_B, \mathcal{E}_B) = H^0(X, \mathcal{E}) \otimes_A B \). Thus if \( \mathcal{E}_B \) is free of rank \( r \), then the sections in \( H^0(X, \mathcal{E}) \) generate the free \( B \)-module \( \tau^* \mathcal{E} = \sigma^* \mathcal{E}_B \). In particular, we can find \( r \) global sections \( s_1, \ldots, s_r \) of \( \mathcal{E} \) which generate \( \tau^* \mathcal{E} \). Then

\[
s_1, \ldots, s_r : \mathcal{O}_X^{\oplus r} \to \mathcal{E}
\]

is a map of finite locally free \( \mathcal{O}_X \)-modules of rank \( r \) and the pullback to \( X_B \) is a map of free \( \mathcal{O}_{X_B} \)-modules which restricts to an isomorphism in one point of each fibre. Taking the determinant we get a function \( g \in \Gamma(X_n, \mathcal{O}_{X_B}) \) which is invertible in one point of each fibre. As the fibres are proper and connected, we see that \( g \) must be invertible (details omitted; hint: use Varieties, Lemma 9.3). Thus it suffices to prove the lemma for the base change \( X_B \to \text{Spec}(B) \).

Assume we have a section \( \sigma : S \to X \). Let \( \mathcal{E} \) be a finite locally free \( \mathcal{O}_X \)-module which is assumed free on the generic fibre and on \( X_n \) (we will choose \( n \) later). Choose an isomorphism \( \sigma^* \mathcal{E} = \mathcal{O}_S^{\oplus r} \). Consider the map

\[
K = R\Gamma(X, \mathcal{E}) \to R\Gamma(S, \sigma^* \mathcal{E}) = A^{\oplus r}
\]

in \( D(A) \). Arguing as above, we see \( \mathcal{E} \) is free if (and only if) the induced map \( H^0(K) = H^0(X, \mathcal{E}) \to A^{\oplus r} \) is surjective.

Set \( L = R\Gamma(X, \mathcal{O}_X^{\oplus r}) \) and observe that the corresponding map \( L \to A^{\oplus r} \) has the desired property. Observe that \( K \otimes_A Q(A) \cong L \otimes_A Q(A) \) by flat base change and the assumption that \( \mathcal{E} \) is free on the generic fibre. Let \( \pi \in A \) be a uniformizer. Observe that

\[
K \otimes_A L A/\pi^m A = R\Gamma(X, \mathcal{E} \pi^m) \xrightarrow{\pi^m} \mathcal{E}
\]

and similarly for \( L \). Denote \( \mathcal{E}_{\text{tors}} \subset \mathcal{E} \) the coherent subsheaf of sections supported on the special fibre and similarly for other \( \mathcal{O}_X \)-modules. Choose \( k \geq 0 \) such that \( (\mathcal{O}_X)_{\text{tors}} \to \mathcal{O}_X / \pi^k \mathcal{O}_X \) is injective (Cohomology of Schemes, Lemma 10.3). Since \( \mathcal{E} \) is locally free, we see that \( \mathcal{E}_{\text{tors}} \subset \mathcal{E} / \pi^k \mathcal{E} \). Then for \( n \geq m + k \) we have isomorphisms

\[
(\mathcal{E} \xrightarrow{\pi^m} \mathcal{E}) \cong (\mathcal{E} / \pi^k \mathcal{E} \xrightarrow{\pi^m} \mathcal{E} / \pi^{k+m} \mathcal{E}) \\
\cong (\mathcal{O}_X^{\oplus r} / \pi^k \mathcal{O}_X^{\oplus r} \xrightarrow{\pi^m} \mathcal{O}_X^{\oplus r} / \pi^{k+m} \mathcal{O}_X^{\oplus r}) \\
\cong (\mathcal{O}_X^{\oplus r} \xrightarrow{\pi^m} \mathcal{O}_X^{\oplus r})
\]

in \( D(\mathcal{O}_X) \). This determines an isomorphism

\[
K \otimes_A L A/\pi^m A \cong L \otimes_A L A/\pi^m A
\]

in \( D(A) \) (holds when \( n \geq m + k \)). Observe that these isomorphisms are compatible with pulling back by \( \sigma \) hence in particular we conclude that \( K \otimes_A L A/\pi^m A \to \).
Let $an$ isomorphism for every codimension point $s$ assumptions (1) and (3) we see that the pullback of this to $an$ isomorphism. By flat base change (Cohomology of Schemes, Lemma 5.2) and

Proof. We will prove the canonical map $E$ then

Lemma 39.6. Let $f : X \to S$ be a morphism of schemes. Let $E$ be a finite locally free $O_X$-module. Assume

(1) $f$ is flat and proper and $O_S = f_*O_X$,  
(2) $S$ is a normal Noetherian scheme,  
(3) the pullback of $E$ to $X \times_S \text{Spec}(O_{S,s})$ is free for every codimension 1 point $s \in S$.

Then $E$ is isomorphic to the pullback of a finite locally free $O_S$-module.

Proof. We will prove the canonical map

$$\Phi : f^*f_*E \longrightarrow E$$

is an isomorphism. By flat base change (Cohomology of Schemes, Lemma 5.2) and assumptions (1) and (3) we see that the pullback of this to $X \times_S \text{Spec}(O_{S,s})$ is an isomorphism for every codimension 1 point $s \in S$. By Divisors, Lemma 2.11 it suffices to prove that depth $((f^*f_*E)_x) \geq 2$ for any point $x \in X$ mapping to a point $s \in S$ of codimension $\geq 2$. Since $f$ is flat and $(f^*f_*E)_x = (f_*E)_x \otimes_{O_{S,s}} O_{X,x}$, it suffices to prove that depth $(f_*E)_s \geq 2$, see Algebra, Lemma 158.2. Since $S$ is a normal Noetherian scheme and dim$(O_{S,s}) \geq 2$ we have depth$(O_{S,s}) \geq 2$, see Properties, Lemma 12.5. Thus we get what we want from Divisors, Lemma 6.6. □

We can use the results above to prove the following miraculous statement.
Theorem 39.7. Let \( p \) be a prime number. Let \( Y \) be a quasi-compact and quasi-separated scheme over \( \mathbb{F}_p \). Let \( f : X \to Y \) be a proper, surjective morphism of finite presentation with geometrically connected fibres. Then the functor

\[
\colim_F \text{Vect}(Y) \to \colim_F \text{Vect}(X)
\]

is fully faithful with essential image described as follows. Let \( \mathcal{E} \) be a finite locally free \( \mathcal{O}_X \)-module. Assume for all \( y \in Y \) there exists integers \( n_y, r_y \geq 0 \) such that

\[
F^{n_y,r_y} \mathcal{E}|_{X, red} \cong \mathcal{O}_{X,red}^{\oplus r_y}
\]

Then for some \( n \geq 0 \) the \( n \)-th Frobenius power pullback \( F^{n,*} \mathcal{E} \) is the pullback of a finite locally free \( \mathcal{O}_Y \)-module.

