

ALGEBRAIC GEOMETRY 1, WINTER TERM 2025/26. LECTURE NOTES.

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1. INTRODUCTION

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We will start with a relatively long *introductory chapter*, in order to ...

- provide some motivation for the (partly more technical) content that will come later,
- give those participants who were not in the Algebra 2 class last term a little more time to brush up their commutative algebra knowledge:
 - (Prime) ideals, quotients
 - localization (with respect to a multiplicative subset; in particular with respect to one element and localization at a prime ideal),
 - spectrum of a ring, Zariski topology (this we will redo in the class, but ideally you are already a little familiar with the notion of *topological space*).

I will try to address the question *What is algebraic geometry?*, and at the same time give, towards the end of the chapter, a rough survey of this class.

(1.1) What Algebraic Geometry is about.

In one sentence: Study “geometric properties” of solution sets of systems of polynomial equations (over a field, or more generally a commutative ring).

Example 1.1.

$$\{(x, y) \in \mathbb{R}^2 \mid y^2 = x^2(x + 1)\} \subset \mathbb{R}^2.$$

Comparison with Previous/Other Courses

Linear Algebra	Systems of <i>linear</i> equations
Algebra	polynomial equations (1 variable, 1 polynomial)
Algebraic Geometry	systems of polynomial equations
Algebraic Number Theory	...coefficients/solutions in $\mathbb{Z}, \mathbb{Q}, K/\mathbb{Q}$ fin., \mathbb{F}_q

Here *algebraic* refers to the fact that we

- study solution sets (zero sets) of polynomials (not power series, differential/holomorphic functions, etc.),

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- use algebraic methods (specifically commutative algebra) to study these objects.

In particular, at least in principle, we may hence work over an arbitrary field (not only \mathbb{R} or \mathbb{C}).

(1.2) The Cayley–Hamilton Theorem: A Geometric View.

Theorem 1.2. [Cayley–Hamilton] *Let k be a field, $A \in M_n(k)$. Then $\text{charpol}_A(A) = 0$.*

We want to look at this result from the perspective of an algebraic geometer, i.e., we view $M_n(k)$ as n -dimensional (vector) space.

Let us consider the case $k = \mathbb{R}$, $n = 2$ and restrict to matrices A with trace $\text{tr}(A) = 0$. (This does not change the main argument, but simplifies the discussion a little bit and will allow us to draw a picture later.)

We want to use that the theorem is obviously true, if A is a diagonal matrix. From this, it follows easily that the theorem holds whenever A is diagonalizable. In fact, if $A = SDS^{-1}$ for a diagonal matrix D , then $\text{charpol}_A = \text{charpol}_D$. Since conjugation is a ring automorphism of the ring of matrices (over any ring), we may “pull it out” of any polynomial. Together we obtain

$$\text{charpol}_A(A) = \text{charpol}_D(SAS^{-1}) = S \text{charpol}_D(D)S^{-1},$$

and the term on the right vanishes, since $\text{charpol}_D(D) = 0$ by the case of diagonal matrices. Furthermore, in this argument we may just as well allow matrices S with entries in some extension field of k , and we see that it suffices to assume that A is *diagonalizable over \mathbb{C}* . But of course, there are also non-diagonalizable matrices.

So we consider a matrix

$$A = \begin{pmatrix} a & b \\ c & -a \end{pmatrix} \in M_2(\mathbb{R})^{\text{tr}=0} \cong \mathbb{R}^3,$$

where we use a, b, c as coordinates on \mathbb{R}^3 . We then have

$$\text{charpol}_A = (T - a)(T + a) - bc = T^2 - (a^2 + bc).$$

In particular we see that all matrices $A = \begin{pmatrix} a & b \\ c & -a \end{pmatrix}$ with $a^2 + bc \neq 0$ are diagonalizable over \mathbb{C} . On the other hand, if $a^2 + bc = 0$, then A is not necessarily diagonalizable.

We now consider the map:

$$\chi : M_2(\mathbb{R})^{\text{tr}=0} \rightarrow M_2(\mathbb{R}), \quad A \mapsto \text{charpol}_A.$$

Our goal is to show that the map χ is constant with image the zero matrix. By what we have said, $\chi(A) = 0$ for all those A that are diagonalizable over \mathbb{C} .

Since the map $\chi: \mathbb{R}^3 \rightarrow \mathbb{R}^4$ is given by polynomials, it is continuous. Therefore for every closed subset of \mathbb{R}^4 , its inverse image under χ is again closed. We apply this to the set $\{0\}$ containing only the zero matrix; clearly this is a closed set. Its inverse image contains, by what we know already, all those traceless matrices that are diagonalizable over \mathbb{C} , and in particular all matrices $\begin{pmatrix} a & b \\ c & -a \end{pmatrix}$ with $a^2 + bc \neq 0$. But this set is dense in $M_2(\mathbb{R})^{\text{tr}=0}$, i.e., its closure is the whole space. It follows that $\chi^{-1}(\{0\}) = M_2(\mathbb{R})^{\text{tr}=0}$, as we wanted to show.

The same argument, with small modifications, applies when we drop the condition on the trace, and also for square matrices of arbitrary size.

Question: How to deal with other fields?

For this, we need a *notion of continuous map* in a more general context.

(1.3) The Zariski topology on k^n .

Let k be a field. Since we want to study solution sets of systems of polynomial equations, we introduce the following notation:

Definition 1.3.

- (1) Given $f_1, \dots, f_m \in k[T_1, \dots, T_n]$, we define the vanishing set (in German: Verschwindungsmenge)

$$V(f_1, \dots, f_m) := \{(t_i) \in k^n; f_j(t_1, \dots, t_n) = 0 \forall j\}.$$

- (2) More generally, for any subset $\mathcal{F} \subset k[T_1, \dots, T_n]$, we define the vanishing set of \mathcal{F} as

$$V(\mathcal{F}) = \{(t_i) \in k^n; f(t_1, \dots, t_n) = 0 \forall f \in \mathcal{F}\}.$$

If k'/k is a field extension, then we set

$$V(f_1, \dots, f_m)(k') := \{(t_i) \in (k')^n; f_j(t_i) = 0 \forall j\},$$

and analogously define $V(\mathcal{F})(k')$.

Remark 1.4. Let $\mathcal{F} \subset k[T_1, \dots, T_n]$, and let $\mathfrak{a} \subset k[T_\bullet]$ be the ideal generated by \mathcal{F} . Then $V(\mathcal{F}) = V(\mathfrak{a})$, as is easily checked. From this it also follows that

$$V(\mathcal{F}) = V(\mathfrak{a}) = V(f_1, \dots, f_m),$$

whenever f_1, \dots, f_m is a generating system for the ideal \mathfrak{a} . By Hilbert's Basis Theorem, every ideal in $k[T_1, \dots, T_n]$ admits a finite generating system. (We say that the polynomial ring in finitely many variables over a field, or more generally over any noetherian ring, is noetherian.) Therefore, every vanishing set $V(\mathcal{F})$ can be written in the form $V(f_1, \dots, f_m)$ for finitely many, suitably chosen polynomials f_j .

Proposition 1.5. The sets $V(\mathcal{F})$, $\mathcal{F} \subset k[T_\bullet]$, form the closed sets of a topology on k^n , the Zariski topology.

Spelled out explicitly, this means that

- (1) \emptyset, k^n are of this form,
- (2) finite unions of such sets are again of this form,
- (3) arbitrary intersections of such sets are of this form.

Proof. (1) We have $\emptyset = V(1)$, $k^n = V(0)$.

(2) By induction, it is enough to consider the union of two closed subsets, say $V(\mathcal{F})$ and $V(\mathcal{G})$. But

$$V(\mathcal{F}) \cup V(\mathcal{G}) = V(fg; f \in \mathcal{F}, g \in \mathcal{G}).$$

In fact, the inclusion \subseteq is clear. For the other inclusion, take a point t in the right hand side which does not lie in $V(\mathcal{F})$. That means $f(t) \neq 0$ for some $f \in \mathcal{F}$. But since $f(t)g(t) = (fg)(t) = 0$ for all $g \in \mathcal{G}$, it follows, that $t \in V(\mathcal{G})$.

(3) For $\mathcal{F}_j \subseteq k[T_1, \dots, T_n]$, $j \in J$, we have

$$\bigcap_{j \in J} V(\mathcal{F}_j) = V\left(\bigcup_{j \in J} \mathcal{F}_j\right).$$

□

Definition 1.6. *The topological space k^n with the Zariski topology is denoted by $\mathbb{A}^n(k)$ and called affine space (over k , of dimension n).*

(1.4) Bézout's Theorem.

Oct. 15, 2025

Next, let us look at *Bézout's theorem*, a relatively elementary, but still non-trivial result in algebraic geometry which at the same time illustrates a typical type of question asked in this theory and several methods that are crucial in (almost) all of algebraic geometry. In particular, it will serve as a motivation for introducing the so-called *projective space*, see Section (1.5).

Let k be a field. For a polynomial $f \in k[X, Y]$, as before we write

$$V(f) = \{(x, y) \in k^2; f(x, y) = 0\},$$

and call this set the *vanishing set of f* .

We want to study what we can say, given two such polynomials f, g , about the set $V(f) \cap V(g)$. More specifically, examples show that typically, this is a finite set, and it is a natural question whether we can determine its cardinality. We start with the following observations:

- (1) For a polynomial $p \in k[X]$, $n = \deg(p) > 0$, we have

$$\#\{x \in k; p(x) = 0\} \leq n,$$

with equality if k is algebraically closed and if we count each zero x of p with its multiplicity $\text{ord}_x(p) = \max\{r; (X - x)^r \mid p\}$.

- (2) Let $p \in k[X]$ non-constant and let $f = Y - p(X)$, $g = Y$. We then have a bijection

$$\{x \in k; p(x) = 0\} \longleftrightarrow V(f) \cap V(g), \quad x \mapsto (x, 0).$$

Coming back to the general case, let $f, g \in k[X, Y]$. Recall that $k[X, Y]$ is a unique factorization domain. It is easy to see that in case f and g have a common divisor of positive degree, then $V(f) \cap V(g)$ is infinite, at least when k is algebraically closed. Since here we are interested in counting points, we rule out that case, and require that f, g are coprime. For a polynomial $f \in k[X, Y]$, we denote by $\deg(f)$ its *total degree*, i.e., for $f = \sum_{i,j} a_{ij}X^iY^j$, $\deg(f) = \max\{i+j; a_{ij} \neq 0\}$.

Proposition 1.7. *Let k be a field, and let $f, g \in k[X, Y]$ be coprime, non-constant polynomials. Then*

$$\#(V(f) \cap V(g)) \leq \deg(f) \cdot \deg(g).$$

We will prove this result later, in an improved form. For now, our goal is to discuss this “improved form”, by which we mean a refined statement where we actually have equality.

Looking back at the case of a single-variable polynomial p above, it is reasonable to require that k is algebraically closed, and also to expect that we will have to count intersection points with their correct “multiplicity”. It is not so hard to write down the definition of multiplicity that will work; we will discuss this in more detail later.

Definition 1.8. [Local intersection multiplicity] *Let k be a field, $f, g \in k[X, Y]$, $P = (x, y) \in k^2$ a point. Let $\mathfrak{m} = (X - x, Y - y) \subset k[X, Y]$ (a maximal ideal of the polynomial ring). Then we define*

$$i_P(f, g) = \dim_k k[X, Y]_{\mathfrak{m}} / (f, g),$$

where $k[X, Y]_{\mathfrak{m}}$ denotes the localization at \mathfrak{m} (i.e., the localization with respect to the multiplicative subset $k[X, Y] \setminus \mathfrak{m}$). (Note that the intersection multiplicity depends on the polynomials f, g ; not just on their vanishing sets.)

However, looking at the case where $V(f)$ and $V(g)$ are parallel lines in k^2 (e.g., $f = Y$, $g = Y - 1$), we see that these changes are not enough in order to obtain equality.

(1.5) The projective plane $\mathbb{P}^2(k)$.

Idea. Add points to k^2 so that any two different lines intersect in a point. (While this at first may feel like cheating, it turns out that the resulting construction is extremely useful in algebraic geometry, far beyond Bézout’s theorem, also in the sense that it will allow to come back and answer questions that do not mention the newly constructed space.) Setting up the theory

will also involve suitably modifying the notion of line; we will come to that later, and then also relate it to lines in k^2 .

Definition 1.9. *Let k be a field. We define the projective plane $\mathbb{P}^2(k)$ over k , as a set, as*

$$\mathbb{P}^2(k) := \{L \subset k^3 \text{ linear subspace of dimension } 1\},$$

the set of all lines through the origin in k^3 .

Viewing k^2 as the affine plane $\{(x, y, 1) \in k^3; x, y \in k\}$ in k^3 , every line through the origin in k^3 which is not contained in the x - y -plane intersects k^2 in exactly one point. Thus we obtain an injective map $k^2 \rightarrow \mathbb{P}^2(k)$ which we may also write as

$$k^2 \longrightarrow \mathbb{P}^2(k), \quad (x, y) \mapsto \left\langle \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \right\rangle.$$

In this way, we may view $\mathbb{P}^2(k)$ as “ k^2 with some points added”, namely the lines in the x - y -plane (note that thus for any equivalence class of parallel lines in k^2 we have one additional point, and it will turn out that this point “is” (in a sense that we yet must define) the missing intersection point of these parallel lines).

Usually we denote elements of $\mathbb{P}^2(k)$ in terms of their *homogeneous coordinates* which we are going to define next. (That also facilitates, hopefully, to think of elements of $\mathbb{P}^2(k)$, typically, as *points of some space* rather than as lines in some other space, similarly as we think of the elements of k^2 as points in the plane.)

