

# Algebraic Geometry

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These notes, taken by Markus Himmel, will at times differ significantly from what was lectured. In particular, all errors are almost certainly my own.

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## Introduction

DEFINITION 0.1. Let  $A$  be a ring. Then  $\text{Spec } A := \{p \subseteq A \mid p \text{ a prime ideal}\}$ . For  $I \subseteq A$  an ideal, define

$$V(I) := \{p \subseteq A \mid p \text{ prime}, p \supseteq I\}.$$

PROPOSITION 0.2. The sets  $V(I)$  form the closed sets of a topology on  $\text{Spec } A$ , called the Zariski topology.

PROOF. (1)  $V(A) = \emptyset$

(2)  $V(0) = \text{Spec } A$

(3) If  $\{I_i\}_{i \in J}$  is a collection of ideals, then  $V(\sum_{i \in J} I_i) = \bigcap V(I_i)$ .

(4) We claim:  $V(I_1 \cap I_2) = V(I_1) \cup V(I_2)$ .

“ $\supseteq$ ” is obvious.

“ $\subseteq$ ”: Follows from the fact that  $p \supseteq I_1 \cap I_2$  is prime, then  $p \supseteq I_1$  or  $p \supseteq I_2$ .

□

EXAMPLE 0.3. Let  $A = k[X_1, \dots, X_n]$  with  $k$  algebraically closed. Let  $I \subseteq A$  be an ideal. Then the maximal ideals  $m$  of  $A$  containing  $I$  are in one-to-one correspondence with  $V(I)$  in  $\mathbb{A}^n(k)$ : by Nulstellensatz, every maximal ideal is of the form  $(X_1 - a_1, \dots, X_n - a_n)$ , which corresponds to  $(a_1, \dots, a_n)$  in the old  $V(I)$ .

The new  $V(I)$  now extends this notion of zero set by including other prime ideals.

EXAMPLE 0.4. If  $k$  is a field, then  $\text{Spec } k = \{0\}$ , so the topological space cannot see the field. We fix this by also thinking about what functions are on these spaces.



## CHAPTER 1

### Sheaves

REMARK. Fix a topological space  $X$ .

DEFINITION 1.1. A presheaf  $\mathcal{F}$  on  $X$  consists of

- (1) For every open set  $U \subseteq X$  an abelian group  $\mathcal{F}U$ ,
- (2) for every inclusion  $V \subseteq U \subseteq X$  a restriction map  $\rho_{UV}: \mathcal{F}U \rightarrow \mathcal{F}V$  such that  $\rho_{UU} = \text{id}_{\mathcal{F}U}$  and  $\rho_{UV} = \rho_{VW} \circ \rho_{UV}$ .

REMARK 1.2. A presheaf is just a contravariant functor from the poset category of open sets of  $X$  to the category of abelian groups.

We can generalize this to any contravariant functor  $X^{\text{op}} \rightarrow \mathcal{C}$  for some category  $\mathcal{C}$ .

DEFINITION 1.3. A morphism of presheaves  $f: \mathcal{F} \rightarrow \mathcal{G}$  on  $X$  is a collection of morphisms  $f_U: \mathcal{F}U \rightarrow \mathcal{G}U$  such that for all  $V \subseteq U$  the diagram

$$\begin{array}{ccc} \mathcal{F}U & \xrightarrow{f_U} & \mathcal{G}U \\ \downarrow \rho_{UV} & & \downarrow \rho_{UV} \\ \mathcal{F}V & \xrightarrow{f_V} & \mathcal{G}V \end{array}$$

commutes.

DEFINITION 1.4. A presheaf  $\mathcal{F}$  is called a sheaf if it satisfies additional axioms:

- (S1) If  $U \subseteq X$  is covered by an open cover  $\{U_i\}$  and  $s \in \mathcal{F}U$  satisfies  $s|_{U_i} := \rho_{UU_i}(s) = 0$  for all  $i$ , then  $s = 0$
- (S2) If  $U$ , and  $U_i$  are as before, and if  $s_i \in \mathcal{F}U_i$  such that for all  $i$  and  $j$  we have  $s_i|_{U_i \cap U_j} = s_j|_{U_i \cap U_j}$ , then there is some  $s \in \mathcal{F}U$  such that  $s|_{U_i} = s_i$  for all  $i$ .

REMARK 1.5. (1) If  $\mathcal{F}$  is a sheaf, then  $\emptyset \subseteq X$  is covered by the empty covering; hence  $\mathcal{F}(\emptyset) = 0$ .

- (2) The two sheaf axioms can be described as saying that given  $U, \{U_i\}$ ,

$$0 \longrightarrow \mathcal{F}U \xrightarrow{\alpha} \prod_i \mathcal{F}U_i \xrightarrow[\beta_2]{\beta_1} \prod_{i,j} \mathcal{F}(U_i \cap U_j)$$

is exact, where  $\alpha(s) = (s|_{U_i})_{i \in I}$ ,  $\beta_1((s_i)_{i \in I}) = (s_i|_{U_i \cap U_j})$ ,  $\beta_2((s_i)_{i \in I}) = (s_j|_{U_i \cap U_j})_{i,j}$ .

Exactness means that  $\alpha$  is injective,  $\beta_1 \circ \alpha = \beta_2 \circ \alpha$ , and for any  $(s_i) \in \prod_{i \in I} \mathcal{F}U_i$ , with  $\beta_1((s_i)) = \beta_2((s_i))$ , there exists  $s \in \mathcal{F}U$  with  $\alpha(s) = (s_i)$ .

This is all subsumed by saying that  $\alpha$  is the equalizer of  $\beta_1$  and  $\beta_2$ .

EXAMPLE. (1) Let  $X$  be any topological space,  $\mathcal{F}U$  the continuous functions  $U \rightarrow \mathbb{R}$ .

This is a sheaf:  $\rho_{UV}: \mathcal{F}U \rightarrow \mathcal{F}V$  is just the restriction.

The first sheaf axiom says that a continuous function is zero if it is zero on every open set of cover.

The second sheaf axiom says that continuous functions can be glued.

- (2) Let  $X = \mathbb{C}$  with the Euclidean topology.

Define  $\mathcal{F}U$  to be the set of bounded analytic functions  $f: U \rightarrow \mathbb{C}$ .

This is a presheaf, since the restriction of bounded analytic functions is bounded analytic. It also satisfies the first sheaf axiom. However, it does not satisfy the second sheaf axiom.

For example, consider the cover  $\{U_i\}_{i \in \mathbb{N}}$  of  $\mathbb{C}$  given by  $U_i = \{z \in \mathbb{C} \mid |z| < i\}$ . Define  $s_i: U_i \rightarrow \mathbb{C}$  by  $z \mapsto z$ . Note that if  $i < j$ , then  $U_i \cap U_j = U_i$  and  $s_i|_{U_i \cap U_j} = s_j|_{U_i \cap U_j}$ . However, gluing yields the identity function on  $\mathbb{C}$ , which is not bounded (note that complex analysis tells us that  $\mathcal{F}\mathbb{C} = \mathbb{C}$ ).

The underlying problem is that sheafs can only track properties that can be tested locally.

- (3) Let  $G$  be a group and set  $\mathcal{F}U := G$  for any open set  $U$ . This is called the constant presheaf. This is in general not a sheaf (unless  $G$  is trivial).

Take  $U$  to be a disjoint union of open sets  $U_1 \cup U_2$ . If  $\mathcal{F}U_1 = G$  and  $\mathcal{F}U_2 = G$ , then we need  $\mathcal{F}(U_1 \cap U_2) = 0$ .

If the second sheaf axiom was to be satisfied, we would want  $s_1 \in \mathcal{F}U_1$  and  $s_2 \in \mathcal{F}U_2$  to glue, so we should have  $\mathcal{F}U = G \times G$ .

Now give  $G$  the discrete topology, and define instead  $\mathcal{F}U$  to be the set of continuous maps  $f: U \rightarrow G$ . By our choice of topology, this means that  $f$  is locally constant, i.e., for every  $x \in U$  we have a neighborhood  $V \subseteq U$  of  $x$  such that  $f|_V$  is constant.

This is called the constant sheaf and if  $U$  is nonempty and connected then  $\mathcal{F}U = G$ .

- (4) If  $X$  is an algebraic variety,  $U \subseteq X$  a Zariski open subset, then define  $\mathcal{O}_X(U)$  to be the regular functions  $f: U \rightarrow k$ .

Roughly,  $f$  regular means that every point of  $U$  has an open neighborhood on which  $f$  is expressed as a ratio of polynomials  $g/h$  with  $h$  nonvanishing on the neighborhood.

$\mathcal{O}_X$  is a sheaf, called the structure sheaf of  $X$ .

**DEFINITION 1.6.** Let  $\mathcal{F}$  be a presheaf on  $X$  and let  $x \in X$ . Then the stalk of  $\mathcal{F}$  at  $x$  is  $\mathcal{F}_x := \{(U, s) \mid U \subseteq X \text{ open neighborhood at } x, s \in \mathcal{F}U\} / \sim$ , where  $(U, s) \sim (V, s')$  if there is a neighborhood  $W \subseteq U \cap V$  of  $x$  such that  $s|_W = s'|_W$ . An equivalence class of a pair  $(U, s)$  is called a germ.

**REMARK.**  $\mathcal{F}_x$  is just the colimit of  $\mathcal{F}U$  where  $U$  ranges over the open neighborhoods of  $x$ .

Note that a morphism  $f: \mathcal{F} \rightarrow \mathcal{G}$  of presheaves induces a morphism  $f_p: \mathcal{F}_p \rightarrow \mathcal{G}_p$  via  $f_p(U, s) := (U, f_U(s))$ .

**PROPOSITION 1.7.** Let  $f: \mathcal{F} \rightarrow \mathcal{G}$  be a morphism of sheaves. Then  $f$  is an isomorphism if and only if  $f_p$  is an isomorphism for every  $p \in X$ .

**PROOF.** “ $\implies$ ” is obvious.

“ $\impliedby$ ”: Assume that  $f_p$  is an isomorphism for all  $p \in X$ . Need to show that  $f_U: \mathcal{F}U \rightarrow \mathcal{G}U$  is an isomorphism for all  $U \subseteq X$ , as then we can define  $(f^{-1})_U = (f_U)^{-1}$ . This defines a morphism of sheaves, as

$$\begin{aligned} \rho_{UV}^{\mathcal{F}} \circ f_U^{-1} &= f_V^{-1} \circ f_V \circ \rho_{UV}^{\mathcal{F}} \circ f_U^{-1} \\ &= f_V^{-1} \circ \rho_{UV}^{\mathcal{G}} \circ f_U \circ f_U^{-1} \\ &= f_V^{-1} \circ \rho_{UV}^{\mathcal{G}}. \end{aligned}$$

We will first check that  $f_U$  is injective. Suppose  $s \in \mathcal{F}U$  and  $f_U(s) = 0$ . Then for all  $p \in U$ , we have  $f_p(U, s) = (U, f_U(s)) = (U, 0) = 0 \in \mathcal{G}_p$ . Since  $f_p$  is injective,



this means that  $(U, s) = 0$  in  $\mathcal{F}_p$ . This means that there is an open neighborhood  $V_p$  of  $p$  in  $U$  such that  $s|_{V_p} = 0$ . Since the sets  $\{V_p\}_{p \in U}$  cover  $U$ , we see by sheaf axiom 1 that we have  $s = 0$ .

Next, we will show that  $f_U$  is surjective. Let  $t \in \mathcal{G}U$  and write  $t_p := (U, t) \in \mathcal{G}_p$ . Since  $f_p$  is surjective, we find  $s_p \in \mathcal{F}_p$  with  $f_p(s_p) = t_p$ . This means that we find an open neighborhood  $V_p \subseteq U$  of  $p$  and a germ  $(V_p, s_p)$  such that  $(V_p, f_{V_p}(s_p)) \sim (U, t)$ . By shrinking  $V_p$  if necessary we can assume that  $t|_{V_p} = f_{V_p}(s_p)$ .

Now on  $V_p \cap V_q$ ,  $f_{V_p \cap V_q}(s_p|_{V_p \cap V_q} - s_q|_{V_p \cap V_q}) = t|_{V_p \cap V_q} - t|_{V_p \cap V_q} = 0$  and hence by injectivity of  $f_{V_p \cap V_q}$  already proved, we have  $s_p|_{V_p \cap V_q} = s_q|_{V_p \cap V_q}$ . By the second sheaf axiom, the  $s_p$  glue to give an element  $s \in \mathcal{F}U$  with  $s|_{V_p} = s_p$  for every  $p \in U$ .

Now  $f_U(s)|_{V_p} = f_{V_p}(s|_{V_p}) = f_{V_p}(s_p) = t|_{V_p}$ . By the first sheaf axiom applied to  $f_U(s) - t$  we get  $f_U(s) = t$ . This shows surjectivity of  $f_U$ , completing the proof.  $\square$

**THEOREM 1.8.** Given a presheaf  $\mathcal{F}$  there is a sheaf  $\mathcal{F}^+$  and a morphism  $\theta: \mathcal{F} \rightarrow \mathcal{F}^+$  satisfying the following universal property:

For any sheaf  $\mathcal{G}$  and morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  there is a unique morphism  $\varphi^+: \mathcal{F}^+ \rightarrow \mathcal{G}$  such that  $\varphi^+ \circ \theta = \varphi$ .

The pair  $(\mathcal{F}^+, \theta)$  is unique up to unique isomorphism and is called the sheafification of  $\mathcal{F}$ .

**PROOF.** See exercises.  $\square$

**DEFINITION.** Let  $f: \mathcal{F} \rightarrow \mathcal{G}$  be a morphism of presheaves on a space  $X$ . We define

- (1) The presheaf kernel of  $f$ ,  $\ker f$ , is the presheaf given by

$$(\ker f)(U) := \ker f_U.$$

One should check that this is a presheaf.

- (2) The presheaf cokernel of  $f$ ,  $\operatorname{coker} f$ , is the presheaf given by

$$(\operatorname{coker} f)(U) := \operatorname{coker} f_U.$$

- (3) The presheaf image  $\operatorname{im} f$  is the presheaf given by

$$(\operatorname{im} f)(U) = \operatorname{im} f_U.$$

**REMARK.** If  $f: \mathcal{F} \rightarrow \mathcal{G}$  is a morphism of sheaves, then  $\ker f$  is also a sheaf. The identity axiom is certainly satisfied: If  $s \in (\ker f)(U) \subseteq \mathcal{F}U$  satisfies  $s|_{U_i} = 0$  for all  $U_i$  in a cover of  $U$ , then we use the identity axiom for  $\mathcal{F}$  to find that  $s = 0$ .

Given  $s_i \in (\ker f)(U_i)$  with  $\{U_i\}$  an open cover of  $U$ , and with  $s_i|_{U_i \cap U_j} = s_j|_{U_i \cap U_j}$ , then we find  $s \in \mathcal{F}U$  with  $s|_{U_i} = s_i$ . But  $f_U(s) = 0$  since

$$f_U(s)|_{U_i} = f_{U_i}(s|_{U_i}) = f_{U_i}(s_i) = 0,$$

and we can use the identity axiom to conclude that  $f_U(s) = 0$ .

**EXAMPLE.** Let  $X = \mathbb{P}^1$  (or think of the Riemann sphere). Let  $P, Q \in X$  be distinct points. Let  $\mathcal{G}$  be the sheaf of regular functions on  $X$  (alternatively, think of holomorphic functions on the Riemann sphere). Next, let  $\mathcal{F}$  be the sheaf of regular functions which vanish on  $P$  and  $Q$ . Notice that  $\mathcal{F}U = \mathcal{G}U$  if  $U \cap \{P, Q\} = \emptyset$ .

Let  $U := \mathbb{P}^1 \setminus \{P\}$ ,  $V = \mathbb{P}^1 \setminus \{Q\}$ .

Note that  $\mathcal{F}(\mathbb{P}^1) = 0$ ,  $\mathcal{G}(\mathbb{P}^1) = k$ , because regular functions on  $\mathbb{P}^1$  are constants. Let  $f: \mathcal{F} \rightarrow \mathcal{G}$  be the inclusion.

Then  $(\operatorname{coker} f)(\mathbb{P}^1) \cong k$ ,  $(\operatorname{coker} f)(U) = \mathcal{G}U/\mathcal{F}U = k[X]/(X) \cong ka$ ,  $(\operatorname{coker} f)(V) \cong k$ . However,  $(\operatorname{coker} f)(U \cap V) = \mathcal{G}(U \cap V)/\mathcal{F}(U \cap V) \cong 0$ .

Therefore, if the gluing axiom held, then we could need to have

$$(\operatorname{coker} f)(\mathbb{P}^1) \cong k \oplus k.$$

Note that this failure to be a sheaf is not a bug, but a feature!

DEFINITION. Let  $f: \mathcal{F} \rightarrow \mathcal{G}$  be a morphism of sheaves. The sheaf kernel of  $f$  is just the presheaf kernel.

The sheaf cokernel is the sheaf associated to the presheaf cokernel of  $f$ .

The sheaf image is the sheaf associated to the presheaf image of  $f$ .

We can check that these notions give kernels, cokernels and images in the category of sheaves.

EXERCISE. The sheaf image  $\text{im } f$  is a subsheaf of  $\mathcal{G}$ , where  $\mathcal{F}$  is called a subsheaf of  $\mathcal{G}$  if we have a morphism  $f: \mathcal{F} \rightarrow \mathcal{G}$  such that  $f_U$  is a monomorphism for every open set  $U$ .

SOLUTION. See exercises.  $\square$

DEFINITION. We say that  $f$  is injective if  $\ker f = 0$ . We say that  $f$  is surjective if  $\text{im } f = \mathcal{G}$ .

Note that surjectivity does not imply that  $f_U$  is surjective for every  $U$ .

We say that a sequence of morphisms of sheaves

$$\dots \longrightarrow \mathcal{F}^{i-1} \xrightarrow{f^i} \mathcal{F}^i \xrightarrow{f^{i+1}} \mathcal{F}^{i+1} \longrightarrow \dots$$

is exact if  $\ker f^{i+1} = \text{im } f^i$  for all  $i$ .

If  $\mathcal{F}' \subseteq \mathcal{F}$  is a subsheaf, then we write  $\mathcal{F}/\mathcal{F}'$  for the sheaf associated to the presheaf  $U \mapsto \mathcal{F}U/\mathcal{F}'U$ , so  $\mathcal{F}/\mathcal{F}'$  is the cokernel of the inclusion  $\mathcal{F}' \rightarrow \mathcal{F}$ .

LEMMA 1.9. Let  $f: \mathcal{F} \rightarrow \mathcal{G}$  be a morphism of sheaves. Then for all  $p \in X$  we have

$$\begin{aligned} (\ker f)_p &= \ker(f_p: \mathcal{F}_p \rightarrow \mathcal{G}_p) \\ (\text{im } f)_p &= \text{im } f_p \end{aligned}$$

PROOF. We first define a map  $(\ker f)_p \rightarrow \ker f_p$ . If  $(U, s) \in (\ker f)_p$ , then  $(U, s) \in \mathcal{F}_p$  and

$$f_p(U, s) = (U, f_U(s)) = (U, 0) = 0 \in \mathcal{G}_p.$$

Therefore,  $(U, s) \in \ker f_p$ .

We will check injectivity and surjectivity of this map.

For injectivity, assume that  $(U, s) = 0$  in  $\mathcal{F}_p$ , then there is  $V \subseteq U$  of  $p$  such that  $s|_V = 0$ . Then we also have the equality

$$(U, s) = (V, s|_V) = (V, 0) = 0$$

in  $(\ker f)_p$ .

For surjectivity, assume that  $(U, s) \in \ker f_p$ . This means that  $(U, f_U(s)) = 0$  in  $\mathcal{G}_p$ , so there is  $V \subseteq U$  of  $p$  such that  $0 = f_U(s)|_V = f_V(s|_V)$ . Thus,  $s|_V \in (\ker f)(V)$ , and  $(V, s|_V) \in (\ker f)_p$ , and  $(V, s|_V)$  maps to the element in  $\ker f_p$  represented by  $(U, s)$ .

For images: Let  $\text{im}' f$  be the presheaf image.

From the exercises we know that  $\theta_p: \mathcal{F}_p \rightarrow \mathcal{F}_p^+$  is an isomorphism for every  $p$ .

Therefore  $(\text{im } f)_p \cong (\text{im}' f)_p$ , so we need to show that  $(\text{im}' f)_p \cong \text{im } f_p$ . Define a map  $(\text{im}' f)_p \rightarrow \text{im } f_p$  by

$$(U, s) \in (\text{im}' f)_p \mapsto (U, s) \in \text{im } f_p.$$

Once again, we will check that this is injective and surjective.

For injectivity: if  $(U, s) = 0$  in  $\mathcal{G}_p$  then there is a neighborhood  $V \subseteq U$  of  $p$  such that  $s|_V = 0$ . Then  $(U, s) = (V, 0)$  in  $(\text{im}' f)_p$ .

For surjectivity: if  $(U, s) \in \text{im } f_p$ , then there is  $(V, t) \in \mathcal{F}_p$  with  $(V, f_V(t)) = f_p(V, t) = (U, s)$ , so after shrinking  $U$  and  $V$  if necessary, then we can take  $U = V$  and  $f_U(t) = s$ . Then  $(U, s) \in (\text{im}' f)_p$ .  $\square$

PROPOSITION. Let  $f: \mathcal{F} \rightarrow \mathcal{G}$  be a morphism of sheaves. Then  $f$  is injective if and only if for every  $p \in X$  the map  $f_p: \mathcal{F}_p \rightarrow \mathcal{G}_p$  is injective and  $f$  is surjective if and only if for every  $p \in X$  the map  $f_p: \mathcal{F}_p \rightarrow \mathcal{G}_p$  is surjective.

