

# 256A: Algebraic Geometry

Nir Elber

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# THEME 1

## INTRODUCTION

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*Hold tight to your geometric motivation as you learn the formal structures which have proved to be so effective in studying fundamental questions.*

—Ravi Vakil, [Vak17]

### 1.1 August 24

A feeling of impending doom overtakes your soul.

#### 1.1.1 Administrative Notes

Here are housekeeping notes.

- Here are some housekeeping notes. There is a syllabus on [bCourses](#).
- We hope to cover Chapter II of [Har77], mostly, supplemented with examples from curves.
- There are lots of books.
  - We use [Har77] because it is short.
  - There is also [Vak17], which has more words.
  - The book [Liu06] has notes on curves.
  - There are more books in the syllabus. Professor Tang has some opinions on these.
- Some proofs will be skipped in lecture. Not all of these will appear on homework.
- Some examples will say lots of words, some of which we won't have good definitions for until later. Do not be afraid of words.

Here are assignment notes.

- Homework is 70% of the class.
- Homework is due on noon on Fridays. There will be 6–8 problems, which means it is pretty heavy. The lowest homework score will be dropped.

- Office hours exist. Professor Tang also answers emails.
- The term paper covers the last 30% of the grade. They are intended to be extra but interesting topics we don't cover in this class.

### 1.1.2 Motivation

We're going to talk about schemes. Why should we care about schemes? The point is that schemes are "correct."

**Example 1.1.** In algebraic topology, there is a cup product map in homology, which is intended to algebraically measure intersections. However, intersections are hard to quantify when we aren't dealing with, say manifolds.

Here is an example of algebraic geometry helping us with this rigorization.

**Theorem 1.2 (Bézout).** Let  $C_1$  and  $C_2$  be curves in  $\mathbb{P}^2(k)$ , for some algebraically closed  $k$ , where  $C_1$  and  $C_2$  are defined by homogeneous polynomials  $f_1$  and  $f_2$ . Then the "intersection number" between the curves  $C_1$  and  $C_2$  is  $(\deg f_1)(\deg f_2)$ .

This is a nice result, for example because it automatically accounts for multiplicities, which would be difficult to deal with directly using (say) geometric techniques. Schemes will help us with this.

**Example 1.3.** Moduli spaces are intended to be geometric objects which represent a family of geometric objects of interest. For example, we might be interested in the moduli space of some class of elliptic curves.

It turns out that the correct way to define these objects is using schemes as a functor; we will see this in this class.

**Remark 1.4.** One might be interested in when a functor is a scheme. We will not cover this question in this class in full, but it is an interesting question, and we will talk about this in special cases.

### 1.1.3 Elliptic Curves

For the last piece of motivation, let's talk about elliptic curves, over a field  $k$ .

**Definition 1.5 (Elliptic curve).** An *elliptic curve* over  $k$  is a smooth projective curve of genus 1, with a marked  $k$ -rational point.

Remember that we said that we not to be afraid of words. However, we should have some notion of what these words mean: being a curve means that we are one-dimensional, being smooth is intuitive, and having genus 1 roughly means that base-changing to a complex manifold has one hole. Lastly, the  $k$ -rational point requires defining a scheme as a functor.

Here's another (more concrete) definition of an elliptic curve.

**Definition 1.6 (Elliptic curve).** An *elliptic curve* over  $k$  is an affine variety in  $\mathbb{A}^2(k)$  cut out by a polynomial of the form

$$y^2 + a_1xy + a_3y^2 = x^3 + a_2x^2 + a_4x + a_6$$

with nonzero discriminant plus a point  $\mathcal{O}$  at infinity.

**Remark 1.7.** Why are these equivalent? Well, the Riemann–Roch theorem approximately lets us take a smooth projective curve of genus 1 and then write it as an equation; the marked point goes to  $\mathcal{O}$ . In the reverse direction, one merely needs to embed our affine curve into projective space and verify its smoothness and genus.

Instead of working with affine varieties, we can also give a concrete description of an elliptic curve using projective varieties.

**Definition 1.8 (Elliptic curve).** An *elliptic curve* over  $k$  is a projective variety in  $\mathbb{P}^2(k)$  cut out by a polynomial of the form

$$Y^2Z + a_1XYZ + a_3YZ^2 = X^3 + a_2X^2Z + a_4XZ^2 + a_6Z^3$$

with nonzero discriminant.

We get the equivalence of the previous two definitions via the embedding  $\mathbb{A}_2(k) \hookrightarrow \mathbb{P}^2(k)$  by  $(x, y) \mapsto [x : y : 1]$ ; the point at infinity  $\mathcal{O}$  is  $[0 : 1 : 0]$ .

### 1.1.4 Crackpot Varieties

In order to motivate schemes, we should probably mention varieties, so we will spend some time in class discussing affine and projective varieties. For convenience, we work over an algebraically closed field  $k$ .

**Definition 1.9 (Affine space).** Given a field  $k$ , we define *affine  $n$ -space* over  $k$ , denoted  $\mathbb{A}^n(k)$ . An *affine variety* is a subset  $Y \subseteq \mathbb{A}^n(k)$  of the form

$$Y = V(S) := \{p \in \mathbb{A}^n(k) : f(p) = 0 \text{ for all } f \in S\},$$

where  $S \subseteq k[x_1, \dots, x_n]$ .

**Remark 1.10.** The set  $S \subseteq k[x_1, \dots, x_n]$  in the above definition need not be finite or countable. In certain cases, we can enforce this condition; for example, if  $n = 1$ , then  $k[x]$  is a principal ideal domain, so we may force  $\#S = 1$ .

Note that we have defined vanishing sets  $V(S)$  from subsets  $S \subseteq k[x_1, \dots, x_n]$ . We can also go from vanishing sets to subsets.

**Definition 1.11.** Fix a field  $k$  and subset  $Y \subseteq \mathbb{A}^n(k)$ . Then we define the ideal

$$I(Y) := \{f \in \mathbb{A}^n(k) : f(p) = 0 \text{ for all } p \in Y\}.$$

**Remark 1.12.** One should check that this is an ideal, but we won't bother.

So we've defined some geometry. But we're in an algebraic geometry class; where's the algebra?

**Theorem 1.13 (Hilbert's Nullstellensatz).** Fix an algebraically closed field  $k$  and ideal  $J \subseteq k[x_1, \dots, x_n]$ . Then

$$I(V(J)) = \text{rad } I,$$

where  $\text{rad } I$  is the radical of  $I$ .

**Remark 1.14.** The Nullstellensatz has no particularly easy proof.

The point of this result is that it ends up giving us a contravariant equivalence of posets of radical ideals and affine varieties.

Why do we care? In some sense, we prefer to work with ideals because it “remembers” more information than merely the points on the variety. To see this, note that elements  $f \in k[x_1, \dots, x_n]$  we are viewing as giving functions on  $\mathbb{A}^n(k)$ . However, when we work on a variety  $Y \subseteq \mathbb{A}^n(k)$ , then sometimes two functions will end up being identical on  $Y$ . So the correct ring of functions on  $Y$  is

$$k[x_1, \dots, x_n]/I(Y),$$

so indeed keeping track of the (algebraic) ideal  $V(Y)$  gets us some extra (geometric) information.

We will use this discussion as a jumping-off point to discuss affine schemes and then schemes. Affine schemes will have the following data.

- A commutative ring  $A$ , which we should think of as the ring of functions on a variety.
- A topological space  $\text{Spec } A$ , which has more information than merely points on the variety.
- A structure sheaf of functions on  $\text{Spec } A$ .

**Remark 1.15.** Our topological space  $\text{Spec } A$  will contain more points than just the points on the variety. In some sense, these extra points make the topology more apparent.

**Remark 1.16.** Going forward, one might hope to remove requirements that the field  $k$  is algebraically closed (e.g., to work with a general ring) or talk about ideals which are not radical. This is the point of scheme theory.

## 1.2 August 26

Let’s finish up talking varieties, and then we’ll move on to affine schemes.

### 1.2.1 Projective Varieties

We’re going to briefly talk about projective varieties. Let’s start with projective space.

**Definition 1.17 (Projective space).** Given a field  $k$ , we define *projective  $n$ -space over  $k$* , denoted  $\mathbb{P}^n(k)$  as

$$\frac{k^{n+1} \setminus \{(0, \dots, 0)\}}{\sim},$$

where  $\sim$  assigns two points being equivalent if and only if they span the same 1-dimensional subspace of  $k^{n+1}$ . We will denote the equivalence class of a point  $(a_0, \dots, a_n)$  by  $[a_0 : \dots : a_n]$ .

To work with varieties, we don’t quite cut out by general polynomials but rather by homogeneous polynomials.

**Definition 1.18 (Projective variety).** Given a field  $k$  and a set of some homogeneous polynomials  $T \subseteq k[x_1, \dots, x_n]$ , we define the *projective variety* cut out by  $T$  as

$$V(T) := \{p \in \mathbb{P}^n(k) : f(p) = 0 \text{ for all } f \in T\}.$$

**Example 1.19.** The elliptic curve corresponding to the affine algebraic variety in  $\mathbb{A}^2(k)$  cut out by  $y^2 - x^3 - 1$  becomes the projective variety in  $\mathbb{P}^2(k)$  cut out by

$$Y^2Z - X^3 - Z^3 = 0.$$

**Remark 1.20.** One can give projective varieties some Zariski topology as well, which we will define later in the class.

What to remember about projective varieties is that we can cover  $\mathbb{P}^2(k)$  (say) by affine spaces as

$$\begin{aligned}\mathbb{P}^2(k) &= \{[X : Y : Z] : X, Y, Z \in k \text{ not all } 0\} \\ &= \{[X : Y : Z] : X, Y, Z \in k \text{ and } X \neq 0\} \\ &\quad \cup \{[X : Y : Z] : X, Y, Z \in k \text{ and } Y \neq 0\} \\ &= \{[1 : y : z] : y, z \in k\} \\ &\quad \cup \{[x : 1 : z] : x, z \in k\} \\ &\simeq \mathbb{A}^2(k) \cup \mathbb{A}^2(k).\end{aligned}$$

The point is that we can decompose  $\mathbb{P}^2(k)$  into an affine cover.

**Example 1.21.** Continuing from [Example 1.19](#), we can decompose  $Z(Y^2Z - X^3 - Z^3)$  into having an affine open cover by

$$\underbrace{\{(x, y) : y^2 - x^3 - 1 = 0\}}_{z \neq 0} \cup \underbrace{\{(x, z) : z - x^3 - z^3 = 0\}}_{y \neq 0} \cup \underbrace{\{(y, z) : y^2z - 1 - z^3 = 0\}}_{x \neq 0}.$$

Notably, we get almost everything from just one of the affine chunks, and we get the point at infinity by taking one of the other chunks.

**Remark 1.22.** It is a general fact that we only need two affine chunks to cover our projective curve.

## 1.2.2 The Spectrum

The definition of a(n affine) scheme requires a topological space and its ring of functions. We will postpone talking about the ring of functions until we discuss sheaves, so for now we will focus on the space.

**Definition 1.23 (Spectrum).** Given a ring  $A$ , we define the *spectrum*

$$\text{Spec } A := \{\mathfrak{p} \subseteq A : \mathfrak{p} \text{ is a prime ideal}\}.$$

**Example 1.24.** Fix a field  $k$ . Then  $\text{Spec } k = \{(0)\}$ . Namely, non-isomorphic rings can have homeomorphic spectra.

**Exercise 1.25.** Fix a field  $k$ . We show that

$$\text{Spec } k[x] = \{(0)\} \cup \{(\pi) : \pi \text{ is monic, irred., } \deg \pi > 0\}.$$

*Proof.* To begin, note that  $(0)$  is prime, and  $(\pi)$  is prime for irreducible non-constant polynomials  $\pi$  because irreducible elements are prime in principal ideal domains. Additionally, we note that all the given primes are distinct: of course  $(0)$  is distinct from any prime of the form  $(\pi)$ , but further, given monic non-constant irreducible polynomials  $\alpha$  and  $\beta$ , having

$$(\alpha) = (\beta)$$

forces  $\alpha = c\beta$  for some  $c \in k[x]^\times$ . But  $k[x]^\times = k^\times$ , so  $c \in k^\times$ , so  $c = 1$  is forced by comparing the leading coefficients of  $\alpha$  and  $\beta$ .

It remains to show that all prime ideals  $\mathfrak{p} \subseteq k[x]$  take the desired form. Well,  $k[x]$  is a principal ideal domain, so we may write  $\mathfrak{p} = (\pi)$  for some  $\pi \in k[x]$ . If  $\pi = 0$ , then we are done. Otherwise,  $\deg \pi \geq 0$ , but  $\deg \pi > 0$  because  $\deg \pi = 0$  implies  $\pi \in k[x]^\times$ . By adjusting by a unit, we may also assume that  $\pi$  is monic. And lastly, note that  $(\pi)$  is prime means that  $\pi$  is prime, so  $\pi$  is irreducible. ■

**Example 1.26.** If  $k$  is an algebraically closed field, then the only nonconstant irreducible polynomials are linear (because all nonconstant polynomials have a root and hence a linear factor), and of course any linear polynomial is irreducible. Thus,

$$\operatorname{Spec} k[x] = \{(0)\} \cup \{(x - \alpha) : \alpha \in k\}.$$

Set  $\mathfrak{m}_\alpha := (x - \alpha)$  so that  $\alpha \mapsto \mathfrak{m}_\alpha$  provides a natural map from  $\mathbb{A}_k^1$  to  $\operatorname{Spec} k[x]$ . In this way we can think of  $\operatorname{Spec} k[x]$  as  $\mathbb{A}_k^1$  with an extra point  $(0)$ .

**Remark 1.27.** Continuing from [Example 1.26](#), observe that we can also recover function evaluation at a point  $\alpha \in \mathbb{A}_k^1$ : given  $f \in k[x]$ , the value of  $f(\alpha)$  is the image of  $f$  under the canonical map

$$k[x] \twoheadrightarrow \frac{k[x]}{\mathfrak{m}_\alpha} \cong k,$$

where the last map is the forced  $x \mapsto \alpha$ . Observe running this construction at the point  $(0) \in \operatorname{Spec} k[x]$  makes the “evaluation” map just the identity.

**Example 1.28.** Similar to  $k[x]$ , we can classify  $\operatorname{Spec} \mathbb{Z}$ : all ideals are principal, so our primes look like  $(p)$  where  $p = 0$  or is a rational prime. Namely, essentially the same proof gives

$$\operatorname{Spec} \mathbb{Z} = \{(0)\} \cup \{(p) : p \text{ prime}, p > 0\}.$$

The condition  $p > 0$  is to ensure that all the points on the right-hand side are distinct; certainly we can write all nonzero primes  $(p) \subseteq \mathbb{Z}$  for some nonzero  $(p)$ , and we can adjust  $p$  by a unit to ensure  $p > 0$ . Conversely,  $(p) = (q)$  with  $p, q > 0$  forces  $p \mid q$  and  $q \mid p$  and so  $p = q$ .

We might hope to have a way to view  $\operatorname{Spec} k[x]$  as points even when  $k$  is not algebraically closed.

**Example 1.29.** Set  $k = \mathbb{Q}$ . There is a map sending a nonconstant monic irreducible polynomial  $\pi \in \mathbb{Q}[x]$  to its roots in  $\overline{\mathbb{Q}}$ , and note that this map is injective because one can recover a polynomial from its roots. Further, all the roots of  $\pi$  are Galois conjugate because  $\pi$  is irreducible, and a Galois orbit  $S_\alpha$  of a root  $\alpha$  corresponds to the polynomial

$$\pi(x) = \prod_{\beta \in S_\alpha} (x - \beta),$$

where  $\pi(x) \in \mathbb{Q}[x]$  because its coefficients are preserved the Galois action. Thus, there is a bijection between the nonconstant monic irreducible polynomials  $\pi \in \mathbb{Q}[x]$  and Galois orbits of elements in  $\overline{\mathbb{Q}}$ .

So far, all of our examples have been “dimension 0” (namely, a field  $k$ ) or “dimension 1” (namely,  $\mathbb{Z}$  and  $k[x]$ ). Here is an example in dimension 2.

**Exercise 1.30.** Let  $k$  be algebraically closed. Any  $\mathfrak{p} \in \operatorname{Spec} k[x, y]$  is one of the following types of prime.

- Dimension 2:  $\mathfrak{p} = (0)$ .
- Dimension 1:  $\mathfrak{p} = (f(x, y))$  where  $f$  is nonconstant and irreducible.
- Dimension 0:  $\mathfrak{p} = (x - \alpha, y - \beta)$ , where  $\alpha, \beta \in k$ .



*Proof.* We follow [Vak17, Exercise 3.2.E]. If  $\mathfrak{p} = (0)$ , then we are done. If  $\mathfrak{p}$  is principal, then we can write  $\mathfrak{p} = (f)$  where  $f \in k[x, y]$  is a prime element and hence irreducible. Observe that if  $f$  is irreducible, then  $f$  is also a prime element because  $k[x, y]$  is a unique factorization domain.

Lastly, we suppose that  $\mathfrak{p}$  is not principal. We start by finding  $f, g \in \mathfrak{p}$  with no nonconstant common factors. Because  $\mathfrak{p} \neq 0$ , we can find  $f_0 \in \mathfrak{p} \setminus \{0\}$ , and assume that  $(f_0)$  is maximal with respect to this (namely,  $f_0 \notin (f'_0)$  for any  $f'_0 \in \mathfrak{p}$ ). Because  $\mathfrak{p}$  is not principal, we can find  $g_0 \in \mathfrak{p} \setminus (f_0)$ . Now, we can use unique prime factorization of  $f_0$  and  $g_0$  to find some  $d \in k[x, y]$  such that

$$f_0 = fd \quad \text{and} \quad g_0 = gd$$

where  $f$  and  $g$  share no common factors. (Namely,  $\nu_\pi(d) = \min\{\nu_\pi(f_0), \nu_\pi(g_0)\}$  for all irreducible factors  $\pi \in k[x, y]$ .) Note  $d \notin \mathfrak{p}$  by the maximality of  $f_0$ , so  $f, g \in \mathfrak{p}$  is forced.

Continuing, embedding  $f$  and  $g$  into  $k(x)[y]$  and using the Euclidean algorithm there, we can write

$$af + bg = 1$$

where  $a, b \in k(x)[y]$ , because  $f$  and  $g$  have no common factors in  $k(x)[y]$ . (Any common factor would lift to a common factor in  $k[x, y]$ .<sup>1</sup>) Clearing denominators, we see that we can find  $h(x) \in k[x] \cap \mathfrak{p}$ , but by factoring  $h(x)$  using the fact that  $k$  is algebraically closed, we see that we can actually enforce  $(x - \alpha) \in \mathfrak{p}$  for some  $\alpha \in k$ .

By symmetry, we can force  $(y - \beta) \in \mathfrak{p}$  for some  $\beta \in \mathfrak{p}$  as well, so  $(x - \alpha, y - \beta) \subseteq \mathfrak{p}$ . However, we see that  $(x - \alpha, y - \beta)$  is maximal because of the isomorphism

$$\frac{k[x, y]}{(x - \alpha, y - \beta)} \rightarrow k$$

by  $x \mapsto \alpha$  and  $y \mapsto \beta$ . Thus,  $\mathfrak{p} = (x - \alpha, y - \beta)$  follows. ■

**Remark 1.31.** The intuition behind [Exercise 1.30](#) is that the prime ideal  $(x - \alpha, y - \beta)$  “cuts out” the zero-dimensional point  $(\alpha, \beta) \in \mathbb{A}_k^2$ . Then the prime ideal  $(f)$  cuts out some one-dimensional curve in  $\mathbb{A}_k^2$ , and the prime ideal  $(0)$  cuts out the entire two-dimensional plane. We have not defined dimension rigorously, but hopefully the idea is clear.

**Remark 1.32.** It is remarkable that the number of equations we need to cut out a variety of dimension  $d$  is  $2 - d$ . This is not always true.

The point is that we seem to have recovered  $\mathbb{A}_k^1$  by looking at  $\text{Spec } k[x]$  and  $\mathbb{A}_k^2$  by looking at  $\text{Spec } k[x, y]$ , so we can generalize this to arbitrary rings cleanly, realizing some part of [Remark 1.16](#).

**Definition 1.33** (Affine space). Given a ring  $R$ , we define *affine  $n$ -space over  $R$*  as

$$\mathbb{A}_R^n := \text{Spec } R[x_1, \dots, x_n].$$

So far all the rings we’ve looked at so far have been integral domains, but it’s worth pointing out that working with general rings allows more interesting information.

**Example 1.34.** We classify  $\text{Spec } k[\varepsilon]/(\varepsilon^2)$ . Notably, all prime ideals here must correspond to prime ideals of  $k[\varepsilon]$  containing  $(\varepsilon^2)$  and hence contain  $\text{rad } (\varepsilon^2) = (\varepsilon)$ , which allows only the prime  $(\varepsilon)$ . (We will make this correspondence precise later.) So  $\text{Spec } k[\varepsilon]/(\varepsilon^2)$  has a single point.

<sup>1</sup> If  $d(x, y)/e(x)$  divides both  $f$  and  $g$  in  $k(x)[y]$ , where  $d$  and  $e$  share no common factors, then  $d \mid fe, ge \in k[x, y]$ . Unique prime factorization now forces  $d \mid f, g$  in  $k[x, y]$ .

**Remark 1.35.** In some sense,  $\text{Spec } k[\varepsilon]/(\varepsilon^2)$  will be able to let us talk about differential information algebraically:  $\varepsilon$  is some very small nonzero element such that  $\varepsilon^2 = 0$ . So we can study a “function”  $f \in k[x]$  locally at a point  $p$  by studying  $f(p + \varepsilon)$ . Rigorously,  $f(x) = \sum_{i=0}^d a_i x^i$  has

$$f(x + \varepsilon) = \sum_{i=0}^d a_i (x + \varepsilon)^i = \sum_{i=0}^d a_i x^i + \sum_{i=1}^d i a_i x^{i-1} \varepsilon = f(x) + f'(x) \varepsilon.$$

One can recover more differential information by looking at  $k[\varepsilon]/(\varepsilon^n)$  for larger  $n$ .

### 1.2.3 The Zariski Topology

Thus far we’ve defined our space. Here’s our topology.

**Definition 1.36** (Zariski topology). Fix a ring  $A$ . Then, for  $S \subseteq A$ , we define the *vanishing set*

$$V(S) := \{\mathfrak{p} \in \text{Spec } A : S \subseteq \mathfrak{p}\}$$

Then the *Zariski topology* on  $\text{Spec } A$  is the topology whose closed sets are the  $V(S)$ .

Intuitively, we are declaring  $A$  as the (continuous) functions on  $\text{Spec } A$ , and the evaluation of the function  $f \in A$  at the point  $\mathfrak{p} \in \text{Spec } A$  is  $f \pmod{\mathfrak{p}}$  (using the ideas of [Remark 1.27](#)). Then the vanishing sets of a continuous function must be closed, and without easy access to any other functions on  $\text{Spec } A$ , we will simply declare that these are all of our closed sets.

In the affine case, we can be a little more rigorous.

**Example 1.37.** Set  $A := k[x_1, \dots, x_n]$ , where  $k$  is algebraically closed. Then, given  $f \in k[x_1, \dots, x_n]$ , we want to be convinced that  $V(\{f\})$  matches up with the affine  $k$ -points  $(a_1, \dots, a_n)$  which vanish on  $f$ . Well,  $(a_1, \dots, a_n)$  corresponds to the prime ideal  $(x_1 - a_1, \dots, x_n - a_n) \in \text{Spec } A$ , and

$$\{f\} \subseteq (x_1 - a_1, \dots, x_n - a_n)$$

is equivalent to  $f$  vanishing in the evaluation map

$$k[x_1, \dots, x_n] \twoheadrightarrow \frac{k[x_1, \dots, x_n]}{(x_1 - a_1, \dots, x_n - a_n)} \rightarrow k,$$

which is equivalent to  $f(a_1, \dots, a_n) = 0$ . So indeed,  $f$  vanishes on  $(a_1, \dots, a_n)$  if and only if the corresponding maximal ideal is in  $V(\{f\})$ .

With intuition out of the way, we should probably check that the sets  $V(S)$  make a legitimate topology. To begin, here are some basic properties.

**Lemma 1.38.** Fix a ring  $A$ .

- (a) If subsets  $S, T \subseteq A$  have  $S \subseteq T$ , then  $V(T) \subseteq V(S)$ .
- (b) A subset  $S \subseteq A$  has  $V(S) = V((S))$ .
- (c) An ideal  $\mathfrak{a} \subseteq A$  has  $V(\mathfrak{a}) = V(\text{rad } \mathfrak{a})$ .

*Proof.* We go in sequence.

- (a) Note  $\mathfrak{p} \in V(T)$  implies that  $T \subseteq \mathfrak{p}$ , which implies  $S \subseteq \mathfrak{p}$ , so  $\mathfrak{p} \in V(S)$ .

(b) Surely  $S \subseteq (S)$ , so  $V((S)) \subseteq V(S)$ . Conversely, if  $\mathfrak{p} \in V(S)$ , then  $S \subseteq \mathfrak{p}$ , but then the generated ideal  $(S)$  must also be contained in  $\mathfrak{p}$ , so  $\mathfrak{p} \in V((S))$ .

(c) Surely  $\mathfrak{a} \subseteq \text{rad } \mathfrak{a}$ , so  $V(\text{rad } \mathfrak{a}) \subseteq V(\mathfrak{a})$ . Conversely, if  $\mathfrak{p} \in V(\mathfrak{a})$ , then  $\mathfrak{p} \subseteq \mathfrak{a}$ , so

$$\mathfrak{p} \subseteq \bigcap_{\mathfrak{q} \supseteq \mathfrak{a}} \mathfrak{q} = \text{rad } \mathfrak{a},$$

so  $\mathfrak{p} \in V(\text{rad } \mathfrak{a})$ . ■

**Remark 1.39.** In light of (b) and (c) of [Lemma 1.38](#), we can actually write all closed subsets of  $\text{Spec } A$  as  $V(\mathfrak{a})$  for a radical ideal  $\mathfrak{a}$ . We will use this fact freely.

And here are our checks.

**Lemma 1.40.** Fix a ring  $A$ .

- (a)  $V(A) = \emptyset$  and  $V((0)) = \text{Spec } A$ .
- (b) Given ideals  $\mathfrak{a}, \mathfrak{b} \subseteq A$ , then  $V(\mathfrak{a}) \cup V(\mathfrak{b}) = V(\mathfrak{a}\mathfrak{b})$ .
- (c) Given a collection of ideals  $\mathcal{I} \subseteq \mathcal{P}(A)$ , we have

$$\bigcap_{\mathfrak{a} \in \mathcal{I}} V(\mathfrak{a}) = V\left(\sum_{\mathfrak{a} \in \mathcal{I}} \mathfrak{a}\right).$$

*Proof.* We go in sequence.