For $(x, y, z), (x', y', z') \in k^3 \setminus \{0\}$, define:

$$\begin{aligned} (x, y, z) \sim (x', y', z') &\iff \left\langle \begin{pmatrix} x \\ y \\ z \end{pmatrix} \right\rangle = \left\langle \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} \right\rangle \\ &\iff \exists \lambda \in k^\times : (x', y', z') = \lambda(x, y, z). \end{aligned}$$

This is an equivalence relation on $k^3 \setminus \{0\}$. We denote by $(x : y : z)$ the equivalence class of (x, y, z) and obtain a bijection

$$(k^3 \setminus \{0\}) / \sim \xrightarrow{1:1} \mathbb{P}^2(k), \quad (x : y : z) \mapsto \left\langle \begin{pmatrix} x \\ y \\ z \end{pmatrix} \right\rangle.$$

Our next task is to define a suitable notion of *line in the projective plane*. The resulting notion should satisfy (at least) the properties that through any two distinct points, there is a unique line; and that any two distinct lines intersect in a unique point (because our goal was a situation where there are no more “parallel lines”). For the definition, however, a general construction is better suited, namely an analog of the notion of vanishing set of polynomials. However, we have to be careful here, because for an

arbitrary polynomial $F \in k[X, Y, Z]$ the value on a point $(x : y : z)$ given in homogeneous coordinates is obviously not well-defined, but will depend on the choice of representative. On the other hand, in order to define vanishing sets, we do not need to compute values, but only need to check whether the outcome is $= 0$ or $\neq 0$. Even this is not possible for general polynomials, but it is possible for the class of *homogeneous* polynomials, which is still large enough to give all that we need. We give the definition in a general form.

Definition 1.10. *Let R be a ring. A polynomial $F \in R[X_0, \dots, X_n]$ is called homogeneous of degree d , if it can be written as a (finite) linear combination of monomials of degree d , i.e., in the form*

$$F = \sum_{i_0, \dots, i_n} a_{i_0, \dots, i_n} X_0^{i_0} \cdots X_n^{i_n}$$

with $a_{i_0, \dots, i_n} \in R$ and $a_{i_0, \dots, i_n} = 0$ whenever $i_0 + \cdots + i_n \neq d$.

Lemma 1.11. *Let R be a ring, and let $F \in R[X_0, \dots, X_n]$ be homogeneous of degree d . Then for all $\lambda, x_0, \dots, x_n \in R$, we have*

$$F(\lambda x_0, \dots, \lambda x_n) = \lambda^d F(x_0, \dots, x_n).$$

If R is an infinite field, then the converse is true, as well.

Proof. The first statement is clear. The second one follows (how?) from the fact that over an infinite field, the zero polynomial is the only polynomial in $n + 2$ variables which vanishes at every point of k^{n+2} . \square

Therefore we may define the vanishing set of a homogeneous polynomial, and more generally, the common vanishing set of a family of homogeneous polynomials (possibly of different degrees). We will look at several explicit examples soon.

Definition 1.12. *Let $\mathcal{F} \subseteq k[X, Y, Z]$ be a set of homogeneous polynomials. We define the vanishing set as*

$$V_+(\mathcal{F}) = \{(x : y : z); F(x, y, z) = 0 \text{ for all } F \in \mathcal{F}\} \subseteq \mathbb{P}^2(k).$$

Similarly as for k^n , one proves the following.

Oct. 21, 2025

Proposition 1.13. *The sets of the form $V_+(\mathcal{F})$, $\mathcal{F} \subseteq k[X, Y, Z]$ a set of homogeneous polynomials, form the closed sets of a topology on $\mathbb{P}^2(k)$, the so-called Zariski topology.*

Lines in $\mathbb{P}^2(k)$. We can now define the notion of line in the projective plane and conclude this section by stating the final form of Bézout's theorem.

Definition 1.14. *Let k be a field. A line in $\mathbb{P}^2(k)$ is a subset of the form $V_+(F)$ for a non-zero homogeneous polynomial of degree 1.*

Explicitly, F as in the definition has the form $aX + bY + cZ$, with $(a, b, c) \neq (0, 0, 0)$. For example $V_+(Z) = \mathbb{P}^2(k) \setminus \iota(k^2)$ (where $\iota: k^2 \rightarrow \mathbb{P}^2(k)$ is the

embedding defined above) is a line. This line is called the *line at infinity* (with respect to our chosen embedding $k^2 \subset \mathbb{P}^2(k)$).

Proposition 1.15.

- (1) Let $P_1, P_2 \in \mathbb{P}^2(k)$, $P_1 \neq P_2$. Then there exists $F \in k[X, Y, Z]$ homogeneous of degree 1, $F \neq 0$, such that $P_1, P_2 \in V_+(F)$, and F is uniquely determined up to multiplication by an element $\lambda \in k^\times$.
- (2) For non-zero linear homogeneous polynomials $F_1, F_2 \in k[X, Y, Z]$, we have

$$V_+(F_1) = V_+(F_2) \iff \text{there exists } \lambda \in k^\times : F_2 = \lambda F_1.$$

- (3) Let $F_1, F_2 \in k[X, Y, Z]$ be non-zero linear homogeneous polynomials with $V_+(F_1) \neq V_+(F_2)$. Then the set $V_+(F_1) \cap V_+(F_2)$ consists of exactly one element.

Proof. (1) Phrase the problem as a system of linear equations on the coefficients of F . We obtain a system with two linearly independent equations and three variables, so the space of solutions is 1-dimensional.

(2) This follows from Part (1) (because any $V_+(F_1)$ contains at least 2 points (more precisely: $\#k + 1$ points)).

(3) Similarly as Part (1) this can be shown by considering a suitable system of linear equations, where the coefficients are given by the coefficients of the equations of F_1 and F_2 , and the variables correspond to the homogeneous coordinates of the point(s) we are looking for in the intersection. \square

We can now state the final version of Bézout's theorem. Here, $i_P(F, G)$ is defined similarly as above. (As before, it depends on the actual polynomials F, G , not just on their vanishing sets.) We will come back to this, and also give a proof of the theorem, later in the course.

Theorem 1.16. [Bézout] Let $F, G \in k[X, Y, Z]$ be non-constant coprime homogeneous polynomials. Then

$$\sum_{P \in V_+(F) \cap V_+(G)} i_P(F, G) = \deg(F) \cdot \deg(G),$$

in particular $\#(V_+(F) \cap V_+(G)) \leq \deg(F) \cdot \deg(G)$.

Similarly to the projective plane, we can analogously define *projective space of dimension n over k* ,

$$\mathbb{P}^n(k) = (k^{n+1} \setminus \{0\}) / \sim,$$

where $(x_0, \dots, x_n) \sim (x'_0, \dots, x'_n)$ if there exists $\lambda \in k^\times$ such that $x'_i = \lambda x_i$ for all i .

(1.6) Homogenization and dehomogenization of polynomials.

Let us look at the relationship between vanishing sets in k^2 and in $\mathbb{P}^2(k)$.

Remark 1.17. Let $F \in k[X, Y, Z]$ be a homogeneous polynomial. Then $V_+(F) \cap V_+(Z) = V_+(F, Z)$ and thus we can write $V_+(F)$ as the disjoint union

$$V_+(F) = (V_+(F) \cap \iota(k^2)) \sqcup V_+(F, Z).$$

Furthermore, under the identification $k^2 \xrightarrow{1:1} \iota(k^2)$, $V_+(F) \cap \iota(k^2)$ is in bijection with $V(f)$ for $f = F(x, y, 1) \in k[x, y]$. Here f is a polynomial of degree $\leq \deg(F)$, with equality, if F is not divisible by Z .

Conversely, given a polynomial $f \in k[x, y]$ we can easily find a homogeneous polynomial such that $f(x, y) = F(X, Y, 1)$ (and hence, by the above remark, $V(f) = V_+(F) \cap \iota(k^2)$, or in other words, $V_+(F)$ consists of $V(f)$ and (possibly) further points lying on the line at infinity $V_+(Z)$).

Namely, we just “fill in powers of Z ” so as to construct a homogeneous polynomial of degree $\deg(f)$. For example, for $f = y^2 - x^3 + x + 1$, we would take $F = Y^2Z - X^3 + XZ^2 + Z^3$. Generally, given $f = \sum_{i,j} a_{i,j} x^i y^j$ of degree d , take $F = \sum_{i,j} a_{i,j} X^i Y^j Z^{d-i-j}$. We call F the dehomogenization (of degree d) of f .

Note that for f and F related in this way, the polynomial $G = Z \cdot F$ still has the property that $G(x, y, 1) = f(x, y)$, however $V_+(G) = V_+(F) \cup V_+(Z)$, i.e., we get an “unnecessary” (and unwanted) copy of the line at infinity.

(1.7) More examples.

Let k be a field, $\text{char}(k) \neq 2$. A vanishing set $V(f) \subset \mathbb{A}^2(k)$ for a polynomial f of degree 3 is called a *cubic curve*.

Oct. 22, 2025

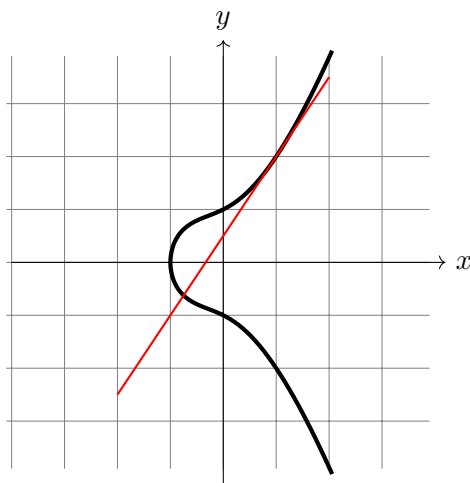
Example 1.18. Consider $C = V(f) \subset \mathbb{A}^2(k)$ with

$$f = y^2 - (x+1)(x^2+1).$$

We have

$$\frac{\partial f}{\partial x} = -3x^2 - 2x - 1, \quad \frac{\partial f}{\partial y} = 2y.$$

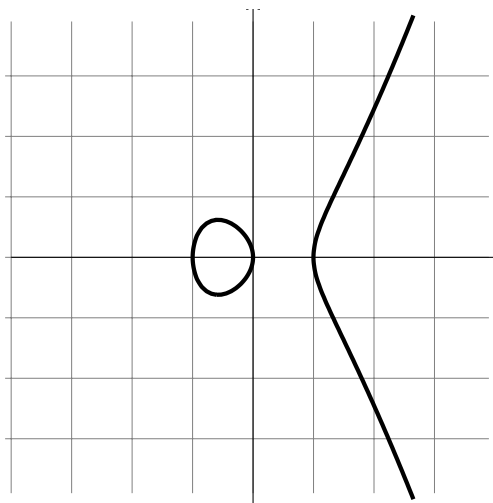
Let $P = (1, 2) \in C$. We have $\frac{\partial f}{\partial x}(P) = -6$, $\frac{\partial f}{\partial y}(P) = 4$. This implies that over \mathbb{R} (and similarly over \mathbb{C}) the function $(x, y) \mapsto f(x, y)$ is approximated well by the linear function $(x, y) \mapsto -6x + 4y - 2$, and the zero set $V(f)$ is approximated, “in a small neighborhood of P ” by the zero set of the above linear function, i.e., by the line $V(-6x + 4y - 2)$ (drawn in red).



Example 1.19.

Consider $C = V(f) \subset \mathbb{A}^2(k)$ with

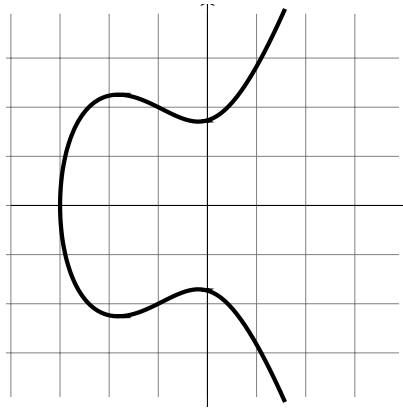
$$f = y^2 - x(x+1)(x-1).$$



Example 1.20.

Consider $C = V(f) \subset \mathbb{A}^2(k)$
with

$$f = y^2 - (x+3)(x^2+1).$$



Example 1.21. Consider $C = V(f) \subset \mathbb{A}^2(k)$ with

$$f = y^2 - x^2(x+1).$$

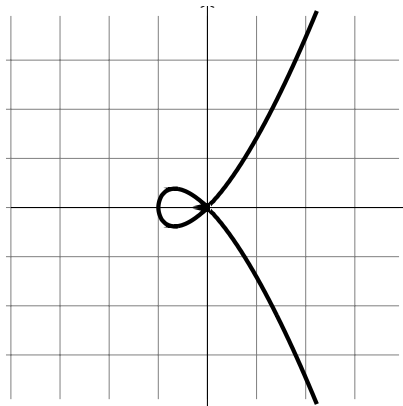
In this case,

$$\frac{\partial f}{\partial x} = -3x^2 - 2x, \quad \frac{\partial f}{\partial y} = 2y$$

and in particular

$$\frac{\partial f}{\partial x}(0,0) = \frac{\partial f}{\partial y}(0,0) = 0.$$

This corresponds to the fact that there is no well-defined tangent line to $V(f)$ at the point $(0,0)$.

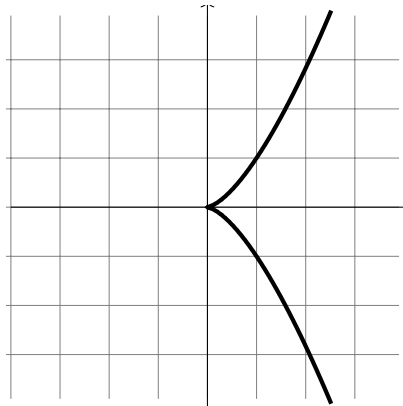


Example 1.22.