PROOF.  $f_p$  is injective for every  $p$  if and only if  $\ker f_p = 0$  for every  $p$  if and only if  $(\ker f)_p = 0$  for every  $p$ .

In the exercises, we show that for any sheaf  $\mathcal{F}$ , the map

$$\mathcal{F}U \rightarrow \prod_{p \in U} \mathcal{F}_p$$

is injective. Now if all of the  $\mathcal{F}_p$  are trivial, then so is  $\mathcal{F}U$ .

Therefore  $(\ker f)_p = 0$  for every  $p$  if and only if  $\ker f = 0$ .

Similarly,  $f_p$  is surjective for every  $p$  iff  $\text{im } f_p = \mathcal{G}_p$  for every  $p$ . Now consider the diagram

$$\begin{array}{ccc} \text{im } f_p & \xrightarrow{\quad} & \mathcal{G}_p \\ \downarrow \cong & \nearrow & \uparrow \\ (\text{im}' f)_p & \xrightarrow{\cong} & (\text{im } f)_p \end{array}$$

where

- the top arrow is the inclusion,
- the left arrow is the isomorphism defined in Lemma 1.9,
- the bottom arrow is the isomorphism on stalks induced by the inclusion into the associated sheaf,
- the diagonal arrow is the morphism on stalks induced by the inclusion of the presheaf image, and
- the right arrow is induced by the arrow making the sheaf image into a subsheaf.

The upper triangle commutes trivially, and the lower triangle commutes because by construction the right arrow is induced by the unique arrow making the non-stalk version of the triangle commute. Thus, since the bottom and left arrows are isomorphisms and the diagram commutes, we have that  $\text{im } f_p \rightarrow \mathcal{G}_p$  is an isomorphism (which just means that  $\text{im } f_p = \mathcal{G}_p$ ) if and only if  $(\text{im } f)_p \rightarrow \mathcal{G}_p$  is an isomorphism.

Now, the arrow  $(\text{im } f)_p \rightarrow \mathcal{G}_p$  is an isomorphism for every  $p$  if and only if  $\text{im } f \rightarrow \mathcal{G}$  is an isomorphism (Proposition 1.7), and this is the definition of surjectivity.  $\square$

EXERCISE. Given  $f: \mathcal{F} \rightarrow \mathcal{G}$ , then we have  $\mathcal{G}/\text{im } f \cong \text{coker } f$ .

### 1. Passing between spaces

REMARK. Let  $f: X \rightarrow Y$  be a continuous map between topological spaces,  $\mathcal{F}$  a sheaf on  $X$ ,  $\mathcal{G}$  a sheaf on  $Y$ .

DEFINITION. Define  $f_*\mathcal{F}$  by setting

$$(f_*\mathcal{F})(U) := \mathcal{F}(f^{-1}(U))$$

for  $U \subseteq Y$  open.

EXERCISE.  $f_*\mathcal{F}$  is a sheaf on  $Y$ .

SOLUTION. TODO  $\square$

DEFINITION. Define  $f^{-1}\mathcal{G}$  to be the sheaf associated to the presheaf

$$U \mapsto \{(V, s) \mid f(U) \subseteq V, s \in \mathcal{G}V\} / \sim$$

where  $(V, s) \sim (V', s')$  if there is some  $W \subseteq V \cap V'$  such that  $f(U) \subseteq W$  and  $s|_W = s'|_W$ .

EXAMPLE. If  $f: \{p\} \rightarrow X$  is an inclusion of a point, then  $f^{-1}\mathcal{G}$  is the sheaf on the one-point space given by  $\mathcal{G}_p$ .

More generally, if  $i: Z \rightarrow X$  is the inclusion of a subspace, we often write  $\mathcal{F}|_Z := i^{-1}\mathcal{F}$ . If  $Z$  is open in  $X$ , then we have

$$F|_Z(U) \cong \mathcal{F}U.$$

NOTATION 1.10. If  $s \in \mathcal{F}U$ , then we say that  $s$  is a section of  $\mathcal{F}$  over  $U$ .

We often write  $\mathcal{F}U = \Gamma(U, \mathcal{F})$ . This allows us to think of  $\Gamma(U, \cdot)$  as a functor from the category of presheaves on  $X$  to the category of abelian groups.

## CHAPTER 2

### Affine schemes

REMARK. Our goal is to construct a sheaf  $\mathcal{O}$  on  $\text{Spec } A$ , analogous to the sheaf of regular functions on a variety.

$\mathcal{O}$  will be a sheaf of rings, i.e.,  $\mathcal{O}U$  will be a ring for each open set  $U$  and restriction maps will be ring homomorphisms.

REMARK. Let  $A$  be a ring and let  $S \subseteq A$  be a multiplicative subset (i.e.,  $1 \in S$  and  $S$  is closed under multiplication). We define a ring

$$S^{-1}A = \{(a, s) \mid a \in A, s \in S\} / \sim,$$

where  $(a, s) \sim (a', s')$  iff there is  $s'' \in S$  such that  $s''(as' - a's) = 0$ .

We write  $a/s$  for the equivalence class of  $(a, s)$ .

Observe that the usual equivalence relation on fractions suggests that we should have  $a/s = a'/s' \iff as' = a's$ . We need the extra possibility of killing  $as' - a's$  with  $s''$  if  $A$  is not an integral domain.

The ring  $S^{-1}A$  is called the localization of  $A$  at  $S$ .

EXAMPLE. (1) Take  $f \in A$  and  $S := \{f^n \mid n \in \mathbb{N}_0\}$ . Then we write  $A_f := S^{-1}A$ .

This example will correspond to open subsets.

(2) Let  $p \subseteq A$  be a prime ideal of  $A$ . Then  $S := A \setminus p$  satisfies  $1 \in S$  and is closed under multiplication since  $p$  is prime. We define  $A_p := S^{-1}A$ . This is the localization of  $A$  at (or rather, away from?)  $p$ .

This example will correspond to taking stalks.

DEFINITION.  $\mathcal{O}$  should satisfy  $\mathcal{O}_p = A_p$ .

Define

$$\mathcal{O}U := \{s: U \rightarrow \prod_{p \in U} A_p \mid (\star)\},$$

where  $(\star)$  means that

- (1)  $\forall p \in U: s(p) \in A_p$ ,
- (2) for each  $p \in U$  there is some  $p \in V \subseteq U$  with  $V$  open and  $a, f \in A$  such that for all  $q \in V: f \notin q \wedge s(q) = a/f$ .

LEMMA. For any  $p \in \text{Spec } A$ , we have  $\mathcal{O}_p \cong A_p$ .

PROOF. We define a map

$$\begin{aligned} \mathcal{O}_p &\rightarrow A_p \\ (U, s) &\mapsto s(p) \end{aligned}$$

and will show that it is injective and surjective.

For surjectivity, notice that every element of  $A_p$  can be written as  $a/f$  for some  $a \in A, f \notin p$ . Then

$$D(f) := \text{Spec } A \setminus V(f) = \{p \in \text{Spec } A \mid f \notin p\}$$

is an open set (in fact it is called a standard open). Now  $a/f$  defines an element of  $s \in \mathcal{O}(D(f))$  given by  $q \mapsto a/f \in A_q$ . In particular,  $s(p) = a/f \in A_p$ .

For injectivity, let  $p \in U \subseteq \operatorname{Spec} A$ ,  $s \in \mathcal{O}_U$  with  $s(p) = 0$  in  $A_p$ . We need to show that  $(U, s) = 0$  in  $\mathcal{O}_p$ . By shrinking  $U$  we can assume that  $s$  is given by  $a, f \in A$  with  $s(q) = a/f$  for all  $q \in U$ . In particular  $f \notin q$  for every  $q \in U$ .

Thus,  $a/f = 0/1$  in  $A_p$ . By definition of localization, this means that there is  $h \in A \setminus p$  such that  $h \cdot (a \cdot 1 + f \cdot 0) = 0$  in  $A$ , so we have  $ah = 0$ .

Now let  $V = D(f) \cap D(h)$ . Then  $(V, s|_V) = 0$  in  $\mathcal{O}_p$ , since for  $q \in V$ ,  $s|_v(q) = s(q) = a/f \in A_q$  and  $ha = 0$ ,  $h \notin A \setminus q$ , so  $ha = 0$  implies  $a/f = 0/1$  in  $A_q$ . Thus  $(U, s) = 0$  in  $\mathcal{O}_p$ .  $\square$

LEMMA. For any  $f \in A$ , we have  $\mathcal{O}(D(f)) \cong A_f$ .

In particular, since  $\operatorname{Spec} A = D(1)$ , we have  $\mathcal{O}(\operatorname{Spec} A) \cong A_1 \cong A$ .

PROOF. Define

$$\begin{aligned} \Psi: A_f &\rightarrow \mathcal{O}(D(f)) \\ a/f^n &\mapsto (p \mapsto a/f^n). \end{aligned}$$

This makes sense since if  $f \notin p$ , then  $f^n \notin p$ . As usual, we will verify injectivity and surjectivity.

For injectivity, assume that  $\Psi(a/f^n) = 0$ . Then for all  $p \in D(f)$ , we have  $a/f^n = 0$  in  $A_p$ , i.e., there is  $h \in A \setminus p$  such that  $ha = 0$  in  $A$ .

Let  $I = \{q \in A \mid q \cdot a = 0\}$  (the annihilator of  $a$ ). So  $h \in I$ , but  $h \notin p$ , so  $I \not\subseteq p$ . This is true for all  $p \in D(f)$ , so  $V(I) \cap D(f) = \emptyset$ . Thus  $f \in \bigcap_{p \in V(I)} p = \sqrt{I}$ , as we know from commutative algebra. This means that  $f^n \in I$  for some  $n > 0$ . Thus  $f^n \cdot a = 0$ , so  $a/f^n = 0$  in  $A_f$ , so  $\Psi$  is injective.

Next, we will prove surjectivity. Let  $s \in \mathcal{O}(D(f))$ . Cover  $D(f)$  with open sets  $V_i$  on which  $s$  is represented by  $a_i/g_i$  with  $a_i, g_i \in A$ ,  $g_i \notin p$  whenever  $p \in V_i$ . Thus  $V_i \subseteq D(g_i)$ . By question 1 on the first example sheet, the sets of the form  $D(h)$  form a base for the Zariski topology on  $\operatorname{Spec} A$ . Thus we can assume  $V_i = D(h_i)$  for some  $h_i \in A$ . Since  $D(h_i) \subseteq D(g_i)$ , we have  $V(h_i) \supseteq V(g_i)$ , so  $\sqrt{(h_i)} \subseteq \sqrt{(g_i)}$ , since the radical is the intersection of all the primes of  $V(\cdot)$ . Hence,  $h_i^n \in (g_i)$  for some  $n$ , say  $h_i^n = c_i g_i$ , so we have  $\frac{a_i}{g_i} = \frac{c_i a_i}{h_i^n}$ . Now replace  $h_i$  by  $h_i^n$ . This does not change the open sets because in general  $D(h_i) = D(h_i^n)$  and replace  $a_i$  by  $c_i a_i$ .

The situation so far is that we may assume that  $D(f)$  is covered by sets  $D(h_i)$  such that  $s$  is represented by  $a_i/h_i$  on  $D(h_i)$ .

We now claim that  $D(f)$  can be covered by a finite number of the  $D(h_i)$ , i.e.,  $D(f)$  is quasicompact. Indeed,  $D(f) \subseteq \bigcup_i D(h_i)$ , which is equivalent to  $V(f) \supseteq \bigcap_i V(h_i) = V(\sum_i (h_i))$ . This in turn is equivalent to  $f \in \sqrt{\sum_i (h_i)}$  (because it just says that  $f$  is in every prime ideal containing  $\sum_i (h_i)$ ), which is equivalent to there being some  $n$  such that  $f^n \in \sum_i (h_i)$ . Hence, we can write  $f^n = \sum_{i \in I} b_i h_i$  for some finite set  $I$ .

Reversing this argument yields that  $D(f) \subseteq \bigcup_{i \in I} D(h_i)$  as required, completing the proof of the claim.

We now pass to this finite subcover  $\{D(h_i)\}_{i \in I}$ . On  $D(h_i) \cap D(h_j) = D(h_i h_j)$ , note  $a_i/h_i$  and  $a_j/h_j$  both represent  $s$ . Since we have already shown injectivity, this means that  $a_i h_j / h_i h_j = a_j h_i / h_i h_j$  in  $A_{h_i h_j}$ .

Thus, for some  $n$ ,  $(h_i h_j)^n (h_j a_i - h_i a_j) = 0$  in  $A$ . We can pick an  $n$  sufficiently large to work for all pairs  $i, j$  (since there are only finitely many such pairs).

We rewrite this equality as  $h_j^{n+1} (h_i^n a_i) - h_i^{n+1} (h_j^n a_j) = 0$ . Now replace  $h_i$  by  $h_i^{n+1}$ , and  $a_i$  by  $h_i^n a_i$  (this is allowed because  $\frac{a_i}{h_i} = \frac{a_i h_i^n}{h_i^{n+1}}$ ). Thus we can assume that  $s$  is still represented on  $D(h_i)$  by  $a_i/h_i$  but also for each  $i, j$  we have  $h_i a_j = h_j a_i$ .

Since  $D(f) \subseteq \bigcup_{i \in I} D(h_i)$ , we have  $V(\sum (h_i)) = \bigcap_{i \in I} V(h_i) \subseteq V(f)$ , hence  $f^n = \sum b_i h_i$  for some  $h_i$ . Define  $a := b_i a_i$ .

Then for any  $j$ , we have

$$h_j a = \sum_i b_i a_i h_j = \sum_i b_i a_j h_i = f^n a_j.$$

This means that  $a/f^n = a_j/h_j$  on  $D(h_j)$ . Hence  $\Psi(a/f^n) = s$ , completing the proof of surjectivity.  $\square$

REMARK. We now have a topological space  $\text{Spec } A$  equipped with a sheaf of rings  $\mathcal{O}$ .

DEFINITION. A ringed space is a pair  $(X, \mathcal{O}_X)$  where  $X$  is a topological space and  $\mathcal{O}_X$  is a sheaf of rings on  $X$ .

A morphism of ringed spaces  $f: (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$  consists of a continuous map  $X \rightarrow Y$  and a morphism of sheaves of rings  $f^\#: \mathcal{O}_Y \rightarrow f_* \mathcal{O}_X$ , i.e., for every open  $O \subseteq Y$ , a homomorphism of rings  $f_U^\#: \mathcal{O}_Y(U) \rightarrow \mathcal{O}_X(f^{-1}(U))$ .

- EXAMPLE. (1) Let  $X, Y$  be topological spaces and  $\mathcal{O}_X$  and  $\mathcal{O}_Y$  the sheaf of continuous  $\mathbb{R}$ -valued functions. Given  $f: X \rightarrow Y$ , we get  $f^\#: \mathcal{O}_Y \rightarrow f_* \mathcal{O}_X$  defined by  $f_U^\#(\varphi) = \varphi \circ f$ .
- (2) Let  $X$  be a variety and  $\mathcal{O}_X$  the sheaf of regular functions on  $X$ . A morphism of varieties  $f: X \rightarrow Y$  is a continuous map inducing

$$\begin{aligned} \mathcal{O}_Y(U) &\rightarrow \mathcal{O}_X(f^{-1}(U)), \\ \varphi &\mapsto \varphi \circ f. \end{aligned}$$

DEFINITION. A locally ringed space  $(X, \mathcal{O}_X)$  is a ringed space such that  $\mathcal{O}_{X,p}$  is a local ring (i.e., has a unique maximal ideal) for every  $p \in X$ .

A morphism  $f: (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$  of locally ringed spaces is a morphism of ringed spaces such that the induced map  $f_p^\#: \mathcal{O}_{Y,f(p)} \rightarrow \mathcal{O}_{X,p}$  is a local homomorphism. Here,

- the map  $f_p^\#$  is defined by  $(U, s) \mapsto (f^{-1}(U), f_U^\#(s))$  for a section  $s \in \mathcal{O}_Y(U)$ , and
- a local homomorphism  $\varphi: (A, m_A) \rightarrow (B, m_B)$  is a ring homomorphism between local rings such that  $\varphi^{-1}(m_B) = m_A$ . Note that  $\varphi(A \setminus m_A) = \varphi(A^\times) \subseteq B^\times = B \setminus m_B$ . Hence,  $\varphi^{-1}(m_B) \subseteq m_A$  is always true, and the opposite inclusion is what makes a ring homomorphism local.

REMARK. In the case of varieties,  $\mathcal{O}_{X,p}$  has a unique maximal ideal  $\{(U, f) \in \mathcal{O}_X(U) \mid f(p) = 0\} / \sim$ , i.e., if  $f(p) \neq 0$ , then  $f$  is nowhere vanishing on some neighborhood of  $p$ , so after shrinking  $U$ , we can invert  $f$ .

The local homomorphism condition just follows from the pullback of a function  $\varphi$  vanishing at  $f(p)$  vanishes at  $p$ .

EXAMPLE.  $(\text{Spec } A, \mathcal{O})$  is a locally ringed space; which we call an affine scheme.

THEOREM. The category of affine schemes with locally ringed morphisms is equivalent to the opposite of the category of rings.

PROOF. We need to show the following things.

- (1) If  $\varphi: A \rightarrow B$  is a ring homomorphism, we obtain an induced morphism

$$(f, f^\#): (\text{Spec } B, \mathcal{O}_B) \rightarrow (\text{Spec } A, \mathcal{O}_A).$$

- (2) Any morphism of affine schemes as locally ringed spaces arises in this way.

For the first part, let  $\varphi: A \rightarrow B$  be a ring homomorphism and define

$$\begin{aligned} f: \text{Spec } B &\rightarrow \text{Spec } A \\ p &\mapsto \varphi^{-1}(p), \end{aligned}$$

where we use that  $\varphi^{-1}(p)$  is prime: if  $ab \in \varphi^{-1}(p)$ , then  $\varphi(ab) = \varphi(a)\varphi(b) \in p$ . Hence  $\varphi(a) \in p$  or  $\varphi(b) \in p$ , hence  $a \in \varphi^{-1}(p)$  or  $b \in \varphi^{-1}(p)$ .

We also need to show that  $f$  is continuous. Any closed set is of the form  $V(I)$ . We calculate

$$\begin{aligned} f^{-1}(V(I)) &= f^{-1}(\{p \in \operatorname{Spec} A \mid p \supseteq I\}) \\ &= \{q \in \operatorname{Spec} B \mid f(q) \supseteq I\} \\ &= \{q \in \operatorname{Spec} B \mid \varphi^{-1}(q) \supseteq I\} \\ &= \{q \in \operatorname{Spec} B \mid q \supseteq \varphi(I)\} \\ &= V(\varphi(I)). \end{aligned}$$

Hence the preimage of a closed set is closed, so  $f$  is continuous.

We need to construct a morphism of sheaves

$$f_{\#}: \mathcal{O}_{\operatorname{Spec} A} \rightarrow f_* \mathcal{O}_{\operatorname{Spec} B}.$$

For  $p \in \operatorname{Spec} B$ , we obtain a natural homomorphism

$$\begin{aligned} \varphi_p: A_{\varphi^{-1}(p)} &\rightarrow B_p \\ \frac{a}{s} &\mapsto \frac{\varphi(a)}{\varphi(s)}, \end{aligned}$$

where  $a \in A$ ,  $s \notin \varphi^{-1}(p)$ . This makes sense since  $\varphi(a) \in B$  and  $\varphi(s) \notin p$ .

The maximal ideal  $pB_p$  of  $B_p$  is generated by the image of  $p$  under the map  $B \rightarrow B_p$ . The maximal ideal  $\varphi^{-1}(p)A_{\varphi^{-1}(p)}$  of  $A_{\varphi^{-1}(p)}$  is generated by the image of  $\varphi^{-1}(p)$  under the map  $A \rightarrow A_p$ .

Given  $V \subseteq \operatorname{Spec} A$  open, we may define

$$\begin{aligned} f_V^{\#}: \mathcal{O}_{\operatorname{Spec} A}(V) &\rightarrow \mathcal{O}_{\operatorname{Spec} B}(f^{-1}(V)) \\ s &\mapsto (q \mapsto \varphi_q(s(f(q)))) \end{aligned}$$

We now have to check the local coherence condition of  $\mathcal{O}$ , i.e., if  $s$  is locally given by  $a/h$ , then  $f_V^{\#}(s)$  is locally given by  $\frac{\varphi(a)}{\varphi(h)}$ . Indeed, let  $s \in \mathcal{O}_{\operatorname{Spec} A}(V)$  and  $p \in f^{-1}(V)$ . Then we find  $f(p) \in W \subseteq V$ ,  $a, h \in A$  such that for all  $q \in W$ ,  $h \notin q$ ,  $s(q) = a/h$ . Define  $U := f^{-1}(W)$ . We have  $p \in U$ , since  $f(p) \in W$ . If  $q \in U$ , we have  $\varphi(h) \notin q$ , since  $h \notin \varphi^{-1}(q) = f(q) \in W$ . Hence,

$$f_V^{\#}(s)(q) = \varphi_q(s(f(q))) = \varphi_q(a/h) = \varphi(a)/\varphi(h)$$

as required.