- (a) All primes are proper, so no prime  $\mathfrak{p}$  has  $A \subseteq \mathfrak{p}$ , so  $V(A) = \emptyset$ . Also,  $0$  is an element of all ideals, so all  $\mathfrak{p} \in \text{Spec } A$  have  $(0) \subseteq \mathfrak{p}$ , so  $V((0)) = \text{Spec } A$ .
- (b) Note  $\mathfrak{a}\mathfrak{b} \subseteq \mathfrak{a}, \mathfrak{b}$ , so  $V(\mathfrak{a}) \cup V(\mathfrak{b}) \subseteq V(\mathfrak{a}\mathfrak{b})$  follows. Conversely, take  $\mathfrak{p} \in V(\mathfrak{a}\mathfrak{b})$ , and suppose  $\mathfrak{p} \notin V(\mathfrak{a})$  so that we need  $\mathfrak{p} \in V(\mathfrak{b})$ . Well,  $\mathfrak{p} \notin V(\mathfrak{a})$  implies  $\mathfrak{a} \not\subseteq \mathfrak{p}$ , so we can find  $a \in \mathfrak{a} \setminus \mathfrak{p}$ . Now, for any  $b \in \mathfrak{b}$ , we see

$$ab \in \mathfrak{a}\mathfrak{b} \subseteq \mathfrak{p},$$

so  $a \notin \mathfrak{p}$  forces  $b \in \mathfrak{p}$ . Thus,  $\mathfrak{b} \subseteq \mathfrak{p}$ , so  $\mathfrak{p} \in V(\mathfrak{b})$ .

- (c) Certainly any  $\mathfrak{b} \in \mathcal{I}$  has  $\mathfrak{b} \subseteq \sum_{\mathfrak{a} \in \mathcal{I}} \mathfrak{a}$ , so  $V(\sum_{\mathfrak{a} \in \mathcal{I}} \mathfrak{a}) \subseteq \bigcap_{\mathfrak{a} \in \mathcal{I}} V(\mathfrak{a})$  follows.

Conversely, suppose  $\mathfrak{p} \in \bigcap_{\mathfrak{a} \in \mathcal{I}} V(\mathfrak{a})$ . Then  $\mathfrak{a} \subseteq \mathfrak{p}$  for all  $\mathfrak{a} \in \mathcal{I}$ , so  $\sum_{\mathfrak{a} \in \mathcal{I}} \mathfrak{a} \subseteq \mathfrak{p}$  follows. Thus,  $\mathfrak{p} \in V(\sum_{\mathfrak{a} \in \mathcal{I}} \mathfrak{a})$ . ■

**Remark 1.41.** For ideals  $I, J \subseteq A$ , note that  $IJ \subseteq I \cap J$ . Additionally,  $I \cap J \subseteq \text{rad}(IJ)$ : if  $f \in I \cap J$ , then  $f^2 \in (I \cap J)^2 \subseteq IJ$ . It follows from [Lemma 1.38](#) that

$$V(IJ) \supseteq V(I \cap J) \supseteq V(\text{rad}(IJ)) = V(IJ),$$

so  $V(I) \cup V(J) = V(IJ) = V(I \cap J)$ . So  $V$  does respect some poset structure.

It follows that the collection of vanishing sets is closed under finite union and arbitrary intersection, so they do indeed specify the closed sets of a topology.

### 1.2.4 Easy Nullstellensatz

While we're here, let's also generalize [Definition 1.11](#) in the paradigm that  $\text{Spec } A$  is the analogue for affine space.

**Definition 1.42.** Fix a ring  $A$ . Then, given a subset  $Y \subseteq \text{Spec } A$ , we define

$$I(Y) := \bigcap_{\mathfrak{p} \in Y} \mathfrak{p}.$$

**Remark 1.43.** To see that this is the correct definition, note we want  $f \in I(Y)$  if and only if  $f$  vanishes at all points  $\mathfrak{p} \in Y$ . We said earlier that the value of  $f$  at  $\mathfrak{p}$  should be  $f \pmod{\mathfrak{p}}$  (using the ideas of [Remark 1.27](#)), so  $f$  vanishes at  $\mathfrak{p}$  if and only if  $f \in \mathfrak{p}$ . So we want

$$I(Y) = \{f \in A : f \in \mathfrak{p} \text{ for all } \mathfrak{p} \in Y\} = \bigcap_{\mathfrak{p} \in Y} \mathfrak{p}.$$

As before, we'll write in a few basic properties of  $I$ .

**Lemma 1.44.** Fix a ring  $A$ , and fix subsets  $X, Y \subseteq \text{Spec } A$ .

- (a) If  $X \subseteq Y$ , then  $I(Y) \subseteq I(X)$ .
- (b) The ideal  $I(X)$  is radical.

*Proof.* We go in sequence.

(a) Note

$$I(Y) = \bigcap_{\mathfrak{p} \in Y} \mathfrak{p} \subseteq \bigcap_{\mathfrak{p} \in X} \mathfrak{p} = I(X).$$

(b) Suppose that  $f^n \in I(X)$  for some positive integer  $n$ , and we need to show  $f \in I(X)$ . Then  $f^n \in \mathfrak{p}$  for all  $\mathfrak{p} \in X$ , so  $f \in \mathfrak{p}$  for all  $\mathfrak{p} \in X$ , so  $f \in I(X)$ . ■

And here is our nice version of [Theorem 1.13](#).

**Proposition 1.45.** Fix a ring  $A$ .

- (a) Given an ideal  $\mathfrak{a} \subseteq A$ , we have  $I(V(\mathfrak{a})) = \text{rad } \mathfrak{a}$ .
- (b) Given a subset  $X \subseteq \text{Spec } A$ , we have  $V(I(X)) = \overline{X}$ .
- (c) The functions  $V$  and  $I$  provide an inclusion-reversing bijection between radical ideals of  $A$  and closed subsets of  $\text{Spec } A$ .

*Proof.* We go in sequence.

(a) Observe

$$I(V(\mathfrak{a})) = \bigcap_{\mathfrak{p} \in V(\mathfrak{a})} \mathfrak{p} = \bigcap_{\mathfrak{p} \supseteq \mathfrak{a}} \mathfrak{p} = \text{rad } \mathfrak{a}.$$

(b) Using [Lemma 1.40](#), we find

$$\overline{X} = \bigcap_{V(\mathfrak{a}) \supseteq X} V(\mathfrak{a}) = V\left(\sum_{V(\mathfrak{a}) \supseteq X} \mathfrak{a}\right).$$

Now,  $X \subseteq V(\mathfrak{a})$  if and only if  $\mathfrak{a} \subseteq \mathfrak{p}$  for all  $\mathfrak{p} \in X$ , which is equivalent to  $\mathfrak{a} \subseteq I(X)$ . Thus,

$$\overline{X} = V\left(\sum_{\mathfrak{a} \subseteq I(X)} \mathfrak{a}\right) = V(I(X)).$$

- (c) Note that  $V$  sends (radical) ideals to closed subsets of  $\text{Spec } A$  by the definition of the Zariski topology. Also,  $I$  sends (closed) subsets of  $\text{Spec } A$  to radical ideals by [Lemma 1.44](#). Additionally, for a closed subset  $X \subseteq \text{Spec } A$ , we have

$$V(I(X)) = \overline{X} = X,$$

and for a radical ideal  $\mathfrak{a}$ , we have

$$I(V(\mathfrak{a})) = \text{rad } \mathfrak{a} = \mathfrak{a},$$

so  $I$  and  $V$  are in fact mutually inverse. ■

**Remark 1.46.** Given  $X \subseteq \text{Spec } A$ , we claim  $I(X) = I(\overline{X})$ . Well, these are both radical ideals, so it suffices by [Proposition 1.45](#) (c) to show  $V(I(X)) = V(I(\overline{X}))$ , which is clear because these are both  $\overline{X}$ .

**Remark 1.47.** Intuitively, what makes proving [Proposition 1.45](#) so much easier than [Theorem 1.13](#) is that we've added extra points to our space in order to track varieties better.

### 1.2.5 Some Continuous Maps

As a general rule, we will make continuous maps between our spectra by using ring homomorphisms. Here is the statement.

**Lemma 1.48.** Given a ring homomorphism  $\varphi: A \rightarrow B$ , the pre-image function  $\varphi^{-1}: \mathcal{P}(B) \rightarrow \mathcal{P}(A)$  induces a continuous function  $\varphi^{-1}: \text{Spec } B \rightarrow \text{Spec } A$ .

*Proof.* We begin by showing  $\varphi^{-1}: \text{Spec } B \rightarrow \text{Spec } A$  is well-defined: given a prime  $\mathfrak{q} \subseteq \text{Spec } B$ , we claim that  $\varphi^{-1}\mathfrak{q}$  is a prime in  $\text{Spec } A$ . Well, if  $ab \in \varphi^{-1}\mathfrak{q}$ , then  $\varphi(a)\varphi(b) \in \mathfrak{q}$ , so  $\varphi(a) \in \mathfrak{q}$  or  $\varphi(b) \in \mathfrak{q}$ . So indeed,  $\varphi^{-1}\mathfrak{q}$  is prime.

We now show that  $\varphi^{-1}: \text{Spec } B \rightarrow \text{Spec } A$  is continuous. It suffices to show that the pre-image of a closed set  $V(\mathfrak{a}) \subseteq \text{Spec } A$  under  $\varphi^{-1}$  is a closed set. For concreteness, we will make  $\text{Spec } \varphi: \text{Spec } B \rightarrow \text{Spec } A$  our pre-image map so that we want to show  $(\text{Spec } \varphi)^{-1}(V(\mathfrak{a}))$  is closed. Well,

$$\begin{aligned} (\text{Spec } \varphi)^{-1}(V(\mathfrak{a})) &= \{\mathfrak{q} \in \text{Spec } B : (\text{Spec } \varphi)(\mathfrak{q}) \in V(\mathfrak{a})\} \\ &= \{\mathfrak{q} \in \text{Spec } B : \mathfrak{a} \subseteq (\text{Spec } \varphi)(\mathfrak{q})\} \\ &= \{\mathfrak{q} \in \text{Spec } B : \mathfrak{a} \subseteq \varphi^{-1}\mathfrak{q}\}. \end{aligned}$$

Now, if  $\mathfrak{a} \subseteq \varphi^{-1}\mathfrak{q}$ , then any  $a \in \mathfrak{a}$  has  $\varphi(a) \in \mathfrak{q}$ , so  $\varphi(\mathfrak{a}) \subseteq \mathfrak{q}$ . Conversely, if  $\varphi(\mathfrak{a}) \subseteq \mathfrak{q}$ , then any  $a \in \mathfrak{a}$  has  $\varphi(a) \in \mathfrak{q}$  and hence  $a \in \varphi^{-1}\mathfrak{q}$ , so  $\mathfrak{a} \subseteq \varphi^{-1}\mathfrak{q}$  follows. In total, we see

$$(\text{Spec } \varphi)^{-1}(V(\mathfrak{a})) = \{\mathfrak{q} \in \text{Spec } B : \varphi(\mathfrak{a}) \subseteq \mathfrak{q}\} = V(\varphi(\mathfrak{a})),$$

which is closed. ■

In fact, we have defined a (contravariant) functor.

**Proposition 1.49.** The mapping  $\text{Spec}$  sending rings  $A$  to topological spaces  $\text{Spec } A$  and ring homomorphisms  $\varphi: A \rightarrow B$  to continuous maps  $\text{Spec } \varphi = \varphi^{-1}$  assembles into a functor  $\text{Spec}: \text{Ring}^{\text{op}} \rightarrow \text{Top}$ .

*Proof.* Thus far our data is sending objects to objects and morphisms to (flipped) morphisms, so we just need to run the functoriality checks.

- Identity: note that  $\text{Spec } \text{id}_A$  sends a prime  $\mathfrak{p} \in \text{Spec } A$  to

$$(\text{Spec } \text{id}_A)(\mathfrak{p}) = \text{id}_A^{-1}(\mathfrak{p}) = \{a \in A : \text{id}_A a \in \mathfrak{p}\} = \mathfrak{p},$$

so indeed,  $\text{Spec } \text{id}_A = \text{id}_{\text{Spec } A}$ .

- Functoriality: given morphisms  $\varphi: A \rightarrow B$  and  $\psi: B \rightarrow C$ , as well as a prime  $\mathfrak{r} \in \text{Spec } C$ , we compute

$$\begin{aligned} (\text{Spec}(\psi \circ \varphi))(\mathfrak{r}) &= (\psi \circ \varphi)^{-1}(\mathfrak{r}) \\ &= \{a \in A : \psi(\varphi(a)) \in \mathfrak{r}\} \\ &= \{a \in A : \varphi(a) \in (\text{Spec } \psi)(\mathfrak{r})\} \\ &= \{a \in A : a \in (\text{Spec } \varphi)((\text{Spec } \psi)(\mathfrak{r}))\} \\ &= (\text{Spec } \varphi \circ \text{Spec } \psi)(\mathfrak{r}). \end{aligned}$$

So indeed,  $\text{Spec}(\psi \circ \varphi) = \text{Spec } \varphi \circ \text{Spec } \psi$ . ■

Here is a quick example.

**Definition 1.50** (*k*-points). Given a ring  $A$  and field  $k$ , a *k*-point of  $\text{Spec } A$  is a ring homomorphism  $\iota: A \rightarrow k$ .

**Remark 1.51.** To see that [Definition 1.50](#) does indeed cut out a single point, note  $\iota: A \rightarrow k$  induces  $\text{Spec } \iota: \text{Spec } k \rightarrow \text{Spec } A$  and therefore picks out a single point of  $\text{Spec } A$  because  $\text{Spec } k = \{(0)\}$ .

**Remark 1.52.** To see that [Definition 1.50](#) is reasonable, let  $A = k[x_1, \dots, x_n]$  so that  $\text{Spec } A = \mathbb{A}_k^n$ . Then a map  $\iota: A \rightarrow k$  is determined by  $a_i := \iota(x_i)$ , so we expect this  $\iota$  to correspond to the point  $(a_1, \dots, a_n)$ . Indeed, [Remark 1.51](#) says we should compute

$$(\text{Spec } \iota)((0)) = \iota^{-1}((0)) = \ker \iota = (x_1 - a_1, \dots, x_n - a_n),$$

which does indeed correspond to the point  $(a_1, \dots, a_n)$ .

Here is a more elaborate example: closed subsets can be realized as spectra themselves!

**Exercise 1.53.** Fix a ring  $A$  and ideal  $\mathfrak{a} \subseteq A$ . Letting  $\pi: A \rightarrow A/\mathfrak{a}$  be the natural projection, we have that

$$\text{Spec } \pi: \text{Spec } A/\mathfrak{a} \rightarrow V(\mathfrak{a})$$

is a homeomorphism.

*Proof.* To be more explicit, we claim that the maps

$$\begin{aligned} \text{Spec } A/\mathfrak{a} &\cong V(\mathfrak{a}) \\ \mathfrak{q} &\mapsto \pi^{-1}\mathfrak{q} \\ \pi(\mathfrak{p}) &\leftarrow \mathfrak{p} \end{aligned}$$

are continuous inverses. Here are our well-definedness and continuity checks.

- That  $\mathfrak{q} \mapsto \pi^{-1}\mathfrak{q}$  is continuous follows from [Lemma 1.48](#). Note  $\pi^{-1}\mathfrak{q}$  contains  $\mathfrak{a}$  because any  $a \in \mathfrak{q}$  has  $\pi(a) = [0]_{\mathfrak{a}} \in \mathfrak{q}$ .
- For any  $\mathfrak{p}$  containing  $\mathfrak{a}$ , we need to show that  $\pi(\mathfrak{p})$  is prime. Of course, if  $\mathfrak{p}$  is proper, then  $\pi(\mathfrak{p})$  is proper as well. For the primality check, note  $[a]_{\mathfrak{a}} \cdot [b]_{\mathfrak{a}} \in \pi(\mathfrak{p})$  implies  $ab \in \mathfrak{p} + \mathfrak{a} = \mathfrak{p}$ , so  $a \in \mathfrak{p}$  or  $b \in \mathfrak{p}$ , so  $[a]_{\mathfrak{a}} \in \pi(\mathfrak{p})$  or  $[b]_{\mathfrak{a}} \in \pi(\mathfrak{p})$ .
- To show that  $\mathfrak{p} \mapsto \pi\mathfrak{p}$  is continuous, note that a closed set  $V(\overline{S}) \subseteq \text{Spec } A/\mathfrak{a}$  has pre-image

$$\pi^{-1}(V(\overline{S})) = \{\mathfrak{p} : \pi\mathfrak{p} \supseteq \overline{S}\}.$$

Now, set  $S = \pi^{-1}(\overline{S})$ . Now  $\pi\mathfrak{p} \supseteq \overline{S}$  if and only if each  $a \in S$  has  $\pi(a) \in \pi\mathfrak{p}$ , which is equivalent to  $a \in \mathfrak{a} + \mathfrak{p} = \mathfrak{p}$ . Thus,

$$\pi^{-1}(V(\overline{S})) = V(S),$$

which is closed.

Here are our inverse checks.

- Given  $\mathfrak{p} \in V(\mathfrak{a})$ , note

$$\pi^{-1}(\pi\mathfrak{p}) = \{a \in A : \pi(a) \in \pi\mathfrak{p}\} = \{a \in A : a \in \mathfrak{a} + \mathfrak{p}\} = \mathfrak{a} + \mathfrak{p} = \mathfrak{p}.$$

- Given  $\mathfrak{q} \in \text{Spec } A/\mathfrak{a}$ , note

$$\pi(\pi^{-1}\mathfrak{q}) = \pi(\{a \in A : \pi(a) \in \mathfrak{q}\}).$$

Because  $\pi: A \twoheadrightarrow A/\mathfrak{a}$  is surjective, the output here is just  $\mathfrak{q}$ . ■

A similar story exists for open sets, but we must be more careful. Here are our open sets.

**Definition 1.54 (Distinguished open sets).** Given a ring  $A$  and element  $f \in A$ , we define the *distinguished open set*

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

Intuitively, these are the points on which  $f$  does not vanish.

**Remark 1.55.** In fact, the distinguished open sets form a base: any open set takes the form  $(\text{Spec } A) \setminus V(S)$  for some  $S \subseteq A$ , so we write

$$(\text{Spec } A) \setminus V(S) = \{\mathfrak{p} : S \not\subseteq \mathfrak{p}\} = \bigcup_{f \in S} \{\mathfrak{p} : f \notin \mathfrak{p}\} = \bigcup_{f \in S} D(f).$$

Here is our statement.

**Exercise 1.56.** Fix a ring  $A$  and element  $f \in A$ . Letting  $\iota: A \rightarrow A_f$  be the localization map,

$$\text{Spec } \iota: \text{Spec } A_f \rightarrow D(f)$$

is a homeomorphism.

*Proof.* The arguments here are analogous to [Exercise 1.53](#). To be explicit, we will say that our maps are

$$\begin{array}{c} \text{Spec } A_f \cong D(f) \\ \mathfrak{q} \mapsto \iota^{-1}\mathfrak{q} \\ \mathfrak{p}A_f \hookleftarrow \mathfrak{p} \end{array}$$

and reassure the reader that the checks are fairly routine. For example, the inverse checks are done in [Eis95, Proposition 2.2]. ■

**Remark 1.57.** Not every open set is a distinguished open set. For example, taking  $k$  algebraically closed,

$$\mathbb{A}_k^2 \setminus \{(0, 0)\} \subseteq \mathbb{A}_k^2$$

is an open set not in the form  $D(f)$ ; equivalently, we need to show  $V(\{f\}) \neq \{(x, y)\}$  for any  $f \in k[x, y]$ . Intuitively, this is impossible because a curve cuts out a one-dimensional variety of  $\mathbb{A}_k^2$ , not a zero-dimensional point.

Rigorously, we are requiring  $f \in k[x, y]$  to have  $f \in \mathfrak{p}$  if and only if  $\mathfrak{p} = (x, y)$ . However,  $f$  is certainly nonzero and nonconstant, so  $f$  has an irreducible factor  $\pi$ , which means that  $f \in (\pi)$ , where  $(\pi)$  is prime because  $k[x, y]$  is a unique factorization domain.

## 1.3 August 29

Today we talk about the structure sheaf. To review, so far we have defined the spectrum  $\text{Spec } A$  of a ring  $A$  and given it a topology. The goal for today is to define its structure sheaf. Here is a motivating example.

**Example 1.58.** Set  $A := \mathbb{C}[x_1, \dots, x_n]$  so that  $\text{Spec } A = \mathbb{A}_k^n$ . Recall that  $\{D(f)\}_{f \in A}$  is a base for the Zariski topology, and we would like the functions on this ring to be  $A_f$ , the rational polynomials which allow some  $f$  in the denominator. In other words, these are rational functions on  $\mathbb{C}^n$  whose poles are allowed on  $V(\{f\})$  only.

### 1.3.1 Sheaves

Sheaves are largely a topological object, so we will forget that we are interested in the Zariski topology for now. Throughout,  $X$  will be a topological space.

**Notation 1.59.** Given a topological space  $X$ , we let  $\text{Op } X$  denote the poset (category) of its open sets.

Namely, the objects of  $\text{Ob } X$  are open sets, and

$$\text{Mor}(V, U) = \begin{cases} \{*\} & V \subseteq U, \\ \emptyset & \text{else.} \end{cases}$$

Here is our definition.

**Definition 1.60 (Presheaf).** A presheaf  $\mathcal{F}$  on a topological space  $X$  valued in a category  $\mathcal{C}$  is a contravariant functor  $\mathcal{F}: (\text{Op } X)^{\text{op}} \rightarrow \mathcal{C}$ . More concretely,  $\mathcal{F}$  has the following data.

- Given an open set  $U \subseteq X$ , we have  $\mathcal{F}(U) \in \mathcal{C}$ .
- Given open sets  $V \subseteq U \subseteq X$ , we have a restriction map  $\text{res}_{U,V}: \mathcal{F}(U) \rightarrow \mathcal{F}(V)$  in  $\mathcal{C}$ .

This data satisfies the following coherence conditions.

- Identity: given an open set  $U \subseteq X$ ,  $\text{res}_{U,U} = \text{id}_{\mathcal{F}(U)}$ .
- Functoriality: given open sets  $W \subseteq V \subseteq U$ , the following diagram commutes.

$$\begin{array}{ccc} \mathcal{F}(U) & \xrightarrow{\text{res}_{U,V}} & \mathcal{F}(V) \\ & \searrow \text{res}_{U,W} & \downarrow \text{res}_{V,W} \\ & & \mathcal{F}(W) \end{array}$$



**Notation 1.61.** We might call an element  $f \in \mathcal{F}(U)$  a *section over  $U$* .

As suggested by our language and notation, we should think about (pre)sheaves as mostly being “sheaves of functions.” We will see a few examples shortly.

**Notation 1.62.** Given  $f \in \mathcal{F}(U)$ , we might write  $f|_V := \text{res}_{U,V} f$ .

**Remark 1.63.** In principle, one can have any target category  $\mathcal{C}$  for our presheaf. However, we will only work  $\text{Set}$ ,  $\text{Ab}$ ,  $\text{Ring}$ ,  $\text{Mod}_R$  in this class. In particular, we will readily assume that  $\mathcal{C}$  is a concrete category.

Now that we’ve defined an algebraic object, we should discuss its morphisms.

**Definition 1.64 (Presheaf morphism).** Fix a topological space  $X$ . A *presheaf morphism* between  $\mathcal{F}$  and  $\mathcal{G}$  is a natural transformation  $\eta: \mathcal{F} \Rightarrow \mathcal{G}$ . In other words, for each open set  $U \subseteq X$ , we have a morphism  $\eta_U: \mathcal{F}(U) \rightarrow \mathcal{G}(U)$ ; these morphisms make the following diagram commute.

$$\begin{array}{ccc} \mathcal{F}(U) & \xrightarrow{\eta_U} & \mathcal{G}(U) \\ \text{res}_{U,V} \downarrow & & \downarrow \text{res}_{U,V} \\ \mathcal{F}(V) & \xrightarrow{\eta_V} & \mathcal{G}(V) \end{array}$$

We’ve talked about presheaves a lot; where are sheaves?

**Definition 1.65 (Sheaf).** Fix a topological space  $X$ . A presheaf  $\mathcal{F}: (\text{Ob } X)^{\text{op}} \rightarrow \mathcal{C}$  is a *sheaf* if and only if it satisfies the following for any open set  $U \subseteq X$  with an open cover  $\mathcal{U}$ .

- Identity: if  $f_1, f_2 \in \mathcal{F}(U)$  have  $f_1|_V = f_2|_V$  for all  $V \in \mathcal{U}$ , then  $f_1 = f_2$ .
- Glueability: if we have  $f_V \in \mathcal{F}(V)$  for all  $V \in \mathcal{U}$  such that

$$f_{V_1}|_{V_1 \cap V_2} = f_{V_2}|_{V_1 \cap V_2}$$

for all  $V_1, V_2 \in \mathcal{U}$ , then there is  $f \in \mathcal{F}(U)$  such that  $f|_V = f_V$  for all  $V \in \mathcal{U}$ .

Ok, so we’ve defined the sheaf as an algebraic object, so here are its morphisms.

**Definition 1.66 (Sheaf morphism).** A *sheaf morphism* is a morphism of the (underlying) presheaves.

Because there is an identity natural transformation and because the composition of natural transformations is a natural transformation, we see that we have the necessary data for a category  $\text{PreSh}_X$  of presheaves on  $X$  and a category  $\text{Sh}_X$  of sheaves on  $X$ .

As an aside, we note that we can succinctly write the sheaf conditions in an exact sequence.

**Lemma 1.67.** Fix a topological space  $X$  and presheaf  $\mathcal{F}: (\text{Ob } X)^{\text{op}} \rightarrow \mathcal{C}$ , where  $\mathcal{C}$  is an abelian category or  $\text{Grp}$ . Then  $\mathcal{F}$  is a sheaf if and only if the sequence

$$\begin{aligned} 0 \rightarrow \mathcal{F}(U) \rightarrow \prod_{V \in \mathcal{U}} \mathcal{F}(V) &\rightarrow \prod_{V_1, V_2 \in \mathcal{U}} \mathcal{F}(V_1 \cap V_2) \\ f &\mapsto (f|_V)_{V \in \mathcal{U}} \\ (f_V)_{V \in \mathcal{U}} &\mapsto (f_{V_1}|_{V_1 \cap V_2} - f_{V_2}|_{V_1 \cap V_2})_{V_1, V_2} \end{aligned} \tag{1.1}$$

is exact.

*Proof.* In one direction, suppose that  $\mathcal{F}$  is a sheaf, and we will show that (1.1) is exact for any open cover  $\mathcal{U}$  of an open set  $U$ .

- Exact at  $\mathcal{F}(U)$ : suppose  $f_1, f_2 \in \mathcal{F}(U)$  have the same image in  $\prod_{V \in \mathcal{U}} \mathcal{F}(V)$ . This means that

$$f_1|_V = f_2|_V$$

for all  $V \in \mathcal{U}$ , so the identity axiom tells us that  $f_1 = f_2$ .