Consider $C = V(f) \subset \mathbb{A}^2(k)$
with

$$f = y^2 - x^3.$$

In this case once again both partial derivatives of f vanish at $(0,0)$.



(1.8) Singular and nonsingular points.

From the examples and the situation over the real and complex numbers, we would like to make the following definition, as one example that we can use some geometric insight, while formally “only manipulating algebraic expressions” (in this case, taking derivatives of polynomials).

Definition* 1.23. *Let k be a field and let $f \in k[X, Y]$ be a non-constant polynomial. We say that a point $P = (x_0, y_0) \in V(f)$ is smooth (or non-singular), if $\left(\frac{\partial f}{\partial X}(P), \frac{\partial f}{\partial Y}(P)\right) \neq (0, 0)$, and in this case call the line*

$$V\left(\frac{\partial f}{\partial X}(P) \cdot (X - x_0) + \frac{\partial f}{\partial Y}(P) \cdot (Y - y_0)\right)$$

the tangent line to $V(f)$ at P . Otherwise we call P a singular point of $V(f)$.

Remark 1.24. This definition does not really make sense! (that’s why I put a *) – more precisely, the property of being a smooth point depends on the polynomial f , not just on the subset $V(f) \subset k^2$. For example, $V(X) = V(X^2)$, and using the partial derivatives of $f = X$, all points are smooth, but using $f = X^2$ instead, all points are singular. This illustrates that the set $V(f)$ (even if we equip it with the induced topology for the embedding into k^2 with the Zariski topology) alone does not carry enough “structure” in order to really do geometry.

For now we will therefore view this as a “definition we would like to make for $V(f)$, but can currently only make after fixing f ”. A little later in the course we will be in a position to fix this problem.

If k is algebraically closed, then there is another option to proceed. (The fact that this is option is not viable for general fields is the reason that “classical” algebraic geometry, e.g., as in [GW1] Chapter 1 or [Ha] Chapter I, is done over an algebraically closed base field.)

To formulate this, recall that a ring R is called *reduced*, if it has no non-zero nilpotent elements, i.e., whenever $x^n = 0$ for some $x \in R$, $n \geq 1$, we must have $x = 0$. For a polynomial $f \in k[x, y]$, the quotient is reduced if and only if there does not exist an irreducible polynomial $g \in k[x, y]$ such that $g^2 \mid f$. In other words, in the decomposition of f into irreducible polynomials in the unique factorization domain $k[x, y]$ each irreducible factor occurs only once.

If $f \in k[x, y]$ is a non-constant polynomial and $f = f_1^{i_1} \cdots f_r^{i_r}$ is a decomposition of f with f_i irreducible and pairwise distinct, then clearly $V(f) = V(f_1 \cdots f_r)$, i.e., changing the exponents does not change the vanishing set. It is therefore clear that every $V(f)$ can also be written as the vanishing set of a polynomial for which $k[x, y]/(f)$ is reduced.

Over an algebraically closed field, we have the following strong converse: Given $V \subset k^2$ that has the form “vanishing set of one non-constant polynomial”, there is a unique (up to multiplication by scalars in k^\times) polynomial $f \in k[x, y]$ such that $V = V(f)$ and such that the ring $k[x, y]/(f)$ is *reduced* (i.e., it has no non-trivial nilpotent elements). When we use this f , we get

the “right” notion of smooth points. (In fact, it is not difficult to show that for f such that $k[x, y]/(f)$ is *not* reduced, all points are non-smooth in the sense of the above definition applied to f .)

In fact, there is the following more general version of this statement. For an ideal $\mathfrak{a} \subset k[T_1, \dots, T_n]$ we denote by

$$\sqrt{\mathfrak{a}} = \{x \in k[T_\bullet]; x^n \in \mathfrak{a} \text{ for some } n \geq 0\}$$

its radical. (With notation as above, $\sqrt{(f)} = (f_1 \cdots f_r)$.) It is easy to see that $k[T_1, \dots, T_n]/\mathfrak{a}$ is reduced if and only if $\mathfrak{a} = \sqrt{\mathfrak{a}}$, and that $V(\mathfrak{a}) = V(\sqrt{\mathfrak{a}})$. Furthermore, we have:

Theorem 1.25. *Let k be an algebraically closed field, and let $\mathfrak{a}, \mathfrak{b} \subseteq k[T_1, \dots, T_n]$ be ideals. Then*

$$V(\mathfrak{a}) = V(\mathfrak{b}) \iff \sqrt{\mathfrak{a}} = \sqrt{\mathfrak{b}}.$$

This is (one version of) Hilbert’s Nullstellensatz. The implication \Leftarrow is easy, as indicated above, and does not require the assumption that k is algebraically closed. The other implication is non-trivial already in the case that $\mathfrak{a} = (1)$, so $V(\mathfrak{a}) = \emptyset$. In this case the statement is equivalent to saying that any family f_1, \dots, f_r of polynomials that does not generate the unit ideal has a common zero, whence the name *Nullstellensatz* (*Nullstelle* is German for *zero* (of a polynomial)).

We will take up this discussion again, and in more detail, later.

Remark 1.26. Another perspective on the situation over the real numbers (and similarly over the complex numbers) is the Theorem on inverse functions. It implies, if P is a smooth point of $V(f)$ in the sense of the above definition, that locally (in the analytic, “usual”, topology) around P the set $V(f)$ is diffeomorphic to an open interval in \mathbb{R} , i.e., there exists an open $U \subset V(f)$, $P \in U$, and an open interval $V \subset \mathbb{R}$, and bijective differentiable functions $U \rightarrow V$ and $V \rightarrow U$ that are inverse to each other.

More generally, there is a version for vanishing sets (or more generally, level sets) of continuously differentiable maps $\mathbb{R}^n \rightarrow \mathbb{R}$, and even more generally for fibers of continuously differentiable maps $f: \mathbb{R}^n \rightarrow \mathbb{R}^m$, $x \mapsto (f_1(x), \dots, f_m(x))$, such that the Jacobi matrix (at some point P),

$$\left(\frac{\partial f_j}{\partial x_i}(P) \right)_{i,j}$$

has rank m . Then locally around P , the fiber over $f(P)$ is a differentiable manifold, i.e., is diffeomorphic to an open of \mathbb{R}^{n-m} .

See Inverse function theorem (Wikipedia)¹, in particular the section Giving a manifold structure.

¹https://en.wikipedia.org/wiki/Inverse_function_theorem

For the projective plane, we make the following analogous definition (which again depends on the polynomial F , not only on the vanishing set, cf. Remark 1.24.)

Definition 1.27. *Let k be a field and let $F \in k[X, Y, Z]$ be a non-constant homogeneous polynomial. We call a point $P \in V_+(F)$ a smooth (or non-singular) point of $V_+(F)$, if*

$$\left(\frac{\partial F}{\partial X}(P), \frac{\partial F}{\partial Y}(P), \frac{\partial F}{\partial Z}(P) \right) \neq (0, 0, 0),$$

and in this case call the line

$$V_+ \left(\frac{\partial F}{\partial X}(P) \cdot X + \frac{\partial F}{\partial Y}(P) \cdot Y + \frac{\partial F}{\partial Z}(P) \cdot Z \right)$$

the tangent line to $V_+(F)$ at P . Otherwise, we call P a singular point.

For the following remarks, the next lemma will be useful; we record it here in the general case of $n + 1$ variables. Also note that for a homogeneous polynomial of degree d , all partial derivatives are homogeneous of degree $d - 1$.

Lemma 1.28. (Euler identity) *Let $F \in k[X_0, \dots, X_n]$ be a homogeneous polynomial of degree d . Then*

$$\frac{\partial F}{\partial X_0} X_0 + \dots + \frac{\partial F}{\partial X_n} X_n = dF.$$

Proof. Since both sides are k -linear in F , it is enough to check this in case $F = X_0^{\nu_0} \dots X_n^{\nu_n}$ is a monomial. But then $\frac{\partial F}{\partial X_i} X_i = \nu_i F$ and the stated identity follows immediately. \square

Remark 1.29.

- (1) Euler's identity shows that the tangent line to a smooth point of $V_+(F)$ contains the point P .
- (2) The two definitions of smooth point are related as follows. Let $F \in k[X, Y, Z]$ be a homogeneous polynomial, $f = F(x, y, 1)$, so that $V_+(F) \cap \iota(k^2)$ may be identified with $V(f) \subset k^2$. Cf. Section (1.6). We assume that f is non-constant, and take $P \in V(f)$, say $P = (x_0, y_0)$, and $\iota(P) = (x_0 : y_0 : 1)$.

Then

$$(1.8.1) \quad \frac{\partial F}{\partial X}(x, y, 1) = \frac{\partial f}{\partial x}, \quad \frac{\partial F}{\partial Y}(x, y, 1) = \frac{\partial f}{\partial y},$$

as is easily checked, and in particular

$$\frac{\partial F}{\partial X}(x_0, y_0, 1) = \frac{\partial f}{\partial x}(P), \quad \frac{\partial F}{\partial Y}(x_0, y_0, 1) = \frac{\partial f}{\partial y}(P).$$

This already shows that if $P \in V(f)$ is smooth (with respect to the polynomial f , that is), then $\iota(P)$ is a smooth point of $V_+(F)$ (i.e., for

F). To show the equivalence, assume that $\iota(P) \in V_+(F)$ such that the partial derivatives of F with respect to X and to Y both vanish. Then Euler's identity shows, since $F(\iota(P)) = 0$, that the partial derivative with respect to Z vanishes, as well, so $\iota(P)$ is not smooth.

Finally, for a smooth point with tangent line $V_+(L)$ to $V_+(F)$ at $\iota(P)$,

$$L = \frac{\partial F}{\partial X}(P) \cdot X + \frac{\partial F}{\partial Y}(P) \cdot Y + \frac{\partial F}{\partial Z}(P) \cdot Z,$$

equation (1.8.1) shows that $V(L(x, y, 1))$ is the tangent to $V(f)$ at P . In this sense, the two definitions are compatible.

(1.9) Smoothness for Cubic Curves.

Let us understand the notion of smoothness in the special case of cubic curves (compare the earlier examples), more precisely for $V(f)$ with f of the form

$$f = y^2 - (x^3 + ax^2 + bx + c) = y^2 - g(x).$$

As before, assume $\text{char}(k) \neq 2$.

Then

$$\frac{\partial f}{\partial x} = -g'(x), \quad \frac{\partial f}{\partial y} = 2y.$$

(This shows why the situation is different in characteristic 2, namely then the partial derivative with respect to y vanishes for all points.)

The points $(x_0, y_0) \in V(f)$ where both partial derivatives vanish satisfy

$$y_0 = 0, \quad g(x_0) = g'(x_0) = 0,$$

i.e. x_0 is a multiple root of g .

Proposition 1.30. *For f as above, $V(f)$ is smooth if and only if g is separable (i.e. g has no multiple roots in an algebraic closure \bar{k}).*

We may homogenize f to obtain

$$F(X, Y, Z) = Y^2Z - X^3 - aX^2Z - bXZ^2 - cZ^3.$$

homogeneous of degree 3. By Remark 1.29, $P \in V(f)$ is smooth if and only if $\iota(P) \in V_+(F)$ is smooth, where as usual ι denotes the embedding $k^2 \rightarrow \mathbb{P}^2(k)$. Let us check smoothness at those points of $V_+(F)$ that lie on the line at infinity, i.e., points of the form $(x_0 : y_0 : 1) \in V_+(F)$. Then the vanishing of F amounts to $x_0 = 0$, and since this excludes the possibility of y_0 vanishing as well, and we can scale the homogeneous coordinates, we see that $V_+(F) \cap V_+(Z)$ consists of the one point $(0 : 1 : 0)$.

At this point, the partial derivative $\frac{\partial F}{\partial Z} = Y^2 - aX^2 - 2bXZ - 3cZ^2$ does not vanish, so it is a smooth point, independently of the choice of a, b, c . Therefore, for this special form of f and F , $V_+(F)$ is smooth if and only if $V(f)$ is smooth, if and only if g is separable.

Oct. 28, 2025

(1.10) Elliptic Curves and the Group Law.

Definition* 1.31. Let k be a field. An elliptic curve over k is given by a homogeneous polynomial F of degree 3 such that the vanishing set $V_+(F)$ is smooth (“for F ”, at all points of $V_+(F)(\bar{k})$, for an algebraic closure \bar{k} of k), together with a fixed point $\mathcal{O} \in E$.

Typical examples are the curves defined by homogenizations of polynomials of the form

$$y^2 - g(x), \quad g \in k[x] \text{ a separable polynomial of degree 3}$$

that we have studied above. In this case, we can (and typically do) choose the unique point $(0 : 1 : 0)$ of $V_+(F)$ on the line at infinity as the distinguished point \mathcal{O} .

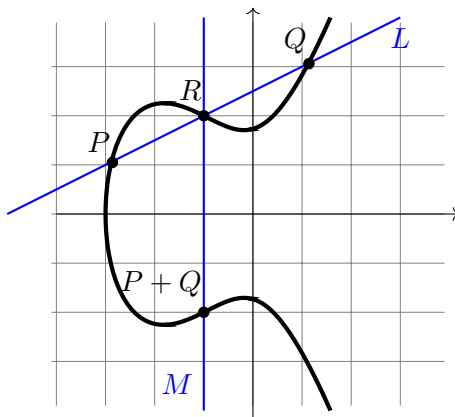
These elliptic curves have an extremely surprising additional structure, as shown by the next proposition. We will assume that k is algebraically closed, so that we can use Bézout’s theorem; but see the following remark.