Proof. Proof of fully faithfulness. Since vectorbundles on \( Y \) are locally trivial, this reduces to the statement that

\[
\colim_F \Gamma(Y, \mathcal{O}_Y) \to \colim_F \Gamma(X, \mathcal{O}_X)
\]

is bijective. Since \( \{ X \to Y \} \) is an \( h \) covering, this will follow from Lemma 38.2 if we can show that the two maps

\[
\colim_F \Gamma(X, \mathcal{O}_X) \to \colim_F \Gamma(X \times_Y X, \mathcal{O}_{X \times_Y X})
\]

are equal. Let \( q \in \Gamma(X, \mathcal{O}_X) \) and denote \( g_1 \) and \( g_2 \) the two pullbacks of \( g \) to \( X \times_Y X \). Since \( X_{y,red} \) is geometrically connected, we see that \( F^0(X, \mathcal{O}_{X, red}) \) is a purely inseparable extension of \( \kappa(y) \), see Varieties, Lemma 9.3. Thus \( g^0 \mid_{X_{y, red}} \) comes from an element of \( \kappa(y) \) for some \( p \)-power \( q \) (which may depend on \( y \)). It follows that \( g_1^n \) and \( g_2^n \) map to the same element of the residue field at any point of \( (X \times_Y X)_y = X_y \times_Y X_y \). Hence \( g_1 - g_2 \) restricts to zero on \( (X \times_Y X)_{red} \). Hence \( (g_1 - g_2)^n = 0 \) for some \( n \) which we may take to be a \( p \)-power as desired.

Description of essential image. Let \( \mathcal{E} \) be as in the statement of the proposition. We first reduce to the Noetherian case.

Let \( y \in Y \) be a point and view it as a morphism \( y \to Y \) from the spectrum of the residue field into \( Y \). We can write \( Y \to Y \) as a filtered limit of morphisms \( Y_i \to Y \) of finite presentation with \( Y_i \) affine. (It is best to prove this yourself, but it also follows formally from Limits, Lemma 7.1 and 4.13.) For each \( i \) set \( Z_i = Y_i \times_Y X \). Then \( X_y = \lim Z_i \) and \( X_{y,red} = \lim Z_{i,red} \). By Limits, Lemma 10.2 we can find an \( i \) such that \( F^{n_y,*} \mathcal{E}|_{Z_{i,red}} \cong \mathcal{O}_{Z_{i,red}}^{\oplus r_y} \). Fix \( i \). We have \( Z_{i,red} = \lim Z_{i,j} \) where \( Z_{i,j} \to Z_i \) is a thickening of finite presentation (Limits, Lemma 9.4). Using the same lemma as before we can find a \( j \) such that \( F^{n_y,*} \mathcal{E}|_{Z_{i,j}} \cong \mathcal{O}_{Z_{i,j}}^{\oplus r_y} \). We conclude that for each \( y \in Y \) there exists a morphism \( Y_y \to Y \) of finite presentation whose image contains \( y \) and a thickening \( Z_y \to Y_y \times_Y X \) such that \( F^{n_y,*} \mathcal{E}|_{Z_y} \cong \mathcal{O}_{Z_y}^{\oplus r_y} \). Observe that the image of \( Y_y \to Y \) is constructible (Morphisms, Lemma 21.2). Since \( Y \) is quasi-compact in the constructible topology (Topology, Lemma 23.2 and Properties, Lemma 2.4) we conclude that there are a finite number of morphisms

\[
y_1 \to Y, \ y_2 \to Y, \ldots, y_N \to Y
\]

of finite presentation such that \( Y = \bigcup \text{Im}(Y_a \to Y) \) set theoretically and such that for each \( a \in \{ 1, \ldots, N \} \) there exist integers \( n_a, r_a \geq 0 \) and there is a thickening \( Z_a \subset Y_a \times_Y X \) of finite presentation such that \( F^{n_a,*} \mathcal{E}|_{Z_a} \cong \mathcal{O}_{Z_a}^{\oplus r_a} \).
Formulated in this way, the condition descends to an absolute Noetherian approximation. We strongly urge the reader to skip this paragraph. First write $Y = \lim_{i \in I} Y_i$ as a cofiltered limit of schemes of finite type over $\mathbf{F}_p$ with affine transition morphisms (Limits, Lemma 7.1). Next, we can assume we have proper morphisms $f_i : X_i \to Y_i$ whose base change to $Y$ recovers $f : X \to Y$, see Limits, Lemma 10.1. After increasing $i$ we may assume there exists a finite locally free $\mathcal{O}_{X_i}$-module $E_i$ whose pullback to $X$ is isomorphic to $E$, see Limits, Lemma 10.3. Pick $0 \in I$ and denote $E \subset Y_0$ the constructible subset where the geometric fibres of $f_0$ are connected, see More on Morphisms, Lemma 26.6. Then $Y \to Y_0$ maps into $E$, see More on Morphisms, Lemma 26.2. Thus $Y_i \to Y_0$ maps into $E$ for $i \gg 0$, see Limits, Lemma 10.1. Hence we see that the fibres of $f_i$ are geometrically connected for $i \gg 0$. By Limits, Lemma 10.1 for large enough $i$ we can find morphisms $Y_{i,a} \to Y_i$ of finite type whose base change to $Y$ recovers $Y_a \to Y$, $a \in \{1, \ldots, N\}$. After possibly increasing $i$ we can find thickenings $Z_{i,a} \subset Y_{i,a} \times_{Y_i} X_i$ whose base change to $Y_a \times_Y X$ recovers $Z_a$ (same reference as before combined with Limits, Lemmas 8.5 and 8.14). Since $Z_a = \lim_{i} Z_{i,a}$ we find that after increasing $i$ we may assume $F^m_{\alpha^a} \cdot E_i|_{Z_{i,a}} \cong \mathcal{O}_{Z_{i,a}}^{\geq m}$, see Limits, Lemma 10.2. Finally, after increasing $i$ one more time we may assume $\bigsquare_{Y_{i,a}} \to Y_i$ is surjective by Limits, Lemma 8.14. At this point all the assumptions hold for $X_i \to Y_i$ and $E_i$ and we see that it suffices to prove result for $X_i \to Y_i$ and $E_i$.

Assume $Y$ is of finite type over $\mathbf{F}_p$. To prove the result we will use induction on $\dim(Y)$. We are trying to find an object of $\colim_F \mathop{	ext{Vect}}(Y)$ which pulls back to the object of $\colim_F \mathop{	ext{Vect}}(X)$ determined by $E$. By the fully faithfulness already proven and because of Proposition 39.4 it suffices to construct a descent of $E$ after replacing $Y$ by the members of a $\kappa$ covering and $X$ by the corresponding base change. This means that we may replace $Y$ by a scheme proper and surjective over $Y$ provided this does not increase the dimension of $Y$. If $T \subset T'$ is a thickening of schemes of finite type over $\mathbf{F}_p$, then $\colim_F \mathop{	ext{Vect}}(T) = \colim_F \mathop{	ext{Vect}}(T')$ as $\{T \to T'\}$ is a $\kappa$ covering such that $T \times_{T'} T = T$. If $T' \to T$ is a universal homeomorphism of schemes of finite type over $\mathbf{F}_p$, then $\colim_F \mathop{	ext{Vect}}(T) = \colim_F \mathop{	ext{Vect}}(T')$ as $\{T \to T'\}$ is a $\kappa$ covering such that the diagonal $T \subset T \times_{T'} T$ is a thickening.

Using the general remarks made above, we may and do replace $X$ by its reduction and we may assume $X$ is reduced. Consider the Stein factorization $X \to Y' \to Y$, see More on Morphisms, Theorem 48.4. Then $Y' \to Y$ is a universal homeomorphism of schemes of finite type over $\mathbf{F}_p$. By the above we may replace $Y$ by $Y'$. Thus we may assume $f_*\mathcal{O}_X = \mathcal{O}_Y$ and that $Y$ is reduced. This reduces us to the case discussed in the next paragraph.