- Exact at  $\prod_{V \in \mathcal{U}} \mathcal{F}(V)$ : of course any  $f \in \mathcal{F}(U)$  goes to  $(f|_V)_{V \in \mathcal{U}}$ , which goes to

$$f|_{V_1 \cap V_2} - f|_{V_2 \cap V_1 \cap V_2} = f|_{V_1 \cap V_2} - f|_{V_1 \cap V_2} = 0 \in \prod_{V_1, V_2 \in \mathcal{U}} \mathcal{F}(V_1 \cap V_2)$$

and therefore lives in the kernel. Conversely, suppose  $(f_V)_{V \in \mathcal{U}}$  vanishes in  $\prod_{V_1, V_2} \mathcal{F}(V_1 \cap V_2)$ . Rearranging, this means that

$$f_{V_1}|_{V_1 \cap V_2} = f_{V_2}|_{V_1 \cap V_2},$$

so the gluability axiom tells us that we can find  $f \in \mathcal{F}(U)$  such that  $f|_V = f_V$ . This finishes.

Conversely, suppose that  $\mathcal{F}$  makes (1.1) always exact, and we will show that  $\mathcal{F}$  is a sheaf. Fix an open cover  $\mathcal{U}$  of an open set  $U$ .

- Identity: suppose that  $f_1, f_2 \in \mathcal{F}(U)$  have  $f_1|_V = f_2|_V$  for any  $V \in \mathcal{U}$ . This means that  $f_1$  and  $f_2$  have the same image in  $\prod_{V \in \mathcal{U}} \mathcal{F}(V)$ , so the exactness of (1.1) at  $\mathcal{F}(U)$  enforces  $f_1 = f_2$ .
- Gluability: suppose that we have  $f_V \in \mathcal{F}(V)$  for each  $V \in \mathcal{U}$  in such a way that  $f_{V_1}|_{V_1 \cap V_2} = f_{V_2}|_{V_1 \cap V_2}$  for all  $V_1, V_2 \in \mathcal{U}$ . Then the image of  $(f_V)_{V \in \mathcal{U}}$  in  $\prod_{V_1, V_2 \in \mathcal{U}} \mathcal{F}(V_1 \cap V_2)$  is

$$(f_{V_1}|_{V_1 \cap V_2} - f_{V_2}|_{V_1 \cap V_2})_{V_1, V_2} = (0)_{V_1, V_2},$$

so exactness of (1.1) forces there to be  $f \in \mathcal{F}(U)$  such that  $f|_V = f_V$  for each  $V \in \mathcal{U}$ . This finishes. ■

**Remark 1.68.** One might want to continue this left-exact sequence. To see this, we will have to talk about cohomology, which is a task for later in life.

### 1.3.2 Examples of Sheaves

Sheaves of functions will be our key example here. Intuitively, any type of function which can be determined “locally” will form a sheaf; for example, here are continuous functions.

**Remark 1.69.** For most of our examples, the identity axiom is easily satisfied: intuitively, the identity axiom says that two sections are equal if and only if they agree locally. However, gluability is usually the tricky one: it requires us to build a function from local behavior.

**Exercise 1.70.** Fix topological spaces  $X$  and  $Y$ . For each  $U \subseteq X$ , let  $\mathcal{F}(U)$  denote the set of continuous functions  $f: U \rightarrow Y$ , and equip these sets with the natural restriction maps. Then  $\mathcal{F}$  is a sheaf.

*Proof.* To begin, here are the functoriality checks.

- Identity: for any  $f \in \mathcal{F}(U)$ , we have  $f|_U = f$ .
- Functoriality: if  $W \subseteq V \subseteq U$ , any  $f \in \mathcal{F}(U)$  will have  $(f|_V|_W)(w) = f(w) = (f|_W)(w)$  for any  $w \in W$ , so  $f|_V|_W = f|_W$  follows.

Here are sheaf checks. Fix an open cover  $\mathcal{U}$  of an open set  $U \subseteq X$ .

- Identity: suppose  $f_1, f_2 \in \mathcal{F}(U)$  have  $f_1|_V = f_2|_V$  for all  $V \in \mathcal{U}$ . Now, for all  $x \in U$ , we see  $x \in U_x$  for some  $U_x \in \mathcal{U}$ , so

$$f_1(x) = (f_1|_{U_x})(x) = (f_2|_{U_x})(x) = f_2(x),$$

so  $f_1 = f_2$  follows.

- Glueability: suppose we have  $f_V \in \mathcal{F}(V)$  for each  $V \in \mathcal{U}$  such that  $f_{V_1}|_{V_1 \cap V_2} = f_{V_2}|_{V_1 \cap V_2}$  for each  $V_1, V_2 \in \mathcal{U}$ . Now, for each  $x \in U$ , find  $U_x \in \mathcal{U}$  with  $x \in U_x$  and set

$$f(x) := f_{U_x}(x).$$

Note this is well-defined: if  $x \in U_x$  and  $x \in U_{x'}$ , then  $f_{U_x}(x) = f_{U_x}|_{U_x \cap U_{x'}}(x) = f_{U_{x'}}|_{U_x \cap U_{x'}}(x) = f_{U_{x'}}(x)$ . Additionally, we see that, for each  $V \in \mathcal{U}$  and  $x \in V$ , we have

$$f|_V(x) = f(x) = f_V(x)$$

by construction, so we are done.

Lastly, we need to check that  $f$  is continuous. Well, for any open set  $V_0 \subseteq Y$ , we can compute

$$f^{-1}(V_0) = \{x \in U : f(x) \in V_0\} = \bigcup_{V \in \mathcal{U}} \{x \in V : f(x) \in V_0\} = \bigcup_{V \in \mathcal{U}} \{x \in V : f_V(x) \in V_0\} = \bigcup_{V \in \mathcal{U}} f_V^{-1}(V_0),$$

which is open as the arbitrary union of open sets because  $f_V : V \rightarrow Y$  is a continuous function. ■

Another key geometric example going forward will be the following.

**Exercise 1.71.** Set  $X := \mathbb{C}$ . For each open  $U \subseteq X$ , let  $\mathcal{O}_X(U)$  denote the set of holomorphic functions  $U \rightarrow \mathbb{C}$ , and equip these sets with the natural restriction maps. Then  $\mathcal{O}_X$  is a sheaf.

*Proof.* Again, the point here is that being differentiable can be checked locally. Anyway, we note that our presheaf checks are exactly the same as in [Exercise 1.70](#), as is the check of the sheaf identity axiom.

The glueability axiom is also mostly the same. Given an open cover  $\mathcal{U}$  of an open set  $U \subseteq X$ , pick up  $f_V \in \mathcal{F}(V)$  for each  $V \in \mathcal{U}$  such that

$$f_{V_1}|_{V_1 \cap V_2} = f_{V_2}|_{V_1 \cap V_2}.$$

As before, we note that each  $x \in U$  has some  $U_x \in \mathcal{U}$  containing  $x$ , so we may define  $f : U \rightarrow \mathbb{C}$  by  $f(x) := f_{U_x}(x)$ . The arguments of [Exercise 1.70](#) tell us that this function  $f$  is well-defined and has  $f|_V = f_V$  for each  $V \in \mathcal{U}$ .

It remains to check that  $f$  is actually holomorphic. This requires that, for each  $x \in X$ , the limit

$$\lim_{x' \rightarrow x} \frac{f(x) - f(x')}{x - x'}.$$

However, this limit can be computed locally for  $x' \in U_x$  because  $U_x$  contains an open neighborhood around  $x$ . As such, it suffices to show that the limit

$$\lim_{x' \rightarrow x} \frac{f|_{U_x}(x) - f|_{U_x}(x')}{x - x'} = \lim_{x' \rightarrow x} \frac{f_{U_x}(x) - f_{U_x}(x')}{x - x'}$$

exists, which is true because  $f_{U_x} \in \mathcal{F}(U_x)$  is holomorphic. ■

In contrast, sheaves have trouble keeping track of “global” information.

**Example 1.72.** For each  $U \subseteq \mathbb{R}$ , let  $\mathcal{F}(\mathbb{R})$  denote the set of bounded continuous functions  $f : \mathbb{R} \rightarrow \mathbb{R}$ , and equip these sets with the natural restriction maps. Then  $\mathcal{F}$  is not a sheaf: for each open set  $(n-1, n+1)$  for  $n \in \mathbb{N}$ , the function  $f_{(n-1, n+1)} := \text{id}_{(n-1, n+1)}$  is bounded and continuous, but the glued function  $f = \text{id}_{\mathbb{R}}$  is not bounded on all of  $\mathbb{R}$ . (We glued using [Exercise 1.70](#), which does force the definition of  $f$ .)

### 1.3.3 Sheaf on a Base

In light of our sheaf language, we are trying to define a “structure” sheaf  $\mathcal{O}_{\text{Spec } A}$  on  $\text{Spec } A$ , and we wanted to have

$$\mathcal{O}_{\text{Spec } A}(D(f)) = A_f.$$

We aren’t going to be able to specify a presheaf with this data, but we can specify a sheaf. In some sense, the presheaf is unable to build up locally in the way that a sheaf can, so having the data on a base like  $\{D(f)\}_{f \in A}$  need not be sufficient to define the full presheaf.

But as alluded to, we can do this for sheaves. We begin by defining a sheaf on a base.

**Definition 1.73 (Sheaf on a base).** Fix a topological space  $X$  and a base  $\mathcal{B}$  for its topology. Then a *sheaf on a base valued in  $\mathcal{C}$*  is a contravariant functor  $F: \mathcal{B}^{\text{op}} \rightarrow \mathcal{C}$  satisfying the following identity and gluability axioms: for any  $B \in \mathcal{B}$  with a basic cover  $\{B_i\}_{i \in I}$ , we have the following.

- Identity: if we have  $f_1, f_2 \in F(B)$  such that  $f_1|_{B_i} = f_2|_{B_i}$  for all  $B_i$ , then  $f_1 = f_2$ .
- Gluability: if we have  $f_i \in F(B_i)$  for each  $i$  such that  $f_i|_B = f_j|_B$  for each  $B \subseteq B_i \cap B_j$ , then there is  $f \in F(B)$  such that  $f|_{B_i} = f_i$  for each  $i$ .

**Example 1.74.** Given a topological space  $X$  and a base  $\mathcal{B}$ , any sheaf  $\mathcal{F}: (\text{Op } X)^{\text{op}} \rightarrow \mathcal{C}$  “restricts” to a sheaf on a base  $\mathcal{F}_{\mathcal{B}}$  by setting  $\mathcal{F}_{\mathcal{B}}(B) := \mathcal{F}(B)$  for all  $B \in \mathcal{B}$  and reusing the same restriction maps. The identity and gluability axioms follow from their (stronger) sheaf counterparts; checking this amounts to writing down the axioms.

Morphisms are constructed in the obvious way.

**Definition 1.75 (Sheaf on a base morphisms).** Fix a topological space  $X$  and a base  $\mathcal{B}$  for its topology. Then a *morphism* between two sheaves  $F$  and  $G$  on the base  $\mathcal{B}$  is a natural transformation of the (underlying) contravariant functors.

**Example 1.76.** Given a topological space  $X$  and a base  $\mathcal{B}$ , any sheaf morphism  $\eta: \mathcal{F} \rightarrow \mathcal{G}$  restricts in the obvious way to a morphism  $\eta_{\mathcal{B}}: \mathcal{F}_{\mathcal{B}} \rightarrow \mathcal{G}_{\mathcal{B}}$  (namely,  $(\eta_{\mathcal{B}})_B = \eta_B$ ) on the corresponding sheaves on a base. Checking this amounts to saying out loud that the diagram on the left commutes for any  $B' \subseteq B$  because it is the same as the diagram on the right.

$$\begin{array}{ccc} \mathcal{F}_{\mathcal{B}}(B) & \xrightarrow{(\eta_{\mathcal{B}})_B} & \mathcal{G}_{\mathcal{B}}(B) \\ \text{res}_{B, B'} \downarrow & & \downarrow \text{res}_{B, B'} \\ \mathcal{F}_{\mathcal{B}}(B') & \xrightarrow{(\eta_{\mathcal{B}})_{B'}} & \mathcal{G}_{\mathcal{B}}(B') \end{array} \quad \begin{array}{ccc} \mathcal{F}(B) & \xrightarrow{\eta_B} & \mathcal{G}(B) \\ \text{res}_{B, B'} \downarrow & & \downarrow \text{res}_{B, B'} \\ \mathcal{F}(B') & \xrightarrow{\eta_{B'}} & \mathcal{G}(B') \end{array}$$

We are interested in showing that we can build a sheaf from a sheaf on a base uniquely, but it will turn out to be fruitful to spend a moment to discuss how this behaves on morphisms first for the uniqueness part of this statement.

**Lemma 1.77.** Fix a topological space  $X$  with a base  $\mathcal{B}$  for its topology. Given sheaves  $\mathcal{F}$  and  $\mathcal{G}$  on  $X$  with values in  $\mathcal{C}$  and a morphism of the (underlying) sheaves on a base  $\eta_{\mathcal{B}}: \mathcal{F}_{\mathcal{B}} \rightarrow \mathcal{G}_{\mathcal{B}}$ , there is a unique sheaf morphism  $\eta: \mathcal{F} \rightarrow \mathcal{G}$  such that  $(\eta_{\mathcal{B}})_B = \eta_B$  for each  $B \in \mathcal{B}$ .

*Proof.* We show uniqueness before existence.

- Uniqueness: fix any open  $U \subseteq X$ , and we will try to solve for  $\eta_U : \mathcal{F}(U) \rightarrow \mathcal{G}(U)$ . Well, fix a basic open cover  $\mathcal{U}$  of  $U$ ; then, for any  $B \in \mathcal{U}$ , we need the following diagram to commute.

$$\begin{array}{ccc} \mathcal{F}(U) & \xrightarrow{\eta_U} & \mathcal{G}(U) \\ \text{res}_{U,B} \downarrow & & \downarrow \text{res}_{U,B} \\ \mathcal{F}(B) & \xrightarrow{\eta_B = (\eta_B)_B} & \mathcal{G}(B) \end{array}$$

In particular, for any  $f \in \mathcal{F}(U)$ , we need  $\eta_U(f)|_B = (\eta_B)_B(f|_B)$ . Thus,  $\eta_U(f)|_B$  is fully specified by the data provided by  $\eta_B$ , so the identity axiom for  $\mathcal{G}$  forces  $\eta_U(f)$  to be unique.

- Existence: to begin, fix any open  $U \subseteq X$ , and we will define  $\eta_U : \mathcal{F}(U) \rightarrow \mathcal{G}(U)$ . As alluded to above, we let  $\mathcal{U}$  be the set of basis elements which are contained in  $U$  so that  $\mathcal{U}$  is a (large) basic cover of  $U$ .

Then, picking up  $f \in \mathcal{F}(U)$ , we will try to use the gluability axiom by setting  $g_B := (\eta_B)_B(f|_B)$  for each  $B \in \mathcal{U}$ . In particular, for any  $B, B' \in \mathcal{U}$ , any basic  $B_0 \subseteq B \cap B'$  has

$$(g_B|_{B \cap B'})|_{B_0} = g_B|_{B_0} = (\eta_B)_B(f|_B)|_{B_0} = (\eta_B)_{B_0}(f|_{B|_{B_0}}) = \eta_{B_0}(f|_{B_0}) = g_{B_0},$$

which is also  $(g_{B'}|_{B \cap B'})|_{B_0}$  by symmetry, so the identity axiom applied to  $B \cap B'$  implies  $g_B|_{B \cap B'} = g_{B'}|_{B \cap B'}$ . Thus, the gluability axiom applied to  $U$  gives us a unique  $g \in \mathcal{G}(U)$  such that

$$g|_B = (\eta_B)_B(f|_B)$$

for each basic set  $B \subseteq U$ . We define  $\eta_U(f) := g$ .

It remains to show that  $\eta$  does in fact assemble into a sheaf morphism. Fix open sets  $V \subseteq U$ , and we need the following diagram to commute.

$$\begin{array}{ccc} \mathcal{F}(U) & \xrightarrow{\eta_U} & \mathcal{G}(U) \\ \text{res}_{U,V} \downarrow & & \downarrow \text{res}_{U,V} \\ \mathcal{F}(V) & \xrightarrow{\eta_V} & \mathcal{G}(V) \end{array}$$

Well, pick up any  $f \in \mathcal{F}(U)$ . Then, for any basic  $B \subseteq V \subseteq U$ , we see that

$$\eta_U(f)|_B = (\eta_B)_B(f|_B) = (\eta_B)_B(f|_V|_B),$$

so the uniqueness of  $\eta_V(f|_V)$  forces  $\eta_V(f|_V) = \eta_U(f)|_V$ . This finishes. ■

### 1.3.4 Extending a Sheaf on a Base

We dedicate this subsection to the following result, describing how to extend a sheaf on a base to a full sheaf.

**Proposition 1.78.** Fix a topological space  $X$  with a base  $\mathcal{B}$  for its topology. Given a sheaf on a base  $F : \mathcal{B}^{\text{op}} \rightarrow \mathcal{C}$ , there is a sheaf  $\mathcal{F}$  and isomorphism (of sheaves on a base)  $\iota : F \rightarrow \mathcal{F}_{\mathcal{B}}$  satisfying the following universal property: any sheaf  $\mathcal{G}$  with a morphism (of sheaves on a base)  $\varphi : F \rightarrow \mathcal{G}_{\mathcal{B}}$  has a unique sheaf morphism  $\psi : \mathcal{F} \rightarrow \mathcal{G}$  making the following diagram commute.

$$\begin{array}{ccc} F & \xrightarrow{\iota} & \mathcal{F}_{\mathcal{B}} \\ & \searrow \varphi & \downarrow \psi_{\mathcal{B}} \\ & & \mathcal{G}_{\mathcal{B}} \end{array} \tag{1.2}$$

*Proof.* We begin by providing a construction of  $\mathcal{F}$ . For each open set  $U \subseteq X$ , define

$$\mathcal{F}(U) := \varinjlim_{B \subseteq U} F(B) = \left\{ (f_B)_{B \subseteq U} \in \prod_{B \subseteq U} F(B) : f_B|_{B'} = f_{B'} \text{ for each } B' \subseteq B \subseteq U \right\}.$$

(Namely, we are implicitly assuming that our target category has limits.) Observe that, when  $V \subseteq U$ , the natural surjection

$$\prod_{B \subseteq U} \mathcal{F}(B) \rightarrow \prod_{B \subseteq V} \mathcal{F}(B)$$

induces a map  $\mathcal{F}(U) \rightarrow \mathcal{F}(V)$ . Indeed, an element  $(f_B)_{B \subseteq U} \in \mathcal{F}(U)$  gets sent to  $(f_B)_{B \subseteq V}$ , and it is still the case that  $B' \subseteq B \subseteq V$  implies  $f_B|_{B'} = f_{B'}$  because actually  $B' \subseteq B \subseteq U$ . Thus,  $(f_B)_{B \subseteq V} \in \mathcal{F}(V)$ , so we have a well-defined map

$$\text{res}_{U,V} : \mathcal{F}(U) \rightarrow \mathcal{F}(V) \\ (f_B)_{B \subseteq U} \mapsto (f_B)_{B \subseteq V}$$

which will serve as our restrictions. We start by checking that these data assemble into a presheaf.

- When  $U = V$ , we are sending  $(f_B)_{B \subseteq U} \in \mathcal{F}(U)$  to itself, so  $\text{res}_{U,U} = \text{id}_{\mathcal{F}(U)}$ .
- Given  $W \subseteq V \subseteq U$ , the diagram

$$\begin{array}{ccc} \mathcal{F}(U) & \xrightarrow{\text{res}_{U,V}} & \mathcal{F}(V) \\ & \searrow \text{res}_{U,W} & \downarrow \text{res}_{V,W} \\ & & \mathcal{F}(W) \end{array} \quad \begin{array}{ccc} (f_B)_{B \subseteq U} & \longmapsto & (f_B)_{B \subseteq V} \\ & \searrow & \downarrow \\ & & (f_B)_{B \subseteq W} \end{array}$$

commutes, which is our functoriality check.

We now show that these data make a sheaf. Fix an open set  $U \subseteq X$  with an open cover  $\mathcal{U}$ . To help our constructions, given any open subset  $V \subseteq X$ , let  $\mathcal{B}_V$  denote the collection of basis elements  $B$  contained in  $V$ ; notably  $\mathcal{B}_V$  is a basic cover for  $V$ . Then, for any open  $U' \subseteq U$ , we let

$$\mathcal{S}_{U'} := \bigcup_{V \subseteq U} \mathcal{S}_{U' \cap V}.$$

Notably,  $\mathcal{S}_{U'}$  is a basic cover for  $U'$  such that any  $B \in \mathcal{S}_{U'}$  is contained in some element of  $\mathcal{U}$ .

- **Identity:** suppose that  $(f_B)_{B \subseteq U}, (g_B)_{B \subseteq U} \in \mathcal{F}(U)$  restrict to the same element on any  $V \in \mathcal{U}$ . Now, fix any  $B_0 \subseteq U$ , and we will show  $f_{B_0} = g_{B_0}$ .

Now consider  $\mathcal{S}_{B_0}$ : for each  $B' \in \mathcal{S}$ , we can find  $V \in \mathcal{U}$  so that  $B' \subseteq V$ , for which we know

$$(f_B)_{B \subseteq V} = (g_B)_{B \subseteq V}.$$

In particular  $f_{B_0}|_{B'} = f_{B'} = g_{B'} = g_{B_0}|_{B'}$  for any  $B \in \mathcal{S}$ , so the identity axiom for the sheaf on a base  $\mathcal{F}$  forces  $f_{B_0} = g_{B_0}$ .

- **Gluability:** suppose we are given some  $(f_{V,B})_{B \subseteq V} \in \mathcal{F}(V)$  for each  $V \in \mathcal{U}$  such that

$$(f_{V,B})_{B \subseteq V \cap V'} = (f_{V,B})_{B \subseteq V}|_{V \cap V'} = (f_{V',B})_{B \subseteq V}|_{V \cap V'} = (f_{V',B})_{B \subseteq V \cap V'}$$

for any  $V, V' \in \mathcal{U}$ . In other words, for any basic  $B \subseteq V \cap V'$ , we have  $f_{V,B} = f_{V',B}$ .

Now, for any basic  $B_0 \subseteq U$ , we will solve for  $f_{B_0}$ . Using  $\mathcal{S}_{B_0}$ , note that any  $B \in \mathcal{S}_{B_0}$  has some  $V_B \in \mathcal{U}$  such that  $B \subseteq V_B$ , so we will use  $f_{V_B,B}$  at this point. Note that if  $B \subseteq V'_B$  as well, then  $f_{V_B,B} = f_{V'_B,B}$ , so our  $f_{V_B,B}$  is independent of  $V_B$ . Continuing, if we have  $B \subseteq B_1 \cap B_2$ , then

$$f_{V_{B_1}, B_1}|_B = f_{V_{B_1}, B} = f_{V_{B_2}, B} = f_{V_{B_2}, B_2}|_B,$$

so gluability applied to our sheaf  $F$  on a base promises us a unique  $f_{B_0}$  such that  $f_{B_0}|_B = f_{V_B, B}$  for any  $B \in \mathcal{S}_{B_0}$ .

We now need to show that the  $(f_B)_{B \subseteq U}$  assemble into an element of  $\mathcal{F}(U)$ . Namely, if we have  $B'_0 \subseteq B_0$ , we need to show that  $f_{B_0}|_{B'_0} = f_{B'_0}$ . Well, for any  $B \in \mathcal{S}_{B'_0}$ , we compute

$$f_{B_0}|_{B'_0}|_B = f_{B_0}|_B = f_{V_B, B} = f_{B_0}|_B,$$

so the uniqueness of  $f_{B_0}$  gives the equality.

For our next step, we define  $\iota_{B_0} : F(B) \rightarrow \mathcal{F}_B(B_0)$  by

$$\iota_{B_0}(f) := (f|_B)_{B \subseteq B_0}.$$

Here are the checks on  $\iota$ .

- Well-defined: note  $\iota_{B_0}(f)$  is an element of  $\mathcal{F}_B(B_0)$  because  $B' \subseteq B \subseteq B_0$  will have  $f|_B|_{B'} = f|_{B'}$ .
- Natural: if  $B \subseteq B'$ , then note that the diagrams

$$\begin{array}{ccc} F(B_0) & \xrightarrow{\iota_{B_0}} & \mathcal{F}_B(B_0) \\ \text{res}_{B, B'} \downarrow & & \downarrow \text{res}_{B, B'} \\ F(B'_0) & \xrightarrow{\iota_{B'_0}} & \mathcal{F}_B(B'_0) \end{array} \quad \begin{array}{ccc} f & \longmapsto & (f|_B)_{B \subseteq B_0} \\ \downarrow & & \downarrow \\ f|_{B'_0} & \longmapsto & (f|_B)_{B \subseteq B'_0} \end{array}$$

commute, finishing.

- Injective: suppose that  $f, g \in F(B_0)$  have the same image in  $\mathcal{F}_B(B_0)$ . This means that  $(f|_B)_{B \subseteq B_0} = (g|_B)_{B \subseteq B_0}$ , so  $f = f|_{B_0} = g|_{B_0} = g$ , so we are done.
- Surjective: fix some  $(f_B)_{B \subseteq B_0} \in \mathcal{F}_B(B_0)$ . Notably, for any basic  $B_1, B_2 \subseteq B_0$  with some basic  $B \subseteq B_1 \cap B_2$ , we have

$$f_{B_1}|_B = f_B = f_{B_2}|_B,$$

so gluability applied to  $F$  promises  $f \in F(B_0)$  such that  $f|_B = f_B$  for all basic  $B \subseteq B_0$ . So  $\iota_{B_0}(f) = (f_B)_{B \subseteq B_0}$ .

We now begin showing that  $\mathcal{F}$  satisfies the universal property. Fix some sheaf  $\mathcal{G}$  on  $X$  with a morphism  $\varphi : F \rightarrow \mathcal{G}_B$ .

In light of [Lemma 1.77](#), it suffices to show the existence and uniqueness of a morphism  $\psi_B : \mathcal{F}_B \rightarrow \mathcal{G}_B$  on the base  $B$  making (1.2) commute. Namely, the existence of  $\psi_B$  promises a full sheaf morphism  $\psi : \mathcal{F} \rightarrow \mathcal{G}$  extending via [Lemma 1.77](#); for uniqueness, two possible  $\psi, \psi' : \mathcal{F} \rightarrow \mathcal{G}$  with  $\psi_B$  and  $\psi'_B$  both commuting will enforce  $\psi_B = \psi'_B$  and then  $\psi = \psi'$  by the uniqueness of [Lemma 1.77](#).