Proposition 1.32. Let k be algebraically closed. Let $E = V_+(F) \subset \mathbb{P}^2(k)$ be smooth with $\deg F = 3$, and let $\mathcal{O} \in E$ be a fixed point. For $P, Q \in E$, let $L \subset \mathbb{P}^2(k)$ be the line through P, Q (or, in case $P = Q$, the tangent to $V_+(F)$ at $P = Q$).

Then, counting with multiplicities, the intersection $E \cap L$ has three elements, among them P and Q ; we express this, and give these points names, by saying that “ $E \cap L = \{\{P, Q, R\}\}$ as a multiset”. Let M be the line through \mathcal{O} and R (or, in case of equality, the tangent to $V_+(F)$ at this point), write $E \cap M = \{\{\mathcal{O}, R, S\}\}$ and define

$$P + Q = S.$$

Then $(E, +)$ is a commutative group with neutral element \mathcal{O} .



Proof. All properties except for associativity are easy to check. The neutral element is the point \mathcal{O} . For a point P , its negative $-P$ is the third point in the intersection of $V_+(F)$ and the line through P and \mathcal{O} . The associativity

can, in principle, be checked by “direct computation” (write out equations for all the lines involved in terms of coordinates of the points for which one wants to check associativity), but this leads to long, complicated and tedious calculations which are not at all enlightening. For a better, but still elementary proof, see, e.g., [Kn] Section III.3 for a complete proof; cf. also the discussion in [ST] 1.2.

(We will later, but rather next term than this term, be able to give a more enlightening proof based on the Theorem of Riemann–Roch.) \square

Remark 1.33. One can check that the proposition is still true without the assumption that k be algebraically closed. In fact, for any field extension k'/k , we obtain compatible group structures, i.e., $V_+(F)(k) \subseteq V_+(F)(k')$ is a subgroup. The key reason is that whenever a cubic polynomial in one variable over a field k has 2 zeros in k , then the third zero also lies in k (always counting zeros with multiplicity). To prove the statement, one way to proceed is to write down formulas for the coordinates of $P + Q$ in terms of the coordinates of P and of Q and see that whenever P, Q (and \mathcal{O}) have coordinates in k , then so does $P + Q$ and $-P$. See [ST] 1.4 or [Kn] III.4.

Outlook: Advanced results and some open conjectures.

Oct. 29, 2025

(1.11) The Mordell Conjecture (Faltings’ Theorem).

From a number theoretic view, it is an interesting question to determine the number of points of a vanishing set $V_+(F) \subset \mathbb{P}^2(k)$ when k is a *number field*, i.e., a finite extension of \mathbb{Q} . For example, if F is linear, then $V_+(F)$ evidently has infinitely many points (whenever k is any infinite field; for a finite field of cardinality q , it has $q + 1$ points). For F homogeneous of degree 2 the situation is still relatively easy to understand (but we skip this here). However for F of degree ≥ 3 , this is an extremely difficult question, and although a lot of progress has been made over the last 50 years, there are many questions that are still open. We first mention the Theorem of Mordell and Weil that dates back even further and gives some important information in the case of homogeneous cubic polynomials which define a smooth curve, i.e., an elliptic curve.

Theorem 1.34. [Mordell–Weil, Mordell 1922 für $K = \mathbb{Q}$; Weil 1928] *Let K/\mathbb{Q} be a finite field extension and let E be an elliptic curve over K . Then the abelian group $E(K)$ is finitely generated.*

Depending on the choice of polynomial F , the group might be finite or infinite. By the general theory of finitely generated abelian group, we can find a group isomorphism $E(K) \cong \mathbb{Z}^r \times T$ for a finite group T and some natural

number $r \geq 0$, called the *rank* of E . Even in the case $K = \mathbb{Q}$, there are many open problems around the rank. For example, it is not known whether elliptic curves over \mathbb{Q} of arbitrarily high rank exist. At the time of writing, the best result in this direction is by Elkies and Klagbrun who found (in 2024) an elliptic curve of rank ≥ 29 . The Conjecture of Birch and Swinnerton-Dyer relates the rank of an elliptic curve to a natural number defined in analytic terms (the vanishing order of a certain holomorphic function, the so-called L-function of the elliptic curve).

For a proof of the theorem, see [ST] Chapter 3 (for $K = \mathbb{Q}$), or [Si] Chapter VIII.

For polynomials of higher degree Mordell conjectured that there are only finitely many solutions with coordinates in a fixed number field. This conjecture was proved in 1983 by Faltings, and he received the Fields medal in 1986 in recognition for this proof. We state the result in a slightly more general form (which you can ignore for now, and just read it in the case of the specific example of vanishing sets $V_+(F)$ in $\mathbb{P}^2(k)$).

Theorem 1.35. [Mordell Conjecture = Faltings’s Theorem] *Let K/\mathbb{Q} be a finite field extension and C/K a smooth projective curve of genus $g \geq 2$, e.g., $C = V_+(F) \subset \mathbb{P}^2(k)$ with F homogeneous of degree ≥ 4 such that $V_+(F)$ is smooth.*

Then $C(K)$ is a finite set.

(1.12) Fermat’s Last Theorem and Modular Curves.

Theorem 1.36. [“Fermat’s last theorem”; Wiles] *Let $p > 2$ be prime. Then*

$$V_+(X^p + Y^p + Z^p)(\mathbb{Q}) = \{(0 : 1 : -1), (1 : 0 : -1), (1 : -1 : 0)\},$$

i.e. only the trivial (obvious) solutions exist.

It follows from Faltings’s Theorem that the set on the left hand side is finite whenever $p > 3$, but that theorem does not give any information on the cardinality of this finite set. Wiles’s contribution was the following more specific result about elliptic curves over \mathbb{Q} .

Theorem 1.37. [Taniyama–Shimura–Weil Conjecture; Wiles, 1995] *Every elliptic curve E/\mathbb{Q} is modular.*

Actually, Wiles (together with Taylor) proved a slightly weaker than the theorem stated here; the proof was later completed by Breuil, Conrad, Diamond and Taylor. Ribet, based on an idea of Frey², had shown before that this modularity conjecture implies Fermat’s Last Theorem. The key idea of Frey was that assuming that $a^p + b^p = c^p$ for $abc \neq 0$, the elliptic curve defined by the (homogenization of the) equation

$$y^2 = x(x - a^p)(y - b^p)$$

²Gerhard Frey was a professor at the University of Duisburg-Essen from 1990 to 2009.

has “strange” properties and is seemingly not modular; this was then shown by Ribet.

Remark 1.38. We do not explain here what *modular* means. Roughly, it asserts a strong relation between the elliptic curve and a certain “modular form”.

For example, if E is given by $y^2 = x^3 + Ax + B$ with $A, B \in \mathbb{Z}$, then modularity implies a precise regularity for the numbers of points

$$\#\{(x, y) \in \mathbb{F}_q^2 \mid y^2 = x^3 + Ax + B\},$$

for each prime power q .

(1.13) The abc Conjecture.

We finish this chapter by a brief discussion of another famous conjecture which at first sight does not have much to do with algebraic geometry (but in fact, it does: for instance, it is equivalent to a conjecture by Szpiro on elliptic curves over \mathbb{Q} ; indeed, Masser and Oesterlé made their conjecture after studying Szpiro’s conjecture and its consequences).

We define the *radical* of a positive integer n as

$$\text{rad}(n) := \prod_{p \text{ prime}, p|n} p.$$

Conjecture 1.39. [abc conjecture, Masser–Oesterlé] *For every $\varepsilon > 0$ there are only finitely many coprime triples (a, b, c) of positive integers with $a + b = c$ and*

$$c > \text{rad}(abc)^{1+\varepsilon}.$$

We also state the following stronger variant, an *explicit form of the abc conjecture*. If $a, b, c \in \mathbb{Z}_{>0}$ are coprime with $a + b = c$, then

$$c \leq \text{rad}(abc)^2.$$

Example 1.40. $3 + 125 = 128 = c$, and $c > 30 = \text{rad}(3 \cdot 125 \cdot 128)$ illustrates the inequality.

Remark 1.41.

- (1) It is, somewhat surprisingly, not difficult to prove an analogous statement, where the ring \mathbb{Z} of integers is replaced by the polynomial ring $\mathbb{C}[X]$. See the second problem sheet.
- (2) The abc conjecture implies effective versions of the Mordell Conjecture/Faltings’s Theorem.

Let us illustrate by showing that the above effective version of the abc conjecture easily implies Fermat’s Last Theorem for exponents $n \geq 6$.

In fact, suppose there exist $n \in \mathbb{N}$ and coprime positive integers x, y, z with $x^n + y^n = z^n$. Then

$$z^n \leq \text{rad}(xyz)^2$$

by the abc conjecture, but also

$$\text{rad}(xyz)^2 \leq (xyz)^2 < z^6.$$

Putting both inequalities together, we obtain $n < 6$. The cases $n = 3, 4, 5$ are (relatively) easier and have long been known, so the (effective) *abc*-conjecture implies Fermat's Last Theorem.

(1.14) Problems with Our Approach So Far.

What we have discussed so far was intentionally introductory and not yet systematic. Beyond that, the “theory” so far has some serious problems. Some are easy to fix; others require more serious changes. Desiderata:

- The same vanishing set $V(f)$ (or more generally, $V(f_1, \dots, f_m)$) can be defined by several different polynomials, and the set alone does not “contain enough information” (for example, in order to define smoothness). We would like to equip it with more “geometric structure” which will allow us to not carry around a specific choice of polynomial(s).
- Related to this: A definition of *morphisms* (and hence isomorphisms) between vanishing sets $V(f_1, \dots, f_m)$.
- A more systematic use of *commutative algebra*.
- A theory that works well over *non-algebraically closed fields* (and even over arbitrary commutative rings).
- A more transparent *geometric meaning* of intersection multiplicities $i_P(V_+(F), V_+(G))$ in Bézout's theorem (see earlier sections).

2. THE PRIME SPECTRUM OF A RING

References: [GW1] (2.1)–(2.4) (or other books that cover scheme theory, e.g., [Mu] Ch. II §1; [Ha] II.2).

(2.1) Motivation: Hilbert's Nullstellensatz.

One piece of motivation for the theory we are going to work out is *Hilbert's Nullstellensatz*. To start the discussion, we start with a simple observation. Nov. 4, 2025

Proposition 2.1. *Let k be a field, $(t_1, \dots, t_n) \in k^n$. Then*

$$(T_1 - t_1, \dots, T_n - t_n) \subset k[T_1, \dots, T_n]$$

is a maximal ideal. This ideal is the kernel of the evaluation homomorphism

$$k[T_1, \dots, T_n] \rightarrow k, \quad T_i \mapsto t_i,$$

i.e., a polynomial f lies in the above ideal if and only if $f(t_1, \dots, t_n) = 0$.

Proof. All statements are easy to check. □

Theorem 2.2. *Let k be a field, and $\mathfrak{m} \subset k[T_1, \dots, T_n]$ a maximal ideal. Then the field extension $k \subset k[T_1, \dots, T_n]/\mathfrak{m}$ is finite.*

Proof. See [GW1] Section (1.3), or [Mu] Ch. I §1, or [Alg2] 4.3³ for proofs based on Noether Normalization, or, for instance, [AM] Ch. 5, Ch. 7 for (somewhat) different proofs. □

Corollary 2.3. *Let k be an algebraically closed field. Then the maximal ideals of the ring $k[T_1, \dots, T_n]$ are precisely the ideals of the form*

$$(T_1 - t_1, \dots, T_n - t_n), \quad (t_1, \dots, t_n) \in k^n,$$

and we obtain a bijection between k^n and the set of maximal ideals of $k[T_1, \dots, T_n]$.

Proof. Let $\mathfrak{m} \subset k[T_1, \dots, T_n]$ be a maximal ideal. By the theorem, the inclusion $k \rightarrow k[T_1, \dots, T_n]/\mathfrak{m}$ is a finite field extension, hence – since k is algebraically closed by assumption – an isomorphism. We define t_i as the image of (the residue class of) T_i under its inverse. Then clearly $(T_1 - t_1, \dots, T_n - t_n) \subset \mathfrak{m}$, and since the left hand side is a maximal ideal, equality follows. □

Under the bijection of the corollary (for k algebraically closed), a vanishing set $V(f_1, \dots, f_m)$ corresponds to the set of all maximal ideals that contain f_1, \dots, f_m .

³<https://math.ug/a2-ss23/sec-nullstellensatz.html>

(2.2) The spectrum of a ring.

Following Grothendieck, and in view of Hilbert's Nullstellensatz, we start a general theory of algebraic geometry by replacing polynomial rings over (algebraically closed) fields by arbitrary ring, and defining for a ring R , its prime spectrum

$$\operatorname{Spec}(R) = \{\mathfrak{p} \subset R \text{ prime ideal}\}.$$

(It is better to work with prime ideals than with maximal ideals. One reason is that otherwise the following definition of the map between spectra induced by a ring homomorphism would not work, since in general preimages of maximal ideals under a ring homomorphism are not maximal ideals.)

For an element $f \in R$, we denote by $f(\mathfrak{p})$ the image of f under the ring homomorphism

$$R \longrightarrow R/\mathfrak{p} \longrightarrow \operatorname{Frac}(R/\mathfrak{p}).$$

In particular, we have $f(\mathfrak{p}) = 0$ if and only if $f \in \mathfrak{p}$. (Compare the situation for polynomial rings over fields, and polynomials f .)