Assume $Y$ is reduced and $f_*\mathcal{O}_X = \mathcal{O}_Y$ over a dense open subscheme of $Y$. Then $X \to Y$ is flat over a dense open subscheme $V \subset Y$, see Morphisms, Proposition 26.2. By Lemma 31.1 there is a $V$-admissible blowing up $Y' \to Y$ such that the strict transform $X'$ of $X$ is flat over $Y'$. Observe that $\dim(Y') = \dim(Y)$ as $Y$ and $Y'$ have a common dense open subscheme. By More on Morphisms, Lemma 48.7 and the fact that $V \subset Y'$ is dense all fibres of $f' : X' \to Y'$ are geometrically connected. We still have $(f'_*\mathcal{O}_{X'})|_V = \mathcal{O}_Y$. Write

$$Y' \times_Y X = X' \cup E \times_Y X$$
where $E \subset Y'$ is the exceptional divisor of the blowing up. By the general remarks above, it suffices to prove existence for $Y' \times_Y X \to Y'$ and the restriction of $\mathcal{E}$ to $Y' \times_Y X$. Suppose that we find some object $\xi'$ in \( \text{colim}_F \mathcal{V}ect(Y') \) pulling back to the restriction of $\mathcal{E}$ to $X'$. Then the fully faithfulness determines a unique isomorphism $\xi'|_E \to \xi''$ compatible with the given identifications with the restriction of $\mathcal{E}$ to $E \times_{Y'} X'$. Since 
\[
\{ E \times_Y X \to Y' \times_Y X, X' \to Y' \times_Y X \}
\]
is a h covering given by a pair of closed immersions with 
\[
(E \times_Y X) \times_{(Y' \times_Y X)} X' = E \times_{Y'} X'
\]
we conclude that $\xi'$ pulls back to the restriction of $\mathcal{E}$ to $Y' \times_Y X$. Thus it suffices to find $\xi'$ and we reduce to the case discussed in the next paragraph.

Assume $Y$ is reduced, $f$ is flat, and $f_*\mathcal{O}_X = \mathcal{O}_Y$ over a dense open subscheme of $Y$. In this case we consider the normalization $Y'' \to Y$ (Morphisms, Section 52). This is a finite surjective morphism (Morphisms, Lemma 32.10 and 17.2) which is an isomorphism over a dense open. Hence by our general remarks we may replace $Y$ by $Y''$ and $X$ by $Y'' \times_Y X$. After this replacement we see that $\mathcal{O}_Y = f_*\mathcal{O}_X$ (because the Stein factorization has to be an isomorphism in this case; small detail omitted).

Assume $Y$ is a normal Noetherian scheme, that $f$ is flat, and that $f_*\mathcal{O}_X = \mathcal{O}_Y$. After replacing $\mathcal{E}$ by a suitable Frobenius power pullback, we may assume $\mathcal{E}$ is trivial on the scheme theoretic fibres of $f$ at the generic points of the irreducible components of $Y$ (because colim $\mathcal{V}ect(-)$ is an equivalence on universal homeomorphisms, see above). Similarly to the arguments above (in the reduction to the Noetherian case) we conclude there is a dense open subscheme $V \subset Y$ such that $\mathcal{E}|_{f^{-1}(V)}$ is free. Let $Z \subset Y$ be a closed subscheme such that $Y = V \amalg Z$ set theoretically. Let $z_1, \ldots, z_t \in Z$ be the generic points of the irreducible components of $Z$ of codimension 1. Then $A_i = \mathcal{O}_{Y, z_i}$ is a discrete valuation ring. Let $n_i$ be the integer found in Lemma 39.5 for the scheme $X_{A_i}$ over $A_i$. After replacing $\mathcal{E}$ by a suitable Frobenius power pullback, we may assume $\mathcal{E}$ is free over $X_{A_i/m^{-n_i}}$ (again because the colimit category is invariant under universal homeomorphisms, see above). Then Lemma 39.5 tells us that $\mathcal{E}$ is free on $X_{A_i}$. Thus finally we conclude by applying Lemma 39.5.

40. Blowing up complexes

0ESM This section finds normal forms for perfect objects of the derived category after blowups.

0ESP Lemma 40.1. Let $X$ be a scheme. Let $E \in D(\mathcal{O}_X)$ be pseudo-coherent. For every $p, k \in \mathbb{Z}$ there is an finite type quasi-coherent sheaf of ideals $\text{Fit}_{p,k}(E) \subset \mathcal{O}_X$ with the following property: for $U \subset X$ open such that $E|_U$ is isomorphic to 
\[
\cdots \to \mathcal{O}_U^n_{n_{k-2}} \xrightarrow{d_{k-2}} \mathcal{O}_U^n_{n_{k-1}} \xrightarrow{d_{k-1}} \mathcal{O}_U^n_{n_k} \to 0 \to \cdots
\]
the restriction $\text{Fit}_{p,k}(E)|_U$ is generated by the minors of the matrix of $d_p$ of size 
\[-k + n_{p+1} - n_{p+2} + \ldots + (-1)^{b-p+1} n_b
\]
Convention: the ideal generated by \( r \times r \)-minors is \( \mathcal{O}_U \) if \( r \leq 0 \) and the ideal generated by \( r \times r \)-minors where \( r > \min(n_p, n_{p+1}) \) is zero.

**Proof.** Observe that \( E \) locally on \( X \) has the shape as stated in the lemma, see More on Algebra, Section 62, Cohomology, Section 13, and Derived Categories of Schemes, Section 9. Thus it suffices to prove that the ideal of minors is independent of the chosen representative. To do this, it suffices to check in local rings. Over a local ring \((R, \mathfrak{m}, \kappa)\) consider a bounded above complex

\[
F^* : \ldots \to R^\oplus n_{b-2} \xrightarrow{d_{b-2}} R^\oplus n_{b-1} \xrightarrow{d_{b-1}} R^\oplus n_b \to 0 \to \ldots
\]

Denote \( \text{Fit}_{p,k}(F^*) \subset R \) the ideal generated by the minors of size \( k - n_{p+1} + n_{p+2} - \ldots + (-1)^{b-p}n_b \) in the matrix of \( d_p \). Suppose some matrix coefficient of some differential of \( F^* \) is invertible. Then we pick a largest integer \( i \) such that \( d_i \) has an invertible matrix coefficient. By Algebra, Lemma 101.2 the complex \( F^* \) is isomorphic to a direct sum of a trivial complex \( \ldots \to 0 \to R \to R \to 0 \to \ldots \) with nonzero terms in degrees \( i \) and \( i + 1 \) and a complex \((F')^*\). We leave it to the reader to see that \( \text{Fit}_{p,k}(F^*) = \text{Fit}_{p,k}((F')^*) \); this is where the formula for the size of the minors is used. If \((F')^*\) has another differential with an invertible matrix coefficient, we do it again, etc. Continuing in this manner, we eventually reach a complex \((F^\infty)^*\) all of whose differentials have matrices with coefficients in \( \mathfrak{m} \). Here you may have to do an infinite number of steps, but for any cutoff only a finite number of these steps affect the complex in degrees \( \geq \) the cutoff. Thus the “limit” \((F^\infty)^*\) is a well defined bounded above complex of finite free modules, comes equipped with a quasi-isomorphism \((F^\infty)^* \to F^*\) into the complex we started with, and \( \text{Fit}_{p,k}(F^*) = \text{Fit}_{p,k}((F^\infty)^*) \). Since the complex \((F^\infty)^*\) is unique up to isomorphism by More on Algebra, Lemma 71.5 the proof is complete. \( \square \)

**Lemma 40.2.** Let \( X \) be a scheme. Let \( E \in D(\mathcal{O}_X) \) be perfect. Let \( U \subset X \) be a scheme theoretically dense open subscheme such that \( H^i(E|_U) \) is finite locally free of constant rank \( r_i \) for all \( i \in \mathbb{Z} \). Then there exists a \( U \)-admissible blowup \( i : X' \to X \) such that \( H^i(Lb^*E) \) is a perfect \( \mathcal{O}_{X'} \)-module of tor dimension \( \leq 1 \) for all \( i \in \mathbb{Z} \).