Continuing with the proof, we note that the fact that  $\iota$  is an isomorphism means that the commutativity of (1.2) is equivalent to the diagram

$$\begin{array}{ccc} F & \xleftarrow{\iota^{-1}} & \mathcal{F}_B \\ & \searrow \varphi & \downarrow \psi_B \\ & & \mathcal{G}_B \end{array}$$

commuting. However, the commutativity of this diagram is equivalent to setting  $\psi_B := \varphi \circ \iota^{-1}$ . Thus, uniqueness of  $\psi_B$  is immediate, and existence of  $\psi_B$  amounts to noting the composition of natural transformations remains a natural transformation. ■

**Remark 1.79.** One can also define  $\mathcal{F}(U)$  as compatible systems of stalks, but we have not defined stalks yet.

**Remark 1.80.** The universal property implies that the pair  $(\mathcal{F}, \iota)$  is unique up to unique isomorphism, for a suitable notion of unique isomorphism. Namely, the usual abstract nonsense arguments with universal properties is able to show that if we have another sheaf  $\mathcal{F}'$  with isomorphism  $\iota': F \rightarrow \mathcal{F}'_{\mathcal{B}}$  satisfying the universal property, then  $\mathcal{F}$  and  $\mathcal{F}'$  are isomorphic. (This isomorphism  $\eta: \mathcal{F} \cong \mathcal{F}'$  is unique if we ask for the corresponding diagram

$$\begin{array}{ccc} F & \xrightarrow{\iota} & \mathcal{F}_{\mathcal{B}} \\ & \searrow \iota' & \downarrow \eta_{\mathcal{B}} \\ & & \mathcal{F}'_{\mathcal{B}} \end{array}$$

to commute.)

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We finish defining the structure sheaf  $\mathcal{O}_{\text{Spec } A}$  of an affine scheme today.

**Remark 1.81.** One complaint about sheaves on a base is that we have to choose a base. To be more canonical, we will discuss stalks today, which treats all points the same.

### 1.4.1 The Structure Sheaf

We are now ready to define the structure sheaf  $\mathcal{O}_{\text{Spec } A}$  of a ring  $A$ , which we will define a sheaf on a base. Recall from [Remark 1.55](#) that  $\{D(f)\}_{f \in A}$  forms a base of the Zariski topology of  $\text{Spec } A$ , so it will suffice to set

$$\mathcal{O}_{\text{Spec } A}(D(f)) := A_{S(D(f))},$$

where

$$S(D(f)) := \{g \in A : V(\{g\}) \subseteq (\text{Spec } A) \setminus D(f)\}.$$

In other words,  $S(D(f))$  consists of the set of functions in  $A$  which only vanish outside  $D(f)$  so that we can invert them on  $D(f)$ .

**Remark 1.82.** In essence,  $\mathcal{O}_{\text{Spec } A}(D(f))$  is supposed to be the functions on  $D(f)$ , which is why we want to be able to invert functions which only vanish on  $(\text{Spec } A) \setminus D(f)$ .

**Remark 1.83.** The subset  $S(D(f))$  only depends on  $D(f)$ , not  $f$ , so  $\mathcal{O}_{\text{Spec } A}(D(f))$  is well-defined. With that said, we note that  $f \in S(D(f))$  gives a natural localization map  $A_f \rightarrow A_{S(D(f))}$  induced by  $\text{id}_A$ . Similarly, any  $g \in S(D(f))$  has  $V((g)) \subseteq V((f))$  and so [Proposition 1.45](#) tells us that

$$\text{rad}(f) = I(V((f))) \subseteq I(V((g))) = \text{rad}(g),$$

so  $f \in \text{rad}(g)$ , so  $f^n = ag$  for some positive integer  $n$  and  $a \in A$ ; this means  $g \in A_f^\times$ , so actually  $S(D(f)) \subseteq A_f^\times$ , allowing another natural localization map  $A_{S(D(f))} \rightarrow A_f$  induced by  $\text{id}_A$ . These natural localization maps are inverse (their compositions are induced by  $\text{id}_A$ ), so  $\mathcal{O}_{\text{Spec } A}(D(f)) \cong A_f$ .

**Remark 1.84 (Nir).** In class, Professor Tang defined the structure sheaf on a base by  $\mathcal{O}_{\text{Spec } A}(D(f)) := A_f$ . I have chosen to follow [Vak17] here because I don't like  $\mathcal{O}_{\text{Spec } A}(D(f))$  to depend on  $f \in A$  when it should only depend on  $D(f)$ .



To define our (pre)sheaf on a base, we also need to provide restriction maps. Well, for  $f, f' \in A$  with  $D(f') \subseteq D(f)$ , we see that

$$S(D(f)) = \{g \in A : V(\{g\}) \subseteq (\operatorname{Spec} A) \setminus D(f)\} \subseteq \{g \in A : V(\{g\}) \subseteq (\operatorname{Spec} A) \setminus D(f')\} = S(D(f')),$$

so there is a natural localization map

$$\operatorname{res}_{D(f), D(f')} : A_{S(D(f))} \rightarrow A_{S(D(f'))}$$

induced by  $\operatorname{id}_A$ . These data give all the data we need to define a sheaf on a base. We will throw the remaining checks into the following lemma.

**Lemma 1.85.** Fix a ring  $A$ . The above data define a sheaf  $\mathcal{O}_{\operatorname{Spec} A}$  on the base  $\{D(f)\}_{f \in A}$ .

*Proof.* We begin by showing that the data gives a presheaf.

- Identity: if  $D(f) = D(f')$ , then  $S(D(f)) = S(D(f'))$ , so the localization map

$$\operatorname{res}_{D(f), D(f)} : A_{S(D(f))} \rightarrow A_{S(D(f))}$$

is simply  $\operatorname{id}_{A_{S(D(f))}}$ .

- Functoriality: suppose  $D(f'') \subseteq D(f') \subseteq D(f)$ . Then we note that the diagram

$$\begin{array}{ccc} A_{S(D(f))} & \xrightarrow{\operatorname{res}} & A_{S(D(f'))} \\ & \searrow \operatorname{res} & \downarrow \operatorname{res} \\ & & A_{S(D(f''))} \end{array} \quad \begin{array}{ccc} a/g & \longmapsto & a/g \\ & \searrow & \downarrow \\ & & a/g \end{array}$$

commutes because everything is induced by  $\operatorname{id}_A$ , so we are done.

It remains to check the identity and gluability axioms. For this, we will need a basis set  $D(f)$  and a basic cover  $\{D(f_\alpha)\}_{\alpha \in \lambda}$ . To access this cover, we have the following lemma.

**Lemma 1.86.** Fix a ring  $A$ . Then, given  $f \in A$  and  $\{f_\alpha\}_{\alpha \in \lambda} \subseteq A$ , the following are equivalent.

- (a)  $D(f) \subseteq \bigcup_{\alpha \in \lambda} D(f_\alpha)$ .
- (b)  $f \in \operatorname{rad}(f_\alpha)_{\alpha \in \lambda}$ .

*Proof.* Note that

$$\bigcup_{\alpha \in \lambda} D(f_\alpha) = \operatorname{Spec} A \setminus \bigcap_{\alpha \in \lambda} V((f_\alpha)) = \operatorname{Spec} A \setminus V((f_\alpha)_{\alpha \in \lambda}),$$

so (a) is equivalent to  $V((f_\alpha)_{\alpha \in \lambda}) \subseteq V((f))$ . Now, [Proposition 1.45](#) tells us that (a) implies

$$\operatorname{rad}(f) = I(V((f))) \subseteq I(V((f_\alpha)_{\alpha \in \lambda})) = \operatorname{rad}(f_\alpha)_{\alpha \in \lambda},$$

from which (b) follows. Conversely, if (b) holds, then  $\operatorname{rad}(f) \subseteq \operatorname{rad}(f_\alpha)_{\alpha \in \lambda}$  by taking radicals, so [Proposition 1.45](#) again promises

$$V((f_\alpha)_{\alpha \in \lambda}) = V(\operatorname{rad}(f_\alpha)_{\alpha \in \lambda}) \subseteq V(\operatorname{rad}(f)) = V((f)),$$

which we showed is equivalent to (a). ■

**Corollary 1.87.** Fix a ring  $A$ . Then any cover  $\{D(f_\alpha)\}_{\alpha \in \lambda}$  of  $D(f)$  has a finite subcover.

*Proof.* Note Lemma 1.86 tells us that  $f \in \text{rad}(f_\alpha)_{\alpha \in \lambda}$ , so there is a positive integer  $n$  and finite subset  $\lambda' \subseteq \lambda$  so that

$$f^n = \sum_{\alpha \in \lambda'} a_\alpha f_\alpha,$$

but then  $f \in \text{rad}(f_\alpha)_{\alpha \in \lambda'}$ , so  $D(f)$  is covered by the (finite) cover  $\{D(f_\alpha)\}_{\alpha \in \lambda'}$ .  $\blacksquare$

We now show the identity and gluability axioms separately.

- Identity: note Corollary 1.87 promises us some  $\lambda' \subseteq \lambda$  such that the  $\{D(f_\alpha)\}_{\alpha \in \lambda'}$  still covers  $D(f)$ . We will now forget about  $\lambda$  entirely and deal with the finite  $\lambda'$  instead.

For identity, we suppose that we have  $s \in \mathcal{O}_{\text{Spec } A}(D(f))$  such that  $s|_{D(f_\alpha)} = 0$  for all  $\alpha \in \lambda'$ , and we want to show that  $s = 0$ . Under the (canonical) isomorphism  $\mathcal{O}_{\text{Spec } A}(D(f_\alpha)) \simeq A_{f_\alpha}$ , we see that we must have

$$f_\alpha^{d_\alpha} s = 0$$

for some  $d_\alpha$ , for each  $\alpha$ . Now,  $D(f_\alpha) = D(f_\alpha^{d_\alpha})$ , so the  $D(f_\alpha^{d_\alpha})$  still cover  $D(f)$ ; it follows from Lemma 1.86 that there is some  $d$  for which

$$f^d = \sum_{\alpha \in \lambda'} c_\alpha f_\alpha^{d_\alpha}.$$

Multiplying both sides by  $s$  (after embedding in  $A_{S(D(f))}$ ) tells us that  $f^d s = 0$  in  $A_{S(D(f))}$ , so  $s = 0$  because  $f \in A_{S(D(f))}^\times$ .

- Finite gluability: fix sections  $s_\alpha \in \mathcal{O}_{\text{Spec } A}(D(f_\alpha))$  such that

$$s_\alpha|_{D(f_\alpha) \cap D(f_\beta)} = s_\beta|_{D(f_\alpha) \cap D(f_\beta)}.$$

For concreteness, use  $\mathcal{O}_{\text{Spec } A}(D(f)) \simeq A_f$  to write  $s_\alpha := a_\alpha / f_\alpha^n$ , where  $n$  is the maximum of all the possibly needed denominators.

Noting that  $D(f_\alpha) \cap D(f_\beta) = D(f_\alpha f_\beta)$ , our coherence is equivalent to asking for

$$(f_\alpha f_\beta)^m (f_\beta^n a_\alpha - f_\alpha^n a_\beta) = 0,$$

where again  $m$  is chosen to be large enough among the finitely many possibilities for  $\alpha$  and  $\beta$ . We now notice that

$$s_\alpha = \frac{a_\alpha}{f_\alpha^n} = \frac{f_\alpha^m a_\alpha}{f_\alpha^{n+m}},$$

so we set  $b_\alpha := f_\alpha^m a_\alpha$  and  $g_\alpha := f_\alpha^{n+m}$ , which means

$$g_\beta b_\alpha = g_\alpha b_\beta$$

for all  $\alpha, \beta$ . Notably,  $\text{rad}(f_\alpha) = \text{rad}(g_\alpha)$ , so  $D(f_\alpha) = D(g_\alpha)$ , so the  $\{D(g_\alpha)\}_{\alpha \in \lambda}$  still cover  $D(f)$ , so Lemma 1.86 tells us that we can write

$$f^n = \sum_{\alpha \in \lambda} c_\alpha g_\alpha$$

for some positive integer  $n$ . In particular, we set  $s \in \mathcal{O}_{\text{Spec } A}(D(f)) \simeq A_f$  by

$$s := \frac{1}{f^n} \sum_{\alpha \in \lambda} c_\alpha b_\alpha.$$

In particular, for any  $\beta \in \lambda$ , we see

$$g_\beta s = \frac{1}{f^n} \sum_{\alpha \in \lambda} c_\alpha g_\beta b_\alpha = \frac{1}{f^n} \sum_{\alpha \in \lambda} c_\alpha g_\alpha b_\beta = b_\beta$$

in  $A_f$ , so our restriction is  $s|_{D(g_\beta)} = b_\beta / g_\beta = s_\beta$ , which is what we wanted.

- Gluability: we show general gluability from finite gluability. Fix sections  $s_\alpha \in \mathcal{O}_{\text{Spec } A}(D(f_\alpha))$  such that

$$s_\alpha|_{D(f_\alpha) \cap D(f_\beta)} = s_\beta|_{D(f_\alpha) \cap D(f_\beta)} \quad (1.3)$$

for each  $\alpha, \beta \in \lambda$ . Using [Corollary 1.87](#), we can find a finite subcover using  $\lambda' \subseteq \lambda$ , and the sections  $\{s_\alpha\}_{\alpha \in \lambda'}$  still satisfy (1.3), so finite gluability (and identity!) gives a unique  $s \in \mathcal{O}_{\text{Spec } A}(D(f))$  with

$$s|_{D(f_\alpha)} = s_\alpha.$$

We claim that actually  $s|_{D(f_\alpha)} = s_\alpha$  for all  $\alpha \in \lambda$ . Well, for any  $\beta \in \lambda$ , apply finite gluability to  $\lambda' \cup \{\beta\}$  to find  $s' \in \mathcal{O}_{\text{Spec } A}(D(f))$  such that  $s'|_{D(f_\alpha)} = s_\alpha$  for all  $\alpha \in \lambda' \cup \{\beta\}$ .

It follows from the identity axiom that on the open cover  $\{D(f_\alpha)\}_{\alpha \in \lambda'}$  that  $s = s'$ , so we conclude

$$s|_{D(f_\beta)} = s'|_{D(f_\beta)} = s_\beta$$

for any  $\beta \in \lambda$ . ■

Having finished the last of our checks, we see that our data make a sheaf on a base, so [Proposition 1.78](#) promises a unique sheaf extending this sheaf on a base. This is the (affine) structure sheaf, and it finishes our definition of an affine scheme.

**Definition 1.88 (Affine scheme).** Fix a ring  $A$ . An *affine scheme* is the topological space  $\text{Spec } A$  (given the Zariski topology) together with the sheaf of rings  $\mathcal{O}_{\text{Spec } A}$  such that

$$\mathcal{O}_{\text{Spec } A}(D(f)) = A_{S(D(f))}$$

for each  $f \in A$ ; here  $S(D(f)) = \{g \in A : D(f) \subseteq D(g)\}$ .

Note that we are somewhat sloppily identifying the outputs of the structure sheaf with its outputs on the base.

## 1.4.2 Stalks

To define a morphism of schemes, we will want to discuss stalks.

**Remark 1.89.** We might expect a morphism of (affine) schemes to be merely a continuous map together with a natural transformation of the structure sheaves (perhaps with some coherence conditions). However, this will not be enough data. Namely, we want all of our morphisms of affine schemes to be induced by ring homomorphisms, and this will require exploiting a little more data.

The extra data in those morphisms will come from stalks.

**Definition 1.90 (Stalk).** Fix a presheaf  $\mathcal{F}$  on a topological space  $X$ . For a point  $p \in X$ , we define the *stalk of  $\mathcal{F}$  at  $p$*  to be the direct limit

$$\mathcal{F}_p := \varinjlim_{U \ni p} \mathcal{F}(U).$$

Concretely, elements of  $\mathcal{F}_p$  are ordered pairs  $(U, s)$  where  $s \in \mathcal{F}(U)$  with  $p \in U$ , modded out by an equivalence relation  $\sim$ ; here,  $(U, s) \sim (U', s')$  if and only if there is  $W \subseteq U \cap U'$  such that  $s|_W = s'|_W$ .

**Remark 1.91 (Nir).** In some sense, the stalk is intended to encode “local information” at the point  $p \in X$  in a particularly violent way: whenever two functions  $s_1 \in \mathcal{F}(U_1)$  and  $s_2 \in \mathcal{F}(U_2)$  (where  $p \in U_1 \cap U_2$ ) are equal locally on some open set  $U$  containing  $p$ , then we identify  $s_1$  and  $s_2$ . As such,  $\mathcal{F}_p$  can really study functions locally at  $p$ .

**Remark 1.92.** We go ahead and check that  $\sim$  forms an equivalence relation. Fix  $(U_i, s_i)$  with  $s_i \in \mathcal{F}(U_i)$  for  $i \in \{1, 2, 3\}$ .

- **Reflexive:** note  $U_1 \subseteq U_1$  and  $s_1|_{U_1} = s_1 = s_1|_{U_1}$ , so  $(U_1, s_1) \sim (U_1, s_1)$ .
- **Symmetry:** if  $(U_1, s_1) \sim (U_2, s_2)$ , we can find an open  $V \subseteq U_1 \cap U_2$  with  $s_1|_V = s_2|_V$ , which implies  $s_2|_V = s_1|_V$ , so  $(U_2, s_2) \sim (U_1, s_1)$ .
- **Transitive:** if  $(U_1, s_1) \sim (U_2, s_2)$  and  $(U_2, s_2) \sim (U_3, s_3)$ , we can find open  $V_1 \subseteq U_1 \cap U_2$  and  $V_2 \subseteq U_2 \cap U_3$  such that  $s_1|_{V_1} = s_2|_{V_1}$  and  $s_2|_{V_2} = s_3|_{V_2}$ . Then  $V_1 \cap V_2 \subseteq U_1 \cap U_3$ , and we can see

$$s_1|_{V_1 \cap V_2} = s_1|_{V_1}|_{V_1 \cap V_2} = s_2|_{V_1}|_{V_1 \cap V_2} = s_2|_{V_1 \cap V_2} = s_2|_{V_2}|_{V_1 \cap V_2} = s_3|_{V_2}|_{V_1 \cap V_2} = s_3|_{V_1 \cap V_2}.$$

**Definition 1.93 (Germ).** Fix a presheaf  $\mathcal{F}$  on a topological space  $X$ . For a point  $p \in X$  and section  $s \in \mathcal{F}(U)$  with  $p \in U$ , the *germ of  $s$  at  $p$*  is the element

$$[(U, s)] \in \mathcal{F}_p.$$

**Notation 1.94.** I will write the germ of  $f \in \mathcal{F}(U)$  at  $p \in U$  as  $f|_p$ . This notation is not standard, but I like it because I think of taking the germ of a section at  $p$  as analogous to “restricting” to the point  $p$ .

As a warning, later on, we will want to consider tuples of sections  $(f_p)_p$ , and we will want to distinguish the notation for an element of this tuple as  $f_p$  with the notation for the corresponding germ  $f|_p$ .

**Remark 1.95.** As justification for my notation, if  $f \in \mathcal{F}(U)$  while  $p \in V \subseteq U$ , then

$$f|_p = f|_V|_p$$

because  $[(U, f)] = [(V, f|_V)]$  can be witnessed by  $f|_V = f|_V|_V$ .

Here are some examples of stalks.

**Lemma 1.96.** Fix a presheaf  $\mathcal{F}$  on a topological space  $X$ , and give the topology on  $X$  a base  $\mathcal{B}$ . For a point  $p \in X$ , we have the isomorphism

$$\begin{aligned} \varphi: \varinjlim_{B \ni p} \mathcal{F}(B) &\simeq \mathcal{F}_p \\ [(B, s)] &\mapsto [(B, s)] \end{aligned}$$

where the colimit is taken over  $B \in \mathcal{B}$  such that  $p \in B$ .

*Proof.* The main point to show that  $\varphi$  is well-defined is that the system of maps  $\mathcal{F}(B) \rightarrow \mathcal{F}_p$  for each  $B \in \mathcal{B}$  containing  $p$  induce the map  $\varphi$  by the universal property. Concretely, if  $(B_1, s_1) \sim (B_2, s_2)$ , then we can find  $B \subseteq B_1 \cap B_2$  such that  $s_1|_B = s_2|_B$ , which means that  $[(B_1, s_1)] = [(B_2, s_2)]$  in  $\varinjlim_{B \ni p} \mathcal{F}(B)$  implies the equality in  $\mathcal{F}_p$ . Now, any structure that  $\varphi$  needs to preserve (e.g., being a homomorphism of some kind) will be immediately preserved.

We now exhibit the map in the reverse direction. Note that any  $U \subseteq X$  containing  $p$  can find some basis element  $B \in \mathcal{B}$  such that  $p \in B \subseteq U$ . As such, we define  $\psi: \mathcal{F}_p \rightarrow \varinjlim_{B \ni p} \mathcal{F}(B)$  by

$$\psi: [(U, s)] \mapsto [(B, s|_B)].$$

To show that this map is well-defined, first note that  $\psi$  does not depend on  $B$ : if we have basis sets  $B_1$  and  $B_2$  inside  $U$  containing  $p$ , we can find basis sets  $B \subseteq B_1 \cap B_2$  giving  $s|_{B_1}|_B = s|_B = s|_{B_2}|_B$ , so

$$[(B_1, s|_{B_1})] = [(B_2, s|_{B_2})].$$

Second, note that  $\psi$  does not depend on the representative of  $[(U, s)]$ . Indeed, if  $(U_1, s_1) \sim (U_2, s_2)$ , then we are promised  $U \subseteq U_1 \cap U_2$  such that  $s_1|_U = s_2|_U$ . Now, find  $B$  contained in  $U$  containing  $p$ , so we see  $s_1|_B = s_2|_B$ , so

$$[(B, s_1|_B)] = [(B, s_2|_B)].$$

So we have a well-defined map  $\psi$ .

We now show that  $\psi$  and  $\varphi$  are inverse. In one direction, given some  $[(B, s)]$ , we note we can write

$$\psi(\varphi([(B, s)])) = \psi([(B, s)]) = [(B, s)],$$

where the last equality is legal because  $B$  is a basis set containing  $p$  which is contained in  $B$ . In the other direction, given some  $[(U, s)]$ , find a basis set  $B \subseteq U$  containing  $p$  so that

$$\varphi(\psi([(U, s)])) = \varphi([(B, s|_B)]) = [(B, s|_B)],$$

and we note that  $[(B, s|_B)] = [(U, s)]$  because  $B \subseteq U$  has  $s|_B|_B = s|_B$ . ■

**Lemma 1.97.** Fix a ring  $A$ . Then, for any prime  $\mathfrak{p}$ ,  $A_{\mathfrak{p}} \simeq \mathcal{O}_{\text{Spec } A, \mathfrak{p}}$  induced by  $a \mapsto a|_{\mathfrak{p}}$ .

*Proof.* The point here is that  $\mathcal{O}_{\text{Spec } A, \mathfrak{p}}$  permits denominators from anyone in  $A \setminus \mathfrak{p}$ . In one direction, note that  $A = \mathcal{O}_{\text{Spec } A}(\text{Spec } A)$ , so there is a canonical map

$$\begin{array}{ccc} \mathcal{O}_{\text{Spec } A}(\text{Spec } A) & \rightarrow & \mathcal{O}_{\text{Spec } A, \mathfrak{p}} \\ s & \mapsto & s|_{\mathfrak{p}} \end{array}$$

because  $\mathfrak{p} \in \text{Spec } A$ . Call this map  $\varphi$ . Note, for any  $f \in A \setminus \mathfrak{p}$ , we see that  $\mathfrak{p} \in D(f)$ , so the canonical map

$$\mathcal{O}_{\text{Spec } A}(D(f)) \rightarrow \mathcal{O}_{\text{Spec } A, \mathfrak{p}}$$

permits us to write

$$[(\text{Spec } A, f)] \cdot [(D(f), 1/f)] = [(D(f), f)] \cdot [(D(f), 1/f)] = [(D(f), 1)]$$

is the unit element of  $\mathcal{O}_{\text{Spec } A, \mathfrak{p}}$ . Thus,  $\varphi(f) \in \mathcal{O}_{\text{Spec } A, \mathfrak{p}}^\times$  for each  $f \in A \setminus \mathfrak{p}$ , so  $\varphi$  induces a natural map  $\varphi: A_{\mathfrak{p}} \rightarrow \mathcal{O}_{\text{Spec } A, \mathfrak{p}}$  sending  $a/f$  to  $[(D(f), a/f)]$ .

In the other direction, we can directly pick up any  $[(D(f), a/f^n)] \in \mathcal{O}_{\text{Spec } A, \mathfrak{p}}$ , where we are thinking about the colimit as happening over the distinguished base according to Lemma 1.96. Now,  $\mathfrak{p} \in D(f)$  is equivalent to  $f \notin \mathfrak{p}$ , so  $f \in A_{\mathfrak{p}}^\times$ , so we can define  $\psi: \mathcal{O}_{\text{Spec } A, \mathfrak{p}} \rightarrow A_{\mathfrak{p}}$  by

$$\psi: [(D(f), a/f^n)] \mapsto a/f^n.$$

To see that  $\psi$  is well-defined, note  $(D(f_1), a_1/f_1^{n_1}) \sim (D(f_2), a_2/f_2^{n_2})$  means we can find  $D(f) \subseteq D(f_1) \cap D(f_2)$  containing  $\mathfrak{p}$  with

$$f^n (f_2^{n_2} a_1 - f_1^{n_1} a_2) = 0$$

in  $A$ . Rearranging, it follows that  $a_1/f_1^{n_1} = a_2/f_2^{n_2}$  in  $A_{\mathfrak{p}}$ .

We won't bother checking that  $\psi$  is a ring map; just look at it. However, we will check that  $\psi$  and  $\varphi$  are inverses (which tells us that  $\psi$  is a ring map automatically). Well, given  $a/f \in A_{\mathfrak{p}}$ , we see

$$\psi(\varphi(a/f)) = \psi([(D(f), a/f)]) = a/f.$$

On the other hand, given  $[(D(f), a/f^n)] \in \mathcal{O}_{\text{Spec } A, \mathfrak{p}}$ , write

$$\varphi(\psi([(D(f), a/f^n)])) = \varphi(a/f^n) = [(D(f^n), a/f^n)] = [(D(f), a/f)],$$

where the last equality holds because  $D(f^n) = (\text{Spec } A) \setminus V((f^n)) = (\text{Spec } A) \setminus V(\text{rad}(f^n)) = (\text{Spec } A) \setminus V((f)) = D(f)$ . ■

**Remark 1.98.** Notably,  $\mathcal{O}_{\text{Spec } A, \mathfrak{p}}$  is always a local ring, and the maximal ideal  $\mathfrak{p}A_{\mathfrak{p}}$  corresponds to germs  $[(D(f), a/f)]$  such that  $a/f \in \mathfrak{p}A_{\mathfrak{p}}$ , or equivalently, such that  $a \in \mathfrak{p}$ . Namely, the maximal ideal consists of our germs which vanish at  $\mathfrak{p}$ .