Proposition/Definition 2.4. [Zariski topology on $\operatorname{Spec}(R)$] *Let R be a ring.*

(1) *For a subset $M \subseteq R$, we define the “vanishing set”*

$$V(M) = \{\mathfrak{p} \in \operatorname{Spec}(R); M \subseteq \mathfrak{p}\}.$$

If \mathfrak{a} is the ideal generated by M , then $V(M) = V(\mathfrak{a})$. For $M \subseteq M'$, we have $V(M') \subseteq V(M)$. For an element $f \in R$ we also write $V(f)$ for $V(\{f\})$.

(2) *We have $V(0) = \operatorname{Spec}(R)$, $V(1) = \emptyset$.*

(3) *For a family \mathfrak{a}_i of ideals of R , we have*

$$\bigcap_i V(\mathfrak{a}_i) = V\left(\sum_i \mathfrak{a}_i\right).$$

(4) *For ideals $\mathfrak{a}_1, \mathfrak{a}_2 \subseteq R$ we have*

$$V(\mathfrak{a}_1) \cup V(\mathfrak{a}_2) = V(\mathfrak{a}_1 \cap \mathfrak{a}_2) = V(\mathfrak{a}_1 \mathfrak{a}_2).$$

In particular, the subsets of $\operatorname{Spec}(R)$ of the form $V(\mathfrak{a})$ for ideals $\mathfrak{a} \subseteq R$ form the closed sets of a topology on $\operatorname{Spec}(R)$, the so-called Zariski topology.

Proof. Assertions (1), (2) and (3) are easy to check. For (4) note that

$$\mathfrak{a}_1 \mathfrak{a}_2 \subseteq \mathfrak{a}_1 \cap \mathfrak{a}_2 \cap \mathfrak{a}_1,$$

and likewise for \mathfrak{a}_2 , so that we have

$$V(\mathfrak{a}_1) \cup V(\mathfrak{a}_2) \subseteq V(\mathfrak{a}_1 \cap \mathfrak{a}_2) \subseteq V(\mathfrak{a}_1 \mathfrak{a}_2).$$

Now let $\mathfrak{p} \in V(\mathfrak{a}_1 \mathfrak{a}_2)$ and assume that $\mathfrak{p} \notin V(\mathfrak{a}_1)$, say $f \in \mathfrak{a}_1 \setminus \mathfrak{p}$. But then for every $g \in \mathfrak{a}_2$, we have $fg \in \mathfrak{a}_1 \mathfrak{a}_2 \subseteq \mathfrak{p}$, and since \mathfrak{p} is a prime ideal and $f \notin \mathfrak{p}$, we get $g \in \mathfrak{p}$. We have shown that $\mathfrak{a}_2 \subseteq \mathfrak{p}$, i.e., that $\mathfrak{p} \in V(\mathfrak{a}_2)$. \square

With the notation introduced above, we can also write

$$V(M) = \{\mathfrak{p} \in \operatorname{Spec}(R); f(\mathfrak{p}) = 0 \text{ for all } f \in M\}.$$

This in particular shows the analogy with the notation $V(M)$ introduced in Chapter 1. But note that this is only an analogy; we really *redefine* the notation $V(M)$ and from now on will use it only with the new meaning.

We have attached to every ring R a topological space $\operatorname{Spec}(R)$. We extend this definition to a *contravariant functor* from the category of rings to the category of topological spaces, as follows. (This means simply that to each ring homomorphism $\varphi: R \rightarrow S$ we attach a continuous map $\operatorname{Spec}(S) \rightarrow \operatorname{Spec}(R)$ (note that it goes “in the other direction”, whence the term *contravariant*), and this is compatible with composition of homomorphisms, and for the identity map on rings we get the identity map on topological spaces. For more on categories, see, e.g., [Alg2] Section 3.1⁴ or [GW1] Appendix A.)

Recall that the inverse image of a prime ideal under a ring homomorphism is a prime ideal.

Definition 2.5. Let $\varphi: R \rightarrow S$ be a ring homomorphism. We define a map

$${}^a\varphi: \operatorname{Spec}(S) \rightarrow \operatorname{Spec}(R), \quad \mathfrak{q} \mapsto \varphi^{-1}(\mathfrak{q}).$$

This map is also denoted by $\operatorname{Spec}(\varphi)$.

It is immediate that this construction is compatible with composition of homomorphisms, and for the identity map on rings we get the identity map on topological spaces. Continuity is also easy to check:

Lemma 2.6. Let $\varphi: R \rightarrow S$ be a ring homomorphism. Then the map ${}^a\varphi$ is continuous. More precisely, for every ideal $\mathfrak{a} \subseteq R$, we have

$$({}^a\varphi)^{-1}(V(\mathfrak{a})) = V(\varphi(\mathfrak{a})).$$

Proof. The second statement implies that for every closed subset of $\operatorname{Spec}(R)$ the inverse image under ${}^a\varphi$ is again closed, and hence that the map ${}^a\varphi$ is continuous. To prove it, note that for $\mathfrak{q} \in \operatorname{Spec}(S)$ we have

$$\begin{aligned} \mathfrak{q} \in ({}^a\varphi)^{-1}(V(\mathfrak{a})) &\iff {}^a\varphi(\mathfrak{q}) \in V(\mathfrak{a}) \iff \mathfrak{a} \subseteq \varphi^{-1}(\mathfrak{q}) \\ &\iff \varphi(\mathfrak{a}) \subseteq \mathfrak{q} \iff \mathfrak{q} \in V(\varphi(\mathfrak{a})). \end{aligned}$$

□

Example 2.7.

- (1) $\operatorname{Spec}(k)$ for k a field,
- (2) $\operatorname{Spec}(\mathbb{Z})$,
- (3) $\operatorname{Spec}(k \times k)$ for k a field,
- (4) for R a principal ideal domain, the prime ideals are (0) (with closure all of $\operatorname{Spec}(R)$) and the ideals (f) for f irreducible (the latter being maximal ideals and hence corresponding to closed points). This applies in particular to $\operatorname{Spec}(k[T])$ for k a field. If k is assumed to be algebraically closed

Nov. 5, 2025

⁴<https://math.ug/a2-ss23/subsec-kategorien.html>

then the irreducible polynomials are precisely the linear polynomials and $\text{Spec}(k[T]) = \{(X - a); a \in k\} \cup \{(0)\}$. For $k = \mathbb{R}$, in addition to the linear polynomials, there are irreducible polynomials of degree 2, as well, namely all polynomials that decompose in $\mathbb{C}[T]$ as $(X - a)(X - \bar{a})$ for some $a \in \mathbb{C} \setminus \mathbb{R}$. The map $\text{Spec}(\mathbb{C}[T]) \rightarrow \text{Spec}(\mathbb{R}[T])$ corresponding to the inclusion $\mathbb{R}[T] \subset \mathbb{C}[T]$ maps $(0) \mapsto (0)$ and

$$(X - a) \mapsto (X - a) \quad (a \in \mathbb{R}), \quad (X - a) \mapsto ((X - a)(X - \bar{a})) \quad (a \in \mathbb{C} \setminus \mathbb{R}).$$

Proposition 2.8. *Let R be a ring and $\mathfrak{a} \subseteq R$ an ideal. Denote by $\pi: R \rightarrow R/\mathfrak{a}$ the canonical projection. Then the map ${}^a\pi$ induces a homeomorphism (i.e., a bijective continuous map with continuous inverse map)*

$$\text{Spec}(R/\mathfrak{a}) \rightarrow V(\mathfrak{a}).$$

Proof. Since (prime) ideals in the quotient correspond bijectively to (prime) ideals in R which contain \mathfrak{a} , the map $\text{Spec}(R/\mathfrak{a}) \rightarrow \text{Spec}(R)$ has image $V(\mathfrak{a})$ and is injective. Since we know that it is continuous, it only remains to show that the inverse map is continuous, as well. In other words, we need to check that ${}^a\pi$ maps closed sets to closed sets. But one checks easily that

$${}^a\pi(V(\bar{\mathfrak{b}})) = V(\mathfrak{a}) \cap V(\pi^{-1}(\bar{\mathfrak{b}}))$$

which is closed in $V(\mathfrak{a})$, as desired. \square

Note that it is easy (i.e., you should do it ...) to construct examples of a ring R and ideals $\mathfrak{a} \neq \mathfrak{b}$ with $V(\mathfrak{a}) = V(\mathfrak{b})$. The following result clarifies the situation. Recall the notion of *radical* of an ideal; for $\mathfrak{a} \subseteq R$ its radical is

$$\sqrt{\mathfrak{a}} = \{f \in R; \exists n \geq 1 : f^n \in \mathfrak{a}\} = \bigcap_{\mathfrak{p} \in V(\mathfrak{a})} \mathfrak{p},$$

an ideal containing \mathfrak{a} . For the second equality, see [Alg2] Satz 2.59⁵. We call an ideal $\mathfrak{a} \subseteq R$ a *radical ideal*, if $\sqrt{\mathfrak{a}} = \mathfrak{a}$.

Proposition 2.9. *Let R be a ring. For $Y \subseteq \text{Spec}(R)$, write $I(Y) = \bigcap_{\mathfrak{p} \in Y} \mathfrak{p}$.*

The maps $\mathfrak{a} \mapsto V(\mathfrak{a})$ and $Y \mapsto I(Y)$ satisfy

- (1) $V(I(Y)) = \bar{Y}$,
- (2) $I(V(\mathfrak{a})) = \sqrt{\mathfrak{a}}$,

and in particular induce a bijection between the set of all radical ideals of R and the set of all closed subsets of $\text{Spec}(R)$.

Proof. It is clear that both $V(-)$ and $I(-)$ are inclusion reversing. Furthermore, $I(Y)$, being an intersection of radical ideals, is itself a radical ideal for every Y . Since $V(\mathfrak{a})$ is closed for every \mathfrak{a} , the final statement follows from (1) and (2).

Let us show that $V(I(Y)) = \bar{Y}$ for every subset $Y \subseteq \text{Spec}(R)$. Clearly the left hand side is closed and contains Y , so we have \supseteq . To show \subseteq we need

⁵<https://math.ug/a2-ss23/sec-radikale.html#stz-beschr-rad-a>

to show that $V(I(Y))$ is the smallest closed subset containing Y , i.e., that whenever $Y \subseteq V(\mathfrak{a})$, then $V(I(Y)) \subseteq V(\mathfrak{a})$. But if $Y \subseteq V(\mathfrak{a})$, then $\mathfrak{a} \subseteq \mathfrak{p}$ for all $\mathfrak{p} \in Y$, so $\mathfrak{a} \subseteq I(Y)$, and hence $V(I(Y)) \subseteq V(\mathfrak{a})$ as desired.

Now we show that $I(V(\mathfrak{a})) = \sqrt{\mathfrak{a}}$ for every ideal $\mathfrak{a} \subset R$. But the radical of \mathfrak{a} can be described as

$$\sqrt{\mathfrak{a}} = \bigcap_{\mathfrak{p} \in \text{Spec}(R), \mathfrak{a} \subseteq \mathfrak{p}} \mathfrak{p},$$

and this is precisely $I(V(\mathfrak{a}))$. \square

In particular, for every $\mathfrak{p} \in \text{Spec}(R)$,

$$\overline{\{\mathfrak{p}\}} = V(\mathfrak{p}).$$

From this we see that a point $\mathfrak{p} \in \text{Spec}(R)$ is closed (i.e., $\{\mathfrak{p}\}$ is a closed subset of $\text{Spec}(R)$) if and only if \mathfrak{p} is a maximal ideal.

Definition 2.10. Let R be a ring. For $f \in R$ we define

$$D(f) = \text{Spec}(R) \setminus V(f)$$

and call the subsets of $\text{Spec}(R)$ of this form principal open subsets.

With the notation introduced above we may write

$$D(f) = \{\mathfrak{p} \in \text{Spec}(R); f(\mathfrak{p}) \neq 0\},$$

and correspondingly we sometimes think of $D(f)$ as the *non-vanishing set* of f .

Proposition 2.11. Let R be a ring.

- (1) The sets $D(f)$ for $f \in R$ form a basis of the topology of $\text{Spec}(R)$, i.e., every open subset of $\text{Spec}(R)$ can be written as a union of subsets of this form.
- (2) The family of sets $D(f)$ is stable under taking finite intersections.

Proof. For (1) take $U \subseteq \text{Spec}(R)$ open, say $U = \text{Spec}(R) \setminus V(\mathfrak{a})$. Then $V(\mathfrak{a}) = \bigcap_{f \in \mathfrak{a}} V(f)$, hence $U = \bigcup_{f \in \mathfrak{a}} D(f)$. For (2) note that $D(f) \cap D(g) = D(fg)$ and that the intersection with empty index set, $\text{Spec}(R)$ equals $D(f)$. \square

Proposition 2.12. Let R be a ring and let $f \in R$. Denote by R_f the localization of R with respect to f . Then the ring homomorphism $\tau: R \rightarrow R_f$, $x \mapsto \frac{x}{1}$, induces a homeomorphism

$$\text{Spec}(R_f) \rightarrow D(f).$$

Proof. The set of prime ideals in a localization $S^{-1}R$ of R is in bijection to the set of prime ideals \mathfrak{p} in R with $\mathfrak{p} \cap S = \emptyset$, via $\mathfrak{P} \mapsto \tau^{-1}(\mathfrak{P})$ and $\mathfrak{p} \mapsto \mathfrak{p}S^{-1}R = \left\{ \frac{a}{s}; a \in \mathfrak{p}, s \in S \right\}$. This implies that the continuous map $\text{Spec}(R_f) \rightarrow \text{Spec}(R)$ restricts to a bijective (and, of course, still continuous) map $\text{Spec}(R_f) \rightarrow D(f)$. To check that it is a homeomorphism, we need to check that open sets in $\text{Spec}(R_f)$ have opens in $D(f)$ as their image. It is enough to check this for principal open subsets $D(g/f^i)$, because those are

a basis of the topology, and such a set has image $D(fg) = D(f) \cap D(g)$ in $\text{Spec}(R)$, which is open in $D(f)$. (Equivalently, one could check that closed sets have closed image in $D(f)$. This is also easy: for an ideal $\mathfrak{a} \subseteq R_f$, the image of $V(\mathfrak{a})$ in $\text{Spec}(R)$ is $D(f) \cap V(\tau^{-1}(\mathfrak{a})) \cap D(f)$ which is closed in $D(f)$.) \square

Proposition 2.13. *Let R be a ring and $f \in R$. Then $D(f)$ (with the induced topology) is quasi-compact⁶ (i.e., for every cover $D(f) = \bigcup_{i \in I} U_i$ by open subsets there exists a finite subset $I' \subseteq I$ with $D(f) = \bigcup_{i \in I'} U_i$). In particular, $\text{Spec}(R) = D(1)$ is quasi-compact.*

Proof. Exercise (Problem Sheet 3). \square

(2.3) Generic points.