**Proof.** We will construct the blowup affine locally. Namely, suppose that \( V \subset X \) is an affine open subscheme such that \( E|_V \) can be represented by the complex

\[
\mathcal{O}_V^\oplus n_a \xrightarrow{d_a} \ldots \xrightarrow{d_{n-1}} \mathcal{O}_V^\oplus n_b
\]

Set \( k_i = r_{i+1} - r_{i+2} + \ldots + (-1)^{b-i+1}r_b \). A computation which we omit show that over \( U \cap V \) the rank of \( d_i \) is

\[
\rho_i = -k_i + n_{i+1} - n_{i+2} + \ldots + (-1)^{b-i+1}n_b
\]

in the sense that the cokernel of \( d_i \) is finite locally free of rank \( n_{i+1} - \rho_i \). Let \( I_i \subset \mathcal{O}_V \) be the ideal generated by the minors of size \( \rho_i \times \rho_i \) in the matrix of \( d_i \).

On the one hand, comparing with Lemma 40.1 we see the ideal \( I_i \) corresponds to the global ideal \( \text{Fit}_{i,k_i}(E) \) which was shown to be independent of the choice of the complex representing \( E|_V \). On the other hand, \( I_i \) is the \((n_{i+1} - \rho_i)\)th Fitting ideal of \( \text{Coker}(d_i) \). Please keep this in mind.

We let \( b : X' \to X \) be the blowing up in the product of the ideals \( \text{Fit}_{i,k}(E) \): this makes sense as locally on \( X \) almost all of these ideals are equal to the unit ideal (see above). This blowup dominates the blowups \( b_i : X'_i \to X \) in the ideals \( \text{Fit}_{i,k}(E) \),
see Divisors, Lemma \[32.12\]. By Divisors, Lemma \[35.3\] each \(b_i\) is a \(U\)-admissible blowup. It follows that \(b\) is a \(U\)-admissible blowup (tiny detail omitted; compare with the proof of Divisors, Lemma \[34.4\]). Finally, \(U\) is still a scheme theoretically dense open subscheme of \(X'\). Thus after replacing \(X\) by \(X'\) we end up in the situation discussed in the next paragraph.

Assume \(\text{Fit}_{i,k}(E)\) is an invertible ideal for all \(i\). Choose an affine open \(V\) and a complex of finite free modules representing \(E|_V\) as above. It follows from Divisors, Lemma \[35.3\] that \(\text{Ker}(d_i)\) has tor dimension \(\leq 1\). Thus \(\text{Im}(d_i)\) is finite locally free as the kernel of a map from a finite locally free module to a finitely presented module of tor dimension \(\leq 1\). Hence \(\text{Ker}(d_i)\) is finite locally free as well (same argument). Thus the short exact sequence

\[0 \to \text{Im}(d_{i-1}) \to \text{Ker}(d_i) \to H^i(E)|_V \to 0\]

shows what we want and the proof is complete. \(\square\)

**Lemma 40.3.** Let \(X\) be an integral scheme. Let \(E \in D(\mathcal{O}_X)\) be perfect. Then there exists a nonempty open \(U \subset X\) such that \(H^i(E|_U)\) is finite locally free of constant rank \(r_i\) for all \(i \in \mathbb{Z}\) and there exists a \(U\)-admissible blowup \(b : X' \to X\) such that \(H^i(Lb^*E)\) is a perfect \(\mathcal{O}_{X'}\)-module of tor dimension \(\leq 1\) for all \(i \in \mathbb{Z}\).

**Proof.** We strongly urge the reader to find their own proof of the existence of \(U\). Let \(\eta \in X\) be the generic point. The restriction of \(E\) to \(\eta\) is isomorphic in \(D(\kappa(\eta))\) to a finite complex \(V^*\) of finite dimensional vector spaces with zero differentials. Set \(r_i = \dim_{\kappa(\eta)} V_i^1\). Then the perfect object \(E'\) in \(D(\mathcal{O}_X)\) represented by the complex with terms \(\mathcal{O}_X^{\oplus r_i}\) and zero differentials becomes isomorphic to \(E\) after pulling back to \(\eta\). Hence by Derived Categories of Schemes, Lemma \[32.9\] there is an open neighbourhood \(U\) of \(\eta\) such that \(E|_U\) and \(E'|_U\) are isomorphic. This proves the first assertion. The second follows from the first and Lemma \[40.2\] as any nonempty open is scheme theoretically dense in the integral scheme \(X\). \(\square\)

**Remark 40.4.** Let \(X\) be a scheme. Let \(E \in D(\mathcal{O}_X)\) be a perfect object such that \(H^i(E)\) is a perfect \(\mathcal{O}_X\)-module of tor dimension \(\leq 1\) for all \(i \in \mathbb{Z}\). This property sometimes allows one to reduce questions about \(E\) to questions about \(H^i(E)\). For example, suppose

\[
\mathcal{E}^a \xrightarrow{d^a} \ldots \xrightarrow{d^{b-2}} \mathcal{E}^{b-1} \xrightarrow{d^{b-1}} \mathcal{E}^b
\]

is a bounded complex of finite locally free \(\mathcal{O}_X\)-modules representing \(E\). Then \(\text{Im}(d^i)\) and \(\text{Ker}(d^i)\) are finite locally free \(\mathcal{O}_X\)-modules for all \(i\). Namely, suppose by induction we know this for all indices bigger than \(i\). Then we can first use the short exact sequence

\[0 \to \text{Im}(d^i) \to \text{Ker}(d^{i+1}) \to H^{i+1}(E) \to 0\]

and the assumption that \(H^{i+1}(E)\) is perfect of tor dimension \(\leq 1\) to conclude that \(\text{Im}(d^i)\) is finite locally free. The same argument used again for the short exact sequence

\[0 \to \text{Ker}(d^i) \to \mathcal{E}^i \to \text{Im}(d^i) \to 0\]

then gives that \(\text{Ker}(d^i)\) is finite locally free. It follows that the distinguished triangles

\[
\tau_{\leq k-1}E \to \tau_{\leq k}E \to H^k(E)[-k] \to (\tau_{\leq k-1}E)[1]
\]
are represented by the following short exact sequences of bounded complexes of finite locally free modules

\[
\begin{array}{ccccccc}
0 & & & & & & \\
\downarrow & & & & & & \\
E^n & \rightarrow & \ldots & \rightarrow & E^{k-2} & \rightarrow & \text{Ker}(d^{k-1}) \\
\downarrow & & & & & & \\
E^n & \rightarrow & \ldots & \rightarrow & E^{k-2} & \rightarrow & \text{Ker}(d^k) \\
\downarrow & & & & & & \\
\text{Im}(d^{k-1}) & \rightarrow & \text{Ker}(d^k) & \rightarrow & 0
\end{array}
\]

Here the complexes are the rows and the “obvious” zeros are omitted from the display.

41. Blowing up perfect modules

0F8K This section tries to find normal forms for perfect modules of tor dimension ≤ 1 after blowups. We are only partially successful.

Lemma 41.1. Let X be a scheme. Let \( F \) be a perfect \( \mathcal{O}_X \)-module of tor dimension ≤ 1. For any blowup \( b : X' \rightarrow X \) we have \( Lb^*F = b^*F \) and \( b^*F \) is a perfect \( \mathcal{O}_X \)-module of tor dimension ≤ 1.