**Example 1.99.** Continuing from [Exercise 1.71](#), set  $X := \mathbb{C}$  and  $\mathcal{O}_X$  to be the sheaf of holomorphic functions. Then, for any  $z_0 \in X$ , we have

$$\mathcal{O}_{X, z_0} = \left\{ \sum_{n=0}^{\infty} a_n (z - z_0)^n \text{ with positive radius of convergence} \right\}.$$

Indeed, any germ  $[(U, f)]$  with  $f$  holomorphic actually has  $f$  analytic, so  $f$  is equal to a (unique) power series of the given form in some small enough neighborhood. And of course, each power series with positive radius of convergence gives rise to a germ.

**Remark 1.100** (Nir). As in [Remark 1.98](#), we note that  $\mathcal{O}_{X, z_0}$  is a local ring with maximal ideal

$$\mathfrak{m}_{X, z_0} = \left\{ \sum_{n=1}^{\infty} a_n (z - z_0)^n \text{ with positive radius of convergence} \right\}.$$

Of course  $\mathfrak{m}_{X, z_0} \subseteq \mathcal{O}_{X, z_0}$  is an ideal. Conversely, one can see that any germ  $[(f, U)]$  with  $f(z_0) \neq 0$  is nonzero in some neighborhood around  $z_0$  (by continuity) and therefore is invertible in  $\mathcal{O}_{X, z_0}$ , so  $\mathcal{O}_{X, z_0} \setminus \mathfrak{m}_{X, z_0} = \mathcal{O}_{X, z_0}^{\times}$ .

### 1.4.3 Stalk Memory

Here is why we care about stalks.



**Idea 1.101.** Stalks remember everything about a sheaf.

Again, the reason why we expect [Idea 1.101](#) to be true is that the stalk is able to remember local information, so having all the local information should be able to recover the original sheaf. Here is a rigorization.

**Proposition 1.102.** Fix a sheaf  $\mathcal{F}$  and a presheaf  $\mathcal{G}$  on  $X$ . Also, fix an open subset  $U \subseteq X$ .

(a) The natural embedding

$$\begin{aligned} \iota: \mathcal{F}(U) &\rightarrow \prod_{p \in U} \mathcal{F}_p \\ f &\mapsto (f|_p)_{p \in U} \end{aligned}$$

is injective.

(b) A tuple  $(f_p)_{p \in U} \in \prod_{p \in U} \mathcal{F}_p$  is in  $\text{im } \iota$  if and only if, for each  $p \in U$ , there is an open set  $U_p$  containing  $p$  such that we can find  $\tilde{f}_p \in \mathcal{F}(U_p)$  such that all  $q \in U_p$  have  $f_q = \tilde{f}_p|_q$ .

**Remark 1.103.** Intuitively, part (b) is saying that all stalks in a small neighborhood come from a single section.

*Proof.* Here we go.

- (a) We use the identity axiom on  $\mathcal{F}$ . Suppose that  $f, g \in \mathcal{F}(U)$  have  $f|_p = g|_p$  for all  $p \in U$ . Thus, for each  $p \in U$ , we can find  $U_p \subseteq U$  containing  $p$  such that  $f|_{U_p} = g|_{U_p}$ .

Now,  $U \subseteq \bigcup_{p \in U} U_p \subseteq U$ , so  $\{U_p\}_{p \in U}$  is an open cover for  $U$ , so the identity axiom on  $\mathcal{F}$  forces  $f = g$ .

- (b) We use the gluability axiom on  $\mathcal{F}$ . In one direction, suppose  $\iota(f) = (f_p)_{p \in U}$  so that  $f|_p = f_p$  for each  $p \in U$ . This means that, for each  $p \in U$ , we can set  $U_p := U$  and  $\tilde{f}_p := f \in \mathcal{F}(U_p)$  so that any  $q \in U_p$  have

$$f_q = f|_q = \tilde{f}_p|_q.$$

In the other direction, suppose we have germs  $(f_p)_{p \in U} \in \prod_{p \in U} \mathcal{F}_p$  such that any  $p \in U$  has an open set  $U_p$  and a section  $\tilde{f}_p \in \mathcal{F}(U_p)$  such that  $f_q = \tilde{f}_p|_q$  for any  $q \in U_p$ . We claim that

$$\tilde{f}_p|_{U_p \cap U_q} \stackrel{?}{=} \tilde{f}_q|_{U_p \cap U_q}. \quad (1.4)$$

Well, for any  $r \in U_p \cap U_q$ , we know that  $\tilde{f}_p|_{U_p \cap U_q}|_r = f_r = \tilde{f}_q|_{U_p \cap U_q}|_r$ , so there is an open set  $V_r \subseteq U_p \cap U_q$  containing  $r$  such that

$$\tilde{f}_p|_{U_p \cap U_q}|_{V_r} = \tilde{f}_q|_{U_p \cap U_q}|_{V_r}.$$

Now, applying the identity axiom of  $\mathcal{F}$  on the open cover  $\{V_r\}_{r \in U_p \cap U_q}$  forces (1.4). Thus, the gluability axioms grants  $f \in \mathcal{F}(U)$  such that  $f|_{U_p} = \tilde{f}_p$  for each  $p \in U$ , so it follows that

$$f|_p = f|_{U_p}|_p = \tilde{f}_p$$

for each  $p \in U$ . ■

We are going to want a name for the condition in [Proposition 1.102](#) (b).

**Definition 1.104 (Compatible germ).** Fix a sheaf  $\mathcal{F}$  on a topological space  $X$ . Then, given a subset  $U \subseteq X$ , a *system of compatible germs* is a tuple  $(f_p)_{p \in U}$  such that, for each  $p \in U$ , there is an open set  $U_p$  containing  $p$  with a lift  $\tilde{f}_p \in \mathcal{F}(U_p)$  such that all  $q \in U_p$  have  $f_q = \tilde{f}_p|_q$ .

In addition to sections, stalks also remember morphisms.

**Proposition 1.105.** Fix presheaves  $\mathcal{F}$  and  $\mathcal{G}$  on a topological space  $X$  with a morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$ .

- (a) For any  $p \in X$ , there is a natural map  $\varphi_p: \mathcal{F}_p \rightarrow \mathcal{G}_p$ .
- (b) Suppose  $\mathcal{G}$  is a sheaf. Given presheaf morphisms  $\varphi, \varphi': \mathcal{F} \rightarrow \mathcal{G}$  such that  $\varphi_p = \varphi'_p$  for all  $p \in X$ , we have  $\varphi = \varphi'$ .

*Proof.* We go in sequence.

- (a) It is possible to induce this map from abstract nonsense. Alternatively, we can write this explicitly as being induced by

$$\varphi_p: [(U, s)] \mapsto [(U, \varphi_U(s))].$$

To see that  $\varphi_p$  is well-defined, suppose  $(U_1, s_1) \sim (U_2, s_2)$  so that we have some  $U \subseteq U_1 \cap U_2$  with  $s_1|_U = s_2|_U$ . Then

$$\varphi_{U_1}(s_1)|_U = \varphi_U(s_1|_U) = \varphi_U(s_2|_U) = \varphi_{U_2}(s_2)|_U,$$

so  $(U_1, \varphi_U(s_1)) \sim (U_2, \varphi_U(s_2))$ . Now,  $\varphi_p$  will preserve whatever extra structure we need it to because it is essentially induced by the  $\varphi_U$ .

- (b) Fix an open set  $U \subseteq X$  so that we need  $(\varphi_1)_U = (\varphi_2)_U$ . Now, the point is that any  $\psi: \mathcal{F} \rightarrow \mathcal{G}$  will make the diagram

$$\begin{array}{ccc} \mathcal{F}(U) & \longrightarrow & \prod_{p \in U} \mathcal{F}_p \\ \psi_U \downarrow & & \downarrow \Pi \psi_p \\ \mathcal{G}(U) & \hookrightarrow & \prod_{p \in U} \mathcal{G}_p \end{array} \quad \begin{array}{ccc} f & \longmapsto & (f|_p)_{p \in U} \\ \downarrow & & \downarrow \\ \psi_U f & \longmapsto & ((\psi_U f)|_p)_{p \in U} \end{array}$$

commute. In particular, if  $\varphi_p = \varphi'_p$  for all  $p \in X$ , then we see that  $\varphi_U(f)|_p = \varphi_p(f) = \varphi'_p(f) = \varphi'_U(f)|_p$ . Thus, the injectivity of the map  $\mathcal{G}(U) \rightarrow \prod_{p \in U} \mathcal{G}_p$  of [Proposition 1.102](#) forces  $\varphi_U(f) = \varphi'_U(f)$ . ■

**Remark 1.106.** It is not hard to see that  $(-)_p: \text{PreSh}_X \rightarrow \mathcal{C}$  is a functor, where  $\mathcal{C}$  is the target category for our sheaves. We can see this because we're just computing limits, but we can also see this concretely. We have already described the action on (pre)sheaves and morphisms, so it remains to check functoriality. Fix  $p \in X$ .

- Identity: note that  $[(U, f)] \in \mathcal{F}_p$  has  $(\text{id}_{\mathcal{F}})_p: [(U, f)] \mapsto [(U, f)]$ .
- Functoriality: given  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  and  $\psi: \mathcal{G} \rightarrow \mathcal{H}$  as well as  $[(U, f)] \in \mathcal{F}_p$ , we have

$$\psi_p(\varphi_p([(U, f)])) = \psi_p([U, \varphi_U f]) = [(U, (\psi \circ \varphi)_U f)] = (\psi \circ \varphi)_p([(U, f)]).$$

#### 1.4.4 The Category of Sheaves Is Additive

We are going to want to do category theory on sheaves, so let's begin. Our end goal is to show that the category of (pre)sheaves over a topological space  $X$  valued in an abelian category is itself abelian. Throughout, our target category for our sheaves will be abelian (and concrete). Explicitly, the target category will essentially be a subcategory of  $\text{Mod}_R$  always.

To begin, we need to show that we can give morphisms of sheaves an abelian group structure.

**Lemma 1.107.** Fix presheaves  $\mathcal{F}$  and  $\mathcal{G}$  on a topological space  $X$ . Then, given morphisms  $\varphi, \psi: \mathcal{F} \rightarrow \mathcal{G}$ , we can define

$$(\varphi + \psi)_U := \varphi_U + \psi_U$$

for each  $U \subseteq X$ . Then  $(\varphi + \psi): \mathcal{F} \rightarrow \mathcal{G}$  is a presheaf morphism. This operation  $+$  makes  $\text{Mor}(\mathcal{F}, \mathcal{G})$  an abelian group, and composition of morphisms distributes over addition.

*Proof.* To check that  $\varphi + \psi$  is a presheaf morphism, pick up a containment of open sets  $V \subseteq U$ , and we need to check that the diagram

$$\begin{array}{ccc} \mathcal{F}(U) & \xrightarrow{(\varphi + \psi)_U} & \mathcal{G}(U) \\ \text{res}_{U,V} \downarrow & & \downarrow \text{res}_{U,V} \\ \mathcal{F}(V) & \xrightarrow{(\varphi + \psi)_V} & \mathcal{G}(V) \end{array}$$

commutes. Well, for any  $s \in \mathcal{F}(U)$ , we note

$$(\varphi + \psi)_U(s)|_V = (\varphi_U s + \psi_U s)|_V = \varphi_U(s)|_V + \psi_U(s)|_V \stackrel{*}{=} \varphi_V(s|_V) + \psi_V(s|_V) = (\varphi + \psi)_V(s|_V),$$

where we have used the fact that  $\varphi$  and  $\psi$  are presheaf morphisms in  $\stackrel{*}{=}$ .

To check that  $\text{Mor}(\mathcal{F}, \mathcal{G})$  is an abelian group under  $+$ , we note that

$$\text{Mor}(\mathcal{F}, \mathcal{G}) \subseteq \prod_{U \subseteq X} \text{Mor}(\mathcal{F}(U), \mathcal{G}(U)),$$



where the latter is a product group under the same addition operation. We have already established that  $\text{Mor}(\mathcal{F}, \mathcal{G})$  is closed under the addition operation. So we have two more checks to establish that we have a subgroup.

- **Zero:** the zero element  $0 \in \text{Mor}(\mathcal{F}, \mathcal{G})$  is then made of the zero morphisms  $0_U: \mathcal{F}(U) \rightarrow \mathcal{G}(U)$  sending all elements to zero. The uniqueness of zero morphisms ensures that  $0: \mathcal{F} \rightarrow \mathcal{G}$  is a presheaf morphism. Namely, any  $V \subseteq U$  and  $s \in \mathcal{F}(U)$  gives  $0_U(s)|_V = 0 = 0_V(s|_V)$ .
- **Inverses:** given a sheaf morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$ , we define  $(-\varphi)_U := -\varphi_U$  for each  $U \subseteq X$ . The  $(-\varphi)$  assembles into a presheaf morphism: for any  $V \subseteq U$  and  $s \in \mathcal{F}(U)$ , we see that  $(-\varphi)_U(s)|_V = -\varphi_U(s)|_V = -\varphi_V(s|_V) = (-\varphi)_V(s|_V)$ .

It remains to check distributivity. Let  $\varphi_1, \varphi_2: \mathcal{F} \rightarrow \mathcal{G}$  and  $\psi_1, \psi_2: \mathcal{G} \rightarrow \mathcal{H}$  be presheaf morphisms. Then, for any  $U \subseteq X$  and  $s \in \mathcal{F}(U)$ , we compute

$$\begin{aligned} ((\psi_1 + \psi_2) \circ (\varphi_1 + \varphi_2))_U(s) &= (\psi_1 + \psi_2)_U((\varphi_1 + \varphi_2)_U(s)) \\ &= ((\psi_1)_U + (\psi_2)_U)((\varphi_1)_U(s) + (\varphi_2)_U(s)) \\ &= ((\psi_1)_U + (\psi_2)_U)((\varphi_1)_U(s)) + ((\psi_1)_U + (\psi_2)_U)((\varphi_2)_U(s)) \\ &= (\psi_1 \circ \varphi_1)_U(s) + (\psi_2 \circ \varphi_1)_U(s) + (\psi_1 \circ \varphi_2)_U(s) + (\psi_2 \circ \varphi_2)_U(s) \\ &= (\psi_1 \circ \varphi_1 + \psi_2 \circ \varphi_1 + \psi_1 \circ \varphi_2 + \psi_2 \circ \varphi_2)_U(s), \end{aligned}$$

so  $(\psi_1 + \psi_2) \circ (\varphi_1 + \varphi_2) = \psi_1 \circ \varphi_1 + \psi_2 \circ \varphi_1 + \psi_1 \circ \varphi_2 + \psi_2 \circ \varphi_2$  follows. ■

**Remark 1.108.** Of course, replacing all presheaves with sheaves in [Lemma 1.107](#) makes the statement still true because sheaf morphisms are just presheaf morphisms. This will be a recurring theme.

Continuing, we should define a zero presheaf.

**Definition 1.109 (Zero presheaf).** Given a topological space  $X$ , the *zero presheaf* on  $X$  is the presheaf  $\mathcal{Z}$  such that  $\mathcal{Z}(U) = 0$  for all open  $U \subseteq X$ .

**Lemma 1.110.** The zero presheaf  $\mathcal{Z}$  on  $X$  is the zero object in the category  $\text{PreSh}_X$ .

*Proof.* The restriction maps for  $\mathcal{Z}$  are all zero maps; the functoriality checks are all immediate because zero maps are unique (namely,  $\text{id}_0 = 0$  and  $0 \circ 0 = 0$ ). Now, given any presheaf  $\mathcal{F}$ , we need to exhibit unique presheaf morphisms to and from  $\mathcal{Z}$ .

- **Initial:** we show there is a unique sheaf morphism  $\varphi: \mathcal{Z} \rightarrow \mathcal{F}$ . For uniqueness, note that any  $U \subseteq X$  needs a map

$$\varphi_U: \mathcal{Z}(U) \rightarrow \mathcal{F}(U),$$

so because  $\mathcal{Z}(U) = 0$  is initial, there is a unique possible map. To check that this data actually assembles into a presheaf morphism, we need to check that any containment of open sets  $V \subseteq U$  causes the diagram

$$\begin{array}{ccc} \mathcal{Z}(U) & \xrightarrow{0} & \mathcal{F}(U) \\ \text{res}_{U,V} \downarrow & & \downarrow \text{res}_{U,V} \\ \mathcal{Z}(V) & \xrightarrow{0} & \mathcal{F}(V) \end{array} \quad \begin{array}{ccc} 0 & \xrightarrow{0} & \mathcal{F}(U) \\ \downarrow & & \downarrow \\ 0 & \xrightarrow{0} & \mathcal{F}(V) \end{array}$$

commutes, which is clear by the uniqueness of our zero maps. Namely, the map  $0 \rightarrow 0 \rightarrow \mathcal{F}(V)$  and  $0 \rightarrow \mathcal{F}(U) \rightarrow \mathcal{F}(V)$  must both just be the map  $0 \rightarrow \mathcal{F}(V)$ .

- **Terminal:** one merely has to reverse all the arrows in the previous argument. Notably, the zero object  $0$  in the target category of  $\mathcal{Z}$  is terminal in addition to being initial. ■

As in [Remark 1.108](#), we can quickly move the zero presheaf to being the zero sheaf.

**Corollary 1.111.** The zero presheaf  $\mathcal{Z}$  on a topological space  $X$  is a sheaf and hence the zero object in the category  $\text{Sh}_X$ .

*Proof.* The main point here is that the zero presheaf  $\mathcal{Z}$  is in fact a sheaf. This is easy to check: fix an open cover  $\mathcal{U}$  of an open set  $U \subseteq V$ . If we are given sections  $f, g \in \mathcal{Z}(U)$ , then we don't even need any other conditions to know that

$$f = g \in \mathcal{Z}(U) = 0$$

because there is only one element in the zero object. Similarly, given sections  $f_V \in \mathcal{Z}(V)$  for each  $V \in \mathcal{U}$ , we note that  $f_V = 0$  everywhere, so we can set  $f_U = 0 \in \mathcal{Z}(U)$  so that  $f|_V = f_V$ ; this proves the gluability axiom.

We now check the universal property. Given any sheaf  $\mathcal{F}$ , we know from [Lemma 1.110](#) that there are unique presheaf morphisms  $\mathcal{F} \rightarrow \mathcal{Z}$  and  $\mathcal{Z} \rightarrow \mathcal{F}$ . Because sheaf morphisms are presheaf morphisms, it follows that there are unique sheaf morphisms as well. ■

To show that our category of (pre)sheaves is additive, it remains to exhibit (finite) products.

**Definition 1.112 (Product presheaf).** Given presheaves  $\mathcal{F}_1$  and  $\mathcal{F}_2$  on a topological space  $X$ , the *product presheaf*  $\mathcal{F}_1 \times \mathcal{F}_2$  by

$$(\mathcal{F}_1 \times \mathcal{F}_2)(U) := \mathcal{F}_1(U) \times \mathcal{F}_2(U)$$

with the restriction maps induced by  $\mathcal{F}_1$  and  $\mathcal{F}_2$ .

**Lemma 1.113.** Given presheaves  $\mathcal{F}_1$  and  $\mathcal{F}_2$  on  $X$ , the product presheaf  $\mathcal{F}_1 \times \mathcal{F}_2$  is the categorical product in  $\text{PreSh}_X$ .

*Proof.* We begin by showing that  $\mathcal{F}_1 \times \mathcal{F}_2$  is in fact a presheaf. To be explicit, our restriction maps for opens  $V \subseteq U \subseteq X$  are

$$\begin{aligned} \text{res}_{U,V}: (\mathcal{F}_1 \times \mathcal{F}_2)(U) &\rightarrow (\mathcal{F}_1 \times \mathcal{F}_2)(V) \\ (f_1, f_2) &\mapsto (f_1|_V, f_2|_V). \end{aligned}$$

Here are our presheaf checks.

- Identity: with an open  $U \subseteq X$  and  $(f_1, f_2) \in (\mathcal{F}_1 \times \mathcal{F}_2)(U)$ , we have  $(f_1, f_2)|_U = (f_1|_U, f_2|_U) = (f_1, f_2)$ .
- Functoriality: with opens  $W \subseteq V \subseteq U$  and  $(f_1, f_2) \in (\mathcal{F}_1 \times \mathcal{F}_2)(U)$ , we have

$$(f_1, f_2)|_{V|W} = (f_1|_{V|W}, f_2|_{V|W}) = (f_1|_W, f_2|_W) = (f_1, f_2)|_W.$$

It remains to show our universal property for products. Given an open  $U \subseteq X$ , define  $(\pi_1)_U: (\mathcal{F}_1 \times \mathcal{F}_2)(U) \rightarrow \mathcal{F}_1(U)$  by projection onto the first coordinate. To show that  $\pi_1$  assembles into a presheaf morphism, pick up opens  $V \subseteq U \subseteq X$  and  $(f_1, f_2) \in (\mathcal{F}_1 \times \mathcal{F}_2)(U)$  and check

$$(\pi_1)_U((f_1, f_2))|_V = f_1|_V = (\pi_1)_V((f_1|_V, f_2|_V)).$$

We can define the presheaf morphism  $\pi_2: (\mathcal{F}_1 \times \mathcal{F}_2) \rightarrow \mathcal{F}_2$  by projection onto the second coordinate, which is a presheaf morphism by symmetry.

For our presheaf morphism, suppose that we have a presheaf  $\mathcal{G}$  with maps  $\varphi_1: \mathcal{G} \rightarrow \mathcal{F}_1$  and  $\varphi_2: \mathcal{G} \rightarrow \mathcal{F}_2$ . We need a unique presheaf morphism  $\varphi: \mathcal{G} \rightarrow (\mathcal{F}_1 \times \mathcal{F}_2)$  making the diagram

$$\begin{array}{ccc} \mathcal{G} & & \\ \varphi_1 \searrow & \varphi \searrow & \varphi_2 \searrow \\ & \mathcal{F}_1 \times \mathcal{F}_2 & \xrightarrow{\pi_2} \mathcal{F}_2 \\ & \downarrow \pi_1 & \\ & \mathcal{F}_1 & \end{array} \quad (1.5)$$

commute. We show uniqueness and existence separately.

- Uniqueness: if  $\varphi: \mathcal{G} \rightarrow (\mathcal{F}_1 \times \mathcal{F}_2)$  makes (1.5) commute, at any given open  $U \subseteq X$  and  $g \in \mathcal{G}(U)$ , we must have

$$(\pi_1)_U(\varphi_U g) = (\varphi_1)_U(g) \quad \text{and} \quad (\pi_2)_U(\varphi_U g) = (\varphi_2)_U(g),$$

so  $\varphi_U(g) := ((\varphi_1)_U g, (\varphi_2)_U g)$  is forced.

- Existence: as above, given an open  $U \subseteq X$  and  $g \in \mathcal{G}(U)$ , define

$$\varphi_U(g) := ((\varphi_1)_U g, (\varphi_2)_U g).$$

We can see, as above, that  $(\pi_1)_U \circ \varphi_U = (\varphi_1)_U$  and similar for  $\pi_2$ , so (1.5) will commute as long as  $\varphi$  actually assembles into a presheaf morphism.

Well, given  $V \subseteq U \subseteq X$  and  $g \in \mathcal{G}(U)$ , note

$$\varphi_U(g)|_V = ((\varphi_1)_U g, (\varphi_2)_U g)|_V = ((\varphi_1)_U(g)|_V, (\varphi_2)_U(g)|_V) = ((\varphi_1)_V(g|_V), (\varphi_2)_V(g|_V)) = \varphi_V(g|_V),$$

which finishes. ■

**Corollary 1.114.** Given sheaves  $\mathcal{F}_1$  and  $\mathcal{F}_2$  on  $X$ , the product presheaf  $\mathcal{F}_1 \times \mathcal{F}_2$  is a sheaf and hence the categorical product in  $\mathbf{Sh}_X$ .

*Proof.* As in Corollary 1.111, the main point is to show that  $\mathcal{F}_1 \times \mathcal{F}_2$  is in fact a sheaf. Fix an open cover  $\mathcal{U}$  of  $U$ .

- Identity: given  $(f_1, f_2) \in (\mathcal{F}_1 \times \mathcal{F}_2)(U)$  with  $(f_1, f_2)|_V = 0$  for all  $V \in \mathcal{U}$ , we see  $f_1|_V = f_2|_V = 0$  is forced for all  $V \in \mathcal{U}$ , so the identity axiom on  $\mathcal{F}_1$  and  $\mathcal{F}_2$  forces  $f_1 = f_2 = 0$ . Thus,  $(f_1, f_2) = 0$ .
- Glueability: pick up sections  $(f_{1,V}, f_{2,V}) \in (\mathcal{F}_1 \times \mathcal{F}_2)(V)$  for each  $V \in \mathcal{U}$  such that any  $V, V' \in \mathcal{U}$  have

$$(f_{1,V}|_{V \cap V'}, f_{2,V}|_{V \cap V'}) = (f_{1,V'}, f_{2,V'})|_{V \cap V'} = (f_{1,V'}, f_{2,V'})|_{V \cap V'} = (f_{1,V'}|_{V \cap V'}, f_{2,V'}|_{V \cap V'}).$$

Thus, the glueability axiom on  $\mathcal{F}_1$  and  $\mathcal{F}_2$  promises  $f_1 \in \mathcal{F}_1(U)$  and  $f_2 \in \mathcal{F}_2(U)$  such that  $f_1|_V = f_{1,V}$  and  $f_2|_V = f_{2,V}$  for each  $V \in \mathcal{U}$ . Thus,  $(f_1, f_2)|_V = (f_1|_V, f_2|_V) = (f_{1,V}, f_{2,V})$  for each  $V \in \mathcal{U}$ , as needed.

We now discuss the universal property. This immediately follows from the corresponding statement in the category of presheaves, but for completeness, we will say out loud what's going on. Let  $\pi_1: (\mathcal{F}_1 \times \mathcal{F}_2) \rightarrow \mathcal{F}_1$  and  $\pi_2: (\mathcal{F}_1 \times \mathcal{F}_2) \rightarrow \mathcal{F}_2$  be the projection (pre)sheaf morphisms.

Suppose we have a sheaf  $\mathcal{G}$  with sheaf morphisms  $\varphi_1: \mathcal{G} \rightarrow \mathcal{F}_1$  and  $\varphi_2: \mathcal{G} \rightarrow \mathcal{F}_2$ . Then we are promised a unique presheaf morphism  $\varphi: \mathcal{G} \rightarrow (\mathcal{F}_1 \times \mathcal{F}_2)$  such that  $\varphi_1 = \pi_1 \circ \varphi$  and  $\varphi_2 = \pi_2 \circ \varphi$ . Thus, there is also a unique sheaf morphism  $\varphi$  satisfying the same constraint because sheaf morphisms are just presheaf morphisms. ■

**Remark 1.115.** The above discussion immediately generalizes to arbitrary products, but we will not need these.

**Corollary 1.116.** The category  $\mathbf{Sh}_X$  of sheaves on a topological space  $X$  valued in a (concrete) abelian category  $\mathcal{C}$  is additive.