Nov. 11, 2025

Recall from Problem Sheet 1 the notion of *irreducible* topological space. (A topological space X is called *irreducible*, if $X \neq \emptyset$ and X cannot be written as the union of two proper closed subsets, or equivalently, if $X \neq \emptyset$ and any two non-empty open subsets of X have non-empty intersection.)

Clearly, if X is a topological space and $x \in X$, then the closure $\overline{\{x\}}$ is irreducible (because any non-empty open of this set contains x). Topological spaces that arise as spectra of ring have a sort of converse property:

Proposition 2.14. *Let R be a ring, $X = \text{Spec}(R)$, and $Z \subseteq X$ a closed subset.*

- (1) *The set Z (with the induced topology) is irreducible if and only if $I(Z)$ is a prime ideal.*
- (2) *If the closed subset Z is irreducible, then there exists a unique $\eta \in Z$ such that $\overline{\{\eta\}} = Z$, and we call η the generic point of Z .*

Proof. Let $\mathfrak{a} = I(Z)$, so $\mathfrak{a} \subseteq R$ is a radical ideal with $Z = V(\mathfrak{a})$. If $\mathfrak{a} = \mathfrak{p}$ is a prime ideal, then $Z = V(\mathfrak{p}) = \{\mathfrak{p}\}$ as we have seen above, and in particular Z is irreducible with generic point \mathfrak{p} . Since for prime ideals, $V(\mathfrak{p}) = V(\mathfrak{q})$ if and only if $\mathfrak{p} = \mathfrak{q}$ (because prime ideals are radical ideals) this argument also shows the uniqueness statement of (2).

Thus it only remains to show that whenever Z is irreducible, then $I(Z)$ is prime. First note that $Z \neq \emptyset$ implies $I(Z) \neq R$. Now for $f, g \in R$ with $fg \in I(Z)$, we have $Z \subseteq V(fg) = V(f) \cup V(g)$, and if Z is irreducible, it follows that $Z \subseteq V(f)$ or $Z \subseteq V(g)$. Without loss of generality, we have $Z \subseteq V(f)$, say. But then $f \in \sqrt{(f)} = I(V(f)) \subseteq I(Z)$. \square

⁶The terminology here follows the French/Bourbaki convention, which also became the standard in algebraic geometry, that a *compact* space is quasi-compact in the sense explained here and *Hausdorff* (which $\text{Spec}(R)$ typically is not).

More precisely, one can show that for any subset $Y \subseteq \operatorname{Spec}(R)$ (not necessarily closed), Y is irreducible if and only if $I(Y)$ is a prime ideal. (But Y need not contain a generic point!) This follows from the following lemma.

Lemma 2.15. *Let X be a topological space, and $Y \subseteq X$ a subset with closure \overline{Y} . Then Y is irreducible if and only if \overline{Y} is irreducible.*

Proof. Use that for any open $U \subseteq X$, we have $Y \cap U = \emptyset$ if and only if $\overline{Y} \cap U = \emptyset$. \square

3. SHEAVES

References: [GW1] (2.5)–(2.8) or [Ha] II.1.

(3.1) The notion of sheaf.

We have attached to every ring R a topological space $\mathrm{Spec}(R)$, but this topological space “retains very little information” about the ring R . For example, for every field k we get the same topological space as its prime spectrum. To achieve our goal of “making $\mathrm{Spec}(R)$ into a geometric object”, we follow the slogan that *the geometry of a “space” is determined by the functions on the space*, meaning that for each kind of geometry (topology, differential geometry, complex geometry) there is a natural notion of function (continuous, differentiable, holomorphic), and this is a characteristic feature of the whole theory.

For us, the intuition is that elements of the ring R should be viewed as functions on $\mathrm{Spec}(R)$, but since the elements of R are not “really” functions, it is useful to introduce a more abstract framework that allows us to talk about (and gain intuition from) the previously mentioned cases, but which also applies to the prime spectra of rings.

As it turns out, the following properties are crucial for the “functions” we want to consider. Let X be a topological space.

- A function might be defined on all of X , or on some smaller open subset of X (the “domain of definition” of the function). We want to allow the functions to have poles at some point of X and therefore do not ask that the domain of definition is always equal to X .
- Functions should be determined by “local information” – since we do not want to talk of the values of a function, we will instead talk about restrictions of a function to open subsets within its “domain of definition”, and require that it is determined by the restrictions to open subsets that cover the domain of definition, and also that functions can be defined by “gluing with respect to an open cover” (see below).

(We are deliberately vague about the “target” of our “functions”. In differential geometry it would be \mathbb{R} , in complex geometry it would be \mathbb{C} , but in algebraic geometry we do not really have functions and therefore do not really have a target of functions at our disposal.)

Definition 3.1. *Let X be a topological space. A presheaf \mathcal{F} (of sets) on X is given by the following data:*

- (a) *for each open $U \subseteq X$, a set $\mathcal{F}(U)$,*
- (b) *for each pair $U \subseteq V \subseteq X$ of open subsets, a map (“restriction map”) $\mathrm{res}_U^V: \mathcal{F}(V) \rightarrow \mathcal{F}(U)$,*

such that $\mathrm{res}_U^U = \mathrm{id}_{\mathcal{F}(U)}$ for every U and $\mathrm{res}_U^W = \mathrm{res}_U^V \circ \mathrm{res}_V^W$ for all $U \subseteq V \subseteq W$ open.

Definition 3.2. Let X be a topological space and \mathcal{F}, \mathcal{G} be presheaves on X . A morphism $\varphi: \mathcal{F} \rightarrow \mathcal{G}$ of presheaves is a family of maps $\varphi_U: \mathcal{F}(U) \rightarrow \mathcal{G}(U)$ of maps, $U \subseteq X$ open, such that for all pairs $U \subseteq V \subseteq X$ of open subsets, the diagram

$$\begin{array}{ccc} \mathcal{F}(V) & \xrightarrow{\varphi_V} & \mathcal{G}(V) \\ \downarrow \text{res}_U^V & & \downarrow \text{res}_U^V \\ \mathcal{F}(U) & \xrightarrow{\varphi_U} & \mathcal{G}(U) \end{array}$$

commutes.

Notation: We often write $s|_U$ for $\text{res}_U^V(s)$ ($s \in \mathcal{F}(V)$). The elements of $\mathcal{F}(U)$ are also called *sections* of the presheaf on the open set U . One also writes $\Gamma(U, \mathcal{F})$ instead of $\mathcal{F}(U)$.

While the notion of presheaf provides the basic framework to talk about (generalizations of) functions on a topological space, it is much too general and does not capture enough properties that (even generalized) “functions” should have. It turns out that the crucial property is that functions should be determined by their restrictions to an open cover, and that it should be possible to “specify a function locally”, i.e., on an open cover, provided that the obvious compatibility condition on intersections is satisfied. This observation is turned into the definition of *sheaf*, as follows.

Definition 3.3. Let X be a topological space. A presheaf \mathcal{F} (of sets) on X is called a *sheaf* (of sets), if the following condition is satisfied. For every open subset $U \subseteq X$ and every cover $U = \bigcup_{i \in I} U_i$ by open subsets of X , the diagram

$$\begin{array}{ccc} \mathcal{F}(U) & \xrightarrow{\rho} & \prod_{i \in I} \mathcal{F}(U_i) \xrightarrow[\sigma']{\sigma} \prod_{(i,j) \in I \times I} \mathcal{F}(U_i \cap U_j) \\ s \longmapsto & & (s|_{U_i})_i \\ & & (s_i)_i \xrightarrow{\sigma} (s_i|_{U_i \cap U_j})_{i,j} \\ & & (s_i)_i \xrightarrow{\sigma'} (s_j|_{U_i \cap U_j})_{i,j} \end{array}$$

is exact, i.e., the map ρ is injective, and the image of ρ is the set of elements $(s_i)_{i \in I}$ such that $\sigma((s_i)_{i \in I}) = \sigma'((s_i)_{i \in I})$.

For sheaves \mathcal{F}, \mathcal{G} on X , a morphism $\mathcal{F} \rightarrow \mathcal{G}$ of sheaves is a morphism between the presheaves \mathcal{F} and \mathcal{G} .

Pedantic remark: It follows from the definition (applied to $U = \emptyset$, $I = \emptyset$) that for every sheaf \mathcal{F} , the set $\mathcal{F}(\emptyset)$ has precisely one element.

Nov. 12, 2025

Examples 3.4. Typical examples of sheaves (and one non-example) one should have in mind are the following.

- (1) Let X be a topological space and Y a set. Setting, for $U \subseteq X$ open, $\mathcal{F}(U) = \text{Map}(X, Y)$ (the set of all maps $U \rightarrow Y$) defines a sheaf on X .

- (2) Let X and Y be topological spaces. Setting $\mathcal{F}(U) = \text{Map}_{\text{cont}}(X, Y)$ (the set of all *continuous* maps $U \rightarrow Y$) defines a sheaf on X .
- (3) Let $X \subseteq \mathbb{R}^n$ open (or any differentiable manifold). Setting $\mathcal{F}(U) = C^\infty(U)$, the set of infinitely often differentiable functions $U \rightarrow \mathbb{R}$, defines a sheaf on X .
- (4) Let $X \subseteq \mathbb{C}^n$ open (or any complex manifold). Setting $\mathcal{F}(U) = \text{Hol}(U)$, the set of holomorphic functions $U \rightarrow \mathbb{C}$, defines a sheaf on X .
- (5) Let $X = \mathbb{R}$ (with the analytic topology). Setting $\mathcal{F}(U) = \{f: U \rightarrow \mathbb{R} \text{ bounded}\}$ defines a presheaf on \mathbb{R} which is not a sheaf. (Similarly: bounded and continuous; or bounded and differentiable.)

Typically, the restriction maps res_U^V are neither injective nor surjective. If the map is not surjective, we may think of it as saying that there are “functions” (more precisely, sections of the sheaf) defined on U but which do not extend (because they may “have poles” at points of $V \setminus U$) to the larger set V . On the other hand, a “function” on V cannot usually be expected to be determined by its values on a smaller open set U ; so in the above examples (1), (2), (3) the restriction maps will be injective only in trivial cases. However in complex analysis (Example (4) above) there is the interesting result (the “identity theorem”) that the restriction map res_U^V is injective whenever $\emptyset \neq U \subseteq V$ and V is connected.

It follows easily from the sheaf axioms that for $U = U_1 \cap U_2$ with U_1, U_2 open and $U_1 \cap U_2 = \emptyset$, the natural map $\mathcal{F}(U) \rightarrow \mathcal{F}(U_1) \times \mathcal{F}(U_2)$ induced by the restriction maps is an isomorphism.

Often the sets of sections carry more structure, for example, in the above examples of sheaves of actual functions (with certain properties such as continuity or differentiability) with target a ring, we can actually add and multiply functions by using the addition and multiplication on the target, so that the sets $\mathcal{F}(U)$ in this case naturally carry a ring structure and the restriction maps are ring homomorphism. This is of course a useful piece of information to remember, and we therefore make the following definition.

Definition 3.5. *If X is a topological space and \mathcal{F} a (pre-)sheaf on X , and all $\mathcal{F}(U)$ are equipped with the structure of group / abelian group / ring / module over a (fixed) ring R / ..., and all restriction maps are homomorphisms for the respective structure, then we speak of a (pre-)sheaf of groups / abelian groups / rings / R -modules / ...*

Often the following construction is useful.

Definition 3.6. [Restriction of (pre-)sheaf to open subset] *Let \mathcal{F} be a presheaf on a topological space X , and let $U \subseteq X$ be an open subset. Then the restriction of \mathcal{F} to U is the presheaf $\mathcal{F}|_U$ on U given by $\mathcal{F}|_U(V) = \mathcal{F}(V)$ for all $V \subseteq U$ open, and the same restriction maps as those for \mathcal{F} . If \mathcal{F} is a sheaf, then so is $\mathcal{F}|_U$.*

Our next goal is to define a sheaf of rings on $X = \operatorname{Spec}(R)$ for a ring R . This sheaf will be denoted \mathcal{O}_X and called the *structure sheaf* on $\operatorname{Spec}(R)$. The underlying idea is the following. We said that we want to view elements of R as (a kind of) functions on X , so we will start by setting $\mathcal{O}_X(X) = R$. For a general open subset $U \subset X$ it is however not so clear what to do. However, for principal opens $D(f) \subseteq X$, there is a natural candidate. Namely, we have seen that there is a natural homeomorphism $\operatorname{Spec}(R_f) \cong D(f)$, and since we have already made a guess what the ring of functions on the left hand side should be (namely R_f), we will set $\mathcal{O}_X(D(f)) = R_f$. (We will check later that this is well-defined, i.e., that whenever $D(f) = D(g)$, we have a canonical identification $R_f = R_g$.) At this point we can already (and will, see below) check that this definition satisfies the conditions in the definition of sheaves (i.e., the “gluing of sections”); the computation is not so difficult, but this is a crucial point of the theory. Having checked this, philosophically, we can expect that this should be enough information in order to define \mathcal{O}_X , because the $D(f)$ form a basis of the topology, and a sheaf should be determined by local information. This is in fact a general result on sheaves, and we will prove it below.