Proof. We may assume \( X = \text{Spec}(A) \) is affine and we may assume the \( A \)-module \( M \) corresponding to \( F \) has a presentation

\[
0 \rightarrow A^{\oplus m} \rightarrow A^{\oplus n} \rightarrow M \rightarrow 0
\]

Suppose \( I \subset A \) is an ideal and \( a \in I \). Recall that the affine blowup algebra \( A[\frac{I}{a}] \) is a subring of \( A_a \). Since localization is exact we see that \( A_a^{\oplus m} \rightarrow A_a^{\oplus n} \) is injective. Hence \( A[\frac{I}{a}]^{\oplus m} \rightarrow A[\frac{I}{a}]^{\oplus n} \) is injective too. This proves the lemma. □

0EST Lemma 41.2. Let X be a scheme. Let \( \mathcal{F} \) be a perfect \( \mathcal{O}_X \)-module of tor dimension ≤ 1. Let \( U \subset X \) be a scheme theoretically dense open such that \( \mathcal{F}|_U \) is finite locally free of constant rank \( r \). Then there exists a \( U \)-admissible blowup \( b : X' \rightarrow X \) such that there is a canonical short exact sequence

\[
0 \rightarrow K \rightarrow b^*\mathcal{F} \rightarrow Q \rightarrow 0
\]

where \( Q \) is finite locally free of rank \( r \) and \( K \) is a perfect \( \mathcal{O}_X \)-module of tor dimension ≤ 1 whose restriction to \( U \) is zero.

Proof. Combine Divisors, Lemma 35.3 and Lemma 41.1 □

0ESU Lemma 41.3. Let X be a scheme. Let \( \mathcal{F} \) be a perfect \( \mathcal{O}_X \)-module of tor dimension ≤ 1. Let \( U \subset X \) be an open such that \( \mathcal{F}|_U = 0 \). Then there is a \( U \)-admissible blowup \( b : X' \rightarrow X \)

such that \( \mathcal{F}' = b^*\mathcal{F} \) is equipped with two canonical locally finite filtrations

\[
0 = F^0 \subset F^1 \subset F^2 \subset \ldots \subset \mathcal{F}' \quad \text{and} \quad \mathcal{F}' = F_1 \supset F_2 \supset F_3 \supset \ldots \supset 0
\]

such that for each \( n \geq 1 \) there is an effective Cartier divisor \( D_n \subset X' \) with the property that

\[
F^i/F^{i-1} \quad \text{and} \quad F_i/F_{i+1}
\]
are finite locally free of rank \(i\) on \(D_i\).

**Proof.** Choose an affine open \(V \subset X\) such that there exists a presentation

\[ 0 \to \mathcal{O}_V^{\oplus n} \xrightarrow{A} \mathcal{O}_V^{\oplus n} \to \mathcal{F} \to 0 \]

for some \(n\) and some matrix \(A\). The ideal we are going to blowup in is the product of the Fitting ideals \(\text{Fit}_k(\mathcal{F})\) for \(k \geq 0\). This makes sense because in the affine situation above we see that \(\text{Fit}_k(\mathcal{F})|_V = \mathcal{O}_V\) for \(k > n\). It is clear that this is a \(U\)-admissible blowing up. By Divisors, Lemma 32.12 we see that on \(X\) the ideals \(\text{Fit}_k(\mathcal{F})\) are invertible. Thus we reduce to the case discussed in the next paragraph.

Assume \(\text{Fit}_k(\mathcal{F})\) is an invertible ideal for \(k \geq 0\). If \(E_k \subset X\) is the effective Cartier divisor defined by \(\text{Fit}_k(\mathcal{F})\) for \(k \geq 0\), then the effective Cartier divisors \(D_k\) in the statement of the lemma will satisfy

\[ E_k = D_{k+1} + 2D_{k+2} + 3D_{k+3} + \ldots \]

This makes sense as the collection \(D_k\) will be locally finite. Moreover, it uniquely determines the effective Cartier divisors \(D_k\) hence it suffices to construct \(D_k\) locally.

Choose an affine open \(V \subset X\) and presentation of \(\mathcal{F}|_V\) as above. We will construct the divisors and filtrations by induction on the integer \(n\) in the presentation. We set \(D_k|_V = \emptyset\) for \(k > n\) and we set \(D_n|_V = E_{n-1}|_V\). After shrinking \(V\) we may assume that \(\text{Fit}_{n-1}(\mathcal{F})|_V\) is generated by a single nonzerodivisor \(f \in \Gamma(V, \mathcal{O}_V)\). Since \(\text{Fit}_{n-1}(\mathcal{F})|_V\) is the ideal generated by the entries of \(A\), we see that there is a matrix \(A'\) in \(\Gamma(V, \mathcal{O}_V)\) such that \(A = fA'\). Define \(\mathcal{F}'\) on \(V\) by the short exact sequence

\[ 0 \to \mathcal{O}_V^{\oplus n} \xrightarrow{A'} \mathcal{O}_V^{\oplus n} \to \mathcal{F}' \to 0 \]

Since the entries of \(A'\) generate the unit ideal in \(\Gamma(V, \mathcal{O}_V)\) we see that \(\mathcal{F}'\) locally on \(V\) has a presentation with \(n\) decreased by 1, see Algebra, Lemma 101.3. Further note that \(f^{n-k}\text{Fit}_k(\mathcal{F}') = \text{Fit}_k(\mathcal{F})|_V\) for \(k = 0, \ldots, n\). Hence \(\text{Fit}_k(\mathcal{F}')\) is an invertible ideal for all \(k\). We conclude by induction that there exist effective Cartier divisors \(D'_k \subset V\) such that \(\mathcal{F}'\) has two canonical filtrations as in the statement of the lemma. Then we set \(D_k|_V = D'_k\) for \(k = 1, \ldots, n - 1\). Observe that the equalities between effective Cartier divisors displayed above hold with these choices. Finally, we come to the construction of the filtrations. Namely, we have short exact sequences

\[ 0 \to \mathcal{O}_{D_{n-\emptyset} \cap V}^{\oplus n} \to \mathcal{F} \to \mathcal{F}' \to 0 \quad \text{and} \quad 0 \to \mathcal{F}' \to \mathcal{F} \to \mathcal{O}_{\overline{D}_{n-\emptyset} \cap V}^{\oplus n} \to 0 \]

coming from the two factorizations \(A = A'f = fA'\) of \(A\). These sequences are canonical because in the first one the submodule is \(\ker(f : \mathcal{F} \to \mathcal{F}')\) and in the second one the quotient module is \(\text{coker}(f : \mathcal{F} \to \mathcal{F})\).

**Lemma 41.4.** Let \(X\) be a scheme. Let \(\varphi : \mathcal{F} \to \mathcal{G}\) be a homorphism of perfect \(\mathcal{O}_X\)-modules of tor dimension \(\leq 1\). Let \(U \subset X\) be a scheme theoretically dense open such that \(\mathcal{F}|_U = 0\) and \(\mathcal{G}|_U = 0\). Then there is a \(U\)-admissible blowup \(b : X' \to X\) such that the kernel, image, and cokernel of \(b^*\varphi\) are perfect \(\mathcal{O}_{X'}\)-modules of tor dimension \(\leq 1\).

**Proof.** The assumptions tell us that the object \((\mathcal{F} \to \mathcal{G})\) of \(D(\mathcal{O}_X)\) is perfect. Thus we get a \(U\)-admissible blowup that works for the cokernel and kernel by Lemmas 40.2 and 41.1 (to see what the complex looks like after pullback). The image is the kernel of the cokernel and hence is going to be perfect of tor dimension \(\leq 1\) as well. 

\[\square\]
42. An operator introduced by Berthelot and Ogus

Let $X$ be a scheme and let $D \subset X$ be an effective Cartier divisor with ideal sheaf $\mathcal{I} \subset \mathcal{O}_X$. If $\mathcal{F}$ is an $\mathcal{O}_X$-module, then the following are equivalent

1. the subsheaf $\mathcal{F}^i[1] \subset \mathcal{F}$ of sections annihilated by $\mathcal{I}$ (compare with Properties, Definition [24.3]) is zero,

2. the multiplication map $\mathcal{I} \otimes_{\mathcal{O}_X} \mathcal{F} \to \mathcal{F}$ is injective,

3. for every affine open $U = \text{Spec}(A)$ such that $D \cap U = V(f)$ for a nonzero-divisor $f \in A$ (Divisors, Lemma [13.2]), the map $f : \mathcal{F}|_U \to \mathcal{F}|_U$ is injective,

4. for every $x \in D$ and generator $f$ of the ideal $\mathcal{I}_x \subset \mathcal{O}_{X,x}$ the element $f$ is a nonzerodivisor on the stalk $\mathcal{F}_x$.