This gives the desired map  $f^{\#}: \mathcal{O}_{\operatorname{Spec} A} \rightarrow f_* \mathcal{O}_{\operatorname{Spec} B}$  and the induced map on stalks  $f_p^{\#}: \mathcal{O}_{\operatorname{Spec} A, f(p)} \rightarrow \mathcal{O}_{\operatorname{Spec} B, p}$  agrees with  $\varphi_p: A_{\varphi^{-1}(p)} \rightarrow B_p$  by construction. To be precise, we claim that we have a commutative diagram

$$\begin{array}{ccc} \mathcal{O}_{\operatorname{Spec} A, f(p)} & \xrightarrow{f_p^{\#}} & \mathcal{O}_{\operatorname{Spec} B, p} \\ \downarrow \alpha & & \downarrow \beta \\ A_{f(p)} & \xrightarrow{\varphi_p} & B_p \end{array}$$

for every  $p \in X$ , where  $\alpha$  and  $\beta$  are the canonical isomorphisms defined in a previous result. Indeed, if  $(U, s) \in \mathcal{O}_{\operatorname{Spec} A, f(p)}$ , we have

$$\beta(f_p^{\#}(U, s)) = \beta(f^{-1}(U), f_U^{\#}(s)) = f_U^{\#}(s)(p) = \varphi_p(s(f(p))) = \varphi_p(\alpha(U, s)).$$

Hence, the pair  $(f, f^{\#})$  is a morphism of locally ringed spaces.



Now suppose given a morphism  $(f, f^\#): \text{Spec } B \rightarrow \text{Spec } A$  of locally ringed spaces. We have

$$f^\#_{\text{Spec } A}: \Gamma(\text{Spec } A, \mathcal{O}_{\text{Spec } A}) \rightarrow \Gamma(\text{Spec } B, \mathcal{O}_{\text{Spec } B}),$$

but since the global sections of  $\text{Spec } R$  are just  $R$ , we get  $\varphi: A \rightarrow B$ .

We need to show that  $\varphi$  gives rise to  $(f, f^\#)$ . We have a local homomorphism

$$f^\#_p: A_{f(p)} \cong \mathcal{O}_{\text{Spec } A, f(p)} \rightarrow \mathcal{O}_{\text{Spec } B, p} \cong B_p.$$

This is compatible with the corresponding map on global sections in the sense that

$$\begin{array}{ccc} \Gamma(\text{Spec } A, \mathcal{O}_{\text{Spec } A}) & \xrightarrow{f^\#_{\text{Spec } A}} & \Gamma(\text{Spec } B, \mathcal{O}_{\text{Spec } B}) \\ \downarrow & & \downarrow \\ \mathcal{O}_{\text{Spec } A, f(p)} & \xrightarrow{f^\#_p} & \mathcal{O}_{\text{Spec } B, p} \end{array}$$

is a commutative diagram. By applying our calculations, this yields a diagram

$$\begin{array}{ccc} A & \xrightarrow{\varphi} & B \\ \downarrow & & \downarrow \\ A_{f(p)} & \xrightarrow{f^\#_p} & B_p. \end{array}$$

Recall that  $f^\#_p$  is a local homomorphism. Thus  $(f^\#_p)^{-1}(pB_p) = f(p)A_{f(p)}$ . Along the lower left path, the maximal ideal  $pB_p$  is pulled back to  $f(p)A_{f(p)}$  and then to  $f(p)$ . Along the upper right path, it gets pulled back to  $p$  and then to  $\varphi^{-1}(p)$ . By commutativity, we conclude that  $f(p) = \varphi^{-1}(p)$ .

Thus  $f$  is induced by  $\varphi$  and by commutativity,  $f^\#_p = \varphi_p$ . Then  $f^\#$  is as constructed previously (this needs to be checked).  $\square$

REMARK. Note that demanding that  $(f, f^\#)$  is a morphism of locally ringed spaces rather than merely ringed spaces was crucial to make the proof work.

DEFINITION 2.1. An affine scheme is a locally ringed space that is isomorphic as a locally ringed space to  $(\text{Spec } A, \mathcal{O}_{\text{Spec } A})$  for some ring  $A$ .

A scheme is a locally ringed space  $(X, \mathcal{O}_X)$  with an open cover  $\{(U_i, \mathcal{O}_X|_{U_i})\}$  such that each  $(U_i, \mathcal{O}_X|_{U_i})$  is an affine scheme. Recall that we have  $\mathcal{O}_X|_{U_i}(V) = \mathcal{O}_X(V)$  for  $V \subseteq U$  open.

EXAMPLE. (1) Let  $k$  be a field. Then  $\text{Spec } k = (\{0\}, k)$ .

What does giving a morphism  $f: \text{Spec } k \rightarrow X$  a scheme mean?

First, we need to choose a point  $x \in X$ , the image of  $f$ . Second, we get a local ring homomorphism

$$f^\#_0: \mathcal{O}_{X, x} \rightarrow \mathcal{O}_{\text{Spec } k, 0} \cong k,$$

i.e.,  $(f^\#_0)^{-1}(0) = \mathfrak{m}_x \subseteq \mathcal{O}_{X, x}$ , the maximal ideal of  $\mathcal{O}_{X, x}$ . Thus we get a factorization  $f^\#_0: \mathcal{O}_{X, x} \rightarrow \mathcal{O}_{X, x}/\mathfrak{m}_x \rightarrow k$ . The middle quotient is a field denoted as  $\kappa(x)$ , the residue field of  $X$  at  $x$ .

Thus  $f$  induces an inclusion  $\kappa(x) \rightarrow k$ .

Conversely, given an inclusion  $\iota: \kappa(x) \rightarrow k$  we get a morphism of schemes  $\text{Spec } k \rightarrow X$  by defining  $f(0) = x$  and  $f^\#: \mathcal{O}_X \rightarrow f_*k$  by defining  $s \mapsto \iota(s(x)) \in k$ , where  $s(x)$  means taking the stalk of  $s$  at  $x$ .

Moral: Giving a morphism  $f: \text{Spec } k \rightarrow X$  is equivalent to giving a point  $x \in X$  and an inclusion  $\kappa(x) \rightarrow k$ .

Note: If  $X = \text{Spec } A$ , then giving a morphism  $\text{Spec } k \rightarrow \text{Spec } A$  is equivalent to giving a homomorphism  $A \rightarrow k$ , which we viewed at the beginning of the course as a “ $k$ -valued point” on  $\text{Spec } A$ .

- (2) What does giving a morphism  $X \rightarrow \operatorname{Spec} k$  mean? The continuous map  $X \rightarrow \operatorname{Spec} k$  does not carry any information, since  $\operatorname{Spec} k$  is a singleton space. We also have a map

$$f^\# : k \cong \mathcal{O}_{\operatorname{Spec} k} \rightarrow f_* \mathcal{O}_X,$$

i.e., a map  $k \rightarrow \Gamma(\operatorname{Spec} k, f_* \mathcal{O}_X) = \Gamma(X, \mathcal{O}_X)$ , i.e.,  $\Gamma(X, \mathcal{O}_X)$  carries a  $k$ -algebra structure.

Notice that this induces  $k$ -algebra structures on  $\mathcal{O}_X(U)$  for all open sets  $U$  via the composite

$$k \longrightarrow \mathcal{O}_X(X) \xrightarrow{\rho} \mathcal{O}_X(U),$$

and similarly all stalks  $\mathcal{O}_{X,p}$  are also  $k$ -algebras.

In this situation we say that  $X$  is a scheme (defined) over  $k$ .

- (3) Consider  $A = k[X_1, \dots, X_n]/I$  with  $I = \sqrt{I}$ . Then  $\operatorname{Spec} A$  is a replacement for  $V(I) \subseteq \mathbb{A}_k^n$ , viewing  $\operatorname{Spec} A$  as a scheme over  $k$ .

If  $k \subseteq k'$  is a field extension, a  $k'$ -valued point of  $X/k$  is a commutative diagram

$$\begin{array}{ccc} \operatorname{Spec} k' & \longrightarrow & X \\ & \searrow & \downarrow \\ & & \operatorname{Spec} k, \end{array}$$

which has the dual

$$\begin{array}{ccc} k' & \longleftarrow & A \\ & \nwarrow & \uparrow \\ & & k, \end{array}$$

so the top arrow is a homomorphism of  $k$ -algebras.

We write  $X(k')$  for the set of such morphisms.

REMARK. It is rare in algebraic geometry to work with schemes alone. Rather, we always work over a base scheme.

Fix a base scheme  $S$ . Define the category of schemes over  $S$  to be the category whose objects are morphisms  $T \rightarrow S$  and morphisms are commutative triangles. This is just the normal comma construction.

We will frequently work with schemes over  $\operatorname{Spec} k$ , which we will also refer to as schemes over  $k$ .

Given two schemes over  $S$ ,  $T \rightarrow S$  and  $X \rightarrow S$ , we define a  $T$ -valued point of  $X \rightarrow S$  as a morphism  $T \rightarrow X$  over  $S$ . We write  $X(T)$  for the set of  $T$ -valued points.

By Yoneda, the collection of  $X(T)$  for every  $T$  determines  $X$  up to isomorphism.

EXAMPLE. Fix a field  $k$ , and let  $D = \operatorname{Spec} k[t]/(t^2) = (\{(t)\}, k[t]/(t^2))$ , where  $(t)$  is the unique prime ideal.  $t$  doesn't make sense as a  $k$ -valued function any more, as  $t^2 = 0$ .

Let  $X$  be any scheme over  $k$ . What is  $X(D)$ ? Given a morphism  $f : D \rightarrow X$  of schemes over  $k$ , we get a point  $x \in X$  as the image of  $f$  and a local homomorphism

$$f_x^\# : \mathcal{O}_{X,x} \rightarrow k[t]/(t^2),$$

such that  $(f_x^\#)^{-1}((t)) = \mathfrak{m}_x$ . Note that  $\mathfrak{m}_x^2$  maps to 0, hence we get a  $k$ -linear map

$$\mathfrak{m}_x / \mathfrak{m}_x^2 \rightarrow (t) \cong k,$$

where the isomorphism is as a  $k$ -vector space. We also have a composed  $k$ -algebra homomorphism

$$\mathcal{O}_{X,x} \rightarrow k[t]/(t^2) \rightarrow k[t]/(t) \cong k$$

with kernel  $\mathfrak{m}_x$ , and hence we have  $\kappa(x) = \mathcal{O}_{X,x}/\mathfrak{m}_x \cong k$ . To see this, we must use that this is a homomorphism of  $k$ -algebras, so the  $k$  sitting inside  $\mathcal{O}_{X,x}$  maps to  $k$  on the right, i.e., the composite is surjective.

Se we get:

- (1) a  $k$ -valued point with residue field  $k$ ,
- (2) a morphism of  $k$ -vector spaces  $\mathfrak{m}_x/\mathfrak{m}_x^2 \rightarrow k$ , i.e., an element of  $(\mathfrak{m}_x/\mathfrak{m}_x^2)^*$ , the dual vector space.

The space  $(\mathfrak{m}_x/\mathfrak{m}_x^2)^*$  is called the Zariski tangent space to  $X$  at  $x$ . It can be thought of as a kind of “differentiation rule”.

Think of  $D$  as a point plus an arrow: mapping  $D$  into a scheme  $X$  carries as data a point of  $X$  and a tangent vector<sup>1</sup>.

EXAMPLE (Glued Schemes). This is a special case of a question of Example Sheet 1.

Suppose we are given to schemes  $X_1, X_2$  and open subsets  $U_i \subseteq X_i$ .

Recall  $U_i$  is also a locally ringed space  $(U_i, \mathcal{O}_{X_i}|_{U_i})$  and in fact  $U_i$  is then a scheme (this is not obvious and will be discussed later).

Given an isomorphism  $f: U_1 \rightarrow U_2$ , we can glue  $X_1$  and  $X_2$  along  $U_1$  and  $U_2$  to get a scheme  $X$  with an open cover  $\{X_1, X_2\}$ .

As a topological space,  $X$  is just the topological gluing of  $X_1$  and  $X_2$ . Refer to the example sheet for the construction of  $\mathcal{O}_X$ .

Now take  $\mathbb{A}_k^n := \text{Spec } k[X_1, \dots, X_n]$ . Hence,  $\mathbb{A}_k^1 = \text{Spec } k[X]$ . Take  $X_1 = X_2 = \mathbb{A}_k^1$ . Glue  $U_1 := \mathbb{A}^1 \setminus \{0\} = D(X) \subseteq \mathbb{A}_k^1 = X$ , where 0 is the point corresponding to the prime ideal  $(X)$  and  $U_2 := \mathbb{A}^1 \setminus \{0\} = D(X) \subseteq X_2$  via the identity map. As a topological space,  $X$  is just the line with two origins. The resulting scheme is called the affine line with doubled origin. It is not a variety.

Note that  $U_i = \text{Spec } k[X]_X$  (localization). Hence, we could also glue  $U_1$  and  $U_2$  via the map given by  $X \mapsto X^{-1}$ .

When we glue this way, we get the projective line over  $k$ ,  $\mathbb{P}_k^1$ .

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<sup>1</sup>This is just a vague intuition.



## CHAPTER 3

### Projective schemes

REMARK. Let  $S$  be a graded ring, i.e.,  $S = \bigoplus_{d \geq 0} S_d$  with  $S_d$  an abelian group, and we have the product law  $S_d \cdot S_{d'} \subseteq S_{d+d'}$ .

For example, if  $S = k[X_0, \dots, X_n]$ , then we get a grading such that  $S_d$  is the space of homogeneous polynomials of degree  $d$ .

We write  $S_+ := \bigoplus_{d \geq 1} S_d$ , which we call the irrelevant ideal.

DEFINITION.  $I \subseteq S$  is called a homogeneous ideal if  $I$  is generated by its homogeneous elements, i.e., elements in  $S_d$  for various  $d$ .

DEFINITION.  $\text{Proj } S := \{p \in \text{Spec } S \mid p \text{ homogeneous, } p \not\supseteq S_+\}$ .

For  $I \subseteq S$  a homogeneous ideal, set  $V(I) := \{p \in \text{Proj } S \mid p \supseteq I\}$ .

EXERCISE. Check the  $V(I)$  form the closed sets of a topology on  $\text{Proj } S$ .

SOLUTION. TODO. □

REMARK 3.1. For  $p \in \text{Proj } S$ , let

$$T = \{f \in S \setminus p \mid f \text{ is homogeneous}\}.$$

Then  $T$  is a multiplicatively closed subset of  $S$  and let  $S_{(p)} \subseteq T^{-1}S$  be the subring of elements of degree 0, i.e., written in the form  $s/s'$  with  $s \in S$  homogeneous,  $s' \in T$  with  $\deg s = \deg s'$ .

For  $f \in S$  homogeneous, we write  $S_{(f)} \subseteq S_f$  for the subset of elements of degree 0.

DEFINITION. For  $U \subseteq \text{Proj } S$  open, set

$$\mathcal{O}(U) := \{s: U \rightarrow \coprod_{p \in U} S_{(p)} \mid (\star)\},$$

where  $(\star)$  means that

- (1) for all  $p \in U$ ,  $s(p) \in S_{(p)}$ , and
- (2) for all  $p \in U$  there is  $p \in V \subseteq U$  and  $a, f \in S$  homogeneous of the same degree such that for all  $q \in V$  we have  $f \notin q$  and  $\forall q \in V: s(q) = a/f$ .

As before, we can calculate  $\mathcal{O}_p \cong S_{(p)}$ .

Important question: is the locally ringed space  $(\text{Proj } S, \mathcal{O})$  a scheme?

If  $f \in S$  is homogeneous, then we write  $D_+(f) = \{p \in \text{Proj } S \mid f \notin p\}$ . This is the open set, as we have  $D_+(f) = \text{Proj } S \setminus V(f)$ .

PROPOSITION. We have  $(D_+(f), \mathcal{O}|_{D_+(f)}) \cong \text{Spec } S_{(f)}$  as locally ringed spaces. Further, the open sets  $D_+(f)$  for  $f \in S_+$  cover  $\text{Proj } S$ . Hence  $(\text{Proj } S, \mathcal{O})$  is a scheme.

PROOF. This appears on the second example sheet. □

DEFINITION 3.2. If  $A$  is a ring, define

$$\mathbb{P}_A^n := \text{Proj } A[X_0, \dots, X_n].$$

EXAMPLE. Let  $k$  be an algebraically closed field, consider  $\mathbb{P}_k^1 = \text{Proj } k[X_0, X_1]$ .

The closed points, i.e., points  $p$  such that  $\{p\}$  is closed, correspond to maximal elements of  $\text{Proj } S$  (TODO: exercise!). These maximal elements are ideals of the form  $(aX_0 - bX_1)$ :

Note that the only maximal homogeneous ideal of  $k[X_0, X_1]$  is  $(X_0, X_1) = S_+$ , which is the irrelevant ideal, hence not part of  $\text{Proj } S$  (TODO), since any maximal ideal is of the form  $(X_0 - a_0, X_1 - a_1)$  by the Nullstellensatz.

The other prime ideals of  $k[X_0, X_1]$  are principal, i.e. of the form  $(f)$  with  $f$  irreducible or zero.

For  $(f)$  to be homogeneous,  $f$  must be homogeneous. Any such polynomial splits into linear factors, all homogeneous, so in order for  $f$  to be irreducible, it must be linear.

Note that we have a bijective correspondence between the collection of ideals  $(aX_0 - bX_1)$  with  $a, b \in k$ ,  $a, b$  not both zero and  $(k^2 \setminus \{0, 0\})/k^\times$  given by  $(aX_0 - bX_1) \mapsto (b : a)$ .

Conclusion: The closed points of  $\mathbb{P}_k^1 = \text{Proj } k[X_0, X_1]$  are in one-to-one correspondence with points of  $(k^2 \setminus \{0\})/k^\times$ .

More generally, the closed points of  $P_k^n$  are in one-to-one correspondence with points of  $(k^{n+1} \setminus \{0\})/k^\times$ . This is harder (but a good exercise), but it can be seen by using the open cover  $(D_+(X_i))$  (note that if  $p \notin D_+(X_i)$  for any  $i$ , then  $X_i \in p$  for any  $i$ , hence  $S_+ \subseteq p$ , so  $p \notin \text{Proj } S$ ).

EXAMPLE. Let  $S = k[X_0, \dots, X_n]$ , but grade by  $\deg X_i = w_i$ , where  $w_0, \dots, w_n$  are positive integers. Define weighted projective space via  $W\mathbb{P}^n(w_0, \dots, w_n) = \text{Proj } S$ .

For example, consider  $W\mathbb{P}^2(1, 1, 2)$ . This has an open cover  $\{D_+(X_i)\}$ . We have  $D_+(X_2) \cong \text{Spec } S_{(X_2)}$ . Note

$$S_{(X_2)} = k[u := \frac{X_0^2}{X_2}, v := \frac{X_0X_1}{X_2}, w := \frac{X_1^2}{X_2}] \subseteq S_{X_2} \cong k[u, v, w]/(uw - v^2)$$

$\text{Spec } S_{(X_2)}$  then is a quadric cone (an image is missing here).

$D_+(X_0)$  and  $D_+(X_1)$  are both isomorphic to  $\mathbb{A}_k^2$ .

EXAMPLE. Let  $M = \mathbb{Z}^n$ ,  $M_{\mathbb{R}} = M \otimes_{\mathbb{Z}} \mathbb{R} = \mathbb{R}^n$ . Let  $\Delta \subseteq M_{\mathbb{R}}$  be a compact convex lattice polytope, i.e., there is some finite set  $V \subseteq M$  such that  $\Delta$  is the convex hull of  $V$ , i.e., the smallest convex set containing  $V$ .

(there is a picture missing here)

Let  $C(\Delta) = \{(m, r) \in M_{\mathbb{R}} \oplus \mathbb{R} \mid m \in r\Delta, r \geq 0\}$ . Here  $r\Delta = \{r \cdot m \mid m \in \Delta\}$ . This is the cone over  $\Delta$ .

Let

$$S = k[C(\Delta) \cap (M \oplus \mathbb{Z})] = \bigoplus_{p \in C(\Delta) \cap (M \oplus \mathbb{Z})} k \cdot z^p.$$

The thing in the square bracket is a monoid (use convexity to prove this). We have a multiplication given by  $z^p \cdot z^{p'} = z^{p+p'}$  making  $S$  into a ring, and it is graded by  $\deg z^{m, r} = r$ .

Define  $\mathbb{P}_{\Delta} = \text{Proj } S$ . This is called a projective toric variety.

Examples: If  $\Delta$  is a standard  $n$ -simplex, i.e., the convex hull of  $\{0, e_1, \dots, e_n\}$ , then it is possible to check that  $S \cong k[X_0, \dots, X_n]$  with the standard grading such that  $X_0 \leftrightarrow z^{(0,1)}$ ,  $X_i \leftrightarrow z^{(e_i, 1)}$ . Hence  $\mathbb{P}_{\Delta} = \mathbb{P}_k^n$ .

Let  $n = 2$  and  $\Delta$  be the convex hull of  $\{(0, 0), (1, 0), (0, 1), (1, 1)\}$ , i.e., the unit square. In  $S$ , the degree  $d$  monomials are  $\{z^{(a, b, d)} \mid 0 \leq a, b \leq d\}$ . Any of these monomials can be written as a product of monomials of degree 1, i.e.,  $x := z^{(0, 0, 1)}$ ,  $y := z^{(1, 0, 1)}$ ,  $w := z^{(0, 1, 1)}$ ,  $t := z^{(1, 1, 1)}$ . Thus  $S = k[x, y, w, t]/(xt - yw)$  (it is possible but nontrivial to verify that this is the only relation).

Hence,  $\text{Proj } S$  can be thought of as a quadric surface in  $\mathbb{P}_k^3$ .





## CHAPTER 4

# Properties of schemes

### 1. Open and closed subschemes

**DEFINITION.** An open subscheme of a scheme  $X$  is a scheme  $(U, \mathcal{O}_X|_U)$  for  $U \subseteq X$  an open subset.