(3.2) Sheaves on a basis of the topology.

In this section we fix a topological space X and a basis \mathcal{B} of the topology of X (recall that this means that \mathcal{B} is a set of open subsets of X such that every open subset of X can be written as a union of elements of \mathcal{B}). Things simplify if \mathcal{B} satisfies in addition the property that any finite intersections of open subsets lying in \mathcal{B} is again an element of \mathcal{B} . This is satisfied for the basis of principal open subsets of the Zariski topology of the spectrum of a ring, the situation relevant for us, so the reader is advised to make this extra assumption.

Definition 3.7.

- (1) A presheaf \mathcal{F} on the basis \mathcal{B} of the topology is given by a set $\mathcal{F}(U)$ for every $U \in \mathcal{B}$ and a restriction map $\operatorname{res}_U^V: \mathcal{F}(V) \rightarrow \mathcal{F}(U)$ for every pair of open subsets $U, V \in \mathcal{B}$ with $U \subseteq V$, such that $\operatorname{res}_U^U = \operatorname{id}_{\mathcal{F}(U)}$ for every $U \in \mathcal{B}$ and $\operatorname{res}_U^W = \operatorname{res}_U^V \circ \operatorname{res}_V^W$ for all open subsets $U, V, W \in \mathcal{B}$, $U \subseteq V \subseteq W$.
- (2) A presheaf \mathcal{F} on \mathcal{B} is called a sheaf on \mathcal{B} , if for every $U \in \mathcal{B}$, every cover $U = \bigcup_i U_i$ with $U_i \in \mathcal{B}$ and every open cover $U_i \cap U_j = \bigcup_k U_{ijk}$ with $U_{ijk} \in \mathcal{B}$, the sequence

$$\begin{array}{ccc}
\mathcal{F}(U) & \xrightarrow{\rho} & \prod_{i \in I} \mathcal{F}(U_i) \xrightarrow[\sigma']{\sigma} \prod_{(i,j) \in I \times I} \prod_k \mathcal{F}(U_{ijk}) \\
s & \longmapsto & (s|_{U_i})_i \\
(s_i)_i & \xrightarrow{\sigma} & (s_i|_{U_{ijk}})_{i,j} \\
(s_i)_i & \xrightarrow[\sigma']{} & (s_j|_{U_{ijk}})_{i,j}
\end{array}$$

is exact.

Equivalently, in (2) it suffices to ask the exactness for every open cover $U = \bigcup_i U_i$, but to fix one open cover $U_i \cap U_j = \bigcup_k U_{ijk}$ for each pair i, j , rather than check it for all such covers. In particular, if \mathcal{B} is stable under finite intersections, then one can just cover $U_i \cap U_j$ “by itself”, so that one can use “the same sequence as in the definition of a sheaf”.

Definition 3.8. Let \mathcal{F}, \mathcal{G} be presheaves on \mathcal{B} . A morphism $f: \mathcal{F} \rightarrow \mathcal{G}$ is given by a collection of maps $f_U: \mathcal{F}(U) \rightarrow \mathcal{G}(U)$ for all $U \in \mathcal{B}$, such that for all $U \subseteq V$, $U, V \in \mathcal{B}$, we have $\text{res}_U^V \circ f_V = f_U \circ \text{res}_U^V$ (where on the left we use the restriction map for \mathcal{G} , on the left hand side that for \mathcal{F}).

For sheaves \mathcal{F}, \mathcal{G} a morphism $\mathcal{F} \rightarrow \mathcal{G}$ of sheaves on \mathcal{B} is a morphism of the underlying presheaves.

Together with the obvious identity morphisms and composition of morphisms we obtain the categories of presheaves on \mathcal{B} and of sheaves on \mathcal{B} .

It is clear that we can restrict sheaves (and morphisms) on X to \mathcal{B} .

Proposition 3.9. For every sheaf \mathcal{F} on X (in the sense of Definition 3.3), the restriction $\mathcal{F}|_{\mathcal{B}}$ given by $\mathcal{F}|_{\mathcal{B}}(U) = \mathcal{F}(U)$ for all $U \in \mathcal{B}$, and similarly for the restriction maps, is a sheaf on \mathcal{B} .

Similarly any morphism $f: \mathcal{F} \rightarrow \mathcal{G}$ of sheaves on X induces by restriction a morphism $f|_{\mathcal{B}}: \mathcal{F}|_{\mathcal{B}} \rightarrow \mathcal{G}|_{\mathcal{B}}$.

For sheaves, it is reasonable to expect that we can also go in the other direction, i.e., recover a sheaf from its values (including the restriction maps) on \mathcal{B} , or more generally, given any sheaf \mathcal{F}' on \mathcal{B} construct a sheaf \mathcal{F} on X such that $\mathcal{F}|_{\mathcal{B}}$ is \mathcal{F}' . Furthermore this construction should also be compatible with morphisms. (Of course, a similar result cannot hold true for arbitrary presheaves.)

The restriction to \mathcal{B} and extension to all open subsets of X are inverse to each other – but only if this is formulated in the right way. It is impossible to achieve that the extension of $\mathcal{F}|_{\mathcal{B}}$ is equal to \mathcal{F} ; rather the best one can hope for is that it is *isomorphic* to \mathcal{F} , and that these isomorphisms are compatible with morphisms of sheaves. This situation is best captured by the notion of *equivalence of categories*, see the next section for a short discussion.

Proposition 3.10. The restriction functor $\mathcal{F} \mapsto \mathcal{F}|_{\mathcal{B}}$ from the category of sheaves on X to the category of sheaves on \mathcal{B} is an equivalence of categories.

Sketch of proof. The key point is the construction of a sheaf \mathcal{F} on X given a sheaf \mathcal{F}' on \mathcal{B} . The idea of defining $\mathcal{F}(U)$ for an arbitrary open $U \subseteq X$ is easy to explain. Assume that we already had constructed the sheaf \mathcal{F} . Then for every cover $U = \bigcup U_i$ with $U_i \in \mathcal{B}$, we could recover $\mathcal{F}(U)$ from the sheaf sequence as a subset of $\prod_i \mathcal{F}(U_i) = \prod_i \mathcal{F}'(U_i)$. If \mathcal{B} is stable under finite intersections, then the intersections $U_i \cap U_j$ are also in \mathcal{B} and we can directly express the compatibility condition cutting out $\mathcal{F}(U)$ inside this products in terms of \mathcal{F}' . In general, one can proceed similarly as in the definition of the notion of sheaf on \mathcal{B} .

In order to check that this construction has the correct properties, it is however slightly inconvenient that it depends on the choice of a cover of U . This problem may be circumvented by simply using the cover of U given by *all* elements of \mathcal{B} that are contained in U . This has the additional advantage that all intersections arising in the definition of the sheaf axioms are covered by open subsets that themselves occur in the cover, whence it is enough to simply ask for the compatibility with all restrictions, in the following sense: We define

$$\mathcal{F}(U) = \left\{ (s_V)_V \in \prod_{V \in \mathcal{B}, V \subseteq U} \mathcal{F}'(V); s_{V|W} = s_W \text{ for all } W \subseteq V \subseteq U, V, W \in \mathcal{B} \right\}.$$

Similarly as in the first paragraph, the sheaf axioms imply that this is the only possible candidate for $\mathcal{F}(U)$. It is then not difficult to define restriction maps, to define the extension of morphisms of sheaves, and to show that this extension functor is a quasi-inverse of the restriction functor. \square

All of the above (definitions and) results carry over to the settings of (pre-)sheaves of (abelian) groups, rings, modules over a fixed ring, etc.

(3.3) Categories and functors.

References: [GW1] Appendix A; [Alg2] Section 3.1⁷.

A *category* \mathcal{C} is given by a collection (“class”) of objects $\text{Ob}(\mathcal{C})$, for any two $X, Y \in \text{Ob}(\mathcal{C})$ a collection $\text{Hom}_{\mathcal{C}}(X, Y)$ of morphisms, for any object X a morphism $\text{id}_X \in \text{Hom}_{\mathcal{C}}(X, X)$, and for any three objects X, Y, Z a map

$$\text{Hom}_{\mathcal{C}}(X, Y) \times \text{Hom}_{\mathcal{C}}(Y, Z) \longrightarrow \text{Hom}_{\mathcal{C}}(X, Z), \quad (f, g) \mapsto f \circ g,$$

such that $f \circ \text{id} = f$, $g \circ \text{id} = g$, $(f \circ g) \circ h = f \circ (g \circ h)$ whenever these expressions are defined. We write $f: X \rightarrow Y$ if $f \in \text{Hom}_{\mathcal{C}}(X, Y)$, and accordingly sometimes speak (and think) of morphisms in a category as *arrows*. We sometimes write $X \in \mathcal{C}$ instead of $X \in \text{Ob}(\mathcal{C})$. Set-theoretic remark: We usually implicitly make the assumption that for all X, Y , $\text{Hom}_{\mathcal{C}}(X, Y)$ is a set (i.e., that \mathcal{C} is what is usually called a *locally small* category).

⁷<https://math.ug/a2-ss23/subsec-kategorien.html>

Examples. The categories of sets (with maps of sets as morphisms), of finite sets, of groups (with group homomorphisms), of abelian groups, of rings (with ring homomorphisms), of modules over a fixed ring (with module homomorphisms), of finitely generated modules over a fixed ring, of topological spaces (with continuous maps as morphisms).

Definition 3.11. *Let \mathcal{C} be a category. A morphism $f: X \rightarrow Y$ in \mathcal{C} is called an isomorphism, if there exists a morphism $g: Y \rightarrow X$ in \mathcal{C} such that $g \circ f = \text{id}_X$ and $f \circ g = \text{id}_Y$.*

For objects X, Y in \mathcal{C} we say that X and Y are isomorphic and write $X \cong Y$, if there exists an isomorphism $X \rightarrow Y$ in \mathcal{C} .

Let \mathcal{C}, \mathcal{D} be categories. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is given by the following data: For each object X of \mathcal{C} an object $F(X)$ of \mathcal{D} , and for every morphism $f: X \rightarrow Y$ in \mathcal{C} a morphism $F(f): F(X) \rightarrow F(Y)$, such that $F(\text{id}_X) = \text{id}_{F(X)}$ for all X and such that $F(f \circ g) = F(f) \circ F(g)$.

It is useful to extend this notion in the following way. A *contravariant* functor F from \mathcal{C} to \mathcal{D} is given by the following data: For each object X of \mathcal{C} an object $F(X)$ of \mathcal{D} , and for every morphism $f: X \rightarrow Y$ in \mathcal{C} a morphism $F(f): F(Y) \rightarrow F(X)$, such that $F(\text{id}_X) = \text{id}_{F(X)}$ for all X and such that $F(f \circ g) = F(g) \circ F(f)$.

In order to distinguish between the two sorts of functors, the first variant is called a *covariant* functor. A slightly different way to define (and denote) contravariant functor is as follows. Given a category \mathcal{C} , we define the *opposite* (or *dual*) category \mathcal{C}^{opp} as follows. It has the same objects as \mathcal{C} , and for any two objects X, Y , we set

$$\text{Hom}_{\mathcal{C}^{\text{opp}}}(X, Y) = \text{Hom}_{\mathcal{C}}(Y, X),$$

i.e. “all arrows switch direction”. As identity morphisms we use the identity morphisms in \mathcal{C} . Composition in \mathcal{C}^{opp} is defined using the composition in \mathcal{C} in the obvious way. Then a contravariant functor from \mathcal{C} to \mathcal{D} is a (covariant) functor $\mathcal{C}^{\text{opp}} \rightarrow \mathcal{D}$. In view of this definition, one usually denotes contravariant functors in this way, i.e., as $\mathcal{C}^{\text{opp}} \rightarrow \mathcal{D}$.

If F is a functor and f is an isomorphism, then $F(f)$ is an isomorphism.

The following properties of functors are often interesting, and we will need them later on.

Definition 3.12. *A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is called*

- (1) *faithful, if for all objects $X, Y \in \mathcal{C}$ the map $\text{Hom}_{\mathcal{C}}(X, Y) \rightarrow \text{Hom}_{\mathcal{D}}(F(X), F(Y))$ is injective,*
- (2) *full, if for all objects $X, Y \in \mathcal{C}$ the map $\text{Hom}_{\mathcal{C}}(X, Y) \rightarrow \text{Hom}_{\mathcal{D}}(F(X), F(Y))$ is surjective,*
- (3) *fully faithful, if it is full and faithful, i.e., if for all objects $X, Y \in \mathcal{C}$ the map $\text{Hom}_{\mathcal{C}}(X, Y) \rightarrow \text{Hom}_{\mathcal{D}}(F(X), F(Y))$ is bijective,*
- (4) *essentially surjective, if for every object $Z \in \mathcal{D}$, there exists an object $X \in \mathcal{C}$ such that $F(X) \cong Z$ (NB: isomorphism, not necessarily equality!).*

For contravariant functors, there are analogous definitions.

Next we define morphisms of functors (also called *natural transformations*).