*Proof.* Combine Lemma 1.107, Corollary 1.111, and Corollary 1.114. ■

### 1.4.5 Sheaf Kernels

We continue working with (pre)sheaves valued in a concrete abelian category. The next step to show that the category is abelian is to exhibit kernels and cokernels. Cokernels will turn out to be difficult, so we begin with kernels.

**Definition 1.117 (Presheaf kernel).** Given a morphism of presheaves  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  on a topological space  $X$ , we define the *presheaf kernel* as

$$(\ker \varphi)(U) := \ker \varphi_U$$

for each  $U \subseteq X$ , where restriction maps are induced by  $\mathcal{F}$ . Then  $\ker \varphi$  is our *presheaf kernel*.

**Lemma 1.118.** Given a morphism of presheaves  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  on a topological space  $X$ , the presheaf kernel  $\ker \varphi$  is a categorical kernel.

*Proof.* We haven't actually defined the restriction maps for the presheaf kernel, so we do this now: for each open  $U \subseteq X$  with  $V \subseteq U$ , note  $\ker \varphi_U \subseteq \mathcal{F}(U)$ , so we can restrict the map  $\text{res}_{U,V}: \mathcal{F}(U) \rightarrow \mathcal{F}(V)$  to a map

$$\ker \varphi_U \rightarrow \mathcal{F}(V).$$

Now, for any  $s \in \ker \varphi_U$ , we note that actually  $\varphi_V(s|_V) = \varphi_U(s)|_V = 0$ , so our restriction map restricts to  $\text{res}_{U,V}: \ker \varphi_U \rightarrow \ker \varphi_V$  as needed. The presheaf checks on  $\ker \varphi$  of identity and functoriality checks are inherited from  $\mathcal{F}$ .

It remains to check the universal property: we need  $\ker \varphi$  to be the limit of the following diagram.

$$\begin{array}{ccc} & \mathcal{Z} & \\ & \downarrow & \\ \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \end{array}$$

There is an inclusion  $\ker \varphi_U \subseteq \mathcal{F}(U)$  for each open  $U \subseteq X$ , which induces maps  $\iota_U: (\ker \varphi)(U) \rightarrow \mathcal{F}(U)$ . To see that  $\iota_U$  assembles into a presheaf morphism, pick up a containment  $V \subseteq U$  and  $s \in \mathcal{F}(U)$ , and we check  $\iota_U(s)|_V = s|_V = \iota_V(s|_V)$ . Additionally, there is a canonical 0 map  $0: (\ker \varphi) \rightarrow \mathcal{Z}$ , so we claim that the diagram

$$\begin{array}{ccc} \ker \varphi & \longrightarrow & \mathcal{Z} \\ \downarrow \iota & & \downarrow \\ \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \end{array}$$

commutes. Well, for any  $U \subseteq X$  and  $f \in (\ker \varphi)(U)$ , note  $\varphi_U(\iota_U(f)) = 0$ , so the presheaf morphism  $\varphi \circ \iota$  is just the zero morphism, as needed.

We are now ready to show the universal property. Fix a presheaf  $\mathcal{H}$  with a map  $\psi: \mathcal{H} \rightarrow \mathcal{F}$  such that  $\varphi \circ \psi = 0$ . Then we claim that there is a unique map  $\bar{\psi}$  making the diagram

$$\begin{array}{ccccc} \mathcal{H} & & & & \\ & \searrow \bar{\psi} & & \searrow & \\ & & \ker \varphi & \longrightarrow & \mathcal{Z} \\ & \searrow \psi & \downarrow \iota & & \downarrow \\ & & \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \end{array} \tag{1.6}$$

commute. We show uniqueness and existence separately.

- Uniqueness: for any subset  $U \subseteq X$  and  $h \in \mathcal{H}(U)$ , (1.6) forces

$$\iota_U(\overline{\psi}_U(h)) = \psi_U(h).$$

However,  $\iota_U$  is just an inclusion (of sets, say), so we must have  $\overline{\psi}_U(h) = \iota_U^{-1}(\psi_U(h))$ . As such,  $\overline{\psi}$  is uniquely determined.

- Existence: for any subset  $U \subseteq X$  and  $h \in \mathcal{H}(U)$ , (1.6) forces  $\varphi_U(\psi_U(h)) = 0$ , so  $\psi_U(h) \in \ker \varphi_U$ . So we can restrict the image of  $\psi_U$  to define a map

$$\overline{\psi}_U(h) := \psi_U(h).$$

Of course,  $\iota_U(\overline{\psi}_U(h)) = \psi_U(h)$ , so (1.6) will commute as long as  $\overline{\psi}$  assembles into a presheaf morphism. Well, for a containment  $V \subseteq U$  and  $h \in \mathcal{H}(U)$ , we see

$$\overline{\psi}_U(h)|_V = \psi_U(h)|_V = \psi_V(h|_V) = \overline{\psi}_V(h|_V),$$

as needed. ■

What makes the presheaf kernel nice is that is actually the sheaf kernel.

**Lemma 1.119.** Fix a morphism of sheaves  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$ . Then  $\ker \varphi$  is a sheaf and hence the categorical kernel.

*Proof.* As usual, the main point is to show that  $\ker \varphi$  is a sheaf. For clarity, label the (canonical) inclusion  $\iota: (\ker \varphi) \rightarrow \mathcal{F}$ ; note  $\iota_U$  is injective at each open  $U \subseteq X$ . Now, fix an open cover  $\mathcal{U}$  for an open set  $U \subseteq X$ .

- Identity: fix  $f, g \in (\ker \varphi)(U)$  such that  $f|_V = g|_V$  for all  $V \in \mathcal{U}$ . However, all of this is embedded in  $\mathcal{F}$  by  $\iota$ , so we really have  $\iota f, \iota g \in \mathcal{F}(U)$  with  $(\iota f)|_V = \iota_V(f|_V) = \iota_V(g|_V) = (\iota g)|_V$  for all  $V \in \mathcal{U}$ , so the identity axiom promises that  $\iota_U f = \iota_U g$ . Thus,  $f = g$  follows.
- Glueability: fix sections  $f_V \in (\ker \varphi)(V)$  for each  $V \in \mathcal{F}(V)$  such that

$$f_V|_{V \cap V'} = f_{V'}|_{V \cap V'}$$

for each  $V, V' \in \mathcal{U}$ . Embedding everything in  $\mathcal{F}$ , we see

$$(\iota_V f_V)|_{V \cap V'} = \iota_{V \cap V'}(f_V|_{V \cap V'}) = \iota_{V \cap V'}(f_{V'}|_{V \cap V'}) = (\iota_{V'} f_{V'})|_{V \cap V'},$$

so the glueability axiom on  $\mathcal{F}(U)$  tells us there is  $f \in \mathcal{F}(U)$  with  $f|_V = \iota_V(f_V)$  for each  $V \in \mathcal{U}$ .

We now need to show  $f \in (\ker \varphi)(U)$ . Well, for each  $V \in \mathcal{U}$ , we see

$$\varphi_U(f)|_V = \varphi_V(f|_V) = \varphi_V(f_V) = 0,$$

where the last equality is because  $f_V \in (\ker \varphi)(V)$ . Thus, the identity axiom on  $\mathcal{G}$  tells us  $f \in \ker \varphi_U$ , so we can pull  $f$  back to an element  $f \in (\ker \varphi)(U)$  such that  $f|_V = f_V$  for each  $V \in \mathcal{U}$ .

Checking the universal property is a matter of stating it and noting that working in the category  $\text{PreSh}_X$  immediately forces the universal property to work in the subcategory  $\text{Sh}_X$ . We showed what this looks like in the last paragraph of Corollary 1.114. ■

Now, having a kernel gives us a definition.

**Definition 1.120 (Injective morphism).** A morphism of (pre)sheaves  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  is *injective* if and only if the kernel (pre)sheaf  $\ker \varphi$  is identically zero. Equivalently, we are asking for  $\varphi_U$  to be injective everywhere.

We briefly convince ourselves that this is the correct definition.

**Lemma 1.121.** Let  $\mathcal{C}$  be a category with a zero object and kernels, and fix a morphism  $\varphi: A \rightarrow B$ . Then  $\varphi$  is monic if and only if  $\ker \varphi$  vanishes.

*Proof.* This is purely categorical; let  $\iota: (\ker \varphi) \rightarrow A$  be the kernel map. In one direction, suppose that  $\ker \varphi$  vanishes. To show  $\varphi$  is monic, write down

$$C \begin{array}{c} \xrightarrow{\psi_1} \\ \xrightarrow{\psi_2} \end{array} A \xrightarrow{\varphi} B$$

with  $\varphi \circ \psi_1 = \varphi \circ \psi_2$ , we need to show  $\psi_1 = \psi_2$ . Well,  $\psi := \psi_1 - \psi_2$  has  $\varphi \circ \psi = 0$ , so our kernel promises a unique map  $\bar{\psi}: C \rightarrow (\ker \varphi)$  with  $\psi = \iota \circ \bar{\psi}$ . However,  $\ker \varphi$  is the zero object, so we conclude  $\psi = 0$ .

In the other direction, suppose  $\varphi$  is monic, and we show that the zero object  $Z$  satisfies the universal property of the kernel. Well, fix an object  $C$  with a map  $\psi: C \rightarrow A$  such that  $\varphi \circ \psi = 0$ . Then we need a unique map  $\bar{\psi}: C \rightarrow Z$  making

$$\begin{array}{ccc} C & \xrightarrow{\bar{\psi}} & Z \\ \psi \downarrow & \swarrow & \uparrow \varphi \\ A & \xrightarrow{\varphi} & B \end{array}$$

commute. Well, the map  $C \rightarrow Z$  is certainly unique because  $Z$  is terminal. Additionally, we note that the zero map  $C \rightarrow Z$  does indeed make the diagram commute:  $\varphi \circ \psi = 0 = \varphi \circ 0$  forces  $\psi = 0$ , so  $\psi$  is the zero map. ■

### 1.4.6 Injectivity at Stalks

In our stalk philosophy, we might hope we can detect injectivity at stalks. Indeed, we can.

**Lemma 1.122.** Fix a morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of presheaves on  $X$ . Then, for any  $p \in X$ , the inclusion  $(\ker \varphi) \rightarrow \mathcal{F}$  induces an isomorphism

$$(\ker \varphi)_p \simeq \ker \varphi_p.$$

*Proof.* Let  $\iota: (\ker \varphi) \rightarrow \mathcal{F}$  denote the inclusion. Then [Proposition 1.105](#) grants us a map  $\iota_p: (\ker \varphi)_p \rightarrow \mathcal{F}_p$ . Now, for any  $[(U, f)] \in (\ker \varphi)_p$ , we have

$$\varphi_p(\iota_p([(U, f)])) = [(U, \varphi_U(\iota_U(f)))] = [(U, 0)] = 0$$

by how these maps are defined in [Proposition 1.105](#). Thus, we can restrict the image of  $\iota_p$  to  $\ker \varphi_p \subseteq \mathcal{F}_p$ .

In the other direction, suppose that we have a germ  $[(U, f)] \in \ker \varphi_p$  so that  $[(U, \varphi_U(f))] = 0$ , which means there is  $V \subseteq U$  containing  $p$  such that  $\varphi_V(f|_V) = \varphi_U(f)|_V = 0$ . In particular,  $f|_V \in \ker \varphi_V$ , so we have  $[(V, f|_V)] \in (\ker \varphi)_p$ . Thus, we define the map  $\pi: \ker \varphi_p \rightarrow (\ker \varphi)_p$  by

$$\pi: [(U, f)] \mapsto [(V, f|_V)].$$

Note that  $\pi$  does not depend on the choice of  $V \subseteq U$ : if  $V' \subseteq U$  also have  $\varphi_{V'}(f|_{V'}) = 0$ , then we note  $(V, f|_V) \sim (V', f|_{V'})$  because  $f|_{V|V \cap V'} = f|_{V'|V \cap V'}$ . Additionally,  $\pi$  does not depend on the choice of representative for  $[(U, f)]$ : if  $(U, f) \sim (U', f')$  in  $\ker \varphi_p$ , then find  $V \subseteq U \cap U'$  small enough so that  $f|_V = f'|_V$  and  $\varphi_V(f|_V) = \varphi_V(f'|_V) = 0$  so that  $\pi([(U, f)]) = [(V, f|_V)] = [(V, f'|_V)] = \pi([(U', f')])$ .

Lastly, we check  $\iota_p$  and  $\pi$  are inverse. In one direction, given  $[(U, f)] \in (\ker \varphi)_p$ , we note  $\varphi_U(f) = 0$ , so

$$\pi(\iota_p([(U, f)])) = \pi([(U, f)]) = [(U, f)].$$

In the other direction, given  $[(U, f)] \in \ker \varphi_p$ , find  $V \subseteq U$  small enough so that  $\varphi_V(f|_V) = 0$ . Then

$$\iota_p(\pi([(U, f)])) = \iota([(V, f|_V)]) = [(V, f|_V)] = [(U, f)],$$

finishing. ■

**Lemma 1.123.** Fix a sheaf  $\mathcal{F}$  on a topological space  $X$ . The following are equivalent.

- (a)  $\mathcal{F}$  is the zero sheaf.
- (b)  $\mathcal{F}(U) \simeq 0$  for each open  $U \subseteq X$ .
- (c)  $\mathcal{F}_p \simeq 0$  for each  $p \in X$ .

*Proof.* Our construction of the zero presheaf tells us that (a) implies (c): any germ  $[(U, f)] \in \mathcal{Z}_p$  has  $f \in \mathcal{Z}(U) = 0$ , so  $[(U, f)] = 0$ . Note we are using the fact that isomorphic sheaves have isomorphic stalks. To show that (c) implies (b), we note that  $\mathcal{F}$  being a sheaf grants us the inclusion

$$\mathcal{F}(U) \hookrightarrow \prod_{p \in U} \mathcal{F}_p$$

by [Proposition 1.102](#). However, the right-hand side is 0, so the left-hand side must also be 0.

Lastly, we show that (b) implies (a). Well, note that the restriction maps  $\mathcal{F}(U) \rightarrow \mathcal{F}(V)$  for an inclusion  $V \subseteq U$  are forced because zero morphisms are unique. Similarly, letting  $\mathcal{Z}$  denote the zero sheaf, we have isomorphisms  $\varphi_U: \mathcal{F}(U) \simeq \mathcal{Z}(U)$  induced by these zero maps for all  $U \subseteq X$ , and we thus assemble into a natural isomorphism  $\varphi: \mathcal{F} \rightarrow \mathcal{Z}$  because the uniqueness of zero maps makes the naturality square commute. ■

**Proposition 1.124.** Fix a morphism of sheaves  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$ . The following are equivalent.

- (a)  $\varphi$  is monic.
- (b)  $\varphi_U$  is monic for each open  $U \subseteq X$ .
- (c)  $\varphi_p$  is monic for each  $p \in X$ .

*Proof.* By [Lemma 1.121](#), these are equivalent to the following.

- (a')  $\ker \varphi$  vanishes.
- (b')  $(\ker \varphi)(U)$  vanishes for each open  $U \subseteq X$ .
- (c')  $\ker \varphi_p$  vanishes for each  $p \in X$ . By [Lemma 1.122](#), this is equivalent to  $(\ker \varphi)_p$  vanishing for each  $p \in X$ .

These are equivalent by [Lemma 1.123](#). ■

**Remark 1.125.** Technically, we only need to know that  $\mathcal{F}$  is a sheaf for [Proposition 1.124](#).

Being careful, one can extend [Proposition 1.124](#) as follows.

**Proposition 1.126.** Fix a morphism of sheaves  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$ . The following are equivalent.

- (a)  $\varphi$  is an isomorphism.
- (b)  $\varphi_U$  is an isomorphism for each open  $U \subseteq X$ .
- (c)  $\varphi_p$  is an isomorphism for each  $p \in X$ .

*Proof.* To begin, (a) and (b) are equivalent by category theory: natural isomorphisms are just natural transformations whose component morphisms are isomorphisms. The main check here is that the inverse morphisms  $\varphi^{-1}(U): \mathcal{G}(U) \rightarrow \mathcal{F}(U)$  cohere into a bona fide natural transformation, which is true because, for any containment  $V \subseteq U$ , the commutativity of the left diagram

$$\begin{array}{ccc} \mathcal{F}(U) & \xrightarrow{\varphi_U} & \mathcal{G}(U) \\ \text{res}_{U,V} \downarrow & & \downarrow \text{res}_{U,V} \\ \mathcal{F}(V) & \xrightarrow{\varphi_V} & \mathcal{G}(V) \end{array} \quad \begin{array}{ccc} \mathcal{F}(U) & \xleftarrow{\varphi_U^{-1}} & \mathcal{G}(U) \\ \text{res}_{U,V} \downarrow & & \downarrow \text{res}_{U,V} \\ \mathcal{F}(V) & \xleftarrow{\varphi_V^{-1}} & \mathcal{G}(V) \end{array}$$

is equivalent to the commutativity of the right diagram.

Additionally, it is also fairly easy that (a) implies (c); fix some  $p \in X$ . Give  $\varphi$  an inverse morphism  $\psi$ , and we claim that  $\varphi_p$  is the inverse of  $\psi_p$ . Indeed, for any  $[(U, f)] \in \mathcal{F}_p$ , we see

$$\psi_p(\varphi_p([(U, f)])) = \psi_p([(U, \varphi_U(f))]) = [(U, \psi_U \varphi_U(f))] = [(U, f)].$$

By symmetry, we see  $\varphi_p \circ \psi_p = \text{id}_{\mathcal{G}_p}$  as well, finishing.

Thus, the hard direction is showing that  $\varphi_p$  being an isomorphism for all  $p \in X$  promises that  $\varphi_U$  is an isomorphism for each  $U \subseteq X$ . [Proposition 1.124](#) already tells us that  $\varphi_U$  is injective, so we focus on showing  $\varphi_U$  is surjective. Well, for any  $g \in \mathcal{G}(U)$ , we get a system of compatible germs  $(g|_p)_{p \in U}$  (by [Proposition 1.124](#)), so because  $\varphi_p$  is an isomorphism, we may set

$$f_p := \varphi_p^{-1}(g|_p).$$

We claim that  $f_p$  is a set of compatible germs, which gives rise to a section  $f \in \mathcal{F}(U)$  by [Proposition 1.124](#). For this, we appeal to the following lemma, which is enough because  $(g|_p)_{p \in U}$  is a system of compatible germs.

**Lemma 1.127.** Let  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  be a morphism of presheaves on  $X$ . If  $(f_p)_{p \in U}$  is a system of compatible germs for  $\mathcal{F}(U)$ , then  $(\varphi_p f_p)_{p \in U}$  is a system of compatible germs for  $\mathcal{G}(U)$ .

*Proof.* For each  $p \in U$ , we can find  $U_p \subseteq U$  containing  $p$  and a lift  $\tilde{f}_p$  so that  $\tilde{f}_p|_q = f_q$  for each  $q \in U_p$ . Thus, for each  $p$ , we set  $\tilde{g}_p := \varphi_{U_p}(\tilde{f}_p)$  so that any  $q \in U_p$  has

$$\tilde{g}_p|_q = \varphi_{U_p}(\tilde{f}_p)|_q = [(U_p, \varphi_{U_p}(\tilde{f}_p))] = \varphi_q([(U_p, \tilde{f}_p)]) = \varphi_q(\tilde{f}_p|_q) = \varphi_q(f_q),$$

which finishes our check. ■

Thus,  $(f_p)_{p \in U}$  is a system of compatible germs and therefore lifts to some  $f \in \mathcal{F}(U)$  with  $f|_p = f_p$  everywhere. So  $\varphi_U(f)|_p = \varphi_p(f|_p) = \varphi_p(f_p) = g|_p$  for each  $p \in X$ , so [Proposition 1.124](#) gives  $\varphi_U(f) = g$ . ■

**Remark 1.128.** We are avoiding surjectivity for the moment because it is a little trickier. In particular, a morphism  $\varphi$  will be able to be epic without being each  $\varphi_U$  being epic. However, surjectivity will still be equivalent to surjectivity on the stalks.

**Remark 1.129.** It is possible for sheaves to have isomorphic stalks but to not be isomorphic. At a high level, any line bundle over  $S^1$  has stalks isomorphic to  $\mathbb{R}$ , but not all line bundles are homeomorphic (e.g., the Möbius strip and the trivial line bundle are not homeomorphic). The issue here is that there need not even be a candidate isomorphism between line bundles over  $S^1$  at all!



## 1.5 September 2

It is another day.

**Remark 1.130.** Facts used on the homework from Vakil which are in Vakil without proof should be proven on the homework.

We begin lecture by providing an example which we don't quite have the language to describe yet, but we will elaborate on it more later.

elaborate

**Example 1.131.** Fix  $X = \mathbb{C}$  with the usual topology, and give it the sheaf  $\mathcal{O}_X$  of holomorphic functions. There is a constant sheaf  $\underline{\mathbb{Z}}$  returning  $\mathbb{Z}$  at its stalks. Then there is an exact sequence of sheaves

$$0 \rightarrow \underline{\mathbb{Z}} \xrightarrow{2\pi i} \mathcal{O}_X \xrightarrow{\exp} \mathcal{O}_X^\times \rightarrow 1 \quad (1.7)$$

even though the last map is not always surjective for any  $U \subseteq \mathbb{C}$ ; for example, take  $U = \mathbb{C} \setminus \{0\}$ . (However, if  $U$  is simply connected, then the map will be surjective.)

**Remark 1.132.** Cohomology applied to (1.7) (with  $X$  some smooth projective curve) shows a special case of the Hodge conjecture.

The point here is that surjectivity cannot be checked on open sets the way that injectivity can. At some level, the issue here is that the cokernel presheaf is not a sheaf, so we have to apply a sheafification operation to fix this.

**Remark 1.133.** Setting

$$\mathcal{F}(U) := \text{im exp}(U)$$

makes  $\mathcal{F}$  a presheaf but does not give a sheaf.

### 1.5.1 Sheafification

We introduce sheafification by its universal property.

**Definition 1.134 (Sheafification).** Fix a presheaf  $\mathcal{F}$  on  $X$  valued in a (concrete) category  $\mathcal{C}$ . The *sheafification* of  $\mathcal{F}$  is a pair  $(\mathcal{F}^{\text{sh}}, \text{sh})$  where  $\text{sh}: \mathcal{F} \rightarrow \mathcal{F}^{\text{sh}}$  satisfies the following universal property: any sheaf  $\mathcal{G}$  with a presheaf morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  has a unique sheaf morphism  $\bar{\varphi}: \mathcal{F}^{\text{sh}} \rightarrow \mathcal{G}$  making the following diagram commute.

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\text{sh}} & \mathcal{F}^{\text{sh}} \\ & \searrow \varphi & \downarrow \bar{\varphi} \\ & & \mathcal{G} \end{array}$$

Of course, there are some checks we should do before using this object.

**Lemma 1.135.** The sheafification of a presheaf  $\mathcal{F}$  on  $X$  exists and is unique up to (a suitable notion of) unique isomorphism.

*Proof.* The idea of the construction is to set  $\mathcal{F}^{\text{sh}}(U)$  to be systems of compatible germs; precisely,

$$\mathcal{F}^{\text{sh}}(U) := \left\{ (f_p)_{p \in U} \in \prod_{p \in U} \mathcal{F}_p : (f_p)_{p \in U} \text{ is a compatible system of germs} \right\}.$$

Given open sets  $V \subseteq U$ , we define the restriction map

$$\begin{aligned} \text{res}_{U,V} : \mathcal{F}^{\text{sh}}(U) &\rightarrow \mathcal{F}^{\text{sh}}(V) \\ (f_p)_{p \in U} &\mapsto (f_p)_{p \in V} \end{aligned}$$

though we do have to check this is well-defined: to show  $(f_p)_{p \in V} \in \mathcal{F}^{\text{sh}}(V)$ , we note  $(f_p)_{p \in U} \in \mathcal{F}^{\text{sh}}(U)$  promises that each  $p \in U$  has  $U_p \subseteq U$  containing  $p$  with a lift  $\tilde{f}_p \in \mathcal{F}(U_p)$  so that  $\tilde{f}_p|_q = f_q$  for each  $q \in U_p$ . As such, each  $p \in V$  has  $V_p := U_p \cap V$  containing  $p$  with a lift  $\tilde{f}_p|_{U_p \cap V} \in \mathcal{F}(U_p \cap V)$  so that  $\tilde{f}_p|_{U_p \cap V}|_q = \tilde{f}_p|_q = f_q$  for each  $q \in U_p \cap V$ . Thus,  $(f_p)_{p \in V}$  is indeed a system of compatible germs.

We now check that  $\mathcal{F}^{\text{sh}}$  is a presheaf.

- Identity: given  $(f_p)_{p \in U} \in \mathcal{F}^{\text{sh}}(U)$ , we see  $(f_p)_{p \in U}|_U = (f_p)_{p \in U}$ .
- Functoriality: given open sets  $W \subseteq V \subseteq U$ , we see  $(f_p)_{p \in U}|_V|_W = (f_p)_{p \in V}|_W = (f_p)_{p \in W} = (f_p)_{p \in U}|_W$ .

Next up, we check that  $\mathcal{F}^{\text{sh}}$  is a sheaf. Fix an open cover  $\mathcal{U}$  of an open set  $U \subseteq X$ .

- Identity: suppose that  $(f_p)_{p \in U}, (g_p)_{p \in U} \in \mathcal{F}^{\text{sh}}(U)$  have  $(f_p)_{p \in U}|_V = (g_p)_{p \in U}|_V$  for each  $V \in \mathcal{U}$ . Now, for each  $q \in U$ , there is some  $V \in \mathcal{U}$  containing  $q$ , so we note

$$(f_p)_{p \in V} = (f_p)_{p \in U}|_V = (g_p)_{p \in U}|_V = (g_p)_{p \in V}$$

forces  $f_q = g_q$ . Thus,  $(f_p)_{p \in U} = (g_p)_{p \in U}$ .

- Glueability: suppose we have  $(f_{V,p})_{p \in V} \in \mathcal{F}^{\text{sh}}(V)$  for each  $V \in \mathcal{U}$  so that

$$(f_{V,p})_{p \in V \cap V'} = (f_{V,p})_{p \in V}|_{V \cap V'} = (f_{V',p})_{p \in V'}|_{V \cap V'} = (f_{V',p})_{p \in V \cap V'}.$$

Now, for each  $q \in U$ , find any  $V \in \mathcal{U}$  containing  $q$ , and set  $f_q := f_{V,q}$ . Note that this is independent of the choice of  $V$ : if we have  $q \in V \cap V'$  with  $V, V' \in \mathcal{U}$ , then  $(f_{V,p})_{p \in V \cap V'} = (f_{V',p})_{p \in V \cap V'}$  tells us that  $f_{V,q} = f_{V',q}$ . Further, we note that  $(f_p)_{p \in U}|_V = (f_p)_{p \in V} = (f_{V,p})_{p \in V}$  for any  $V \in \mathcal{U}$ .