If these equivalent conditions hold, then we will say that $\mathcal{F}$ is $\mathcal{I}$-torsion free. If so, then for any $i \in \mathbb{Z}$ we will denote

$$\mathcal{I}^i \mathcal{F} = \mathcal{I}^{\otimes i} \otimes_{\mathcal{O}_X} \mathcal{F} = \mathcal{O}_X(-iD) \otimes_{\mathcal{O}_X} \mathcal{F} = \mathcal{F}(-iD)$$

so that we have inclusions

$$\ldots \subset \mathcal{I}^{i+1} \mathcal{F} \subset \mathcal{I}^i \mathcal{F} \subset \mathcal{I}^{i-1} \mathcal{F} \subset \ldots$$

The modules $\mathcal{I}^i \mathcal{F}$ are locally isomorphic to $\mathcal{F}$ as $\mathcal{O}_X$-modules, but not globally.

Let $\mathcal{F}^\bullet$ be a complex of $\mathcal{O}_X$-modules with differentials $d^i : \mathcal{F}^i \to \mathcal{F}^{i+1}$ and assume $\mathcal{F}^i$ is $\mathcal{I}$-torsion free for all $i$. In this case we define $\eta_{\mathcal{I}} \mathcal{F}^\bullet$ to be the complex with terms

$$(\eta_{\mathcal{I}} \mathcal{F})^i = \text{Ker} \left( d^i, -1 : \mathcal{I}^i \mathcal{F}^i \oplus \mathcal{I}^{i+1} \mathcal{F}^{i+1} \to \mathcal{I}^i \mathcal{F}^{i+1} \right)$$

and differential induced by $d^i$. In other words, a local section $s$ of $(\eta_{\mathcal{I}} \mathcal{F})^i$ is the same thing as a local section $s'$ of $\mathcal{I}^i \mathcal{F}^i$ such that its image $d^i(s)$ in $\mathcal{I}^i \mathcal{F}^{i+1}$ is in the subsheaf $\mathcal{I}^{i+1} \mathcal{F}^{i+1}$. Observe that $\eta_{\mathcal{I}} \mathcal{F}^\bullet$ is another complex whose terms are $\mathcal{I}$-torsion free modules.

Lemma 42.1. Let $X$ be a scheme and let $D \subset X$ be an effective Cartier divisor with ideal sheaf $\mathcal{I} \subset \mathcal{O}_X$. Let $\mathcal{F}^\bullet$ be a complex of $\mathcal{O}_X$-modules such that $\mathcal{F}^i$ is $\mathcal{I}$-torsion free for all $i$.

1. For $x \in X$ choose a generator $f \in \mathcal{I}_x$. Then the stalk of $\eta_{\mathcal{I}} \mathcal{F}^\bullet$ is canonically isomorphic to $\eta_f \mathcal{F}^\bullet$.

2. If the $\mathcal{F}^i$ are quasi-coherent $\mathcal{O}_X$-modules, then so are the $(\eta_{\mathcal{I}} \mathcal{F})^i$ and in this case if $U = \text{Spec}(A) \subset X$ is affine open and $D \cap U = V(f)$, then $\eta_f(\mathcal{F}^\bullet(U))$ is canonically isomorphic to $(\eta_{\mathcal{I}} \mathcal{F}^\bullet)(U)$.

Proof. Omitted.

Lemma 42.2. Let $X$ be a scheme and let $D \subset X$ be an effective Cartier divisor with ideal sheaf $\mathcal{I} \subset \mathcal{O}_X$. Let $\mathcal{F}^\bullet$ be a complex of $\mathcal{O}_X$-modules such that $\mathcal{F}^i$ is $\mathcal{I}$-torsion free for all $i$. There is a canonical isomorphism

$$\mathcal{I}^{\otimes i} \otimes_{\mathcal{O}_X} \left( H^i(\mathcal{F}^\bullet)/H^i(\mathcal{F}^\bullet)[\mathcal{I}] \right) \to H^i(\eta_{\mathcal{I}} \mathcal{F}^\bullet)$$

of cohomology sheaves.

---

4In this section we work with $\mathcal{O}_X$-modules which are not necessarily quasi-coherent.
Proof. Via Lemma 42.1 this translates into the result of More on Algebra, Lemma 87.1.

**Lemma 42.3.** Let $X$ be a scheme and let $D \subset X$ be an effective Cartier divisor with ideal sheaf $I \subset \mathcal{O}_X$. Let $\mathcal{F}^\bullet \to \mathcal{G}^\bullet$ be a map of complexes of $\mathcal{O}_X$-modules such that $\mathcal{F}^i$ and $\mathcal{G}^i$ are $I$-torsion free for all $i$. Then the induced map $\eta_I^* \mathcal{F}^\bullet \to \eta_I^* \mathcal{G}^\bullet$ is a quasi-isomorphism too.

**Proof.** This is true because the isomorphisms of Lemma 42.2 are compatible with maps of complexes.

**Remark 42.4.** Let $X$ be a scheme and let $D \subset X$ be an effective Cartier divisor with ideal sheaf $I \subset \mathcal{O}_X$. Let $\mathcal{F}^\bullet$ be a complex of $\mathcal{O}_X$-modules. By Cohomology, Lemma 26.11 there exists a quasi-isomorphism $F^\bullet \to G^\bullet$ such that $F^i$ and $G^i$ are $I$-torsion free for all $i$. In this situation we define

$$L \eta_I^* \mathcal{G}^\bullet = \eta_I^* \mathcal{F}^\bullet$$

This is independent of the choice of the K-flat resolution by Lemma 42.3. We obtain a functor $L \eta_I : D(\mathcal{O}_X) \to D(\mathcal{O}_X)$.

**Lemma 42.5.** Let $X$ be a scheme and let $D \subset X$ be an effective Cartier divisor with ideal sheaf $I \subset \mathcal{O}_X$. Let $\mathcal{F}^\bullet$ be a complex of $\mathcal{O}_X$-modules such that $\mathcal{F}^i$ is $I$-torsion free for all $i$. Let $\mathcal{L}$ be an invertible $\mathcal{O}_X$-module. Then $\eta_I(\mathcal{F}^\bullet \otimes \mathcal{L}) = (\eta_I \mathcal{F}^\bullet) \otimes \mathcal{L}$.

**Proof.** Immediate from the construction.

### 43. Blowing up complexes, II

The material in this section will be used to construct a version of Macpherson’s graph construction in Section 44.

**Situation 43.1.** Here $X$ is a scheme, $D \subset X$ is an effective Cartier divisor with ideal sheaf $I \subset \mathcal{O}_X$, and $\mathcal{E}^\bullet$ is a bounded complex of finite locally free $\mathcal{O}_X$-modules with differentials $d^i : \mathcal{E}^i \to \mathcal{E}^{i+1}$.

We are going to construct a canonical blowing up of this situation.