This is indeed a scheme, since from questions 1 and 11 on the first example sheet, we know that some open affine subsets of  $X$  form a basis for the topology of  $X$ . In particular, we can cover  $U$  by affine schemes.

An open immersion is a morphism  $f: X \rightarrow Y$  which induces an isomorphism of  $X$  with an open subscheme of  $Y$ .

A closed immersion  $f: X \rightarrow Y$  is a morphism which is a homeomorphism onto a closed subset of  $Y$  and the induced morphism  $f^\#: \mathcal{O}_Y \rightarrow f_*\mathcal{O}_X$  is surjective.

A closed subscheme of  $Y$  is an equivalence class of closed immersions, where two closed immersions are considered equivalent if there is an isomorphism  $i: X \rightarrow X'$  making the diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \downarrow i & \nearrow & \\ X' & & \end{array}$$

commute.

**EXAMPLE.** (1) Let  $Y = \operatorname{Spec} A$ , let  $I \subseteq A$  be an ideal and take  $X = \operatorname{Spec} A/I$ . Note that the map of schemes induced by the quotient map  $A \rightarrow A/I$  identifies  $\operatorname{Spec} A/I$  with  $V(I) \subseteq \operatorname{Spec} A$ . Thus the map  $f: X \rightarrow Y$  induced by  $A \rightarrow A/I$  satisfies the first condition of being a closed immersion.

Note that  $\mathcal{O}_Y \rightarrow f_*\mathcal{O}_X$  is surjective on stalks. Indeed, for  $p \in V(I)$ ,  $\mathcal{O}_{Y,p} \cong A_p$ , and furthermore  $(f_*\mathcal{O}_X)_p \cong \mathcal{O}_{X,p}$ , since all open sets in  $X$  are of the form  $U \cap X$  for  $U \subseteq Y$  open. We have  $\mathcal{O}_{X,p} \cong (A/I)_{(p/I)}$ . The induced map  $A_p \rightarrow (A/I)_{(p/I)}$  is surjective (and we should convince ourselves that this map is indeed the one we get).

(2)

$$\operatorname{Spec} k[X, Y]/(X) \rightarrow \operatorname{Spec} k[X, Y] = \mathbb{A}^2$$

can be thought of as the  $y$ -axis. This gives “a closed subscheme structure” to the set  $V(X)$ .

Observe that  $V(X^2, XY) = V(X)$ . Hence this also gives a closed immersion

$$\operatorname{Spec} k[X, Y]/(X^2, XY) \rightarrow \mathbb{A}^2,$$

but we obtain a different closed subscheme structure on  $V(X)$  (for example, in one we have nilpotents, in the other we do not).

If we were to draw a picture, we would think of the first subscheme as the  $y$ -axis, and the second subscheme as the  $y$ -axis where the origin is a special point.

Note that the subschemes are isomorphic away from the origin, which we can see by looking at  $D(Y) \subseteq \operatorname{Spec} k[X, Y]/(X)$ . Here  $D(Y) \cong$

$\mathrm{Spec}(k[X, Y]/(X))_Y \cong \mathrm{Spec} k[Y]_Y$ . If we instead consider  $D(Y) \subseteq \mathrm{Spec} k[X, Y]/(X^2, XY)$ . Here  $D(Y) \cong \mathrm{Spec}(k[X, Y]/(X^2, XY))_Y \cong \mathrm{Spec}(k[X, Y]_Y/(X)) \cong \mathrm{Spec} k[Y]_Y$ . The second isomorphism is a good exercise in localizations.

### 1.1. Fibre products.

DEFINITION. Let  $\mathcal{C}$  be a category and

$$\begin{array}{ccc} & & Y \\ & & \downarrow g \\ X & \xrightarrow{f} & Z \end{array}$$

be a diagram in  $\mathcal{C}$ .

Then a fibre product, if it exists, is an object  $W$  equipped with morphisms  $p: W \rightarrow X$ ,  $q: W \rightarrow Y$  such that  $f \circ p = g \circ q$  satisfying the following universal property.

$$\begin{array}{ccccc} W' & & & & \\ & \searrow h & & & \\ & & W & \xrightarrow{q} & Y \\ & \swarrow p' & \downarrow p & & \downarrow g \\ & & X & \xrightarrow{f} & Z \end{array}$$

For any  $W'$  equipped with maps  $p': W' \rightarrow X$ ,  $q': W' \rightarrow Y$  such that  $f \circ p' = g \circ q'$ , there exists a unique morphism  $h: W' \rightarrow W$  making the diagram commute, i.e.,  $p \circ h = p'$ ,  $q \circ h = q'$ .

If the fibre product exists, it is unique up to unique isomorphism.

As a key exmple, if  $\mathcal{C}$  is the category of sets, then

$$X \times_Z Y = \{(x, y) \in X \times Y \mid f(x) = g(y)\}.$$

REMARK. It will be helpful to think about the fibre product and more generally other universal properties via the Yoneda lemma.

Let  $\mathcal{C}$  be a category. Write  $h_X$  for the contravariant functor

$$\begin{aligned} h_X: \mathcal{C} &\rightarrow \mathbf{Set} \\ Y &\mapsto \mathrm{Hom}(Y, X) \\ h_X(f: Y \rightarrow Z): \mathrm{Hom}(Z, X) &\rightarrow \mathrm{Hom}(Y, X) \\ \varphi &\mapsto \varphi \circ f. \end{aligned}$$

Recall that a natural transformation of contravariant functors  $F, G: \mathcal{C} \rightarrow \mathcal{D}$  written as  $T: F \rightarrow G$ , consists of data  $T(X): F(X) \rightarrow G(X)$  for every object  $X$  of  $\mathcal{C}$  such that for all  $f: X \rightarrow Y$  in  $\mathcal{C}$  the diagram

$$\begin{array}{ccc} F(X) & \xleftarrow{F(f)} & F(Y) \\ \downarrow T(X) & & \downarrow T(Y) \\ G(X) & \xleftarrow{G(f)} & G(Y) \end{array}$$

commutes.

The Yoneda lemma sats that the set of natural transformations  $h_X \rightarrow G$  for any functor  $G: \mathcal{C} \rightarrow \mathbf{Set}$  is in natural bijection with  $G(X)$ .

A sketch of the proof is as follows: given  $\eta \in G(X)$ , we need to define a map  $h_X(Y) \rightarrow G(Y)$  for all objects  $Y$  in  $\mathcal{C}$ . We do this by sending  $f: Y \rightarrow X$  to  $G(f)(\eta)$ . One can check that this is indeed a natural transformation.

In the converse direction, if  $T: h_X \rightarrow F$  is a natural transformation, we obtain an element  $\eta: T(X)(1_X) \in F(X)$ .

One can check that these two maps are inverse to each other.

The corollary we are interested in is the following: the set of natural transformations  $h_X \rightarrow h_Y$  is in natural bijection with  $h_Y(X) = \text{Hom}(X, Y)$ .

We call a contravariant functor  $F: \mathcal{C} \rightarrow \text{Set}$  representable if  $F$  is naturally isomorphic to  $h_X$  for some object  $X$  of  $\mathcal{C}$ .

Lots of questions in algebraic geometry boil down to whether some functor is representable.

In this light, we can redefine fibre products: a fibre product in a category  $\mathcal{C}$  is an object which represents the functor  $T \mapsto \text{Hom}(T, X) \times_{\text{Hom}(T, Z)} \text{Hom}(T, Y)$ .

The advantage of putting it this way is that we can check identities involving fibre products using identities of fibre products of sets. For example, consider the identity  $(A \times_B C) \times_C D \cong A \times_B D$ . On sets, we find that  $((a, c), d) \mapsto (a, d)$  has the inverse  $((a, f(d)), d)$ , where  $f: D \rightarrow C$  is the map we pulled back.

Then we have functors  $T \mapsto (h_A(T) \times_{h_B(T)} h_C(T)) \times_{h_C(T)} h_D(T)$  and  $T \mapsto h_A(T) \times_{h_B(T)} h_D(T)$ . The bijection of sets above yields a natural isomorphism between the functors, which hence represent isomorphic objects by Yoneda.

**THEOREM 4.1.** The category of schemes has fibre products.

**PROOF.** We will construct  $X \times_S Y$  for various cases, bootstrapping up to the general case.

For the first step,  $X = \text{Spec } A$ ,  $Y = \text{Spec } B$ ,  $S = \text{Spec } R$ . Since we have an equivalence with the opposite category of the category of rings, we are looking for pushouts in the category of rings. But the pushout of  $A$  and  $B$  via  $R$  is just  $A \otimes_R B$ . Thus  $\text{Spec}(A \otimes_R B)$  is  $\text{Spec } A \times_{\text{Spec } R} \text{Spec } B$  in the category of affine schemes.

If  $T$  is an arbitrary scheme, then giving a morphism  $T \rightarrow \text{Spec } A$  (for any ring  $A$ ) is the same as giving a morphism  $A \rightarrow \Gamma(T, \mathcal{O}_T)$  by the first example sheet. Thus giving a diagram

$$\begin{array}{ccc}
 T & & \\
 \downarrow & \searrow & \\
 & \text{Spec } B & \\
 & \downarrow & \\
 \text{Spec } A & \longrightarrow & \text{Spec } R
 \end{array}$$

is equivalent to

$$\begin{array}{ccccc}
 & & \Gamma(T, \mathcal{O}_T) & & \\
 & & \swarrow & \searrow & \\
 & & \exists! h & & \\
 & & A \otimes_R B & \longleftarrow & B \\
 & \uparrow & & & \uparrow g \\
 A & \longleftarrow & R & & 
 \end{array}$$

and  $h: A \otimes_R B \rightarrow \Gamma(T, \mathcal{O}_T)$  induces a map  $T \rightarrow \text{Spec } A \otimes_R B$ . Thus  $\text{Spec } A \otimes_R B$  is the fibre product  $\text{Spec } A \times_{\text{Spec } R} \text{Spec } B$  in the category of schemes.

For the second step, the idea is to construct more general fibre products by gluing of schemes as seen on the first example sheet. We also glue morphisms: if  $X, Y$  are schemes,  $\{U_i\}$  an open cover of  $X$  and we are given morphisms  $f_i: U_i \rightarrow Y$  such that  $f_i|_{U_i \cap U_j} = f_j|_{U_i \cap U_j}$ , then we obtain  $f: X \rightarrow Y$  such that  $f|_{U_i} = f_i$  (this was proved in the examples class).

For the third step, if  $X, Y \rightarrow S$  are given and  $U \subseteq X$  is open, suppose that  $X \times_S Y$  exists, with projectives  $p_1: X \times_S Y \rightarrow X$ ,  $p_2: X \times_S Y \rightarrow Y$ . Then we claim  $p_1^{-1}(U)$  has the universal property of  $U \times_S Y$ .



Note that by commutativity, the image of  $p_1 \circ h'$  is contained in  $U$ , hence the image of  $h'$  is contained in  $p_1^{-1}(U)$ . Hence we get a unique factoring  $h$  as required. Therefore, the universal property holds for  $p^{-1}(U)$ .

For the fourth step, suppose  $\{X_i\}$  is an open cover of  $X$  and  $X_i \times_S Y$  exists for each  $i$ . Then we claim that  $X \times_S Y$  exists.

Indeed, Define  $X_{ij} := X_i \cap X_j$ ,  $U_{ij} = p_1^{-1}(X_{ij}) \subseteq X_i \times_S Y$ . By the third step, we find  $U_{ij} \cong X_{ij} \times_S Y$ . By the universal property of fibre products, there is a unique isomorphism  $\varphi_{ij}: U_{ij} \rightarrow U_{ji}$  compatible with the projections.

As an exercise: check that these gluing maps  $\varphi_{ij}$  satisfy the requirements of question 14 on the first example sheet.

Thus we can glue that  $X_i \times_S Y$  via the  $\varphi_{ij}$  to get a scheme  $X \times_S Y$ , and we need to check that this is indeed a fibre product. So suppose we have a scheme  $T$ ,  $p'_1: T \rightarrow X$  and  $p'_2: T \rightarrow Y$  satisfying the commutativity condition. Let  $T_i := (p'_1)^{-1}(X_i)$ , so we get a morphism  $\theta_i: T_i \rightarrow X_i \times_S Y \hookrightarrow X \times_S Y$ , where the latter is an open immersion by construction. On  $T_i \cap T_j$ , these maps agree, since they factor through  $X_{ij} \times_S Y \subseteq X_i \times_S Y$  and  $X_{ji} \times_S Y \subseteq X_j \times_S Y$  and by the universal property they agree.

Thus using step 2 we can glue the  $\theta_i$  to get  $\theta: T \rightarrow X \times_S Y$ . It is an exercise to check that this is the unique map making the diagram commute.

For step 5, using step 4 and 1, we may construct  $X \times_S Y$  when  $S$  and  $Y$  are affine. Repeating the process for  $Y$ , we obtain fibre products when  $S$  is affine and  $X$  and  $Y$  are arbitrary schemes.

Now, for step 6, if  $X, Y$  and  $S$  are all arbitrary, take an open affine cover  $\{S_i\}$  of  $S$ ,  $f: X \rightarrow S: Y \rightarrow S$ ,  $X_i := f^{-1}(S_i)$ ,  $Y_i := g^{-1}(S_i)$ . Then  $X_i \times_{S_i} Y_i$  exists, and it is an exercise to verify using the universal property that  $X_i \times_{S_i} Y_i \cong X_i \times_S Y_i$  (since the maps  $X_i \rightarrow S$  and  $Y_i \rightarrow S$  factor through  $S_i$ ). Use the same gluing argument as above to glue the  $X_i \times_S Y_i$  to  $X \times_S Y$ .  $\square$

## 2. Fibres of morphisms

REMARK. In the category of sets, if  $f: X \rightarrow Y$  and  $y \in Y$ , then the fibre product  $\{y\} \times_Y X$  is just  $f^{-1}(y)$ .

DEFINITION 4.2. Given a morphism of schemes  $f: X \rightarrow Y$  and  $y \in Y$ , let  $\kappa(y) := \mathcal{O}_{Y,y}/\mathfrak{m}_y$  be the residue field of  $y$ . We get a morphism  $\text{Spec } \kappa(y) \rightarrow Y$  with image  $y$ . Then we define  $X_y := \text{Spec } \kappa(y) \times_Y X$  to be the scheme-theoretic fibre of  $f$  at  $y$ .

EXAMPLE. Let  $f: X = \text{Spec } k[X] \rightarrow Y = \text{Spec } k[t]$  be induced by the map  $k[t] \rightarrow k[X]$  given by  $t \mapsto X^2$ .

For  $y = (t - a) \subseteq k[t]$ ,  $a \in k$ , then notice that  $\kappa(y) \cong k[t]/(t - a) \cong k$  (exercise: verify the first isomorphism)  $X_y \cong \text{Spec } \kappa(y) \otimes_{k[t]} k[X]$ . From commutative

algebra, we know that for an  $A$ -algebra  $B$  we have  $A/I \otimes_A B \cong B/IB$ . Hence  $X_y \cong \operatorname{Spec} k[X]/(X^2 - a)$ . If  $a \neq 0$  and  $\operatorname{char} k \neq 2$ , then we find that either  $X_y$  consists of two distinct points or a single point of  $\sqrt{a} \notin k$ . If  $a = 0$ , then we get  $\operatorname{Spec} k[X]/(X^2)$ .

This can be thought of like collapsing a rotated parabola to a line. There is an image missing here.

- REMARK. (1) In general, it is hard to calculate fibre products. In general,  $X \times_S Y$  will not be the set-theoretic fibre product, for example  $\mathbb{A}_k^1 \times_{\operatorname{Spec} k} \mathbb{A}_k^1 \cong \operatorname{Spec} k[X] \otimes_k k[Y] \cong \operatorname{Spec} k[X, Y] \cong \mathbb{A}_k^2$ .
- (2) If we are interested only in varieties, i.e., schemes over a field  $k$ , the usual product of varieties  $X \times Y$  will correspond to  $X \times_{\operatorname{Spec} k} Y$ . More generally, if we are working in the category of schemes over  $S$ , the categorical product is given by  $X \times_S Y$ .
- (3) Given schemes  $S, T$  with a morphism  $T \rightarrow S$  we get a functor from schemes over  $S$  to schemes over  $T$  given by  $X \rightarrow S \mapsto X \times_S T \rightarrow T$ . This functor is called base change.

EXAMPLE. Consider a scheme  $X$  over  $\operatorname{Spec} \mathbb{Z}$ , for example  $X = \operatorname{Proj} \mathbb{Z}[X, Y, Z]/(X^n + Y^n - Z^n) \rightarrow \operatorname{Spec} \mathbb{Z}$ .

We may consider the base change

$$\operatorname{Spec} \mathbb{F}_p \rightarrow \operatorname{Spec} \mathbb{Z}$$

induced by  $\mathbb{Z} \rightarrow \mathbb{Z}/p\mathbb{Z} \cong \mathbb{F}_p$ . Here we have

$$X \times_{\operatorname{Spec} \mathbb{Z}} \operatorname{Spec} \mathbb{F}_p \cong \operatorname{Proj} \mathbb{F}_p[X, Y, Z]/(X^n + Y^n - Z^n).$$

Another possible base change is  $\operatorname{Spec} \mathbb{Q} \rightarrow \operatorname{Spec} \mathbb{Z}$  induced by  $\mathbb{Z} \rightarrow \mathbb{Q}$ . In this case we have

$$X \times_{\operatorname{Spec} \mathbb{Z}} \operatorname{Spec} \mathbb{Q} \cong \operatorname{Proj} \mathbb{Q}[X, Y, Z]/(X^n, Y^n - Z^n).$$

Yet another example is given by  $\operatorname{Spec} \mathbb{C} \rightarrow \operatorname{Spec} \mathbb{Z}$  induced by  $\mathbb{Z} \rightarrow \mathbb{C}$ . This gives

$$X \times_{\operatorname{Spec} \mathbb{Z}} \operatorname{Spec} \mathbb{C} \cong \operatorname{Proj} \mathbb{C}[X, Y, Z]/(X^n + Y^n - Z^n) \subseteq \mathbb{P}_{\mathbb{C}}^2.$$

This illustrates the power of scheme-theoretic language to translate questions between different areas (e.g., number theory or geometry)

DEFINITION 4.3. A scheme  $X$  is called integral if for every  $U \subseteq X$  open  $\mathcal{O}_X(U)$  is an integral domain.

DEFINITION 4.4. A scheme  $X$  is called reduced if for every  $U \subseteq X$  open  $\mathcal{O}_X(U)$  has no nilpotent elements.

DEFINITION 4.5. A scheme  $X$  is called irreducible if the underlying topological space  $X$  is irreducible, i.e., if  $X = X_1 \cup X_2$  with  $X_1, X_2 \subseteq X$  closed, then  $X_1 = X$  or  $X_2 = X$ .

EXAMPLE. Take  $X = \operatorname{Spec} k[X, Y]/(XY)$ .

- $X$  is not integral because  $\Gamma(X, \mathcal{O}_X) \cong k[X, Y]/(XY)$  is not an integral domain, as  $X \times Y = 0$ .
- We can show that  $X$  is reduced, and this follows from the fact that the global sections to not have nilpotents (TODO: how?).
- $X$  is not irreducible, since  $X = V(X) \cup V(Y)$ . We can think of  $X$  as the union of the  $x$ -axis and the  $y$ -axis.

THEOREM 4.6. A scheme  $X$  is integral if and only if  $X$  is reduced and irreducible.

PROOF. On the second example sheet.  $\square$

DEFINITION 4.7. Let  $X$  be a scheme. We call  $X$  locally Noetherian if there is a cover  $\{U_i\}$  of  $X$  with  $U_i \cong \text{Spec } A_i$  affine and  $A_i$  Noetherian. We call  $X$  Noetherian if the cover may be taken to be finite.

As an example, the scheme  $\text{Spec } k[X_1, X_2, \dots]$  is not locally Noetherian, and this is not obvious.

However, it is possible to show that  $X$  is locally Noetherian if and only if for every affine subset  $U \subseteq X$ ,  $U \cong \text{Spec } A$  we have that  $A$  is Noetherian.

DEFINITION 4.8. A morphism  $f: X \rightarrow Y$  of schemes is called locally of finite type if there is a covering of  $Y$  by affine open sets  $\{V_i \cong \text{Spec } B_i\}$  such that for each  $i$ ,  $f^{-1}(V_i)$  can be covered by affine open sets  $\{U_{ij} \cong \text{Spec } A_{ij}\}$ , where each  $A_{ij}$  is a finitely generated  $B_i$ -algebra. This makes sense:

$$\begin{array}{ccc} U_{ij} & & A_{ij} \\ \downarrow & & \uparrow \\ V_i & & B_i. \end{array}$$

We say that  $f$  is of finite type if for each  $i$  the cover  $U_{ij}$  may be taken to be finite.

DEFINITION 4.9. Let  $k$  be an algebraically closed field. A variety over  $k$  is a scheme  $X$  over  $\text{Spec } k$  which is integral and  $X \rightarrow \text{Spec } k$  is of finite type.

Note that since  $\text{Spec } k$  only has one point, being of finite type just means that  $X$  can be covered by a finite number of open affines  $U_i = \text{Spec } A_i$  with  $A_i$  a finitely generated  $k$ -algebra. The  $A_i$  must be integral domains. In particular, this forces  $A_i = k[X_1, \dots, X_n]/I$ , where  $I$  is a prime ideal.

Note this still allows a “non-Hausdorff” scheme  $\mathbb{A}^1 \cup \mathbb{A}^1$  obtained by gluing  $D(X)$  to  $D(X)$  (this is the line with two origins).