So it remains to show that  $(f_p)_{p \in U} \in \mathcal{F}^{\text{sh}}(U)$ . Well, for each  $p \in U$ , find some  $V \in \mathcal{U}$  containing  $p$ . Then  $(f_{V,p})_{p \in V}$  is a system of compatible germs, so we can find  $U_p \subseteq V$  containing  $p$  and a lift  $\tilde{f}_p \in \mathcal{F}(U_p)$  such that

$$\tilde{f}_p|_q = f_{V,q} = f_q$$

for each  $q \in U_p$ . This finishes checking that  $(f_p)_{p \in U}$  is a compatible system of germs.

We now begin showing the universal property. The sheafification map is defined as

$$\begin{aligned} \text{sh}_U : \mathcal{F}(U) &\rightarrow \mathcal{F}^{\text{sh}}(U) \\ f &\mapsto (f|_p)_{p \in U} \end{aligned}$$

for any open set  $U \subseteq X$ . Note  $f \in \mathcal{F}(U)$  does indeed give  $(f|_p)_{p \in U} \in \mathcal{F}^{\text{sh}}(U)$  because each  $p \in U$  can choose  $U_p := U$  (which contains  $p$ ) with lift  $\tilde{f}_p := f$  so that  $\tilde{f}_p|_q = f|_q$  for each  $q \in U_p$ .

Additionally, it is fairly quick to check that  $\text{sh}$  is actually a presheaf morphism: given open sets  $V \subseteq U$  and  $f \in \mathcal{F}(U)$ , we compute

$$\text{sh}_U(f)|_V = (f|_p)_{p \in U}|_V = (f|_p)_{p \in V} = (f|_V|_p)_{p \in V} = \text{sh}_V(f|_V).$$

We are now ready to prove the universal property. Fix any sheaf  $\mathcal{G}$  with a presheaf morphism  $\varphi : \mathcal{F} \rightarrow \mathcal{G}$ . We need to show there is a unique sheaf morphism  $\bar{\varphi} : \mathcal{F}^{\text{sh}} \rightarrow \mathcal{G}$  such that  $\varphi = \bar{\varphi} \circ \text{sh}$ . We show these separately.

- Uniqueness: fix an open set  $U \subseteq X$  and  $(f_p)_{p \in U} \in \mathcal{F}^{\text{sh}}(U)$ , and we will solve for  $\bar{\varphi}_U((f_p)_{p \in U})$ . Well, each  $p \in U$  has some  $U_p \subseteq U$  containing  $p$  with a lift  $\tilde{f}_p \in \mathcal{F}(U_p)$  such that  $\tilde{f}_p|_q = f_q$  for each  $q \in U_p$ . As such, for each  $q \in U$ ,

$$\bar{\varphi}_U((f_p)_{p \in U})|_{U_q} = \bar{\varphi}_{U_q}((f_p)_{p \in U}|_{U_q}) = \bar{\varphi}_{U_q}((f_p)_{p \in U_q}) = \bar{\varphi}_{U_q}((\tilde{f}_p|_p)_{p \in U_q}) = \bar{\varphi}_{U_q}(\text{sh}_{U_q} \tilde{f}_p) = \varphi_{U_q}(\tilde{f}_p).$$

Thus, restrictions  $\bar{\varphi}_U((f_p)_{p \in U})|_{U_q}$  are fixed by  $\varphi$ , so the identity axiom on  $\mathcal{G}$  makes  $\bar{\varphi}_U((f_p)_{p \in U})$  unique.

- Existence: fix an open set  $U \subseteq X$  and  $(f_p)_{p \in U} \in \mathcal{F}^{\text{sh}}(U)$ , and we will define  $\bar{\varphi}_U((f_p)_{p \in U})$ . Well,  $(\varphi_p f_p)_{p \in U}$  is a system of compatible germs in  $\mathcal{G}(U)$  by [Lemma 1.127](#), so there is a unique  $g \in \mathcal{G}(U)$  such that  $g|_p = \varphi_p(f_p)$  for each  $p \in U$ . (Uniqueness is by [Proposition 1.102](#).) Thus, we set  $\bar{\varphi}_U((f_p)_{p \in U}) := g$  so that  $\bar{\varphi}_U((f_p)_{p \in U})$  is the unique section in  $\mathcal{G}(U)$  such that

$$\bar{\varphi}_U((f_p)_{p \in U})|_q = \varphi_q(f_q)$$

for each  $q \in U$ . Note any section  $f \in \mathcal{F}(U)$  has

$$(\bar{\varphi} \circ \text{sh})_U(f)|_q = \bar{\varphi}_U((f|_p)_{p \in U})|_q = \varphi_q(f|_q) = \varphi_U(f)|_q$$

for any  $q \in U$ , so [Proposition 1.102](#) applied to the sheaf  $\mathcal{G}$  forces equality, implying  $\bar{\varphi} \circ \text{sh} = \varphi$ .

So we will be done as soon as we can show  $\bar{\varphi}_U$  is a (pre)sheaf morphism. Well, given open sets  $V \subseteq U$  and some  $(f_p)_{p \in U} \in \mathcal{F}^{\text{sh}}(U)$ , we note any  $q \in V$  has

$$\bar{\varphi}_U((f_p)_{p \in U})|_V|_q = \bar{\varphi}_U((f_p)_{p \in U})|_q = \varphi_q(f_q),$$

so the uniqueness of  $\bar{\varphi}_V((f_p)_{p \in V})$  forces  $\bar{\varphi}_U((f_p)_{p \in U})|_V = \bar{\varphi}_V((f_p)_{p \in U}|_V)$ , as desired. ■

Here are some basic properties.

**Proposition 1.136.** Fix a presheaf  $\mathcal{F}$  on  $X$  with a sheafification  $\text{sh}: \mathcal{F} \rightarrow \mathcal{F}^{\text{sh}}$ . For given  $p \in X$ , the induced map  $\text{sh}_p: \mathcal{F}_p \rightarrow (\mathcal{F}^{\text{sh}})_p$  on stalks is an isomorphism.

*Proof.* We use the explicit description of the sheafification. To be explicit, our map  $\text{sh}_p: \mathcal{F}_p \rightarrow (\mathcal{F}^{\text{sh}})_p$  sends  $[(U, f)]$  to  $[(U, (f|_q)_{q \in U})]$ .

For the inverse morphism  $\pi_p: (\mathcal{F}^{\text{sh}})_p \rightarrow \mathcal{F}_p$ , we simply send

$$\pi_p: [(U, (f_q)_{q \in U})] \mapsto f_p.$$

Notably, this is well-defined:  $[(U, (f_q)_{q \in U})] = [(U', (f'_q)_{q \in U})]$ , then there is  $V \subseteq U \cap U'$  such that  $(f_q)_{q \in U}|_V = (f'_q)_{q \in U'}|_V$ , which implies  $f_p = f'_p$ .

It remains to show that these are inverse. Well, for  $[(U, f)] \in \mathcal{F}_p$ , we see

$$\pi_p(\text{sh}_p([(U, f)])) = \pi_p([(U, (f|_q)_{q \in U})]) = f|_p.$$

And for  $[(U, (f_q)_{q \in U})] \in (\mathcal{F}^{\text{sh}})_p$ , we see

$$\text{sh}_p(\pi_p([(U, (f_q)_{q \in U})])) = \text{sh}_p(f_p).$$

Now, because  $(f_q)_{q \in U}$  is a compatible system of germs, we may find  $U_p \subseteq U$  containing  $p$  with a lift  $\tilde{f}_p \in \mathcal{F}(U_p)$  such that  $\tilde{f}_p|_q = f_q$  for each  $q \in U_p$ . It follows

$$\text{sh}_p(f_p) = \text{sh}_p(\tilde{f}_p|_p) = [(U_p, (\tilde{f}_p|_q)_{q \in U_p})] = [(U_p, (f_q)_{q \in U_p})] = [(U, (f_q)_{q \in U})],$$

finishing this check. ■

**Remark 1.137.** If  $\mathcal{F}$  is itself a sheaf, then we can see fairly directly that  $\mathcal{F}$  satisfies the universal property for  $\mathcal{F}^{\text{sh}}$ . Alternatively, the sheafification map  $\text{sh}: \mathcal{F} \rightarrow \mathcal{F}^{\text{sh}}$  is a sheaf morphism which is an isomorphism on stalks by [Proposition 1.136](#) and thus an isomorphism of sheaves by [Proposition 1.126](#).

**Proposition 1.138.** Sheafification  $\mathcal{F} \mapsto \mathcal{F}^{\text{sh}}$  defines a functor  $(-)^{\text{sh}}: \text{PreSh}_X \rightarrow \text{Sh}_X$  which is left adjoint to the forgetful functor  $U: \text{Sh}_X \rightarrow \text{PreSh}_X$ .

*Proof.* We begin by describing the functor  $(-)^{\text{sh}}$ . We know its behavior on objects, so we still need to know its behavior on morphisms  $\eta: \mathcal{F} \rightarrow \mathcal{G}$ . Well, note that we have a composite map  $\mathcal{F} \rightarrow \mathcal{G} \rightarrow \mathcal{G}^{\text{sh}}$ , and  $\mathcal{G}^{\text{sh}}$  is a sheaf, so the universal property of  $\mathcal{F}^{\text{sh}}$  induces a unique map  $\eta^{\text{sh}}: \mathcal{F}^{\text{sh}} \rightarrow \mathcal{G}^{\text{sh}}$  making the diagram

$$\begin{array}{ccc} \mathcal{F} & \longrightarrow & \mathcal{F}^{\text{sh}} \\ \eta \downarrow & & \downarrow \eta^{\text{sh}} \\ \mathcal{G} & \longrightarrow & \mathcal{G}^{\text{sh}} \end{array}$$

commute. We quickly check functoriality.

- Identity: note  $\text{id}_{\mathcal{F}^{\text{sh}}}$  makes the diagram

$$\begin{array}{ccc} \mathcal{F} & \longrightarrow & \mathcal{F}^{\text{sh}} \\ \text{id}_{\mathcal{F}} \downarrow & & \downarrow \text{id}_{\mathcal{F}^{\text{sh}}} \\ \mathcal{F} & \longrightarrow & \mathcal{F}^{\text{sh}} \end{array}$$

commute, so by definition, we see  $(\text{id}_{\mathcal{F}})^{\text{sh}} = \text{id}_{\mathcal{F}^{\text{sh}}}$ .

- Functoriality: given presheaf morphisms  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  and  $\psi: \mathcal{G} \rightarrow \mathcal{H}$ , we note that  $\psi^{\text{sh}} \circ \varphi^{\text{sh}}$  makes the outer rectangle of

$$\begin{array}{ccc} \mathcal{F} & \longrightarrow & \mathcal{F}^{\text{sh}} \\ \downarrow \varphi & & \downarrow \varphi^{\text{sh}} \\ \mathcal{G} & \longrightarrow & \mathcal{G}^{\text{sh}} \\ \downarrow \psi & & \downarrow \psi^{\text{sh}} \\ \mathcal{H} & \longrightarrow & \mathcal{H}^{\text{sh}} \end{array} \quad \begin{array}{c} \text{---} \varphi^{\text{sh}} \text{---} \\ \text{---} \psi^{\text{sh}} \text{---} \\ \text{---} \psi^{\text{sh}} \circ \varphi^{\text{sh}} \text{---} \end{array}$$

commute, so by definition, we see  $\psi^{\text{sh}} \circ \varphi^{\text{sh}} = (\psi \circ \varphi)^{\text{sh}}$ .

We will not check that the forgetful functor  $U$  is a functor; the main point is that it does nothing to morphisms. Also, we will not formally check the adjoint pair, but we will say that it requires exhibit a natural isomorphism

$$\text{Mor}_{\text{Sh}_X}(\mathcal{F}^{\text{sh}}, \mathcal{G}) \simeq \text{Mor}_{\text{PreSh}_X}(\mathcal{F}, U\mathcal{G})$$

where  $\mathcal{F} \in \text{PreSh}_X$  and  $\mathcal{G} \in \text{Sh}_X$ . And we will describe this isomorphism: if  $\text{sh}: \mathcal{F} \rightarrow \mathcal{F}^{\text{sh}}$  is the sheafification map, the isomorphism is given by

$$\begin{array}{ccc} \text{Mor}_{\text{Sh}_X}(\mathcal{F}^{\text{sh}}, \mathcal{G}) & \simeq & \text{Mor}_{\text{PreSh}_X}(\mathcal{F}, U\mathcal{G}) \\ \varphi & \mapsto & \varphi \circ \text{sh} \\ \overline{\psi} & \leftarrow & \psi \end{array}$$

where  $\overline{\psi}$  is the morphism induced by the universal property of sheafification applied to the presheaf morphism  $\psi: \mathcal{F} \rightarrow \mathcal{G}$ . That this is an isomorphism follows from the universal property, and the naturality checks for the adjoint pair are a matter of writing down the squares and checking them. ■

**Remark 1.139.** Sheafification being a left adjoint means that it preserves limits. Kernels and limits, so we see that the sheafification of the presheaf kernel is just the presheaf kernel again. The point here is that we don't need to sheafify the kernel, which is why we could talk about them before sheafification, but we will not be so lucky with cokernels.

### 1.5.2 Sheaf Cokernels

Now that we have sheafification, we may continue showing that the category sheaves valued in an abelian category is abelian. For this, we need to understand cokernels.

**Definition 1.140 (Sheaf cokernel).** Fix a morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of presheaves on  $X$ . Then the *presheaf cokernel*  $\text{coker}^{\text{pre}} \varphi$  is the sheaf found by setting

$$(\text{coker}^{\text{pre}} \varphi)(U) := \text{coker } \varphi_U = \mathcal{G}(U) / \text{im } \varphi_U.$$

We define the *sheaf kernel* as the sheafification of the presheaf  $\text{coker}^{\text{pre}} \varphi$ .

We begin by running our checks on the presheaf cokernel.

**Lemma 1.141.** Fix a presheaf morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$ . Then  $\text{coker}^{\text{pre}} \varphi$  is a presheaf, and it is the cokernel of  $\varphi$  in the category  $\text{PreSh}_X$ .

*Proof.* To begin, we must exhibit our restriction maps. Given open sets  $V \subseteq U$  and  $[g] \in (\text{coker}^{\text{pre}} \varphi)(U) = \text{coker } \varphi_U$ , we define

$$\text{res}_{U,V}([g]) := [g|_V].$$

Note this is well-defined: if  $[g] = [g']$ , then  $g - g' \in \text{im } \varphi_U$ , so write  $g - g' = \varphi_U(f)$  for  $f \in \mathcal{F}(U)$ . Thus,  $g|_V - g'|_V = (g - g')|_V = \varphi_U(f)|_V = \varphi_V(f|_V)$  is in the image of  $\varphi_V$ , so  $[g|_V] = [g'|_V]$ .

We quickly check that this data assembles into a presheaf.

- **Identity:** given  $g \in (\text{coker}^{\text{pre}} \varphi)(U)$ , note  $[g]|_U = [g|_U] = [g]$ .
- **Functoriality:** given open sets  $W \subseteq V \subseteq U$  and some  $g \in (\text{coker}^{\text{pre}} \varphi)(U)$ , we see  $[g]|_V|_W = [g|_V]|_W = [g|_V|_W] = [g|_W] = [g]|_W$ .

It remains to check the universal property: we need  $\text{coker}^{\text{pre}} \varphi$  to be the colimit of the following diagram.

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \\ \downarrow & & \\ \mathcal{Z} & & \end{array}$$

To begin, we define a morphism  $\pi: \mathcal{G} \rightarrow \text{coker}^{\text{pre}} \varphi$ . Well, for each open  $U \subseteq X$ , there is a natural projection  $\pi_U: \mathcal{G}(U) \rightarrow \text{coker } \varphi_U$  by  $\pi_U: g \mapsto [g]$ , which we need to assemble into a natural transformation. Indeed, given open sets  $V \subseteq U$  and a section  $g \in \mathcal{G}(U)$ , we compute

$$\pi_U(g)|_V = [g]|_V = [g|_V] = \pi_V(g|_V).$$

This map  $\pi: \mathcal{G} \rightarrow \text{coker}^{\text{pre}} \varphi$  induces the other needed maps  $\mathcal{F} \rightarrow \text{coker}^{\text{pre}} \varphi$  (as  $\pi \circ \varphi$ ) and  $\mathcal{Z} \rightarrow \text{coker}^{\text{pre}} \varphi$  (which is the zero map). Further, note that any open  $U \subseteq X$  has  $(\pi \circ \varphi)_U = \pi_U \circ \varphi_U = 0$  because  $\pi_U$  returns 0 on  $\text{im } \varphi_U$ ; thus,  $\pi \circ \varphi = 0$ . Thus, the diagram

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \\ \downarrow & & \downarrow \pi \\ \mathcal{Z} & \longrightarrow & \text{coker}^{\text{pre}} \varphi \end{array}$$

commutes.

We are now ready to show the universal property. Fix a presheaf  $\mathcal{H}$  with a map  $\psi: \mathcal{G} \rightarrow \mathcal{H}$  such that  $\psi \circ \varphi = 0$ . Then we need a unique map  $\bar{\psi}: (\text{coker}^{\text{pre}} \varphi) \rightarrow \mathcal{H}$  such that  $\psi = \bar{\psi} \circ \pi$ ; i.e., such that the diagram

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \\ \downarrow & & \downarrow \pi \\ \mathcal{Z} & \xrightarrow{\quad} & \text{coker}^{\text{pre}} \varphi \end{array} \quad \begin{array}{c} \searrow \psi \\ \text{---} \bar{\psi} \text{---} \\ \searrow \end{array} \quad \begin{array}{c} \\ \\ \mathcal{H} \end{array}$$

commutes. We show uniqueness and existence of  $\bar{\psi}$  separately.

- Uniqueness: given an open set  $U \subseteq X$  and some  $[g] \in (\text{coker}^{\text{pre}} \varphi)(U)$ , we must have

$$\bar{\psi}_U([g]) = \bar{\psi}_U(\pi_U g) = \psi_U(g),$$

so  $\bar{\psi}_U$  is uniquely determined.

- Existence: given an open set  $U \subseteq X$  and some  $[g] \in (\text{coker}^{\text{pre}} \varphi)(U)$ , we simply define

$$\bar{\psi}_U([g]) := \psi_U(g).$$

Note this is well-defined: if  $[g] = [g']$ , then  $g - g' \in \text{im } \varphi_U$ , so write  $g - g' = \varphi_U(f)$ . Then  $\psi_U(g) - \psi_U(g') = \psi_U(\varphi_U f) = 0$ , so  $\psi_U(g) = \psi_U(g')$ .

Additionally, we note that any  $g \in \mathcal{G}(U)$  will have  $\bar{\psi}_U(\pi_U g) = \bar{\psi}_U([g]) = \psi_U(g)$ , so we conclude  $\bar{\psi} \circ \pi = \psi$ . It remains to show that  $\bar{\psi}$  is actually a presheaf morphism. Well, any open sets  $V \subseteq U$  and  $[g] \in (\text{coker}^{\text{pre}} \varphi)(U)$  has

$$\bar{\psi}_U([g])|_V = \psi_U(g)|_V = \psi_V(g|_V) = \bar{\psi}_V([g|_V]) = \bar{\psi}_V([g]|_V),$$

finishing. ■

And now we run the checks on the sheaf kernel.

**Lemma 1.142.** Fix a morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of sheaves on  $X$ . Then  $\text{coker } \varphi$  is the cokernel in the category  $\text{Sh}_X$ .

*Proof.* Let  $\pi^{\text{pre}}: \mathcal{G} \rightarrow \text{coker}^{\text{pre}} \varphi$  be the projection map of Lemma 1.141 and  $\text{sh}: \text{coker}^{\text{pre}} \varphi \rightarrow \text{coker } \varphi$  be the sheafification map. Then we define  $\pi := \text{sh} \circ \pi^{\text{pre}}$ , so we claim that this map makes  $\text{coker } \varphi$  the colimit of the following diagram.

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \\ \downarrow & & \downarrow \pi \\ \mathcal{Z} & \xrightarrow{\quad} & \text{coker } \varphi \end{array}$$

Notably, we have  $\pi \circ \varphi = \text{sh} \circ \pi^{\text{pre}} \circ \varphi = \text{sh} \circ 0 = 0$ , so  $\pi$  at least works as a candidate morphism.

To show the universal property, fix a sheaf  $\mathcal{H}$  with a map  $\psi: \mathcal{G} \rightarrow \mathcal{H}$  such that  $\psi \circ \varphi = 0$ . Then we need a unique map  $\bar{\psi}: \text{coker } \varphi \rightarrow \mathcal{H}$  such that  $\psi = \bar{\psi} \circ \pi$ , or equivalently, making

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \\ \downarrow & & \downarrow \pi \\ \mathcal{Z} & \xrightarrow{\quad} & \text{coker } \varphi \end{array} \quad \begin{array}{c} \searrow \psi \\ \text{---} \bar{\psi} \text{---} \\ \searrow \end{array} \quad \begin{array}{c} \\ \\ \mathcal{H} \end{array}$$

commute. We show existence and uniqueness separately.

- Existence: working in  $\text{PreSh}_X$  for a moment, the fact that  $\psi \circ \varphi = 0$  promises a map  $\bar{\psi}^{\text{pre}}: \text{coker}^{\text{pre}} \varphi \rightarrow \mathcal{H}$  such that  $\bar{\psi}^{\text{pre}} \circ \pi^{\text{sh}} = \psi$ . Now, from the definition of sheafification, we get a map  $\bar{\psi}: \text{coker} \varphi \rightarrow \mathcal{H}$  such that

$$\bar{\psi} \circ \text{sh} = \bar{\psi}^{\text{pre}}.$$

Thus,  $\bar{\psi} \circ \pi = \bar{\psi} \circ \text{sh} \circ \pi^{\text{pre}} = \bar{\psi}^{\text{pre}} \circ \pi^{\text{pre}} = \psi$ , as needed.

- Uniqueness: suppose  $\bar{\psi}_1, \bar{\psi}_2: \text{coker} \varphi \rightarrow \mathcal{H}$  have  $\psi = \bar{\psi}_1 \circ \pi = \bar{\psi}_2 \circ \pi$ . Then we see that actually

$$\psi = (\bar{\psi}_1 \circ \text{sh}) \circ \pi^{\text{pre}} = (\bar{\psi}_2 \circ \text{sh}) \circ \pi^{\text{pre}},$$

but the universal property of  $\text{coker}^{\text{pre}} \varphi$  has a uniqueness forcing  $\bar{\psi}_1 \circ \text{sh} = \bar{\psi}_2 \circ \text{sh}$ . But then the universal property of sheafification says there is a unique map  $\bar{\psi}: \text{coker} \varphi \rightarrow \mathcal{H}$  such that

$$\bar{\psi} \circ \text{sh} = \bar{\psi}_1 \circ \text{sh} = \bar{\psi}_2 \circ \text{sh},$$

so  $\bar{\psi} = \bar{\psi}_1 = \bar{\psi}_2$  follows. ■

As before, we take a moment to verify that vanishing cokernel does indeed mean epic.

**Lemma 1.143.** Let  $\mathcal{C}$  be a category with a zero object and cokernels. Then a morphism  $\varphi: A \rightarrow B$  is epic if and only if  $\text{coker} \varphi$  vanishes.

*Proof.* Reverse all the arrows in Lemma 1.121. Notably, the dual of the kernel is the cokernel, the dual of a monic map is an epic map, and the dual of the zero object is still the zero object. ■

### 1.5.3 Surjectivity at Stalks

We are now ready to fix our surjectivity. Just like injectivity, we can check surjectivity at stalks.

**Lemma 1.144.** Fix a morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of presheaves on  $X$ . Then, for any  $p$ , the projection  $\mathcal{G} \rightarrow \text{coker}^{\text{pre}} \varphi$  induces an isomorphism

$$\text{coker} \varphi_p \rightarrow (\text{coker}^{\text{pre}} \varphi)_p.$$

Thus, if  $\mathcal{F}$  and  $\mathcal{G}$  are sheaves, then the projection  $\mathcal{G} \rightarrow \text{coker} \varphi$  induces an isomorphism  $\text{coker} \varphi_p \simeq (\text{coker} \varphi)_p$ .

*Proof.* Let  $\pi^{\text{pre}}: \mathcal{G} \rightarrow \text{coker}^{\text{pre}} \varphi$  be the natural projection witnessing that  $\text{coker}^{\text{pre}} \varphi$  is the presheaf cokernel.

To show the second sentence note  $\pi^{\text{pre}}$  induces a map  $\mathcal{G}_p \rightarrow (\text{coker}^{\text{pre}} \varphi)_p$  as

$$\pi_p^{\text{pre}}: [(U, g)] \mapsto [(U, \pi_U^{\text{pre}} g)].$$

Note that, if  $[(U, g)] \in \text{im} \varphi_p$ , then we can write  $[(U, g)] = [(V, \varphi_V f)]$  for some  $f \in \mathcal{F}(V)$ , so

$$\pi_p^{\text{pre}}(f|_p) = (\pi_V^{\text{pre}} f)|_p = 0|_p = 0,$$

so  $\text{im} \varphi_p \subseteq \ker \pi_p^{\text{pre}}$ , so we have actually induced a map  $\text{coker} \varphi_p \rightarrow (\text{coker}^{\text{pre}} \varphi)_p$ .

In the other direction, we define  $\varphi_p: (\text{coker}^{\text{pre}} \varphi)_p \rightarrow \text{coker} \varphi_p$  by

$$\varphi_p: [(U, [g])] \mapsto (g|_p + \text{im} \varphi_p).$$

We do need to check that this is well-defined: if  $(U, [g]) \sim (U', [g'])$ , then we can find  $V \subseteq U \cap U'$  such that  $[(g - g')|_V] = [g]|_V - [g']|_V = 0$ , so there is  $f \in \mathcal{F}(V)$  such that  $(g - g')|_V = \varphi_V(f)$ . Thus,  $g|_p - g'|_p = (g - g')|_p = (g - g')|_V|_p = \varphi_V(f)|_p$  is in  $\text{im} \varphi_p$ .

Lastly, we need to check that  $\pi_p^{\text{pre}}$  and  $\varphi_p$  are inverse. Given  $[(U, g)] + \text{im } \varphi_p \in \text{coker } \varphi_p$ , we note

$$\varphi_p(\pi_p^{\text{pre}}([(U, g)] + \text{im } \varphi_p)) = \varphi_p([(U, [g])]) = g|_p + \text{im } \varphi_p.$$

Conversely, given  $[(U, [g])] \in (\text{coker}^{\text{pre}} \varphi)_p$ , we note

$$\pi_p^{\text{pre}}(\varphi_p([(U, [g])])) = \pi_p^{\text{pre}}([(U, g)] + \text{im } \varphi_p) = [(U, [g])],$$

finishing.