**Remark 43.2.** In Situation 43.1 for any $i \in \mathbb{Z}$ there exists a finite type quasi-coherent sheaf of ideals $\mathcal{J}_i \subset \mathcal{O}_X$ with the following property: for any $U \subset X$ open such that $I(U)$, $\mathcal{E}^i|_U$, and $\mathcal{E}^{i+1}|_U$ are free of ranks $1$, $r_i$, and $r_{i+1}$, the ideal $\mathcal{J}_i$ is generated by the $r_i \times r_i$ minors of the map

$$1, d^i : \mathcal{E}^i \longrightarrow \mathcal{E}^i \oplus I \mathcal{E}^{i+1}$$

with notation as in Section 42. By convention we set $\mathcal{J}_i|_U = \mathcal{O}_U$ if $r_i = 0$. Observe that $I^{r_i}|_U \subset \mathcal{J}_i|_U$ in other words, the closed subscheme $V(\mathcal{J})$ is set theoretically contained in $D$. Formation of the ideal $\mathcal{J}_i$ commutes with base change by any morphism $f : Y \to X$ such that the pullback of $D$ by $f$ is defined (Divisors, Definition 13.12).
Lemma 43.3. In Situation 43.1 let \( D' = b^{-1}D \) with ideal sheaf \( T' \subset \mathcal{O}_{X'} \).

Then

\[
\mathcal{Q}^* = \eta_{T'} b^* \mathcal{E}^*
\]

is a bounded complex of finite locally free \( \mathcal{O}_{X'} \)-modules.

Proof. Recall that \( D' \) is an effective Cartier divisor (Divisors, Lemma 32.11). Observe that \( \mathcal{J}_i \) pulls back to an invertible ideal sheaf on \( X' \) as \( X' \) dominates the blowing up in \( \mathcal{J}_i \), see Divisors, Lemma 32.12. By Remark 43.2 we may replace \( X \) by \( X' \) and assume \( \mathcal{J}_i \) is invertible for all \( i \). Via Lemma 42.1 we obtain the result from More on Algebra, Lemma 88.1 \( \square \)

Lemma 43.4. In Situation 43.1 let \( f : Y \to X \) be a morphism of schemes such that the inverse image \( f^{-1}D \) is an effective Cartier divisor with ideal sheaf \( \mathcal{J} \).

Assume \( \mathcal{J}_i \) as in Remark 43.2 is invertible for all \( i \). Then \( f^*(\eta_{\mathcal{J}} \mathcal{E}^*) = \eta_{\mathcal{J}} (f^* \mathcal{E}^*) \).

Proof. Follows from More on Algebra, Lemma 88.2 via Lemma 42.1 \( \square \)

Lemma 43.5. In Situation 43.1 let \( f : Y \to X \) be a morphism of schemes such that the inverse image \( f^{-1}D \) is an effective Cartier divisor. Let \( X' \to X \) and \( \mathcal{Q}^* \), resp. \( Y' \to Y \) and \( \mathcal{Q}'^* \), be as constructed in Lemma 43.3 for \( D \subset X \) and \( \mathcal{E}^* \), resp. \( f^{-1}D \subset Y \) and \( f^* \mathcal{E}^* \). Then \( Y' \) is the strict transform of \( Y \) with respect to \( X' \to X \) and \( \mathcal{Q}'^* = (Y' \to X')^* \mathcal{Q}^* \).

Proof. In Remark 43.2 we have seen that \( \mathcal{J}_i \) pulls back to the corresponding ideal on \( Y \). Hence \( Y' \) is the strict transform of \( Y \) by Divisors, Lemma 33.2. The final statement follows from Lemma 43.4 applied to \( Y' \to X' \).

Lemma 43.6. In Situation 43.1 let \( U \subset X \) be the maximal open subscheme over which the cohomology sheaves of \( \mathcal{E}^* \) are locally free. Then the blowing up \( b : X' \to X \) of Lemma 43.3 is an isomorphism over \( U \).

Proof. Over \( U \) all of the modules \( \text{Im}(d^i) \) and \( \text{Ker}(d^i) \) are finite locally free, see for example the discussion in Remark 40.4. Let \( x \in U \). Choose an open neighbourhood \( x \in V \subset U \) such that \( \mathcal{I}_V, \mathcal{E}^*, \text{Ker}(d^i), \text{Im}(d^i), \) and \( H^j(\mathcal{E}^*) \) are free and choose splittings for the short exact sequences

\[
0 \to \text{Im}(d^i) \to \text{Ker}(d^{i+1}) \to H^{i+1}(\mathcal{E}^*) \to 0 \quad \text{and} \quad 0 \to \text{Ker}(d^i) \to \mathcal{E}^i \to \text{Im}(d^i) \to 0
\]

Then we see that our complex looks like

\[
\ldots \to \mathcal{O}_V^{\oplus n_{i-1}+m_i+n_i} \to \mathcal{O}_V^{\oplus n_i+m_{i+1}+n_{i+1}} \to \ldots
\]

where the map identifies the last \( n_i \) summands with the first \( n_i \) summands. Thus \( \mathcal{J}_i|_V \) is the ideal generated by \( f^{n_{i-1}+m_i} \) where \( f \in \mathcal{O}_X(V) \) is a generator for \( \mathcal{I}_V \).

Thus over \( V \) we are blowing up an invertible ideal, which produces the identity morphism (Divisors, Lemma 32.7) \( \square \).

Lemma 43.7. In Situation 43.1 let \( b : X' \to X \), \( D' \subset X' \), and \( \mathcal{Q}^* \) be as in Lemma 43.3. Let \( U \subset X \) be as in Lemma 43.6. Then there exists a closed immersion \( T \to D' \) of finite presentation with \( D' \cap b^{-1}(U) \subset T \) scheme theoretically such that \( \mathcal{Q}^*|_T \) has finite locally free cohomology sheaves.
Proof. Arguing exactly as in the proof of Lemma 43.3 we may replace \( X \) by \( X' \) and \( U \) by \( b^{-1}(U) \) and assume that the ideals \( J_i \) are invertible for all \( i \).

Assume \( J_i \) invertible for all \( i \) so that \( b = \text{id}_X \) and \( Q_i^* = \eta_{T'} \mathcal{E}^* \). Let \( x \in D \cap U \) and choose a generator \( f \in \mathcal{I}_x \). Since \( H^i(\mathcal{E}^*)_x \) is a finite free \( \mathcal{O}_{X,x} \)-module for all \( i \) (by choice of \( U \) ), we see that

\[
\text{Ker}(d^i : \mathcal{E}_x^i/f^i \mathcal{E}_x^i \to \mathcal{E}_x^{i+1}/f^{i+1} \mathcal{E}_x^{i+1}) \to \text{Ker}(d^i : \mathcal{E}_x^i/f \mathcal{E}_x^i \to \mathcal{E}_x^{i+1}/f \mathcal{E}_x^{i+1})
\]

is surjective, see More on Algebra, Lemma 88.3. This means that if \( X = \text{Spec}(A) \) is affine, then via Lemma 42.1 we may apply More on Algebra, Lemma 88.4 to get a closed subscheme \( T \subset D \) with all the desired properties (some details omitted).