EXAMPLE 4.10. Let  $X_i = \text{Spec } k[X_i, Y_i]/(X_i Y_i)$ ,  $i \in \mathbb{Z}$ . Glue  $X_i$  to  $X_{i+1}$  along the open subsets  $U_{i,i+1} \subseteq X_i$  given by  $D(X_i)$  and  $U_{i+1,i} \subseteq X_{i+1}$  given by  $D(Y_{i+1})$  via the map

$$U_{i,i+1} \cong \text{Spec} \left( \frac{k[X_i, Y_i]}{(X_i Y_i)} \right)_{X_i} \cong \text{Spec } k[X_i]_{X_i} \rightarrow \text{Spec } k[Y_{i+1}]_{Y_{i+1}} \cong U_{i+1,i}$$

induced by the ring homomorphism sending  $Y_{i+1} \mapsto X_i^{-1}$ .

Do this for all  $i$  to get an infinite chain of  $\mathbb{P}^1$ s.

There is an image missing here.

The  $\{X_i\}$  form an open cover of  $X$  that has no finite subcover, so  $X$  is not quasicompact and only locally of finite type over  $\text{Spec } k$ .

### 3. Separated and proper morphisms

REMARK. A topological space  $X$  is Hausdorff if and only if the diagonal  $\Delta \subseteq X \times X$  is closed.

For example, if  $X$  is the Euclidean line with two origins is not Hausdorff, since every open set containing one origin also contains the other. The space  $X \times X$  is  $\mathbb{R}^2$  with doubled axes and four origin. The diagonal  $\Delta$  only contains two of the origins. But the other two origins are still contained in the closure of  $\Delta$ . There is a picture missing here.

DEFINITION 4.11. If  $f: X \rightarrow Y$  is a morphism of schemes. Define  $\Delta: X \rightarrow X \times_Y X$  to be the unique morphism making the diagram

$$\begin{array}{ccccc}
 & & X & & \\
 & \swarrow \Delta & \searrow \text{id}_X & & \\
 X & & & & X \\
 & \searrow \text{id}_X & \swarrow & & \downarrow f \\
 & X \times_Y X & \longrightarrow & X & \\
 & \downarrow & & \downarrow f & \\
 & X & \xrightarrow{f} & Y &
 \end{array}$$

commute.

Way say that  $f$  is separated if  $\Delta$  is a closed immersion.

THEOREM 4.12. Let  $f: X \rightarrow Y$  be a morphism of schemes, where  $X$  is Noetherian. Then  $f$  is separated if and only if the following condition holds.

For any field  $K$  and any valuation ring  $R \subseteq K$  (i.e., for any  $0 \neq x \in K$ ,  $x \in R \vee x^{-1} \in R$ ), let  $T = \text{Spec } R$ ,  $U = \text{Spec } K$ , and let  $U \rightarrow T$  be the morphism induced by the inclusion  $R \rightarrow K$ . Given a commutative diagram

$$\begin{array}{ccc}
 U & \longrightarrow & X \\
 \downarrow i & & \downarrow f \\
 T & \longrightarrow & Y
 \end{array}$$

there exists at most one morphism  $i': T \rightarrow X$  making the diagram commute.

NOT PROVED IN THIS COURSE. It is recommended to read a proof in II.4 of Hartshorne.  $\square$

REMARK. If  $R$  is a valuation ring, it has 0 as a prime ideal and a unique maximal ideal. The point  $\{0\}$  is dense (i.e., its closure is all of  $\text{Spec } R$ ). The closed point  $\mathfrak{m}$  is in some sense a limit point. Very roughly, the “at most one” condition in the valuative criterion corresponds to the fact that a sequence has at most one limit in a Hausdorff space.

REMARK. We may now define a variety over a field  $k$  as a scheme  $X$  which is integral and finite type and separated over  $\text{Spec } k$ .

DEFINITION 4.13. A morphism  $f: X \rightarrow Y$  is called proper if it is separated, of finite type and universally closed, i.e., for any morphism  $Y' \rightarrow Y$  the induced projection  $X \times_Y Y' \rightarrow Y'$  is a closed map, i.e., sends closed sets to closed sets.

EXAMPLE. (1)  $\mathbb{P}_k^n = \text{Proj } k[X_0, \dots, X_n] \rightarrow \text{Spec } k$  is proper.

(2)  $\mathbb{A}_k^1 \rightarrow \text{Spec } k$  is not proper. It is separated (we have not proved this) and of finite type (TODO: this should be clear). Consider the base change by  $\mathbb{A}_k^1 \rightarrow \text{Spec } k$ . We have the map

$$KP_2: \mathbb{A}_k^1 \times_{\text{Spec } k} \mathbb{A}_k^1 = \mathbb{A}_k^2 = \text{Spec } k[X] \otimes_k k[Y] \rightarrow \text{Spec } k[t] = \mathbb{A}_k^1$$

$$Y \mapsto t$$

$$(X, Y) \mapsto Y.$$

This is not a closed map, e.g.,  $P_2(V(XY - 1)) = D(t)$ , which is open, not closed. We are essentially projecting a hyperbola to the  $x$  axis.

THEOREM 4.14. Let  $f: X \rightarrow Y$  be a morphism of finite type with  $X$  noetherian. Then  $f$  is proper if as in the criterion for separatedness, whenever given a diagram

$$\begin{array}{ccc} \operatorname{Spec} k = U & \xrightarrow{\quad} & X \\ \downarrow & \nearrow \exists! g & \downarrow f \\ \operatorname{Spec} R = T & \xrightarrow{\quad} & Y, \end{array}$$

where  $R$  is a valuation ring, there exists a unique morphism  $g: T \rightarrow X$  making the diagram commute.

EXAMPLE. Projective varieties, i.e., closed subvarieties in  $\mathbb{P}_n^k$  are proper over  $\operatorname{Spec} k$ .



## CHAPTER 5

### Sheaves of $\mathcal{O}_X$ -modules

REMARK. We want to go from the notion of an  $A$ -module  $M$  to the notion of an  $\mathcal{O}_X$ -module  $F$ .

DEFINITION 5.1. Let  $(X, \mathcal{O}_X)$  be a ringed space. A sheaf of  $\mathcal{O}_X$ -modules is a sheaf of abelian groups on  $X$  such that for each  $U \subseteq X$ ,  $\mathcal{F}(U)$  has the structure of an  $\mathcal{O}_X(U)$ -module, compatible with restriction, i.e., if  $s \in \mathcal{O}_X(U)$ ,  $m \in \mathcal{F}(U)$  and  $V \subseteq U$ , then  $s|_V \cdot m|_V = (s \cdot m)|_V$ .

A morphism of sheaves of  $\mathcal{O}_X$ -modules  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  is a morphism of sheaves of abelian groups such that for all  $U \subseteq X$  the map  $\varphi_U: \mathcal{F}(U) \rightarrow \mathcal{G}(U)$  is  $\mathcal{O}_X(U)$ -linear.

Kernels, cokernels and images of morphisms of sheaves of  $\mathcal{O}_X$ -modules are sheaves of  $\mathcal{O}_X$ -modules (TODO: show that sheafification retains the  $\mathcal{O}_X$ -module structure).

We write  $\text{Hom}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{G})$  for the group of  $\mathcal{O}_X$ -module homomorphisms from  $\mathcal{F}$  to  $\mathcal{G}$ . This is an  $\mathcal{O}_X(X)$ -module.

Then  $U \mapsto \text{Hom}_{\mathcal{O}_U}(\mathcal{F}|_U, \mathcal{G}|_U)$  is a sheaf of  $\mathcal{O}_X$ -modules, written as  $\mathcal{H}om(\mathcal{F}, \mathcal{G})$  and pronounced “sheaf hom”.

If  $\mathcal{F}, \mathcal{G}$  are  $\mathcal{O}_X$ -modules, we denote by  $\mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{G}$  with the trivial Lie bracket. the sheaf associated to the presheaf  $U \mapsto \mathcal{F}(U) \otimes_{\mathcal{O}_X(U)} \mathcal{G}(U)$ .

Pushforwards and pullbacks: We will start with some motivation. Consider a map of rings  $\varphi: A \rightarrow B$  and let  $M$  be a  $B$ -module and  $N$  an  $A$ -module. Then  $M$  is also an  $A$ -module via restriction of scalars. Also,  $B \otimes_A N$  is a  $B$ -module via extension of scalars. We want to find analogues of this for sheaves of  $\mathcal{O}_X$ -modules.

Given  $f: X \rightarrow Y$  a morphism of ringed spaces (recall that this includes a map  $f^\#: \mathcal{O}_Y \rightarrow f_*\mathcal{O}_X$ ), a sheaf  $\mathcal{F}$  of  $\mathcal{O}_X$ -modules and a sheaf  $\mathcal{G}$  of  $\mathcal{O}_Y$ -modules, then

- (1)  $f_*\mathcal{F}$  is naturally a sheaf of  $f_*\mathcal{O}_X$ -modules since  $(f_*\mathcal{F})(U) = \mathcal{F}(f^{-1}(U))$ , which is a  $\mathcal{O}_X(f^{-1}(U)) = (f_*\mathcal{O}_X)(U)$ -module and hence  $f_*\mathcal{F}$  becomes a  $\mathcal{O}_Y$ -module via restriction of scalars.
- (2)  $f^{-1}\mathcal{G}$  is naturally an  $f^{-1}\mathcal{O}_Y$ -module. But  $f^\#$  induces the adjoint map  $f^\#: f^{-1}\mathcal{O}_Y \rightarrow \mathcal{O}_X$  by Question 10 on the first example sheet. Define  $f^*\mathcal{G} := f^{-1}\mathcal{G} \otimes_{f^{-1}\mathcal{O}_Y} \mathcal{O}_X$ . This is a sheaf of  $\mathcal{O}_X$ -modules.

DEFINITION 5.2. We call a sheaf  $\mathcal{F}$  of  $\mathcal{O}_X$ -modules free if it is isomorphic to  $\bigoplus_{i \in I} \mathcal{O}_X$  for some index set  $I$ . If  $I$  is finite of cardinality  $r$ , then we say that  $\mathcal{F}$  has rank  $r$ .

A sheaf  $\mathcal{F}$  is called locally free of rank  $r$ , if there exists an open cover  $\{U_i\}$  of  $X$  such that  $\mathcal{F}|_{U_i}$  is free (as a  $\mathcal{O}_X|_{U_i}$ -module!) of rank  $r$  for each  $i$ .

We say that  $\mathcal{F}$  is a line bundle if it is rank 1.

Often, more generally, one might refer to a rank  $r$  locally free sheaf as a rank  $r$  vector bundle.

EXAMPLE. Let  $X = \text{Spec } A$  be an affine scheme and  $M$  an  $A$ -module. For  $p \in \text{Spec } A$ , we have the localization  $M_p$ . Define a sheaf  $\tilde{M}$  on  $\text{Spec } A$  by

$$\tilde{M}(U) = \{s: U \rightarrow \coprod_{p \in U} M_p \mid (\star)\},$$

where  $(\star)$  means that

- (1)  $\forall p \in U: s(p) \in M_p$ ,
- (2) for each  $p \in U$  there is a neighborhood  $p \in V \subseteq U$  and  $m \in M$ ,  $s \in A$  such that  $s \notin q$  for all  $q \in V$  and  $s(q) = m/s$  for all  $q \in V$ .

We notice that  $\tilde{A} = \mathcal{O}_{\text{Spec } A}$ . Observe:

- (1)  $(\tilde{M})_p \cong M_p$ ,
- (2)  $\tilde{M}(D(f)) \cong M_f$ ,
- (3)  $\Gamma(\text{Spec } A, \tilde{M}) \cong M$ .

The proofs are exactly the same as for  $\mathcal{O}_{\text{Spec } A}$ .

REMARK 5.3. One may define the notion of a vector bundle over a scheme  $X$  as another scheme  $E$  with a morphism  $\pi: E \rightarrow X$  whose fibres are  $\mathbb{A}^r$ , and there is an open cover  $\{U_i\}$  such that  $\pi^{-1}(U_i) \cong U_i \times \mathbb{A}^r$  (and some other conditions).

We get a sheaf  $\mathcal{E}(U) = \{s: U \rightarrow \pi^{-1}(U) \mid \pi \circ s = \text{id}_U\}$ . This gives a locally free sheaf on  $X$ . For details, see the exercises of Hartshorne, II.5.

As an example let  $E = X \times \mathbb{A}^1$ , then  $\mathcal{E}(U) = \mathcal{O}_X(U)$ . Giving a morphism  $s: U \rightarrow U \times_{\text{Spec } k} \mathbb{A}_k^1$  whose composition with  $p_1: U \times \mathbb{A}_k^1 \rightarrow U$  is the identity is the same as giving a morphism  $U \rightarrow \mathbb{A}_k^1$ :

$$\begin{array}{ccc}
 U & \xrightarrow{\quad f \quad} & \mathbb{A}_k^1 \\
 \searrow s & & \downarrow \\
 U \times_{\text{Spec } k} \mathbb{A}_k^1 & \longrightarrow & \mathbb{A}_k^1 \\
 \downarrow \text{id}_U & & \downarrow \\
 U & \longrightarrow & \text{Spec } k
 \end{array}$$

But giving a morphism  $f: U \rightarrow \mathbb{A}_k^1$  is the same thing as giving a homomorphism of  $k$ -algebras  $k[X] \rightarrow \mathcal{O}_X(U)$  mapping  $X \mapsto \varphi$  for some  $\varphi \in \mathcal{O}_X(U)$ . Hence the set of such homomorphisms is completely determined by the elements of  $\mathcal{O}_X(U)$ .

DEFINITION 5.4. Let  $X$  be a scheme and  $\mathcal{F}$  a sheaf of  $\mathcal{O}_X$ -modules on  $X$ . We say that  $\mathcal{F}$  is quasi-coherent, if  $X$  can be covered with affines  $U_i = \text{Spec } A_i$  such that  $\mathcal{F}|_{U_i} \cong \tilde{M}_i$  for some  $A_i$ -module  $M_i$ .

We say that  $\mathcal{F}$  is coherent if each  $M_i$  can be taken to be finitely generated.

EXAMPLE. A locally free sheaf is always quasi-coherent and it is coherent if it is of finite rank: if  $U \subseteq X$  (where  $U \cong \text{Spec } A$ ) satisfies  $\mathcal{F}|_U \cong \bigoplus_{i \in I} \mathcal{O}_U$ , then  $\mathcal{F}|_U = \bigoplus_{i \in I} \tilde{A}$

Kernels, cokernels, images, tensor products and hom sheaves of quasi-coherent sheaves of  $\mathcal{O}_X$ -modules are themselves quasi-coherent.

This follows since these operations commute with  $\tilde{\phantom{x}}$ , e.g.,  $\ker(\tilde{M}_1 \rightarrow \tilde{M}_2) = \widetilde{\ker(M_1 \rightarrow M_2)}$ ,  $\tilde{M}_1 \otimes_{\mathcal{O}_X} \tilde{M}_2 = \widetilde{M_1 \otimes_A M_2}$ ,  $\text{Hom}_{\mathcal{O}_X}(\tilde{M}_1, \tilde{M}_2) = \widetilde{\text{Hom}_A(M_1, M_2)}$

Should check (TODO) that a morphism of sheaves is always induced by an underlying morphism of modules (look at global sections).

REMARK. Note that if  $\mathcal{L}$  is a line bundle, say with trivializing cover  $\{U_i\}$ , then we have on  $U_i \cap U_j$ :

$$\mathcal{O}_{U_i}|_{U_i \cap U_j} \xleftarrow{\cong} \mathcal{L}|_{U_i \cap U_j} \xrightarrow{\cong} \mathcal{O}_{U_j}|_{U_i \cap U_j},$$

where the first map comes from trivialization in  $U_i$  and the other using trivialization on  $U_j$ . Composing the second map with the inverse of the first yields a map  $\varphi_{ij}$  from left to right. Then  $\varphi_{ij}$  is an automorphism of  $\mathcal{O}_{U_i \cap U_j}$  as an  $\mathcal{O}_{U_i \cap U_j}$ -module, and as

such is given by multiplication by  $g_{ij} \in \mathcal{O}_X^\times(U_i \cap U_j)$ , where  $\mathcal{O}_X^\times$  is the subsheaf of  $\mathcal{O}_X$  consisting of invertible sections of  $\mathcal{O}_X$ .

Note on  $U_i \cap U_j \cap U_k$  we have  $g_{ij}g_{jk} = g_{ik}$ .

Now suppose given  $f: Y \rightarrow X$  a morphism and  $\mathcal{L}$  still a line bundle on  $X$ . How do we think about  $f^*\mathcal{L}$ ?

Let  $Y_i := f^{-1}(U_i)$ . We get  $f_i: Y_i \rightarrow U_i$ . Then

$$f_i^*(\mathcal{L}|_{U_i}) \cong f_i^*(\mathcal{O}_U) \cong f_i^{-1}(\mathcal{O}_{U_i}) \otimes_{f_i^{-1}\mathcal{O}_{U_i}} \mathcal{O}_{Y_i} \cong \mathcal{O}_{Y_i}.$$

Hence  $(f^*\mathcal{L})|_{Y_i} \cong \mathcal{O}_{Y_i}$ , so  $\{U_i\}$  pulls back to a trivializing cover for  $f^*\mathcal{L}$ , i.e., the pullback of a line bundle is a line bundle.

Further, the transition maps are given by  $f^\#(g_{ij})$  (this can be shown by tracing the previous chain of isomorphisms in a larger pulled back version of the above diagram).

REMARK. The pushforward is not as well-behaved, e.g.,  $f_*\mathcal{L}'$  for  $\mathcal{L}'$  a line bundle on  $Y$  need not be a line bundle. In fact, it will always be quasi-coherent, but not necessarily coherent.

If  $\mathcal{L}_1, \mathcal{L}_2$  are line bundles on  $X$ , with a common trivializing cover  $\{U_i\}$  (this is always possible) and with transition functions  $g_{ij}, h_{ij}$  respectively, then:

- (1) The transition functions of  $\mathcal{L}_1 \otimes_{\mathcal{O}_X} \mathcal{L}_2$  are  $g_{ij}h_{ij}$ . Note that if  $(\cdot g): A \rightarrow A$  and  $(\cot h): A \rightarrow A$  are given, then these two homomorphisms induce the homomorphism  $(\cdot g) \otimes (\cdot h): A \otimes_A A \rightarrow A \otimes_A A$ , but  $A \otimes_A A \cong A$ , and applying this isomorphism on both sides yields the map  $A \rightarrow A$  given by  $(\cdot (g \cdot h))$ .
- (2) Set  $\mathcal{L}_1^\vee \cong \mathcal{H}om_{\mathcal{O}_X}(\mathcal{L}_1, \mathcal{O}_X)$ . This is also a line bundle, because on  $U_i$ ,  $\mathcal{L}_1|_{U_i} \cong \mathcal{O}_{U_i}$ , and  $\mathcal{H}om_{\mathcal{O}_{U_i}}(\mathcal{O}_{U_i}, \mathcal{O}_{U_i}) = \mathcal{O}_{U_i}$ , noting that  $\mathcal{H}om_A(A, A) \cong A$ .

The transition maps are given by  $g_{ij}^{-1}$ :

$$\mathcal{O}_{U_i}|_{U_i \cap U_j} \xrightarrow{\cdot g_{ij}} \mathcal{O}_{U_j}|_{U_i \cap U_j},$$

and we need to take the transpose inverse of this map represented by a  $1 \times 1$  matrix.

Note that  $\mathcal{L}_1^\vee \otimes_{\mathcal{O}_X} \mathcal{L}_1$  has transition maps given by  $g_{ij}^{-1}g_{ij} = 1$ . Thus  $\mathcal{L}_1^\vee \otimes_{\mathcal{O}_X} \mathcal{L}_1 \cong \mathcal{O}_X$ .

DEFINITION 5.5. Let  $X$  be a scheme. Define the Picard group  $\text{Pic}(X)$ , the Picard group of  $X$ , to be the set of isomorphism classes of line bundles on  $X$ . This is a group with product law  $\mathcal{L}_1 \cdot \mathcal{L}_2 := \mathcal{L}_1 \otimes_{\mathcal{O}_X} \mathcal{L}_2$  and inverses given by  $\mathcal{L}^{-1} := \mathcal{L}^\vee = \mathcal{H}om(\mathcal{L}, \mathcal{O}_X)$ .

REMARK 5.6. Why are line bundles important? They tell you about morphisms to projective space.

Fix a base scheme  $\text{Spec } k$ ,  $\mathbb{P}_k^n = \text{Proj } k[X_0, \dots, X_n]$ . Denote by  $\text{Sch}/k$  the category of schemes over  $\text{Spec } k$ . Let  $F$  be the functor taking a scheme  $T$  over  $k$  to the set of surjections  $\mathcal{O}_T^{\oplus(n+1)} \rightarrow \mathcal{L}$  for  $\mathcal{L}$  a line bundle on  $T$  modulo isomorphism, where  $\varphi_i: \mathcal{O}_T^{\oplus(n+1)} \rightarrow \mathcal{L}_i$  for  $i = 1, 2$  are considered isomorphic, if there exists an isomorphism  $f: \mathcal{L}_1 \rightarrow \mathcal{L}_2$  of  $\mathcal{O}_X$ -modules making the diagram

$$\begin{array}{ccc} \mathcal{O}_T^{\otimes(n+1)} & \xrightarrow{\varphi_1} & \mathcal{L}_1 \\ & \searrow \varphi_2 & \downarrow f \\ & & \mathcal{L}_2 \end{array}$$

commute.