We now show the last sentence. Let  $\text{sh}: \text{coker}^{\text{pre}} \varphi \rightarrow \text{coker } \varphi$  be the sheafification map. Then  $\pi_p = (\text{sh} \circ \pi_p^{\text{pre}})_p$  we can check to be  $\text{sh}_p \circ \pi_p^{\text{pre}}$  (by, say, [Remark 1.106](#)). Stringing these isomorphisms together, we see

$$\text{coker } \varphi_p \rightarrow (\text{coker}^{\text{pre}} \varphi)_p \simeq (\text{coker } \varphi)_p,$$

which is what we wanted. ■

And here is our result.

**Proposition 1.145.** Fix a morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of sheaves on  $X$ . The following are equivalent.

- (a)  $\varphi$  is epic.
- (b)  $(\text{coker } \varphi)(U)$  vanishes for all open  $U \subseteq X$ .
- (c)  $\varphi_p$  is epic for all  $p \in X$ .

*Proof.* By [Lemma 1.143](#), these are equivalent to the following.

- (a')  $\text{coker } \varphi$  vanishes.
- (b')  $(\text{coker } \varphi)(U)$  vanishes for all open  $U \subseteq X$ .
- (c')  $\text{coker } \varphi_p$  vanishes for all  $p \in X$ . By [Lemma 1.144](#), this is equivalent to  $(\text{coker } \varphi)_p$  vanishing for all  $p \in X$ .

These are equivalent by [Lemma 1.123](#). ■

### 1.5.4 The Category of Sheaves Is Abelian

Now that our category of sheaves (valued in an abelian category) has kernels and cokernels for our morphisms, we have two more conditions to check.

**Lemma 1.146.** Fix a monic morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of sheaves on  $X$ . Then actually  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  makes  $\mathcal{F}$  the kernel of the cokernel  $\pi: \mathcal{G} \rightarrow \text{coker } \varphi$ .

*Proof.* We need to show that  $\mathcal{F}$  is the limit of the following diagram.

$$\begin{array}{ccc} & \mathcal{G} & \\ & \downarrow \pi & \\ \mathcal{Z} & \longrightarrow & \text{coker } \varphi \end{array}$$

To begin, note that  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  makes the diagram

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \\ \downarrow & & \downarrow \pi \\ \mathcal{Z} & \longrightarrow & \text{coker } \varphi \end{array}$$



commute by the construction of  $\pi: \mathcal{G} \rightarrow \text{coker } \varphi$ . We now show that  $\mathcal{F}$  satisfies the universal property. Fix a sheaf morphism  $\psi: \mathcal{H} \rightarrow \mathcal{G}$  such that  $\pi \circ \psi = 0$ . Then we need a unique map  $\bar{\psi}: \mathcal{H} \rightarrow \mathcal{F}$  making the diagram

$$\begin{array}{ccccc} \mathcal{H} & & & & \\ & \searrow \bar{\psi} & & \searrow \psi & \\ & \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} & \\ & \downarrow & & \downarrow \pi & \\ & \mathcal{Z} & \longrightarrow & \text{coker } \varphi & \end{array}$$

commute; i.e., we need  $\psi = \varphi \circ \bar{\psi}$ . We show uniqueness and existence separately.

- Uniqueness: this follows because  $\varphi$  is monic. Indeed, if  $\bar{\psi}_1, \bar{\psi}_2$  have  $\varphi \circ \bar{\psi}_1 = \psi = \varphi \circ \bar{\psi}_2$ , then  $\bar{\psi}_1 = \bar{\psi}_2$  because  $\varphi$  is monic.
- Existence: this is trickier. Let  $\pi^{\text{pre}}: \mathcal{G} \rightarrow \text{coker}^{\text{pre}} \varphi$  be the natural projection, and let  $\text{sh}: \text{coker}^{\text{pre}} \varphi \rightarrow \text{coker } \varphi$  be the sheafification map.

Now, given  $U \subseteq X$  and  $h \in \mathcal{H}(U)$ , set  $g := \psi_U(h)$  for brevity. Notably, we have  $\pi_U \circ \psi_U = 0$ , so  $\pi_U(g) = 0$ . It follows  $\pi_p(g|_p) = \pi_U(g)|_p = 0$  for each  $p \in U$ , so  $g|_p \in \ker \pi_p$  for each  $p \in U$ . Now, for each  $p \in U$ , by [Lemma 1.144](#),  $\ker \pi_p = \text{im } \varphi_p$ , and by [Proposition 1.124](#),  $\varphi_p$  is monic, so is a unique  $f_p \in \mathcal{F}_p$  such that

$$\varphi_p(f_p) = g|_p.$$

We claim that  $(f_p)_{p \in U}$  is a system of compatible germs. To begin, choose some representative  $f_p = [(U'_p, \tilde{f}_p)]$  and note that we have

$$[(U, g)] = g|_p = \varphi_p(f_p) = [(U'_p, \varphi_{U'_p}(\tilde{f}_p))],$$

so we can find  $U_p \subseteq U'_p$  containing  $p$  with  $\tilde{f}_p = \tilde{f}'_p|_{U_p}$  small enough so that  $g|_{U_p} = \varphi_{U_p}(\tilde{f}_p)$ . As such, any  $q \in U_p$  has

$$\varphi_q(\tilde{f}_p|_q) = [(U_p, \varphi_{U_p}(\tilde{f}_p))] = [(U_p, g|_{U_p})] = g|_p,$$

so  $\tilde{f}_p|_q = f_q$  follows.

Thus, [Proposition 1.102](#) promises a unique  $f \in \mathcal{F}(U)$  such that  $f|_p = f_p$  for each  $p \in U$ . So we define  $\bar{\psi}_U(h) := f$  to be the unique element such that

$$\varphi_p(\bar{\psi}_U(h)|_p) = \psi_U(h)|_p$$

for all  $p \in U$ .

It remains to show that  $\bar{\psi}$  assembles into a presheaf morphism. Well, for open sets  $V \subseteq U$  and  $h \in \mathcal{H}(U)$ , we see that any  $p \in V$  will have

$$\varphi_p(\bar{\psi}_U(h)|_V|_p) = \varphi_p(\bar{\psi}_U(h)|_p) = \psi_U(h)|_p = \psi_V(h|_V)|_p,$$

so the uniqueness of  $\psi_V(h|_V)$  forces  $\bar{\psi}_U(h)|_V = \bar{\psi}_V(h|_V)$ . ■

**Lemma 1.147.** Fix an epic morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of sheaves on  $X$ . Then actually  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  makes  $\mathcal{G}$  the cokernel of the kernel  $\iota: \ker \varphi \rightarrow \mathcal{F}$ .

*Proof.* We need to show that  $\mathcal{G}$  is the colimit of the following diagram.

$$\begin{array}{ccc} \ker \varphi & \longrightarrow & \mathcal{Z} \\ \downarrow \iota & & \\ \mathcal{F} & & \end{array}$$

To begin, note that  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  makes the diagram

$$\begin{array}{ccc} \ker \varphi & \longrightarrow & \mathcal{Z} \\ \downarrow \iota & & \downarrow \\ \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \end{array}$$

commute by the construction of  $\iota: \ker \varphi \rightarrow \mathcal{G}$ . We are now ready to show that  $\mathcal{G}$  satisfies the universal property. Fix a sheaf  $\mathcal{H}$  with a morphism  $\psi: \mathcal{F} \rightarrow \mathcal{H}$  such that  $\psi \circ \iota = 0$ . We need a unique map  $\bar{\psi}: \mathcal{G} \rightarrow \mathcal{H}$  such that  $\psi = \bar{\psi} \circ \varphi$ , or equivalently, making the diagram

$$\begin{array}{ccc} \ker \varphi & \longrightarrow & \mathcal{Z} \\ \downarrow \iota & & \downarrow \\ \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} \end{array} \quad \begin{array}{c} \searrow \psi \\ \downarrow \bar{\psi} \end{array}$$

commute. We show uniqueness and existence separately.

- **Uniqueness:** this follows because  $\varphi$  is epic. Indeed, if  $\bar{\psi}_1, \bar{\psi}_2: \mathcal{G} \rightarrow \mathcal{H}$  have  $\bar{\psi}_1 \circ \varphi = \psi = \bar{\psi}_2 \circ \varphi$ , then  $\bar{\psi}_1 = \bar{\psi}_2$  because  $\varphi$  is epic.
- **Existence:** given  $U \subseteq X$  and  $g \in \mathcal{G}(U)$ , we define  $\bar{\psi}_U(g)$  by hand. By [Proposition 1.145](#), we see that  $\varphi$  being epic means that  $\varphi_p$  is surjective for each  $p \in U$ , we can find  $f_p \in \mathcal{F}_p$  with  $\varphi_p(f_p) = g|_p$  for each  $p$ . We now set

$$h_p := \psi_p(f_p).$$

We claim that  $h_p$  is independent of the choice for  $f_p$ . Indeed, if we have  $[(U, f)]$  and  $[(U', f')]$  in  $\mathcal{F}_p$  with  $[(U, \varphi_U f)] = [(U', \varphi_{U'} f')] = g|_p$ , then there is an open  $V \subseteq U \cap U'$  such that  $\varphi_V(f|_V - f'|_V) = 0$ . Thus,  $f - f' \in \ker \varphi_V = (\ker \varphi)(V)$ , so it follows  $\psi_V((f - f')|_V) = 0$ . Thus, so

$$\psi_p([(U, f)]) - \psi_p([(U', f')]) = \psi_p([(V, \psi_V((f - f')|_V)])] = \psi_p([(V, 0)]) = 0.$$

Next, we claim that the  $(h_p)_{p \in U}$  forms a compatible system of germs. Well, for each  $p \in U$ , we can find a sufficiently small open set  $U_p$  with a lift  $\tilde{f}_p \in \mathcal{F}(U_p)$  such that  $\varphi_{U_p}(\tilde{f}_p) = g|_{U_p}$ . Set  $\tilde{h}_p := \psi_{U_p}(\tilde{f}_p)$  so that for each  $q \in U_p$  has  $\varphi_q(\tilde{f}_p|_q) = \varphi_{U_p}(\tilde{f}_p)|_q = g|_q$  and thus

$$h_q = \psi_q(\tilde{f}_p|_q) = \psi_{U_p}(\tilde{f}_p)|_q.$$

It follows [Proposition 1.102](#) that we have a unique  $h \in \mathcal{H}(U)$  such that  $h|_p = h_p$  for each  $p \in U$ , so we define  $\bar{\psi}_U(g) := h$ . Explicitly,  $\bar{\psi}_U(g)$  is the unique element of  $\mathcal{H}(U)$  such that

$$\bar{\psi}_U(g)|_p = \psi_p(\varphi_p^{-1}(g|_p))$$

for each  $p \in U$ .

We now run checks on  $\bar{\psi}$ . To see that we have a morphism  $\mathcal{G} \rightarrow \mathcal{H}$ , note that any opens  $V \subseteq U$  and  $g \in \mathcal{G}(U)$  will have, for each  $p \in U$ ,

$$\bar{\psi}_U(g)|_V|_p = \bar{\psi}_U(g)|_p = \psi_p(\varphi_p^{-1}(g|_p)) = \psi_p(\varphi_p^{-1}(g|_V|_p)),$$

so the uniqueness of  $\bar{\psi}_V(g|_V)$  forces  $\bar{\psi}_U(g)|_V = \bar{\psi}_V(g|_V)$ .

Lastly, we note that  $\psi = \bar{\psi} \circ \varphi$ : for any open  $U \subseteq X$  and  $f \in \mathcal{F}(U)$ , all points  $p \in U$  give

$$\bar{\psi}_U(\varphi_U(f))|_p = \psi_p(\varphi_p^{-1}(\varphi_U(f)|_p)) = \psi_p(\varphi_p^{-1}(\varphi_p(f|_p))) = \psi_p(f|_p) = \psi_U(f)|_p,$$

so the injectivity of [Proposition 1.102](#) forces our equality. ■

And here is our result.

**Theorem 1.148.** The category  $\text{Sh}_X$  of sheaves on a topological space  $X$  valued in a (concrete) abelian category  $\mathcal{C}$  is additive.

*Proof.* The category is additive by [Corollary 1.116](#). Kernels exist by [Lemma 1.119](#), and cokernels exist by [Lemma 1.142](#). The last conditions to check are [Lemma 1.146](#) and [Lemma 1.147](#). ■

### 1.5.5 Exactness via Stalks

It is a general philosophy, well-exhibited by [Theorem 1.148](#), that we can prove (categorical) facts about sheaves by passing to stalks. Here is an example.

**Proposition 1.149.** Let  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  be a morphism of presheaves on  $X$  valued in an abelian category. Then  $\text{coker } \varphi \simeq \text{coker } \varphi^{\text{sh}}$ .

*Proof.* We merely need to exhibit a candidate isomorphism and then check that it is an isomorphism on stalks. Here is our diagram.

$$\begin{array}{ccccccc} \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} & \xrightarrow{\pi} & \text{coker}^{\text{pre}} \varphi & \xrightarrow{\text{sh}} & \text{coker } \varphi \\ \text{sh} \downarrow & & \downarrow \text{sh} & & & & \\ \mathcal{F}^{\text{sh}} & \xrightarrow{\varphi^{\text{sh}}} & \mathcal{G}^{\text{sh}} & \xrightarrow{\pi'} & \text{coker}^{\text{pre}} \varphi^{\text{sh}} & \xrightarrow{\text{sh}} & \text{coker } \varphi^{\text{sh}} \end{array}$$

Note that the composite  $\mathcal{F} \rightarrow \mathcal{G} \rightarrow \mathcal{G}^{\text{sh}} \rightarrow \text{coker}^{\text{pre}} \varphi \rightarrow \text{coker } \varphi^{\text{sh}}$  is the zero map because it is the same as the same as

$$\mathcal{F} \rightarrow \underbrace{\mathcal{F}^{\text{sh}} \rightarrow \mathcal{G}^{\text{sh}} \rightarrow \text{coker}^{\text{pre}} \varphi^{\text{sh}}}_{0} \rightarrow \text{coker } \varphi^{\text{sh}}.$$

Thus, the universal property of  $\text{coker } \varphi$  induces a unique sheaf morphism  $\psi: \text{coker}^{\text{pre}} \varphi \rightarrow \text{coker } \varphi^{\text{sh}}$  making

$$\begin{array}{ccccccc} \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} & \xrightarrow{\pi} & \text{coker}^{\text{pre}} \varphi & \xrightarrow{\text{sh}} & \text{coker } \varphi \\ \text{sh} \downarrow & & \downarrow \text{sh} & & \downarrow \psi & & \\ \mathcal{F}^{\text{sh}} & \xrightarrow{\varphi^{\text{sh}}} & \mathcal{G}^{\text{sh}} & \xrightarrow{\pi'} & \text{coker}^{\text{pre}} \varphi^{\text{sh}} & \xrightarrow{\text{sh}} & \text{coker } \varphi^{\text{sh}} \end{array}$$

commute. Now, sheafification promises a unique map  $\psi^{\text{sh}}$  making

$$\begin{array}{ccccccc} \mathcal{F} & \xrightarrow{\varphi} & \mathcal{G} & \xrightarrow{\pi} & \text{coker}^{\text{pre}} \varphi & \xrightarrow{\text{sh}} & \text{coker } \varphi \\ \text{sh} \downarrow & & \downarrow \text{sh} & & \downarrow \psi & & \downarrow \psi^{\text{sh}} \\ \mathcal{F}^{\text{sh}} & \xrightarrow{\varphi^{\text{sh}}} & \mathcal{G}^{\text{sh}} & \xrightarrow{\pi'} & \text{coker}^{\text{pre}} \varphi^{\text{sh}} & \xrightarrow{\text{sh}} & \text{coker } \varphi^{\text{sh}} \end{array}$$

commute. We claim that  $\psi^{\text{sh}}$  is the desired isomorphism, for which it suffices by [Proposition 1.126](#) to take stalks at  $p \in X$  everywhere. This gives the following diagram.

$$\begin{array}{ccccccc} \mathcal{F}_p & \xrightarrow{\varphi_p} & \mathcal{G}_p & \xrightarrow{\pi_p} & (\text{coker}^{\text{pre}} \varphi)_p & \xrightarrow{\text{sh}_p} & (\text{coker } \varphi)_p \\ \text{sh}_p \downarrow & & \downarrow \text{sh}_p & & \downarrow \psi_p & & \downarrow \psi_p^{\text{sh}} \\ \mathcal{F}_p^{\text{sh}} & \xrightarrow{\varphi_p^{\text{sh}}} & \mathcal{G}_p^{\text{sh}} & \xrightarrow{\pi'_p} & (\text{coker}^{\text{pre}} \varphi^{\text{sh}})_p & \xrightarrow{\text{sh}_p} & (\text{coker } \varphi^{\text{sh}})_p \end{array}$$

All the  $\text{sh}_p$  morphisms are isomorphisms by [Proposition 1.136](#), so to show  $\psi_p^{\text{sh}}$  is an isomorphism, it suffices to show that  $\psi_p$  is an isomorphism. Now, by [Lemma 1.144](#), we see that  $\text{im } \varphi_p$  lives in the kernel of  $\mathcal{G}_p \rightarrow$

$(\text{coker}^{\text{pre}} \varphi)_p$  and analogously for the bottom row. So the fact that the  $\text{sh}_p$ s are isomorphisms induces the diagram

$$\begin{array}{ccc} \mathcal{G}_p / \text{im } \varphi_p & \xrightarrow{\bar{\pi}_p} & (\text{coker}^{\text{pre}} \varphi)_p \\ \downarrow \text{sh}_p & & \downarrow \psi_p \\ \mathcal{G}_p^{\text{sh}} / \text{im } \varphi_p & \xrightarrow{\bar{\pi}'_p} & (\text{coker}^{\text{pre}} \varphi^{\text{sh}})_p \end{array}$$

where  $\text{sh}_p$  is still an isomorphism because it was an isomorphism before. However, [Lemma 1.144](#) actually tells us that this map  $\pi_p$  from  $\mathcal{G}_p / \text{im } \varphi_p = \text{coker } \varphi_p$  to  $(\text{coker}^{\text{pre}} \varphi)_p$  is an isomorphism, and analogous holds for the bottom row, so it follows that  $\psi_p$  is an isomorphism. This finishes. ■

**Remark 1.150.** Thinking about cokernels as quotients, [Proposition 1.149](#) roughly says that  $(\mathcal{F}/\mathcal{G})^{\text{sh}} \simeq (\mathcal{F}^{\text{sh}}/\mathcal{G}^{\text{sh}})^{\text{sh}}$ , where the “embedding”  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  has been made implicit.

As an example application, we define the sheaf image.

**Definition 1.151 (Sheaf image).** Fix a morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of presheaves on  $X$ . Then the *sheaf image*  $\text{im } \varphi$  of  $\varphi$  is the sheafification of the presheaf image

$$(\text{im}^{\text{pre}} \varphi)(U) = \text{im } \varphi_U.$$

We go ahead and check that we have an image presheaf very quickly.

**Lemma 1.152.** Fix a morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of presheaves on  $X$ . Then  $\text{im}^{\text{pre}} \varphi$  is a presheaf on  $X$ .

*Proof.* We quickly define restriction maps in the obvious way. Given a containment  $U \subseteq V$ , we define  $\text{res}_{U,V}: \text{im } \varphi_U \rightarrow \text{im } \varphi_V$  by restricting  $\text{res}_{U,V}: \mathcal{G}(U) \rightarrow \mathcal{G}(V)$ . This is well-defined: if  $g \in (\text{im}^{\text{pre}} \varphi)(U) = \text{im } \varphi_U$ , then we write  $g = \varphi_U(f)$  for some  $f \in \mathcal{F}(U)$ , so  $g|_V = \varphi_U(f)|_V = \varphi_V(f|_V) \in \text{im } \varphi_V$ .

Now, here are our presheaf checks.

- Identity: note  $g \in \text{im } \varphi_U$  has  $g|_U = g$ .
- Functoriality: given open sets  $W \subseteq V \subseteq U$  and  $g \in \text{im } \varphi_U$ , we have  $g|_V|_W = g|_W$ . ■

**Remark 1.153.** Note there is an obvious inclusion  $\iota_U^{\text{pre}}: (\text{im}^{\text{pre}} \varphi)(U) \rightarrow \mathcal{G}(U)$  by  $g \mapsto g$ . This assembles into a presheaf morphism: given open sets  $V \subseteq U$  and  $g \in (\text{im}^{\text{pre}} \varphi)(U)$ , we have

$$\iota_U^{\text{pre}}(g)|_V = g|_V = \iota_V^{\text{pre}}(g|_V).$$

Thus, when  $\mathcal{G}$  is a sheaf, sheafification induces a unique sheaf morphism  $\iota: \text{im } \varphi \rightarrow \mathcal{G}$ .

We quickly check that our sheaf image is the categorical sheaf.

**Proposition 1.154.** Fix a morphism  $\varphi: \mathcal{F} \rightarrow \mathcal{G}$  of sheaves on  $X$ , and let  $\pi: \mathcal{G} \rightarrow \text{coker } \varphi$  be the canonical projection. Then

$$\text{im } \varphi \simeq \ker \pi.$$

*Proof.* Pass to stalks. ■

Having defined an image sheaf, we may deal with exactness.

**Definition 1.155** (Exact sequence). Fix an abelian category  $\mathcal{C}$ . Then a sequence of maps

$$A \xrightarrow{f} B \xrightarrow{g} C$$

is exact at  $B$  if and only if  $\text{im } f \simeq \ker g$ . More precisely, this is asking for the image of  $f$ , thought of as  $\iota: \text{im } f \rightarrow B$ , to be a kernel of  $g$ .

And here is our main result.

**Proposition 1.156.** A sequence

$$\mathcal{F} \rightarrow \mathcal{G} \rightarrow \mathcal{H}$$

of sheaves on  $X$  is exact (at  $\mathcal{G}$ ) if and only if it is exact at all stalks.

*Proof.* Unsurprisingly, pass to stalks. ■

## 1.5.6 Sheaf Functors

We now discuss how to build some new sheaves from old.

**Definition 1.157** (Direct image sheaf). Fix a continuous map  $f: X \rightarrow Y$  of topological spaces. Given a sheaf  $\mathcal{F}$  on  $X$ , we define the *direct image sheaf* on  $Y$  to be

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

**Remark 1.158.** One can check that, given continuous maps  $f: X \rightarrow Y$  and  $g: Y \rightarrow Z$ , we have

$$(f \circ g)_* = f_* \circ g_*$$

as maps from sheaves to sheaves. As a hint, one should check this on stalks.

**Definition 1.159** (Inverse image sheaf). Fix a continuous map  $f: X \rightarrow Y$  of topological spaces. Given a sheaf  $\mathcal{G}$  on  $Y$ , we define the *inverse image sheaf*  $f^{-1}\mathcal{G}$  on  $X$  to be the sheafification of the presheaf

$$U \mapsto \varinjlim_{V \supseteq f(U)} \mathcal{G}(V).$$

**Remark 1.160.** One can check, as in [Remark 1.158](#), that  $(f \circ g)^{-1} = g^{-1} \circ f^{-1}$  as maps from sheaves to sheaves.

Here is another way to verify our last remark.

**Proposition 1.161.** There is a natural bijection

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

In other words, we have a pair of adjoint functors.

*Proof.* Omitted. ■

**Remark 1.162.** The functor  $f^{-1}$  also has a right adjoint, which will appear on the homework. Thus,  $f^{-1}$  as a functor is exact.

### 1.5.7 More Sheaves

Let's see a few more examples, for fun.

**Definition 1.163** (Constant sheaf). Fix a set  $S$  and a topological space  $X$ . Then the *constant sheaf* is

$$\underline{S}(U) := S^{\oplus \pi_0(U)},$$

where  $\pi_0(U)$  is the number of connected components in  $U$ . Notably, all the stalks of  $\underline{S}$  are  $S$ .

**Definition 1.164** (Skyscraper sheaf). Fix a topological space  $Y$  and a set  $S$ . For  $y \in Y$ , set  $X := \{y\}$  so that there is a continuous map  $\iota: X \hookrightarrow Y$ . Then we define the *skyscraper sheaf* as

$$\iota_* S(U) := \begin{cases} S & y \in U, \\ \{*\} & y \notin U. \end{cases}$$

**Remark 1.165.** For  $z \in Y$ , we can compute the stalk of the skyscraper sheaf as

$$(\iota_* S)_z = \begin{cases} S & z \in \overline{\{y\}}, \\ \{*\} & z \notin \overline{\{y\}}. \end{cases}$$

For another remark, we pick up the following definition.

**Definition 1.166** (Support). Fix a sheaf  $\mathcal{F}$  on a topological space  $x$ . Then we define the *support* of  $\mathcal{F}$  to be

$$\text{supp } \mathcal{F} := \{x \in X : \#\mathcal{F}_x > 1\}.$$

**Remark 1.167.** The support of  $\iota_* S$  is  $\overline{\{y\}}$ .

Here is another result, which explains why we care about the skyscraper sheaf.

**Proposition 1.168.** There is a natural bijection

$$\text{Mor}_{\{y\}}(\mathcal{F}_y, \mathcal{G}) \simeq \text{Mor}_Y(\mathcal{F}, \iota_* \mathcal{G}).$$

In other words, understanding maps from stalks is roughly the same as understanding maps to the corresponding skyscraper sheaf.

### 1.5.8 Schemes

We close lecture by defining schemes. We begin by defining a locally ringed space.

**Definition 1.169** (Locally ringed space). A *locally ringed space* is a sheaf of rings  $\mathcal{O}_X$  on a topological space  $X$  such that all stalks are local rings.

**Example 1.170.** Affine schemes give locally ringed spaces.

**Definition 1.171** (Morphism of locally ringed spaces). A morphism  $\varphi: (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$  of locally ringed spaces consists of an ordered pair  $(f, f^\sharp)$  in such a way that  $f: X \rightarrow Y$  is continuous, and  $f^\sharp: \mathcal{O}_Y \rightarrow f_*\mathcal{O}_X$  is a morphism of sheaves in such a way that the induced map

$$f_p^\sharp: \mathcal{O}_{Y,p} \rightarrow (f_*\mathcal{O}_X)_p$$

of stalks is a map of local rings.

Notably, a morphism of local rings  $\varphi: (R, \mathfrak{m}) \rightarrow (S, \mathfrak{n})$  requires  $\varphi^{-1}\mathfrak{n} = \mathfrak{m}$ .

**Definition 1.172** (Scheme). A scheme is a pair  $(X, \mathcal{O}_X)$  of a topological space  $X$  and a locally ringed space  $\mathcal{O}_X$  such that each  $p \in X$  has a  $U_p \subseteq X$  such that  $(U_p, \mathcal{O}_X|_{U_p})$  is isomorphic (as a locally ringed space) to an affine scheme.

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