To glue this affine local construction, we remark that in the proof of More on Algebra, Lemma 88.6 the ideal cutting out \( T \) is constructed with a certain universal property. Namely, the result of More on Algebra, Lemma 88.1 tells us that the canonical maps

\[
e^j : Q^i \rightarrow T \mathcal{E}^i \oplus T^{i+1} \mathcal{E}^{i+1}
\]

are locally split. The closed subscheme \( T \subset D \) is characterized by the property that a morphism of schemes \( g : W \rightarrow D \) factors through \( T \) if and only if \( g^*Q^i \) is a direct sum of sheaves compatible with the map \( g^*e^j \) for all \( i \). Hence it is clear that the affine locally constructed closed subschemes glue. \( \square \)

Lemma 43.8. In Situation 43.4. Let \( b : X' \rightarrow X \), \( D' \subset X' \), and \( \mathcal{Q}^* \) be as in Lemma 43.3. Given integers \( \rho_i \geq 0 \) almost all zero, let \( U' \subset X \) be the maximal open subscheme where \( H^i(\mathcal{E}^*) \) is finite locally free of rank \( \rho_i \) for all \( i \). Let \( T \subset D' \) be as in Lemma 43.7. Then there exists an open and closed subscheme \( T' \subset T \) containing \( D' \cap b^{-1}(U') \) scheme theoretically such that \( \mathcal{Q}^*|_{T'} \) has finite locally free cohomology sheaves \( H^i(\mathcal{Q}^*|_{T'}) \) of rank \( \rho_i \).

Proof. This is obvious. \( \square \)

Lemma 43.9. Let \( X \) be a scheme and let \( D \subset X \) be an effective Cartier divisor. Let \( E \in D(\mathcal{O}_X) \) be a perfect object. Let \( U \subset X \) be the maximal open over which the cohomology sheaves \( H^i(E) \) are locally free. There exists a proper morphism \( b : X' \rightarrow X \) and an object \( Q \in D(\mathcal{O}_{X'}) \) with the following properties

1. \( D' = b^{-1}(D) \) is an effective Cartier divisor,
2. \( Q = L_{X'X} b^*E \) where \( T' \) is the ideal sheaf of \( D' \),
3. \( Q \) is a perfect object of \( D(\mathcal{O}_{X'}) \),
4. there exists a closed immersion \( T \rightarrow D' \) of finite presentation with \( D' \cap b^{-1}(U) \subset T \) scheme theoretically such that \( Q|_T \) has finite locally free cohomology sheaves,
5. for any open subscheme \( V \subset X \) such that \( E|_V \) can be represented by a bounded complex \( \mathcal{E}^* \) of finite locally free \( \mathcal{O}_V \)-modules, the base changes of \( X' \rightarrow X \), \( Q \), \( D' \), and \( T \) to \( V \) are given by the constructions of Lemmas 43.3 and 43.7.

Proof. We first construct the morphism \( b : X' \rightarrow X \) by glueing the blowings up constructed over opens \( V \subset X \) as in (5). By Constructions, Lemma 2.1 to do this it suffices to show that given \( V \subset X \) open and two bounded complexes \( \mathcal{E}^* \) and \((E')^* \) of finite locally free \( \mathcal{O}_V \)-modules representing \( E|_V \) the resulting blowings ups are canonically isomorphic. To do this, it suffices, by the universal property of blowing up of Divisors, Lemma 32.5, to show that the ideals \( J_i \) and \( J'_i \) from Remark 43.2
In this section we give an "algebra version" of the version of Macpherson's graph when.

From More on Algebra, Lemma 71.7 working locally it suffices to prove the relationship

$$(\mathcal{E}')^* = \mathcal{E}^* \oplus (\ldots \to 0 \to \mathcal{O}_V \xrightarrow{1} \mathcal{O}_V \to 0 \to \ldots)$$

with the two summands $\mathcal{O}_V$ placed in degrees $i$ and $i + 1$ say. Computing minors explicitly one finds that $\mathcal{J}_{i+1} = \mathcal{I} \mathcal{J}_{i+1}$ and all other ideals stay the same.

Thus we have the morphism $b : X' \to X$ agreeing locally with the blowing ups in (5). Of course this immediately gives us the effective Cartier divisor $D' = b^{-1}D$, its invertible ideal sheaf $\mathcal{I}'$ and the object $Q = L\mathcal{I}'_W Lb^*\mathcal{E}$. See Remark 42.4 for the construction of $L\mathcal{I}'_W$. Since the construction commutes with restricting to opens we find that $Q|_{V'}$ is represented by the complex $Q^*$ over the open $V' = b^{-1}(V)$ constructed using $\mathcal{E}^*$ over $V$.

To finish the proof it suffices to show that the closed subschemes $T_V \subset V'$ constructed in Lemma 43.7 glue. Again by relative glueing, it suffices to show that the construction of $T$ does not depend on the choice of the complex $\mathcal{E}^*$ representing $E|_{V'}$. Again we reduce to the case where

$$(\mathcal{E}')^* = \mathcal{E}^* \oplus (\ldots \to 0 \to \mathcal{O}_V \xrightarrow{1} \mathcal{O}_V \to 0 \to \ldots)$$

with the two summands $\mathcal{O}_V$ placed in degrees $i$ and $i + 1$ say. Note that in this case $Q^*$ and $Q^*$ differ as follows

$$(Q^*)^* = Q^* \oplus (\ldots \to 0 \to (\mathcal{I}')^{i+1}|_{V'}, \xrightarrow{1} (\mathcal{I}')^{i+1}|_{V'} \to 0 \to \ldots)$$

In the proof of Lemma 43.7 we defined $T \subset D'$ as the largest closed subscheme of $D'$ such that $Q^*|_T$ is a direct sum of two parts compatible with the restriction to $T$ of the canonical split injective maps

$$c^i : Q^i \to (\mathcal{I}')^{i} b^*\mathcal{E}^i \oplus (\mathcal{I}')^{i+1} b^*\mathcal{E}^{i+1}$$

for all $i$. The direct sum decomposition for $(Q^*)^*$ in terms of $Q^*$ and the explicit complex $(\mathcal{I}')^{i+1}|_{V'} \to (\mathcal{I}')^{i+1}|_{V'}$ implies in a straightforward manner that $T$ plays the same role for $(Q^*)^*$ and the proof is complete.

44. Blowing up complexes, III

In this section we give an “algebra version” of the version of Macpherson’s graph construction given in [Ful98, Section 18.1].

Let $X$ be a scheme. Let $\mathcal{E}^*$ be a bounded complex of finite locally free $\mathcal{O}_X$-modules. Let $U \subset X$ be the maximal open subscheme such that $\mathcal{E}^*|_U$ has finite locally free cohomology sheaves.

Consider the projection morphism $p : \mathbf{P}_X^1 \to X$. The complement of the open subscheme $A_X \subset \mathbf{P}_X^1$ is the image $(\mathbf{P}_X^1)_\infty$ of the section $\infty : X \to \mathbf{P}_X^1$ of $p$ or equivalently the inverse image of the divisor at $\infty$ in $\mathbf{P}_Z^1$. Thus $(\mathbf{P}_X^1)_\infty \subset \mathbf{P}_X^1$ is an effective Cartier divisor.

Let

$$b : W \to \mathbf{P}_X^1$$

be the blowing up constructed in Lemma 43.3 starting with the effective Cartier divisor $(\mathbf{P}_X^1)_\infty \subset \mathbf{P}_X^1$ and the bounded complex $p^*\mathcal{E}^*$ of finite locally free modules. We also denote

$$Q^* = \eta_2 b^* p^* \mathcal{E}^*$$
the complex considered in Lemma 43.3 where \( \eta_I \) is the operator of Section 42 associated to the ideal sheaf \( I \) of the effective Cartier divisor \( W_\infty = b^{-1}(P^1_X)_\infty \) on \( W \).

**Lemma 44.1.** The construction above has the following properties:

1. \( b \) is an isomorphism over \( \mathbb{P}^1_U \cup \mathbb{A}^1_X \),
2. the restriction of \( Q^* \) to \( \mathbb{A}^1_X \) is equal to the pullback of \( E^* \),
3. there exists a closed immersion \( T \to W_\infty \) of finite presentation such that \( \infty(U) \subset T \) scheme theoretically and such that \( Q^*_T \) has finite locally free cohomology sheaves.

**Proof.** This follows immediately from the results in Section 43 especially Lemma 43.7.

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