Given a morphism  $f: T_1 \rightarrow T_2$  over  $k$ , we get a map of sets  $F(T_2) \rightarrow F(T_1)$  by mapping  $\varphi: \mathcal{O}_{T_2}^{\oplus(n+1)} \rightarrow \mathcal{L}$  to  $f^*\varphi: \mathcal{O}_{T_1}^{\oplus(n+1)} = f^*(\mathcal{O}_{T_2}^{\oplus(n+1)}) \rightarrow f^*\mathcal{L}$ . We use that  $f^*\varphi$  is still surjective, which follows from right exactness of the tensor product.

**THEOREM 5.7.** The functor  $F$  is represented by  $\mathbb{P}_k^n$ , i.e.,  $F \cong h_{\mathbb{P}_k^n}$ . In other words, giving a morphism to  $\mathbb{P}_k^n$  is the same as giving a surjective morphism as above.

**PROOF.** If the statement holds, then there is a “universal object”, i.e., an element of  $F(\mathbb{P}_k^n)$  corresponding to the identity  $1_{\mathbb{P}_k^n} \in h_{\mathbb{P}_k^n}(\mathbb{P}_k^n)$ , i.e., a surjective map  $\varphi: \mathcal{O}_{\mathbb{P}_k^n}^{\oplus(n+1)} \rightarrow \mathcal{L}$ . Further, following the proof of Yoneda, given  $f: X \rightarrow \mathbb{P}_k^n$  and  $T: h_{\mathbb{P}_k^n} \rightarrow F$  the natural transformation giving the natural isomorphism of functors, we get a commutative diagram

$$\begin{array}{ccc} h_{\mathbb{P}_k^n}(\mathbb{P}_k^n) & \xrightarrow{T(\mathbb{P}_k^n)} & F(\mathbb{P}_k^n) \\ \downarrow h_{\mathbb{P}_k^n}(f) & & \downarrow F(f) \\ h_{\mathbb{P}_k^n}(X) & \xrightarrow{T(X)} & F(X) \end{array}$$

By commutativity of the diagram, we find that  $f^*\varphi: \mathcal{O}_X^{\oplus(n+1)} \rightarrow f^*\mathcal{L}$  is the same as  $T(X)(f)$ .

So the representing scheme  $\mathbb{P}^n$  comes with the universal object (surjective morphism)  $\mathcal{O}_{\mathbb{P}^n}^{\otimes(n+1)} \rightarrow \mathcal{L}$ .

Hence, our proof strategy will be to construct this universal object. The line bundle we construct has a name:  $\mathcal{O}_{\mathbb{P}^n}(1)$ .

Recall that  $\mathbb{P}^n$  has an open cover  $\{D_+(X_i) \mid 1 \leq i \leq n\}$ , where  $S = k[X_0, \dots, X_n]$ ,  $\mathbb{P}_k^n = \text{Proj } S$ ,  $D_+(X_i) = \{\mathfrak{p} \in \text{Proj } S \mid X_i \in \mathfrak{p}\}$ .

We will take  $U$  to be the trivializing cover for  $\mathcal{O}_{\mathbb{P}^n}(1)$  with transition map  $g_{ij} \in \mathcal{O}_{\mathbb{P}^n}^\times(D_+(X_i) \cap D_+(X_j)) = \mathcal{O}_{\mathbb{P}^n}^\times(D_+(X_i X_j)) \cong S_{(X_i X_j)}$  given by  $g_{ij} = X_i/X_j = X_i^2/X_i X_j$ . Note that  $g_{ji} = X_j/X_i$ , so  $g_{ij}$  is invertible and the compatibility condition  $g_{ij} \cdot g_{jk} = g_{ik}$  is satisfied.

We have a morphism  $\mathcal{O}_{\mathbb{P}^n}^{\oplus(n+1)} \rightarrow \mathcal{O}_{\mathbb{P}^n}(1)$  defined on  $D_+(X_i)$  by  $e_j \mapsto \frac{X_j}{X_i}$  using the trivialization of  $\mathcal{O}_{\mathbb{P}^n}(1)$  on  $D_+(X_i)$ , i.e., we have an isomorphism  $\mathcal{O}_{\mathbb{P}^n}(1)|_{U_i} \cong \mathcal{O}_{U_i}$ .

We need to check that this is well-defined globally. We have maps

$$\begin{aligned} \mathcal{O}_{\mathbb{P}^n}^{\oplus(n+1)}|_{D_+(X_i X_k)} &\rightarrow \mathcal{O}_{D_+(X_i)}|_{D_+(X_j X_k)}, \\ e_j &\mapsto X_j/X_i, \\ \mathcal{O}_{\mathbb{P}^n}^{\oplus(n+1)}|_{D_+(X_i X_k)} &\rightarrow \mathcal{O}_{D_+(X_k)}|_{D_+(X_j X_k)}, \\ e_j &\mapsto X_j/X_k, \\ \mathcal{O}_{D_+(X_i)}|_{D_+(X_j X_k)} &\xrightarrow{g_{ik}} \mathcal{O}_{D_+(X_k)}|_{D_+(X_i X_k)} \end{aligned}$$

And the triangle they form commutes:

$$g_{ik} \cdot \frac{X_j}{X_i} = \frac{X_i}{X_k} \cdot \frac{X_j}{X_i} = \frac{X_j}{X_k}.$$

Note in particular, that each  $e_j$  maps to a global section of  $\mathcal{O}_{\mathbb{P}^n}(1)$ . (Remark: if instead we have chosen  $g_{ij} = X_j/X_i$  we would have obtained the line bundle  $\mathcal{O}_{\mathbb{P}^n}(1)^\vee =: \mathcal{O}_{\mathbb{P}^n}(-1)$ , and  $\Gamma(\mathbb{P}^n, \mathcal{O}_{\mathbb{P}^n}(-1)) = 0$ ).

We now have a morphism  $\mathcal{O}_{\mathbb{P}^n}^{\oplus(n+1)} \rightarrow \mathcal{O}_{\mathbb{P}^n}(1)$ , and we need to check that it is surjective. On  $D_+(X_i)$ , we have  $e_i \mapsto X_i/X_i = 1 \in \Gamma(D_+(X_i), \mathcal{O}_{\mathbb{P}^n})$ , so in

particular, looking at sections over  $D_+(X_i)$ , we get a homomorphism of  $S_{(X_i)}$ -modules  $S_{(X_i)}^{\oplus(n+1)} \rightarrow S_{(X_i)}$  sending  $e_i \mapsto 1$ , so it is clearly a surjective map of modules.

Thus,  $(\psi: \mathcal{O}_{\mathbb{P}^n}^{\oplus(n+1)} \rightarrow \mathcal{O}_{\mathbb{P}^n}(1)) \in F(\mathbb{P}^n)$ .

It remains to show that given  $(X, \varphi: \mathcal{O}_X^{\oplus(n+1)} \rightarrow \mathcal{L})$ , there exists a unique morphism  $f: X \rightarrow \mathbb{P}^n$  such that  $\varphi \cong (f^*\psi: \mathcal{O}_X^{\oplus(n+1)} \rightarrow f^*\mathcal{O}_{\mathbb{P}^n}(1))$ . Indeed, this will give the natural transformation  $F \rightarrow h_{\mathbb{P}^n}$  and the inverse natural transformation  $h_{\mathbb{P}^n} \rightarrow F$  is given by pullback,  $X \rightarrow \mathbb{P}^n$  gives  $f^*\psi: \mathcal{O}_X^{\oplus(n+1)} \rightarrow f^*\mathcal{O}_{\mathbb{P}^n}(1)$ .

To prove the existence of the unique morphism, let  $\varphi(e_i) = s_i \in \Gamma(X, \mathcal{L})$ . Define  $Z_i := \{x \in X \mid (s_i)_x \in \mathfrak{m}_x \mathcal{L}_x\}$ , where  $(s_i)_x$  is the germ of  $s_i$  at  $x$  and  $\mathfrak{m}_x \subseteq \mathcal{O}_{X,x}$  is the maximal ideal. We claim that  $Z_i$  is a closed set.

Observe that being a closed set can be checked on an open cover  $\{U_i\}$ , since  $Z \subseteq X$  if and only if  $Z \cap U_i$  is closed on  $U_i$  for all  $i$ .

Thus we may use a trivializing affine cover  $\{U_i\}$  of  $X$ , so we reduce to the case that  $X = \text{Spec } A$ ,  $\mathcal{L} \cong \mathcal{O}_{\text{Spec } A}$ , so  $\Gamma(X, \mathcal{L}) \cong A$ , so by abuse of notation we have  $s_i \in A$ . This induces  $(s_i)_{\mathfrak{p}} = \frac{s_i}{1} \in A_{\mathfrak{p}}$ .

Now  $\frac{s_i}{1} \in \mathfrak{p}A_{\mathfrak{p}}$  if and only if  $s_i$  lies in the inverse image of  $\mathfrak{p}A_{\mathfrak{p}}$  under the localization map  $A \rightarrow A_{\mathfrak{p}}$ . Hence,  $Z_i = V(s_i)$  is closed.

Let  $U_i := X|_{Z_i}$ . Then there is an isomorphism  $\mathcal{O}_{U_i} \rightarrow \mathcal{L}|_{U_i}$  sending  $1 \mapsto s_i$ , and the inverse sends  $s \mapsto s/s_j$ . We should interpret this as the element of  $\mathcal{O}_{U_i}$  such that  $\frac{s}{s_j} \cdot s_j = s$ . Injectivity is obvious, surjectivity is by definition of  $Z_i$ .

(Remark: If we were working in the world of varieties, locally the section  $s_i$  is viewed as a function and  $Z_i$  is the locus where  $s_i$  vanishes. On  $U_i$ , we will define a morphism to projective space  $U_i \rightarrow D_+(X_i) \subseteq \mathbb{P}^n$  via  $p \mapsto (\frac{s_0(p)}{s_i(p)}, \dots, \frac{s_n(p)}{s_i(p)})$ . Equivalently, on  $X$ , we can view this function as  $X \rightarrow \mathbb{P}^n$ ,  $p \mapsto (s_0(p), \dots, s_n(p))$ .)

We may now define a morphism

$$f: U_i = X \setminus Z_i \rightarrow D_+(X_i) \cong \text{Spec } S_{(X_i)}$$

by giving a homomorphism of rings  $f_i^{\#}: S_{(X_i)} \rightarrow \Gamma(U_i, \mathcal{O}_X)$ . But  $S_{(X_i)}$  should be thought of as  $k[\frac{X_0}{X_i}, \dots, \frac{X_n}{X_i}]$ , so we define our map by sending  $\frac{X_j}{X_i} \mapsto \frac{s_j}{s_i}$ , which defines  $f_i^{\#}$  as a homomorphism of  $k$ -algebras. To get a morphism  $f: Z \rightarrow \mathbb{P}_k^n$  such that  $f|_{U_i} = f_i$ , we need to check  $f_i|_{U_i \cap U_j} = f_j|_{U_i \cap U_j}$ . We can now check that check that

$$(f_i^{\#})_{U_i \cap U_j}: S_{(X_i X_j)} \cong \Gamma(D_+(X_i X_j), \mathcal{O}_{\mathbb{P}^n}) = \Gamma(D_+(X_i) \cap D_+(X_j), \mathcal{O}_{\mathbb{P}^n}) \rightarrow \Gamma(U_i \cap U_j, \mathcal{O}_X)$$

maps  $\frac{X_k}{X_i} \mapsto \frac{s_k}{s_i}$  and  $\frac{X_k}{X_j} = \frac{X_k/X_i}{X_j/X_i} \mapsto \frac{s_k/s_i}{s_j/s_i} = \frac{s_k}{s_j}$  and similarly for  $(f_j^{\#})_{U_i \cap U_j}$ , and we find that they agree, i.e.,  $(f_i^{\#})_{U_i \cap U_j} = (f_j^{\#})_{U_i \cap U_j}$ , so  $f_i|_{U_i \cap U_j} = f_j|_{U_i \cap U_j}$ , so the morphisms glue to give  $f: X \rightarrow \mathbb{P}_k^n$ .

This defines our morphism, and we have to show that  $f^*\mathcal{O}_{\mathbb{P}^n}(1) \cong \mathcal{L}$ . This is the case because the transition maps  $g_{ij} = X_i/X_j$  of  $\mathcal{O}_{\mathbb{P}^n}(1)$  pull back under  $f^{\#}$  to  $s_i/s_j$ , which are the transition maps for  $\mathcal{L}$  using the trivializations for  $\mathcal{L}_{U_i}$  which we used above (this needs to be checked). We should also check that this isomorphism is suitably compatible.

For uniqueness, suppose given a surjection  $\varphi: \mathcal{O}_X^{\oplus(n+1)} \rightarrow \mathcal{L}$  and a morphism  $g: X \rightarrow \mathbb{P}^n$  such that  $g^*(\mathcal{O}_{\mathbb{P}^n}^{\oplus(n+1)} \rightarrow \mathcal{O}_{\mathbb{P}^n}(1)) \cong (\mathcal{O}_X^{\oplus(n+1)} \rightarrow \mathcal{L})$ . We may think of  $\varphi$  as given by  $n+1$  sections  $s_0, \dots, s_n \in \Gamma(X, \mathcal{L})$  with  $s_i = \varphi(p_i)$ . Similarly, the universal object on  $\mathbb{P}^n$  is given by sections  $X_i \in \Gamma(\mathbb{P}^n, \mathcal{O}_{\mathbb{P}^n}(1))$ .

Note that by the construction of the universal object, the section  $X_j$  is given on  $D_+(X_i)$  by  $X_j/X_i \in S_{(X_i)}$ . In particular, the pullback of the section  $X_i \in \Gamma(\mathbb{P}^n, \mathcal{O}_{\mathbb{P}^n}(1))$  is  $s_i$ .

A short remark on pullbacks: if  $f: X \rightarrow Y$ , and  $\mathcal{F}$  is a sheaf of  $\mathcal{O}_Y$ -modules, then  $s \in \Gamma(Y, \mathcal{F})$  induces a section  $(Y, s)$  in  $\Gamma(X, f^{-1}\mathcal{F})$ , and hence a section  $f^*s = (Y, s) \otimes 1 \in \Gamma(X, f^{-1}\mathcal{F} \otimes_{f^{-1}\mathcal{O}_Y} \mathcal{O}_X) = \Gamma(X, f^*\mathcal{F})$ .

In particular,  $(s_i)_x \in \mathfrak{m}_x \mathcal{L}_X$  for some  $x \in X$  if and only if  $(x_i)_{g(x)} \in \mathfrak{m}_{g(x)} \mathcal{O}_{\mathbb{P}^n}(1)_{g(x)}$ . Thus,  $U_i = \{x \in X \mid (s_i)_x \notin \mathfrak{m}_x \mathcal{L}_X\}$  satisfies  $U_i = g^{-1}(D_+(X_i))$  (things need to be checked here).

So we have  $g_i = g|_{U_i}: U_i \rightarrow D_+(X_i)$  and it is enough to show that  $g_i = f_i$ , where  $f_i$  was constructed previously from  $\mathcal{O}_X^{\oplus(n+1)} \rightarrow \mathcal{L}$ . For this, it suffices to show  $g_i^\# = f_i^\#$ . But we have  $g_i^\#(X_j/X_i) = \frac{g^\#(X_j)}{g^\#(X_i)} = \frac{s_j}{s_i} = f_i^\#(\frac{X_j}{X_i})$  (the first equality needs to be checked), and uniqueness follows.  $\square$

REMARK. This is an example of a so-called Quot scheme, which is a scheme which represents a functor of the form  $T \mapsto \{f: \mathcal{O}_T^{\oplus k} \rightarrow \mathcal{E}\}$ , where  $f$  must be surjective and  $\mathcal{E}$  is a coherent sheaf satisfying some properties.

## CHAPTER 6

### Divisors and the Picard Group

REMARK. Very roughly, we will encounter two notions: Weil divisors, which can be thought of as “subvarieties of codimension one”, and Cartier divisors, which can be thought of as “subschemes defined by a single equation”.

DEFINITION 6.1. The dimension of a topological space  $X$  is the length of the longest chain  $Z_0 \subsetneq Z_1 \subsetneq \cdots \subsetneq Z_n$  of irreducible closed subsets of  $X$ .

For example  $\dim \mathbb{A}_k^1 = 1$ , and the chains are  $\{\star\} \subseteq \mathbb{A}_k^1$ , where  $\star$  is any closed point.

The Krull dimension of a ring  $A$ ,  $\dim A$ , is the dimension of  $\operatorname{Spec} A$  as a topological space. Equivalently, this is the length of the longest chain  $\mathfrak{p}_0 \subsetneq \cdots \subsetneq \mathfrak{p}_n$  of prime ideals.

If  $Z \subseteq X$  is an irreducible closed subset, then  $\operatorname{codim}(Z, X)$  is the length  $n$  of the longest chain  $Z = Z_0 \subsetneq \cdots \subsetneq Z_n$  of irreducible closed subsets.

Note that the intuition on dimension may be faulty, even for Noetherian affine schemes.

However, if  $B$  is a domain and a finitely generated  $k$ -algebra for  $k$  a field, then for any prime ideal  $\mathfrak{p} \subseteq B$ , then  $\operatorname{ht} \mathfrak{p} + \dim B/\mathfrak{p} = \dim B$ . Here,  $\operatorname{ht} \mathfrak{p}$  is the length of the longest chain of primes  $\mathfrak{p}_0 \subsetneq \mathfrak{p}_1 \subsetneq \cdots \subsetneq \mathfrak{p}_n = \mathfrak{p}$ . Note  $\dim B/\mathfrak{p} = \dim V(\mathfrak{p})$  and  $\operatorname{ht} \mathfrak{p} = \operatorname{codim}(V(\mathfrak{p}), \operatorname{Spec} B)$ , so we have from  $(\star)$  that  $\operatorname{codim}(V(\mathfrak{p}), \operatorname{Spec} B) + \dim V(\mathfrak{p}) = \dim \operatorname{Spec} B$ . This implies that if  $X$  is a variety over  $k$  (integral and of finite type over  $k$ ), and  $Z \subseteq X$  is an irreducible closed subset, then  $\dim Z + \operatorname{codim}(Z, X) = \dim X$ .

Also, if  $\eta \in Z \subseteq X$  is the generic point of  $Z$ , then  $\dim \mathcal{O}_{X, \eta} = \operatorname{codim}(Z, X)$ . This is shown on the third example sheet.

PROPOSITION. If  $X$  is a Noetherian scheme, then  $X$  is a Noetherian topological space, i.e., every decreasing sequence of closed sets becomes stationary and every closed subset of  $X$  has a decomposition into a finite number of irreducible closed subsets.

PROOF. Let  $\{U_i\}$  be a finite cover such that  $U_i \cong \operatorname{Spec} A_i$ , where  $A_i$  is a Noetherian ring. If  $V_1 \supseteq V_2 \supseteq \cdots$  is a decreasing sequence of closed subsets of  $X$ , then for every  $i$ ,  $V_1 \cap U_i \supseteq V_2 \cap U_i \supseteq \cdots$  is a decreasing sequence of subsets which are closed in  $U_i$ . Hence there exist ideals  $I_{i1} \subseteq I_{i2} \subseteq \cdots$  of  $A_i$  such that  $V_j \cap U_i = V(I_{ij})$  for all  $j$ . Since  $A_i$  is Noetherian, this means that there is some  $K_i$  such that  $V_j \cap U_i = V_{K_i} \cap U_i$  for all  $j \geq K_i$ . Since there are finitely many  $U_i$  and they cover  $X$ , we can define  $K := \max_i K_i$  and for all  $j \geq K$  we have  $V_j = V_K$ , so  $X$  is a Noetherian topological space.

Now let  $V$  be any closed subset of  $X$ . If it is irreducible, we are done. Otherwise, decompose it as the union of two closed subsets. If possible, decompose these again, and so on. This process yields a tree structure of closed sets in  $X$ , but the tree must be finite, since otherwise we would find an infinite descending sequence of closed sets in  $X$ , which does not exist. Hence the tree has a finite number of leaves, and this is the desired decomposition into irreducible closed subsets.  $\square$

REMARK. In this chapter, we will use the symbol  $(\star)$  for the following assumption:  $X$  is a Noetherian integral scheme over  $\operatorname{Spec} k$  which is regular in codimension one, i.e., whenever a local ring  $\mathcal{O}_{X,x}$  is of dimension one, it is regular, i.e.,  $\dim_{\mathcal{O}_{X,x}/\mathfrak{m}_x} \mathfrak{m}_x/\mathfrak{m}_x^2 = \dim \mathcal{O}_{X,x}$ , i.e., the dimension of the Zariski tangent space to  $X$  at  $x$  coincides with  $\dim \mathcal{O}_{X,x}$ .



# Exercises

## Example Sheet 1

### Exercise 1.

EXERCISE. Let  $A$  be a ring. Show that the sets  $D(f) := \{\mathfrak{p} \in \text{Spec } A \mid f \notin \mathfrak{p}\}$  with  $f$  ranging over elements of  $A$  form a basis of the topology on  $\text{Spec } A$ .

SOLUTION. We have  $\text{Spec } A = D(1)$  and for  $f, g \in A$  we have

$$\begin{aligned} D(f) \cap D(g) &= \{\mathfrak{p} \in \text{Spec } A \mid f \notin \mathfrak{p} \wedge g \notin \mathfrak{p}\} \\ &= \{\mathfrak{p} \in \text{Spec } A \mid fg \notin \mathfrak{p}\} \\ &= D(fg), \end{aligned}$$

so the collection  $\{D(f)\}$  forms the basis of a topology, and it remains to show that the topology generated by the  $D(f)$  is the Zariski topology. Firstly, for any  $f \in A$  we have

$$\begin{aligned} \text{Spec } A \setminus D(f) &= \{\mathfrak{p} \in \text{Spec } A \mid f \in \mathfrak{p}\} \\ &= \{\mathfrak{p} \in \text{Spec } A \mid (f) \subseteq \mathfrak{p}\} \\ &= V((f)), \end{aligned}$$

so each  $D(f)$  is open. It remains to show that every open set is the union of sets of the form  $D(f)$ . Indeed, if  $I$  is any ideal of  $A$ , then

$$\begin{aligned} \text{Spec } A \setminus V(I) &= \{\mathfrak{p} \in \text{Spec } A \mid I \not\subseteq \mathfrak{p}\} \\ &= \{\mathfrak{p} \in \text{Spec } A \mid \exists f \in I: f \notin \mathfrak{p}\} \\ &= \bigcup_{f \in I} D(f) \end{aligned}$$

as required. □

EXERCISE. An element  $f \in A$  is nilpotent if and only if  $D(f) = \emptyset$ .

SOLUTION. If  $f$  is nilpotent, say  $f^n = 0$ , and  $\mathfrak{p}$  is a prime ideal, then we have  $f^n = 0 \in \mathfrak{p}$ , so  $f \in \mathfrak{p}$ . Hence,  $D(f) = \emptyset$ .

If  $f$  is not nilpotent, then define  $\mathcal{S}$  to be the collection of all ideals  $I$  such that  $f^n \notin I$  for every  $n > 0$ . Since  $f$  is not nilpotent,  $(0) \in \mathcal{S}$ . The set  $\mathcal{S}$  is partially ordered by inclusion and admits upper bounds, since the increasing union of ideals disjoint from  $\{f^n\}$  is still an ideal disjoint from  $\{f^n\}$ . Hence  $\mathcal{S}$  admits a maximal member  $I$ . We will show that  $I$  is prime.

Let  $x, y \in A$  such that  $xy \in I$  and suppose that  $x \notin I$ ,  $y \notin I$ . Then  $I + Ax$  and  $I + Ay$  are not disjoint from  $\{f^n\}$  so we find  $n, m \in \mathbb{N}$ ,  $i, j \in I$  and  $a, b \in A$  such that  $f^n = i + ax$ ,  $f^m = j + by$ . But then  $f^{n+m} = ij + iby + jax + abxy \in I$ , a contradiction, so  $x \in I$  or  $y \in I$  and  $I$  is prime. Hence,  $I \in D(f)$ , so  $D(f) \neq \emptyset$ . □

**Exercise 4.**

NOTATION. For  $s \in \mathcal{F}U$  and  $p \in U$  we will write  $s_p := (U, s) \in \mathcal{F}_p$ .

DEFINITION. Let  $\mathcal{F}$  be a presheaf and  $U \subseteq X$  an open set. Define

$$\mathcal{F}^+U := \{s: U \rightarrow \prod_{p \in U} \mathcal{F}_p \mid \forall p \in U: s(p) \in \mathcal{F}_p, (\star)\},$$

where  $(\star)$  is the following statement: for every  $p \in U$  there is an open  $p \in V_p \subseteq U$  and a section  $s_{V_p} \in \mathcal{F}V_p$  such that for every  $q \in V_p$  we have  $(s_{V_p})_q = s(q)$ .

EXERCISE.  $\mathcal{F}^+$  together with the obvious restriction maps forms a sheaf.

SOLUTION.  $\mathcal{F}^+U$  is an abelian group with pointwise addition, as the sum of  $s, t \in \mathcal{F}^+U$  still satisfies  $(\star)$  by taking the intersection of the  $V_p$  obtained from  $s$  and  $t$ .

It is obvious that  $\mathcal{F}^+$  is a presheaf.

Next, let  $s \in \mathcal{F}^+U$  and  $\{U_i\}$  an open cover such that  $\forall i, s|_{U_i} = 0$ . Let  $p \in U$ . Then  $p \in U_i$  for some  $i$  and we have  $s(p) = (s|_{U_i})(p) = 0$ , so  $s = 0$ , so the identity axiom is satisfied.

Next, let  $\{U_i\}_{i \in I}$  be a cover,  $s_i \in \mathcal{F}^+U_i$  such that  $\forall i, j: s_i|_{U_i \cap U_j} = s_j|_{U_i \cap U_j}$ . Given  $p \in U$ , define  $s(p) := s_i(p)$  for  $p \in U_i$ . This is well-defined because of the compatibility condition. We need to show that  $s \in \mathcal{F}^+U$ . Indeed, let  $p \in U$ . Then  $s(p) = s_i(p)$  for some  $i$ , and since  $s_i \in \mathcal{F}^+U_i$  and taking stalks is compatible with restrictions, we get a neighborhood that satisfies the required condition. It remains to show that for all  $i$ ,  $s|_{U_i} = s_i$ , but that is true by definition.  $\square$

DEFINITION. For a presheaf  $\mathcal{F}$  and an open set  $U$ , define

$$\theta_U: \mathcal{F}U \rightarrow \mathcal{F}^+U; \quad s \mapsto (p \mapsto s_p).$$

This is obviously a homomorphism of groups. It also defines a morphism of shaves, because for  $s \in \mathcal{F}U$ ,  $V \subseteq U$  and  $p \in V$  we have

$$\theta_U(s)|_V(p) = \theta_U(s)(p) = s_p = (s|_V)_p = \theta_V(s|_V)(p).$$

LEMMA. Let  $\mathcal{F}$  be a sheaf and  $U$  an open set. Then the natural map

$$\mathcal{F}U \rightarrow \prod_{p \in U} \mathcal{F}_p$$

is injective.

PROOF. Let  $s, t \in \mathcal{F}U$  such that  $s_p = t_p$  for every  $p$ . Let  $p \in U$ . By definition of a stalk,  $s_p = t_p$  means that there is an open  $p \in V_p \subseteq U$  such that  $s|_{V_p} = t|_{V_p}$ . These  $V_p$  cover  $U$  so by the identity axiom we have  $s = t$ .  $\square$

LEMMA. Let  $\mathcal{F}$  be a sheaf. Let  $U$  be an open set. Let  $s: U \rightarrow \prod_{p \in U} \mathcal{F}_p$  such that for every  $p \in U$  we have  $s(p) \in \mathcal{F}_p$  and there is an open  $p \in V_p \subseteq U$  together with  $s_{V_p} \in \mathcal{F}V_p$  such that for every  $q \in V_p$  we have  $(s_{V_p})_q = s(q)$ . Then there is a unique  $t \in \mathcal{F}U$  such that  $t_q = s(q)$  for every  $q \in U$ .

PROOF. Uniqueness follows from the previous lemma. For existence, notice that the  $V_p$  cover  $U$ . Let  $p, q \in U$ . The  $s_{V_p}$  are glueable because their stalks agree on the intersection, so the conditions of the gluing axiom are satisfied by the previous lemma. Since taking stalks is compatible with restrictions, the glued section has the correct stalks.  $\square$

EXERCISE. Let  $\mathcal{F}$  be a presheaf,  $\mathcal{G}$  a sheaf and  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  a morphism of presheaves. Then there is a unique morphism of sheaves  $\varphi^+: \mathcal{F}^+ \rightarrow \mathcal{G}$  such that  $\varphi = \varphi^+ \circ \theta$ .

SOLUTION. Let  $U$  be an open and let  $s \in \mathcal{F}^+U$ . Cover  $U$  with the  $V_p$  from the definition of  $\mathcal{F}^+$  and obtain the associated  $s_{V_p} \in \mathcal{F}V_p$ . Define  $t_{V_p} := \varphi_{V_p}(s_{V_p}) \in \mathcal{G}V_p$ . We can calculate that for  $q \in V_p$  we have

$$(t_{V_p})_q = (\varphi_{V_p}(s_{V_p}))_q = \varphi_q((s_{V_p})_q) = \varphi_q(s(q)).$$

Therefore, Lemma 2 gives us a unique  $t_U \in \mathcal{G}U$  such that

$$(\star) \quad \forall q \in U: (t_U)_q = \varphi_q(s(q)).$$

We define  $\varphi_U^+(s) = t_U$ .

This is indeed a morphism of sheaves: if  $V \subseteq U$  and  $s \in \mathcal{F}^+U$ , then

$$\varphi^+(s|_V) = \varphi^+(s)|_V$$

follows from the fact that, using  $(\star)$ , the germ of both sides at  $p \in V$  is just  $\varphi_p(s(p))$ . By Lemma 1, the two sides are equal.

Similarly, if  $s \in \mathcal{F}U$  and  $p \in U$ , then

$$(\varphi_U^+ \theta_U(s))_p \stackrel{(\star)}{=} \varphi_q(\theta(s)(q)) = \varphi_q(s_q) = (\varphi_U(s))_q,$$

so  $\varphi_U^+ \circ \theta_U = \varphi_U$  by Lemma 1, so  $\varphi^+ \circ \theta = \varphi$ .

Finally, to see uniqueness, assume that  $\varphi^\#$  satisfies  $\varphi^\# \circ \theta = \varphi$ . Let  $s \in \mathcal{F}^+U$  and  $p \in U$ . By definition of  $\mathcal{F}^+$  there is  $p \in V_p \subseteq U$ ,  $s_{V_p} \in \mathcal{F}V_p$  such that  $\forall q \in V_p: (s_{V_p})_q = s(q)$ . The condition can be rephrased as  $s|_{V_p} = \theta(s_{V_p})$  and we calculate

$$\begin{aligned} (\varphi_U^\#(s))_p &= (\varphi_U^\#(s)|_{V_p})_p = (\varphi_{V_p}^\#(s|_{V_p}))_p = (\varphi_{V_p}^\#(\theta(s_{V_p})))_p \\ &= (\varphi_{V_p}^+(\theta(s_{V_p})))_p = \dots = (\varphi_U^+(s))_p, \end{aligned}$$

so by Lemma 1, we have  $\varphi_U^+ = \varphi_U^\#$ , so  $\varphi^+ = \varphi^\#$ , completing the proof of uniqueness.  $\square$

EXERCISE. We have  $(\mathcal{F}^+)_p = \mathcal{F}_p$  for  $p \in X$ . Show that if  $f: \mathcal{F} \rightarrow \mathcal{G}$  is a morphism of presheaves, then there is an induced morphism  $f^+: \mathcal{F}^+ \rightarrow \mathcal{G}^+$  with  $(f^+)_p = f_p$ .

SOLUTION. Let  $p \in X$ . Of course,  $(\mathcal{F}^+)_p$  and  $\mathcal{F}_p$  cannot be literally equal. Instead, we show the following more precise statement: The map  $\theta_p: \mathcal{F}_p \rightarrow \mathcal{F}_p^+$  is an isomorphism.

Indeed, we define  $g_p: \mathcal{F}_p^+ \rightarrow \mathcal{F}_p$  as follows: for an open  $U$  and  $s \in \mathcal{F}^+U$  we define  $g_p(s_p) := s(p)$ . This is well-defined because sections  $s \in \mathcal{F}^+U$ ,  $t \in \mathcal{F}^+V$  that have the same germ at  $p$  must satisfy  $s|_W = t|_W$  for some  $W$  that contains  $p$ , so  $s(p) = s|_W(p) = t|_W(p) = t(p)$ .

Next, let  $U$  be an open and  $s \in \mathcal{F}_p^+$ . By definition of  $\mathcal{F}^+$ , there is some  $p \in V_p \subseteq U$  open,  $s_{V_p} \in \mathcal{F}V_p$  such that for all  $q \in V_p$  we have  $(s_{V_p})_q = s(q)$ . This is equivalent to saying that  $s|_{V_p} = \theta_{V_p}(s_{V_p})$ , so in particular, in  $\mathcal{F}_p^+$ , we have  $s_p = (\theta_{V_p}(s_{V_p}))_p$ . This lets us calculate

$$\theta_p(g_p(s_p)) = \theta_p(s(p)) = \theta_p((s_{V_p})_p) = (\theta_{V_p}(s_{V_p}))_p = s_p,$$

so we have  $\theta_p \circ g_p = \text{id}_{\mathcal{F}_p^+}$ .

Next, let  $U$  be an open and  $s \in \mathcal{F}U$ . Then we have

$$g_p(\theta_p(s_p)) = g_p(\theta_U(s)_p) = g_p((q \mapsto s_q)_p) = (q \mapsto s_q)(p) = s_p,$$

so  $g_p \circ \theta_p = \text{id}_{\mathcal{F}_p}$ , and  $\theta_p$  is an isomorphism as required.

Next, let  $\mathcal{F}$  and  $\mathcal{G}$  be presheaves and let  $\theta: \mathcal{F} \rightarrow \mathcal{F}^+$  and  $\iota: \mathcal{G} \rightarrow \mathcal{G}^+$  denote the natural maps to the associated sheaf. If  $f: \mathcal{F} \rightarrow \mathcal{G}$  is a map of presheaves, we can

invoke the universal property of  $\mathcal{F}^+$  on the composite  $\iota \circ f$  and find a morphism  $f^+: \mathcal{F}^+ \rightarrow \mathcal{G}^+$  making the diagram

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\theta} & \mathcal{F}^+ \\ \downarrow f & & \downarrow f^+ \\ \mathcal{G} & \xrightarrow{\iota} & \mathcal{G}^+ \end{array}$$

commute.

On stalks, we have

$$f_p^+ \circ \theta_p = (f^+ \circ \theta)_p = (\iota \circ f)_p = \iota_p \circ f_p,$$

and since  $\theta_p$  is an isomorphism, we have

$$f_p^+ = \iota_p \circ f_p \circ \theta_p^{-1},$$

which is how we should interpret the “equality”  $(f^+)_p = f_p$  under the natural identifications  $\theta_p$  and  $\iota_p$ .  $\square$

### Exercise 5.

EXERCISE. Show that if  $f: \mathcal{F} \rightarrow \mathcal{G}$  is a morphism between sheaves, then the sheaf image  $\text{im } f$  can be naturally identified with a subsheaf of  $\mathcal{G}$ .

SOLUTION. We will prove the following more general statement: if  $\mathcal{F}$  is a presheaf satisfying the identity axiom,  $\mathcal{G}$  is a sheaf and  $f: \mathcal{F} \rightarrow \mathcal{G}$  is a morphism of presheaves such that  $f_U$  is injective for every  $U$ , then the induced morphism  $f_U^+: \mathcal{F}^+U \rightarrow \mathcal{G}U$  is injective for every  $U$ .

Indeed, the inclusion of the presheaf image into  $\mathcal{G}$  satisfies these conditions. It satisfies sheaf axiom 1 for the same reason that the presheaf kernel does.

We will now prove the claim. Let  $U$  be an open set,  $s \in \mathcal{F}^+U$  such that  $f_U^+(s) = 0$ . From the construction of the associated sheaf we see that  $f_U^+(s) = f_U(t)$  where  $t$  is the unique element of  $\mathcal{F}U$  such that  $\forall q \in U: t_q = f_q(s(q))$ .

So we have  $0 = f_U^+(s) = f_U(t)$ , so since  $f_U$  is injective we have  $t = 0$ . Let  $q \in U$ . Then  $f_q(s(q)) = t_q = 0_q = 0$ . The element  $s(q)$  of  $\mathcal{F}_q$  is represented by some open set  $V$  and a section  $u \in \mathcal{F}V$ . Thus  $0 = f_q(s(q)) = f_q(V, u) = (V, f_V(u))$ . Thus, there is some open  $W \subseteq V$  such that  $0 = f_V(u)|_W = f_W(u|_W)$ . Since  $f_W$  is injective, we conclude  $u|_W = 0$ , and  $u|_W$  represents the same element in  $\mathcal{F}_q$  as  $u$ , but that element is just  $s(q)$ , so  $s(q) = 0$ . Since  $q$  was arbitrary, we conclude  $s = 0$ .  $\square$

### Exercise 6.

EXERCISE. A sequence of sheaves is exact if and only if for every  $p \in X$  the corresponding sequence of maps of abelian groups is exact.

SOLUTION. Assume that  $f: \mathcal{F} \rightarrow \mathcal{G}$  and  $g: \mathcal{G} \rightarrow \mathcal{H}$  are morphisms of sheaves such that  $g \circ f = 0$ . Consider the diagram

$$\begin{array}{ccccc} \mathcal{F} & \xrightarrow{f} & \mathcal{G} & \xrightarrow{g} & \mathcal{H} \\ \downarrow & \nearrow & \uparrow & \nwarrow & \\ \text{im}' f & \xrightarrow{\theta} & \text{im } f & \xrightarrow{\varphi} & \ker g, \\ & & \searrow \iota & & \end{array}$$

where the map  $\iota$  is an inclusion of subpresheaves of  $\mathcal{G}$  and  $\varphi$  is induced by  $\iota$ . We say that  $\text{im } f = \ker g$  if  $\varphi$  is an isomorphism. By a result of the lecture, this is the case if and only if for all  $p \in X$ , the induced map  $\varphi_p: (\text{im } f)_p \rightarrow (\ker g)_p$  is an isomorphism. Since  $\theta$  induces isomorphisms on stalks and the bottom triangle commutes, this is the case if and only if  $\iota_p: (\text{im } f)_p \rightarrow (\ker g)_p$  is an isomorphism for every  $p \in X$ . Now consider the diagram

$$\begin{array}{ccc} (\text{im } f)_p & \xrightarrow{\iota_p} & (\ker g)_p \\ \downarrow \cong & & \downarrow \cong \\ \text{im } f_p & \xrightarrow{i} & \ker g_p, \end{array}$$

where the left and right maps are the isomorphisms defined in the proof of a result from the lecture and the bottom map is just the inclusion (this makes sense since  $g \circ f = 0 \iff \forall p \in X: g_p \circ f_p = 0$  as stalks characterize morphisms). The diagram commutes since none of the maps actually does anything. Since the left and right maps are isomorphisms, we have that the top map is an isomorphism if and only if the bottom map is an isomorphism.

But the bottom map is an isomorphism if and only if the sequence

$$\mathcal{F}_p \xrightarrow{f_p} \mathcal{G}_p \xrightarrow{g_p} \mathcal{H}_p$$

is exact, so putting everything together, we find that  $(f, g)$  is exact if and only if  $(f_p, g_p)$  is exact for every  $p \in X$ .  $\square$

### Exercise 7.

EXERCISE. Show that a morphism of sheaves is an isomorphism if and only if it is injective and surjective.

SOLUTION. Let  $f: \mathcal{F} \rightarrow \mathcal{G}$  be a morphism of sheaves. By a result from the lecture,  $f$  is an isomorphism if and only if  $f_p: \mathcal{F}_p \rightarrow \mathcal{G}_p$  is an isomorphism for every  $p$ . Since  $f_p$  is a morphism of abelian groups, this is the case if and only if  $f_p$  is injective and surjective for every  $p$ . By another result from the lecture, this is the case if and only if  $f$  is injective and surjective.  $\square$

### Exercise 8.

EXERCISE. Let  $\mathcal{F}'$  be a subsheaf of a sheaf  $\mathcal{F}$ . Then the natural map  $\mathcal{F} \rightarrow \mathcal{F}/\mathcal{F}'$  is surjective and has kernel  $\mathcal{F}'$  so that there is an exact sequence

$$0 \longrightarrow \mathcal{F}' \longrightarrow \mathcal{F} \longrightarrow \mathcal{F}/\mathcal{F}' \longrightarrow 0.$$

SOLUTION. The natural map  $e: \mathcal{F} \rightarrow \mathcal{F}/\mathcal{F}'$  is given as the composite  $\theta \circ \hat{e}$ , where  $\hat{e}$  is the map  $\mathcal{F} \rightarrow \text{coker}' i$ , where  $i: \mathcal{F}' \rightarrow \mathcal{F}$  is the inclusion and  $\text{coker}' i$  is the presheaf cokernel of  $i$ , and  $\theta$  is the natural map into the sheafification.

For every  $p \in X$ ,  $\theta_p$  is surjective because  $\theta$  induces isomorphisms on stalks, and  $\hat{e}_p$  is surjective, because  $\hat{e}$  is surjective on open sets, which in particular implies surjectivity on stalks. Hence  $e_p$  is surjective as the composite of two open maps. By a result from the lecture, this implies that  $e$  is surjective.

Since for any open set  $U$  and  $s \in \mathcal{F}'U$  we have  $e_U(s) = \theta_U(\hat{e}_U(s)) = \theta_U(0) = 0$ , we obtain a map  $\varphi: \mathcal{F}' \rightarrow \ker e$ . Let  $p \in X$ .

$$\begin{array}{ccccc} \mathcal{F}'_p & \xrightarrow{i_p} & \mathcal{F}_p & \xrightarrow{e_p} & (\mathcal{F}/\mathcal{F}')_p \\ \downarrow \varphi_p & \nearrow & \uparrow & \searrow \hat{e}_p & \uparrow \theta_p \\ (\ker e)_p & \xrightarrow{\cong} & \ker e_p & & (\text{coker}' i)_p \end{array}$$

The map  $\varphi_p$  is injective because  $i_p$  is, and it is surjective, because  $\ker e_p = \ker \hat{e}_p = i_p$ . Hence  $\ker e = \mathcal{F}'$  as subsheaves of  $\mathcal{F}$ .

Now we have  $\text{im } i = \mathcal{F}'$  as subsheaves of  $\mathcal{F}$ , since the map  $\theta: \mathcal{F}' = \text{im}' i \rightarrow \text{im } i$  induces isomorphisms on stalks, but since the domain already is a sheaf this forces  $\theta$  to be an isomorphism. Hence  $\text{im } i = \ker e$  as subsheaves of  $\mathcal{F}$ , so the sequence is exact at  $\mathcal{F}$ . Exactness at  $\mathcal{F}'$  and  $\mathcal{F}/\mathcal{F}'$  is trivially checked on stalks using Exercise 6.  $\square$

EXERCISE. If

$$0 \longrightarrow \mathcal{F}' \longrightarrow \mathcal{F} \longrightarrow \mathcal{F}'' \longrightarrow 0$$

is an exact sequence, then  $\mathcal{F}'$  is isomorphic to a subsheaf of  $\mathcal{F}$  and  $\mathcal{F}''$  is isomorphic to the quotient of  $\mathcal{F}$  by this subsheaf.

SOLUTION. We have a commutative diagram

$$\begin{array}{ccc} \mathcal{F}' & \xrightarrow{i} & \mathcal{F} \\ \downarrow \hat{i} & \nearrow & \uparrow \iota \\ \text{im}' i & \xrightarrow{\theta} & \text{im } i, \end{array}$$

where the diagonal arrow is the inclusion, the bottom arrow is the natural map into the associated sheaf, and the right arrow is induced by the diagonal arrow. By Exercise 5,  $\text{im } i$  can be regarded as a subsheaf of  $\mathcal{F}$ . Since  $i$  is injective, for every  $p \in X$ ,  $i_p$  is injective, so by commutativity,  $\hat{i}_p$  is injective. Furthermore, for every  $p \in X$ ,  $\hat{i}$  is surjective, because it is surjective on open sets. Hence, the composite  $\theta \circ \hat{i}$  is an isomorphism on stalks. Since it is a map between sheaves, this means that it is an isomorphism. Hence,  $\mathcal{F}$  is isomorphic to the subsheaf  $\text{im } i$ .

Next, consider the diagram

$$\begin{array}{ccccc} \text{coker}' \iota & \xrightarrow{\eta} & \text{coker } \iota & & \\ \uparrow \pi & \searrow \hat{p} & \downarrow \hat{p}^+ & & \\ \text{im } i & \xrightarrow{\iota} & \mathcal{F} & \xrightarrow{p} & \mathcal{F}'', \end{array}$$

where the map  $\hat{p}$  is defined on open sets using the fact that  $p \circ \iota = 0$ , hence  $p_U \circ \iota_U = 0$ , hence  $(\text{im } i)(U) \subseteq (\ker p)(U)$ . The map,  $\eta$  is the natural map into the associated sheaf and  $\hat{p}^+$  is obtained from the universal property. Since  $p$  is surjective, it is surjective on stalks, hence by commutativity  $\hat{p}^+$  must also be surjective on stalks.

I do not have a proof that  $\hat{p}^+$  is injective on stalks.  $\square$

### Exercise 9.

EXERCISE. If  $U \subseteq X$  is an open subset and

$$0 \longrightarrow \mathcal{F}' \xrightarrow{i} \mathcal{F} \xrightarrow{p} \mathcal{F}''$$

is exact, then

$$0 \longrightarrow \Gamma(U, \mathcal{F}') \xrightarrow{i_U} \Gamma(U, \mathcal{F}) \xrightarrow{p_U} \Gamma(U, \mathcal{F}'')$$

is exact.

SOLUTION. Since  $(0, i)$  is exact,  $(0, i_x)$  is exact for every  $x \in U$ , hence  $i_x$  is injective for every  $x \in U$ , hence  $i$  is injective, hence  $\ker i = 0$ , hence  $0 = (\ker i)(U) = \ker i_U$ , hence  $i_U$  is injective, so the sequence is exact at  $\Gamma(U, \mathcal{F}')$ .

It remains to show exactness at  $\Gamma(U, \mathcal{F})$ . Since  $p_U \circ i_U = (p \circ i)_U = 0_U = 0$ , we have  $\text{im } i_U \subseteq \ker i_U$ .

Conversely, let  $s \in \ker p_U$ , i.e.,  $p_U(s) = 0$ . By Exercise 6 we know that  $(i_x, p_x)$  is exact for every  $x \in U$ . Since  $p_U(s) = 0$ , we have  $p_x(U, s) = 0$  for every  $x \in U$ , hence  $(U, s) \in \text{im } i_x$  for all  $x \in U$ , i.e., we find  $(V_x, t_x) \in \mathcal{F}'_x$  such that  $i_x(V_x, t_x) = (U, s)$ . If necessary, shrink  $V_x$  such that  $i_{V_x}(t_x) = s|_{V_x}$ .

For  $x, y \in U$ , we have

$$i_{V_x \cap V_y}(t_x|_{V_x \cap V_y} - t_y|_{V_x \cap V_y}) = s|_{V_x \cap V_y} - s|_{V_x \cap V_y} = 0.$$

Since  $i$  is injective, we conclude  $t_x|_{V_x \cap V_y} = t_y|_{V_x \cap V_y}$ , hence we can glue the  $t_x$  to a  $t \in \mathcal{F}'U$ . For any  $x \in U$  we have

$$\mathcal{F}_x \ni (U, i_U(t)) = (V_x, i_{V_x}(t|_{V_x})) = (V_x, i_{V_x}(t_x)) = (V_x, s|_{V_x}) = (U, s),$$

and since stalks characterize sections, this implies that  $i_U(t) = s$ , hence  $s \in \text{im } i_U$  as required.  $\square$

## Example sheet 2.

### Exercise 7.

EXERCISE. Let  $X$  be an integral scheme. There is a unique point  $\eta$  such that the closure of  $\{\eta\}$  is  $X$ ; this is called the generic point of  $X$ . The stalk of  $\mathcal{O}_X$  at  $\eta$  is a field, called the function field of  $X$ , denote by  $K(X)$ . More precisely, if  $U = \text{Spec } A$  is any open affine subset of  $X$ , then  $K(X)$  is a field of fractions of  $A$ .

SOLUTION. If  $U \cong \text{Spec } A$  is an open affine subset of  $X$ , then  $A \cong \mathcal{O}_X(U)$  is an integral domain. Hence we have a point  $\eta_U \in X$  corresponding to the prime ideal  $(0)$ .

We will show:

- (i)  $\eta_U$  is the unique point of  $U$  that is contained in every nonempty open subset of  $U$ .
- (ii) If  $U$  is an open affine subset of  $X$ , and  $V$  is an open affine subset of  $U$ , then  $\eta_U = \eta_V$ .
- (iii) If  $U, V$  are open affine subsets of  $X$ , then  $\eta_U = \eta_V$ . Thus we may define  $\eta := \eta_U$ , where  $U$  is any open affine subset of  $X$ .
- (iv) The closure of  $\{\eta\}$  is  $X$  and  $\eta$  is the unique point with this property.
- (v) If  $U \cong \text{Spec } A$  is an open affine subset of  $X$ , then the stalk of  $\eta$  is a field of fractions of  $A$ .

For (i), notice that a point  $\mathfrak{p} \in \text{Spec } A$  is contained in every nonempty open subset of  $\text{Spec } A$  if and only if  $\mathfrak{p} \in V(I)$  implies  $V(I) = \text{Spec } A$ . Since  $A$  is an integral domain, then  $V(I) = \text{Spec } A$  is equivalent to  $I = (0)$ . Clearly,  $\mathfrak{p} \in V(\mathfrak{p})$  for any  $\mathfrak{p} \in \text{Spec } A$ , so  $\mathfrak{p}$  is contained in every nonempty open subset of  $\text{Spec } A$  if and only if  $\mathfrak{p} = (0)$ .

For (ii), we observe that every open subset of  $V$  is also an open subset of  $U$ , hence  $\eta_U$  is a point contained in every nonempty open subset of  $V$ , so by uniqueness,  $\eta_U = \eta_V$ .

For (iii), notice that since  $X$  is integral, it is irreducible, so  $U \cap V \neq \emptyset$ . Combining Exercises 1 and 11 from the first example sheet, we know that the affine open subsets of  $X$  form a base for the topology of  $X$ . Hence we find an affine open subset  $W \subseteq U \cap V$ . Hence, by (i), we have  $\eta_U = \eta_W = \eta_V$ .

For (iv), we remark that the closure of  $\{\eta\}$  being  $X$  is the same as saying that  $\eta$  is contained in every nonempty open subset of  $X$ . But since the open affine subsets form a base, it suffices to know that  $\eta$  is contained in every affine open subsets, which is clear from what we have shown previously. Uniqueness follows by applying the uniqueness statement from (i) for any open affine  $U$ .

For (v), note that  $\mathcal{O}_{X, \eta} = \mathcal{O}_{X, \eta_U} \cong A_{(0)} = (A \setminus \{0\})^{-1}A$ , which is precisely the field of fractions of  $A$ .  $\square$





## Examples classes

### Examples class 1

#### Exercise 12.

EXERCISE.

SOLUTION. Want to construct an inverse  $\beta$  to  $\alpha$ . Define for  $\varphi: A \rightarrow \Gamma(X, \mathcal{O}_X)$ . Define  $\beta(\varphi)$  as follows. Cover  $X$  with affine schemes  $\{U_i\}$ ,  $U_i = \text{Spec } B_i$ . We have restriction maps  $\Gamma(X, \mathcal{O}_X) \rightarrow \Gamma(U_i, \mathcal{O}_X) = \Gamma(U_i, \mathcal{O}_{\text{Spec } B_i}) = B_i$ .

This gives by composition with  $\varphi$  maps  $\varphi_i: A \rightarrow B_i$ . This induces a morphism  $f_i: U_i = \text{Spec } B_i \rightarrow \text{Spec } A$ . We want to show that we can glue the  $f_i$ , by first showing that they agree on  $U_i \cap U_j$ .

Using Exercises 1 and 11, we may cover  $U_i \cap U_j$  with affine schemes  $\{U_{ijk}\}$ , where  $U_{ijk} = \text{Spec } B_{ijk}$ . Then we have a commutative diagram

$$\begin{array}{ccc} \Gamma(X, \mathcal{O}_X) & \longrightarrow & B_j \\ \downarrow & & \downarrow \\ B_i & \longrightarrow & B_{ijk} \end{array}$$

of restriction maps for  $\mathcal{O}_X$ .

Thus the compositions

$$U_{ijk} \hookrightarrow U_i \xrightarrow{f_i} \text{Spec } A$$

$$U_{ijk} \hookrightarrow U_j \xrightarrow{f_j} \text{Spec } A$$

agree. Thus  $f_i|_{U_i \cap U_j} = f_j|_{U_i \cap U_j}$ . We can now glue these morphisms to get a morphism  $f: X \rightarrow \text{Spec } A$ .

- Obtaining  $f$  as a continuous map is no problem.
- We need to construct  $f^\#$ .

Given  $V \subseteq \text{Spec } A$ , we need a map  $f_V^\#: \Gamma(V, \mathcal{O}_{\text{Spec } A}) \rightarrow \Gamma(f^{-1}(V), \mathcal{O}_X)$ .

Note  $f^{-1}(V)$  is covered by the sets  $f_i^{-1}(V) = f^{-1}(V) \cap U_i$ . So we have for  $s \in \Gamma(V, \mathcal{O}_{\text{Spec } A})$ ,  $f_i^\#(s) \in \Gamma(f_i^{-1}(V), \mathcal{O}_X)$  and since  $f_i|_{U_i \cap U_j} = f_j|_{U_i \cap U_j}$  we have

$$f_i^\#(s)|_{f_i^{-1}(V) \cap f_j^{-1}(V)} = f_j^\#(s)|_{f_i^{-1}(V) \cap f_j^{-1}(V)}.$$

By the sheaf gluing axiom, we obtain  $f^\#(s) \in \Gamma(f^{-1}(V), \mathcal{O}_X)$ .

Note: This is a general fact: given  $\{U_i\}$  a cover of  $X$  and  $f_i: U_i \rightarrow Y$  morphisms such that  $f_i|_{U_i \cap U_j} = f_j|_{U_i \cap U_j}$ , then we obtain a glued morphism.

This gives  $\beta: \text{Hom}_{\text{Ring}}(A, \Gamma(X, \mathcal{O}_X)) \rightarrow \text{Hom}_{\text{Sch}}(X, \text{Spec } A)$ . Need to check:

- $\alpha \circ \beta$  is the identity: given  $\varphi$ ,  $f = \beta(\varphi)$  is constructed such that the composition

$$A \xrightarrow{f^\#} \Gamma(X, \mathcal{O}_X) \longrightarrow \Gamma(U_i, \mathcal{O}_X)$$

coincides with

$$A \xrightarrow{\varphi} \Gamma(X, \mathcal{O}_X) \longrightarrow \Gamma(U_i, \mathcal{O}_X),$$

so by the first sheaf axiom we must have  $f^\# = \varphi = \alpha(f)$ .

- $\beta \circ \alpha$  is the identity: given a morphism  $f: X \rightarrow \text{Spec } A$ , this induces by restriction to  $U_i$  a morphism  $U_i \rightarrow \text{Spec } A$ ; necessarily induced by the composition

$$A \xrightarrow{f^\#} \Gamma(X, \mathcal{O}_X) \longrightarrow \Gamma(U_i, \mathcal{O}_X) = B_i.$$

SO  $f$  is induced by  $\alpha(f)$  on open sets  $U_i$ . So  $f|_{U_i} = \beta(\alpha(f))|_{U_i}$ . Thus  $f = \beta(\alpha(f))$ .

Note: not every details has been checked here, for example that  $f^\#$  constructed above is indeed a morphism of locally ringed spaces (the reason is because locally, we already started with a morphism). Checking details is essential to understanding what is important and what isn't. During marking, not checking unimportant/easy things is usually not a problem, forgetting to check important things is.

□

### Exercise 11.

EXERCISE. If  $f \in A$ , then  $(D(f), \mathcal{O}_{\text{Spec } A}|_{D(f)}) \cong \text{Spec } A_f$ .

SOLUTION. Note that  $D(f)$  is the set of all prime ideals of  $A$  not containing  $f$ . There is a one-to-one correspondence between primes of  $A$  disjoint from  $S$  and primes of  $S^{-1}A$  for  $S$  any multiplicatively closed subset.

Thus time primes of  $A_f$  are in one-to-one correspondence with primes of  $A$  disjoint from  $\{1, f, f^2, \dots\}$ , i.e., primes in  $D(f)$ . This gives a bijection  $\text{Spec } A_f \rightarrow D(f)$  and the composition with the inclusion  $D(f) \rightarrow \text{Spec } A$  is induced by the localization map  $\varphi: A \rightarrow A_f$ .

Hence, the induced map  $\text{Spec } A_f \rightarrow \text{Spec } A$  is continuous, so  $\text{Spec } A_f \rightarrow D(f)$  is continuous. Note that if  $I \subseteq A_f$  is an ideal, then  $i(V(I)) = V(\varphi^{-1}(I)) \cap D(f)$ , so  $i$  is a homeomorphism.

To check that  $i$  is an isomorphism of schemes, we need to check that we get an isomorphism  $i^\#: \mathcal{O}_{\text{Spec } A}|_{D(f)} \rightarrow \mathcal{O}_{\text{Spec } A_f}$ . Note that it is enough to check that this is an isomorphism on stalks. Note that the stalk of  $\mathcal{O}_{\text{Spec } A}$  at  $p \in D(f)$  is  $A_p$  and the stalk of  $\mathcal{O}_{\text{Spec } A_f}$  at  $pA_f$  is  $(A_f)_{pA_f \leftarrow \cong}$ , by sending  $a/s \mapsto a/s$ . Since  $f \notin p$ , one can check algebraically that this is an isomorphism.

□

### Exercise 10.

EXERCISE.

SOLUTION. Given a continuous map  $f: X \rightarrow Y$  and a sheaf  $\mathcal{F}$  over  $X$  and a sheaf  $\mathcal{G}$  over  $Y$ .

We will first give a morphism  $\Psi: f^{-1}f_*\mathcal{F} \rightarrow \mathcal{F}$ .  $s \in (f^{-1}f_*\mathcal{F})(U) = \{(V, s') \mid V \supseteq f(U)\} / \sim$ , where  $s' \in (f_*\mathcal{F})(V) = \mathcal{F}(f^{-1}(V))$ , i.e.,  $s = (V, s)$ , where  $V \supseteq f(U)$ ,  $s \in \mathcal{F}(f^{-1}(V))$ , but  $f^{-1}(V) \supseteq U$ . Then the natural  $\Psi$  map takes  $(V, s) \mapsto s|_U$ .

Next, we give a morphism  $\Phi: \mathcal{G} \rightarrow f_*f^{-1}\mathcal{G}$ . Given  $s \in \mathcal{G}(U)$ , we have  $f_*f^{-1}\mathcal{G}(U) = (f^{-1}\mathcal{G})(f^{-1}(U))$ . The natural map  $\Phi$  sends  $s \mapsto (U, s)$ , which makes sense since  $U \supseteq f(f^{-1}(U))$ .

We want to construct a bijection

$$F: \text{Hom}_X(f^{-1}\mathcal{G}, \mathcal{F}) \rightarrow \text{Hom}_Y(\mathcal{G}, f_*\mathcal{F}).$$

Given a map  $\varphi: f^{-1}\mathcal{G} \rightarrow \mathcal{F}$ , apply  $f_*$  to get  $f_*\varphi: f_*f^{-1}\mathcal{G} \rightarrow f_*\mathcal{F}$  and then  $(f_*\varphi) \circ \Phi: \mathcal{G} \rightarrow f_*\mathcal{F}$ , so define  $F(\varphi) = (f_*\varphi) \circ \Phi$ .

Similarly, we define

$$G: \text{Hom}_Y(\mathcal{G}, f_*\mathcal{F}) \rightarrow \text{Hom}_X(f^{-1}\mathcal{G}, \mathcal{F}).$$

Given  $\varphi: \mathcal{G} \rightarrow f_*\mathcal{F}$ , apply  $f^{-1}$  to get  $f^{-1}\varphi: f^{-1}\mathcal{G} \rightarrow f^{-1}f_*\mathcal{F}$ , so we can define  $G(\varphi) := \Psi \circ f^{-1}\varphi$ .

Now we need to check that  $F \circ G$  and  $G \circ F$  are identities.

Given  $\psi: \mathcal{G} \rightarrow f_*\mathcal{F}$ , the map  $FG(\psi)$  is given as a composition

$$\mathcal{G} \xrightarrow{\Phi} f_*f^{-1}\mathcal{G} \longrightarrow f_*f^{-1}f_*\mathcal{F} \longrightarrow f_*\mathcal{F}$$

$$s \longmapsto (U, s) \longmapsto (U, \psi_U(s)) \longmapsto \psi_U(s),$$

so  $FG$  is the identity.

Similarly, given  $\varphi: f^{-1}\mathcal{G} \rightarrow \mathcal{F}$  is given as a composition

$$f^{-1}\mathcal{G} \longrightarrow f^{-1}f_*f^{-1}\mathcal{G}, f^{-1}f_*\mathcal{F} \xrightarrow{\Psi} \mathcal{F}$$

A section of  $(f^{-1}\mathcal{G})(U)$  is represented by  $(V, s)$  for  $s \in \mathcal{G}(V)$  with  $V \supseteq f(U)$ .

The sequence of maps is given as

$$(V, s) \mapsto (V, s) \mapsto (V, \varphi(s)) \mapsto \varphi(s),$$

so  $GF$  is the identity.

Note that we are working with presheaves here, so we have to splice in the universal property of sheafification everywhere.  $\square$

#### Exercise 14.

EXERCISE. Given a collection  $\{X_i\}$  of schemes and open sets  $U_{ij} \subseteq X_i$  together with isomorphisms  $\varphi_{ij}: U_{ij} \rightarrow U_{ji}$  such that

- (1)  $\varphi_{ij} = \varphi_{ji}^{-1}$ ,
- (2) for all  $i, j, k$  we have  $\varphi_{ij}(U_{ij} \cap U_{ik}) = U_{ji} \cap U_{jk}$  and  $\varphi_{ik} = \varphi_{jk} \circ \varphi_{ij}$  on  $U_{ij} \cap U_{ik}$ .

SOLUTION. We can glue the  $X_i$  as topological spaces to get a space  $X$  and open subsets  $X_i \subseteq X$  by usual gluing of topological spaces. We have sheaves  $\mathcal{O}_{X_i}$  on  $X_i$  along with isomorphisms

$$\varphi_{ij}^\#: \mathcal{O}_{X_j}|_{X_i \cap X_j} \rightarrow \mathcal{O}_{X_i}|_{X_i \cap X_j},$$

and for each  $i, j, k$ , we have  $\varphi_{ik}^\# = \varphi_{jk}^\# \circ \varphi_{ij}^\#$  on  $X_i \cap X_j \cap X_k$ .

Let's glue these sheaves. Define  $\mathcal{O}_X$  by defining  $\mathcal{O}_X(U)$  to be the set of tuples  $(s_i)_{i \in I}$  with  $s_i \in \mathcal{O}_{X_i}(U \cap X_i)$  subject to the constraint that on  $X_i \cap X_j \cap U$ ,  $\varphi_{ij}^\#(s_j) = s_i$ .

One now checks that this is a sheaf of rings, i.e., we inherit a ring structure, the sheaf axioms are satisfied. This follows from the sheaf axioms for the  $\mathcal{O}_{X_i}$ .

Finally, we need to check that this is a scheme. For this it is enough to show that  $\mathcal{O}_X|_{X_i} \cong \mathcal{O}_{X_i}$ . This isomorphism is given by sending  $s \in \mathcal{O}_{X_i}(U)$  to  $(\varphi_{ij}^\#(s|_{U \cap X_j}))_{j \in I}$ . To see that this is a section of  $\mathcal{O}_X$ , we use the compatibility condition for  $\varphi_{ij}^\#$  from above.  $\square$