Definition 3.13. Let $F, G: \mathcal{C} \rightarrow \mathcal{D}$ be functors. A morphism $\Phi: F \rightarrow G$ of functors is given by a collection $\Phi_X: F(X) \rightarrow G(X)$ of morphisms in \mathcal{D} for every $X \in \mathcal{C}$, such that for every morphism $f: X \rightarrow Y$ in \mathcal{C} , the diagram

$$\begin{array}{ccc} F(X) & \xrightarrow{\Phi_X} & G(X) \\ \downarrow F(f) & & \downarrow G(f) \\ F(Y) & \xrightarrow{\Phi_Y} & G(Y) \end{array}$$

commutes. (Applying the definition to functors $\mathcal{C}^{\text{opp}} \rightarrow \mathcal{D}$, one similarly obtains the notion of morphism between two contravariant functors.)

With this notion of morphism, together with the obvious identity morphisms and composition of morphisms of functors, the collection of all functors between fixed categories \mathcal{C}, \mathcal{D} is itself a category, the *functor category* (however, the collection of all morphisms between two functors might not be a set). In particular, we also obtain the notion of *isomorphism between two functors* $\mathcal{C} \rightarrow \mathcal{D}$.

Nov. 19, 2025

Functors are the natural “morphisms” between categories. In fact, we can define the category of all categories, where functors are the morphisms (again the collections of morphisms in this category are not necessarily sets). Note that we have obvious identity functors and can form the composition of functors. (Since we also defined morphisms between functors, there is, so to say, another level to the story in this case; this is formalized by the notion of *2-category*, but we will not have to go into this.) In particular, we obtain the notion of *isomorphism between categories*. However, it turns out that isomorphisms of categories are rather rare. A much more useful notion is the following weaker one.

Proposition/Definition 3.14. A functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is called an equivalence of categories if the following equivalent properties are satisfied.

- (i) The functor F has a quasi-inverse G (i.e., G is a functor $\mathcal{D} \rightarrow \mathcal{C}$ such that $G \circ F \cong \text{id}_{\mathcal{C}}$, $F \circ G \cong \text{id}_{\mathcal{D}}$; it is crucial here that we only ask for isomorphisms, not equality, of these functors!).
- (ii) The functor F is fully faithful and essentially surjective.

Example 3.15. Some (sketchy) examples of functors and morphisms of functors.

- (1) $\text{Spec}: (\text{Rings})^{\text{opp}} \rightarrow (\text{Top})$
- (2) forgetful functors
- (3) Hom functors
- (4) “adjointness tensor-Hom” as example of isomorphism of functors: for every X , have $\text{Hom}(Y \otimes X, Z) \cong \text{Hom}(Y, \text{Hom}(X, Z))$ functorially in Y and Z .

- (5) dual vector space, morphism to double dual
- (6) localization of a ring, base change (of modules or rings)
- (7) $GL_n(-)$, $\det: GL_n(-) \rightarrow GL_1(-)$.

Example 3.16. Let X be a topological space, and define the category $\text{Ouv}(X)$ as follows. The objects of $\text{Ouv}(X)$ are the open subsets of X . For open subsets $U, V \subseteq X$, we set

$$\text{Hom}_{\text{Ouv}(X)}(U, V) = \begin{cases} \{*\} & \text{if } U \subseteq V, \\ \emptyset & \text{otherwise.} \end{cases}$$

Here $\{*\}$ denotes a set with one element. There is then a unique way to define identity morphisms and composition, and one obtains a category.

With this definition, a presheaf of sets on X is the same as a functor $\text{Ouv}(X)^{\text{opp}} \rightarrow (\text{Sets})$. A morphism of presheaves is the same as a morphism of the corresponding functors. With this interpretation we in particular obtain a natural notion of presheaf on X with values in any category \mathcal{C} (namely a functor $\text{Ouv}(X)^{\text{opp}} \rightarrow \mathcal{C}$) and of morphisms between such presheaves (namely a morphism of the functors).

(3.4) The structure sheaf of the spectrum of a ring.

We can now define the *structure sheaf on the spectrum of a ring*. So fix a ring R and let $X = \text{Spec}(R)$. We want to define a (“natural”) sheaf of rings on X . As we have seen above, it is enough to define a sheaf (of rings) on the basis of the topology given by the principal opens, and we want to set $\mathcal{O}_X(D(f)) = R_f$.

The first step now is to check that this is well-defined (note that we may have $D(f) = D(g)$ for $f \neq g$).

Lemma 3.17.

- (1) For $f, g \in R$, we have $D(f) \subseteq D(g)$ if and only if $\frac{g}{1} \in R_f$ is a unit, i.e., $\frac{g}{1} \in R_f^\times$. In this case, we obtain a commutative diagram

$$\begin{array}{ccc} R_g & \xrightarrow{\quad} & R_f \\ & \nwarrow \quad \nearrow & \\ & R & \end{array}$$

of ring homomorphisms (where $R \rightarrow R_f$ and $R \rightarrow R_g$ are the natural maps into the localizations).

- (2) If $f, g \in R$ satisfy $D(f) = D(g)$, then there is a unique isomorphism $R_f \cong R_g$ of R -algebras.

Proof. (1) We have

$$D(f) \subseteq D(g) \Leftrightarrow V(g) \subseteq V(f) \Leftrightarrow \sqrt{(f)} \subseteq \sqrt{(g)} \Leftrightarrow f \in \sqrt{(g)},$$

and this condition is equivalent to $\frac{g}{1} \in R_f^\times$. In fact, if $f^n = gh$, then $\frac{g}{1} \cdot \frac{h}{f^n} = 1$ in R_f . Conversely, if $\frac{g}{1} \cdot \frac{h'}{f^{n'}} = 1$ in R_f , then there is m such that $gh'f^m = f^{n'+m}$.

The existence of the R -algebra homomorphism $R_g \rightarrow R_f$ then follows from properties of the localization of a ring (and in fact is also equivalent to the condition that g maps to a unit in R_f). Furthermore, this homomorphism is the unique R -algebra homomorphism $R_f \rightarrow R_g$.

(2) follows from (1). \square

Using Part (2) of the lemma, we see that we can attach to each principal open $D(f)$ the ring R_f (well-defined up to *unique* isomorphism, so we can identify the rings R_f, R_g for $D(f) = D(g)$ in a specific way). Alternatively, the lemma implies that we have a unique isomorphism

$$R_f \cong S^{-1}R \quad \text{for } S = \{g \in R; D(f) \subseteq D(g)\},$$

of R -algebras, and the right hand side $S^{-1}R$ only depends on $D(f)$, not on f .

Definition 3.18. Let R be a ring, $X = \text{Spec}(R)$, \mathcal{B} the basis of the Zariski topology on X given by all principal open subsets. We define a presheaf \mathcal{O}'_X on \mathcal{B} by setting

$$\mathcal{O}'_X(D(f)) = R_f$$

and as restriction maps $\mathcal{O}'_X(D(g)) \rightarrow \mathcal{O}'_X(D(f))$ for $D(f) \subseteq D(g)$ use the unique R -algebra homomorphism $R_g \rightarrow R_f$ (cf. Lemma 3.17).

Nov. 25, 2025

Lemma 3.19. Let R be a ring, $f_i \in R$, $i \in I$. Then $\bigcup_{i \in I} D(f_i) = \text{Spec}(R)$ if and only if the elements f_i generate the unit ideal.

Proof. The condition $\bigcup_{i \in I} D(f_i) = \text{Spec}(R)$ is equivalent to saying that the ideal $(f_i; i \in I)$ is not contained in any prime ideal, but then the quotient $R/(f_i; i \in I)$ cannot have a maximal ideal, so is the zero ring. \square

Note that the lemma proves that $\text{Spec}(R)$ is quasi-compact. It also shows that whenever $f_1, \dots, f_r \in R$ generate the unit ideal, then for every $N \geq 1$, also f_1^N, \dots, f_r^N generate the unit ideal.

Theorem 3.20. The presheaf \mathcal{O}'_X on \mathcal{B} of Definition 3.18 is a sheaf.

We denote the sheaf on X that we obtain from \mathcal{O}'_X by Proposition 3.10 by \mathcal{O}_X and call it the *structure sheaf* on X .

Proof. We need to show: For all $f, f_i \in R$ such that $D(f) = \bigcup_{i \in I} D(f_i)$, the sequence

$$0 \rightarrow R_f \xrightarrow{\rho} \prod_i R_{f_i} \xrightarrow{\sigma} \prod_{i,j} R_{f_i f_j},$$

where the maps are $\rho(s) = \left(\frac{s}{1}\right)_i$ (with the i -th entry in R_{f_i}), and $\sigma((s_i)_i) = \left(\frac{s_i}{1} - \frac{s_j}{1}\right)_{i,j}$, is exact.

We first do the following reduction steps:

- Replacing R by R_f , we may assume that $f = 1$, and hence that $R_f = R$.
- Since all principal open subsets are quasi-compact, we may assume that the index set I of the open cover is *finite*. (This requires a small “computation”.)

As the previous lemma shows, the assumption that $\bigcup_i D(f_i) = \operatorname{Spec}(R)$ is equivalent to saying that the elements f_i generate the unit ideal in R . This implies that for every N , the powers f_i^N also generate the unit ideal. We will refer to this property by (*).

Injectivity in the above sequence. Let $s \in R$ such that the image of s in each localization R_{f_i} vanishes. Then for each i there exists N_i such that $f_i^{N_i} s = 0$. Since I is finite, we find N with the property that $f_i^N s = 0$ for all i . Now use (*) to write $1 = \sum_i g_i f_i^N$. We then see that

$$s = \left(\sum_i g_i f_i^N \right) s = 0.$$

Exactness “in the middle”: $\operatorname{Im}(\rho) = \operatorname{Ker}(\sigma)$. The inclusion \subseteq is clear (in fact, it holds for any presheaf). So let $(s_i)_i \in \operatorname{Ker}(\sigma)$. We write

$$s_i = \frac{a_i}{f_i^N}$$

(again we use that I is finite, so that we can find an N that works for all s_i).

The assumption that $(s_i)_i \in \operatorname{Ker}(\sigma)$ means that all the differences $\frac{s_i}{1} - \frac{s_j}{1} \in R_{f_i f_j}$ vanish, so we find $M \geq 0$ such that

$$(f_i f_j)^M (f_j^N a_i - f_i^N a_j) = 0.$$

Now we use (*) to write $1 = \sum g_i f_i^{M+N}$ (these are other g_i ’s than above).

Define $a = \sum_j g_j f_j^M a_j$. We will check that $\rho(a) = (s_i)_i$. For this we need to prove that $\frac{a}{1} - \frac{a_i}{f_i^N} = 0 \in R_{f_i}$ for all i . But from the definition of a it follows that

$$a f_i^{M+N} = \sum_j g_j f_j^M a_j f_i^{M+N} = \sum_j g_j f_i^M a_j f_j^{M+N} = a_i f_i^M,$$

and that implies the result. \square

(3.5) Stalks.

References: For foundational material on the notion of colimit, see [GW1] Appendix A (and the problem sheets).

Let \mathcal{F} be a presheaf on a topological space X , and let x . The “stalk” of the sheaf is the collection of all sections defined on some (possibly very small) open neighborhood of x , in the following precise sense.

Definition 3.21. Let X be a topological space and let $x \in X$. For every presheaf \mathcal{F} on X we define the stalk of \mathcal{F} at x as

$$\mathcal{F}_x = \operatorname{colim}_{x \in U} \mathcal{F}(U) = \left(\bigsqcup_{x \in U} \mathcal{F}(U) \right) / \sim,$$

where the colimit is taken over the restriction maps of \mathcal{F} as transition maps (i.e., the partially ordered index set is the set of all open subsets of X containing x , ordered by $V \leq U :\Leftrightarrow U \subseteq V$). We can construct the colimit explicitly as written on the right hand side. The equivalence relation \sim is defined by setting, for $s \in \mathcal{F}(U)$, $t \in \mathcal{F}(V)$,

$$s \sim t \iff \text{there exists an open } W \subseteq U \cap V, x \in W, \text{ such that } s|_W = t|_W.$$

For presheaves with values in some category \mathcal{C} (rather than sets), we would take the colimit above in the category \mathcal{C} (assuming that it exists). However, the following argument shows that for the categories that we will be concerned with in this class, this distinction is not important.

The index set of the colimit is filtered (for U, V open neighborhoods of x , we have $U \cap V \subseteq U, V$, so $U, V \leq U \cap V$, and $U \cap V$ is again an open neighborhood of x). Therefore, if \mathcal{F} is a presheaf of groups / abelian groups / rings, then the stalk of \mathcal{F} at a point x in the category of sets (i.e., as constructed above) has a natural structure of group / abelian group / ring, etc., and this gives the colimit in the category of groups / etc. For every open neighborhood U of x , we have a natural map $\mathcal{F}(U) \rightarrow \mathcal{F}_x$; if \mathcal{F} is a presheaf of groups (etc.), then this is a group homomorphism (etc.).

If $\mathcal{F} \rightarrow \mathcal{G}$ is a morphism of sheaves, for all open neighborhoods $U \subseteq V$ of x we have a commutative diagram

$$\begin{array}{ccc} \mathcal{F}(V) & \longrightarrow & \mathcal{G}(V) \\ \downarrow & & \downarrow \\ \mathcal{F}(U) & \longrightarrow & \mathcal{G}(U) \\ \downarrow & & \downarrow \\ \mathcal{F}_x & & \mathcal{G}_x \end{array}$$

Here the vertical maps are the restriction map and the natural maps to the stalk.

These diagrams induce a morphism $\mathcal{F}_x \rightarrow \mathcal{G}_x$ between the stalks. This shows that the construction of stalks is a functor from the category of presheaves (of sets) to the category of sets. Likewise, we obtain functors from the category of presheaves of abelian groups to the category of abelian groups, and similarly for presheaves of groups, rings, etc.

Example 3.22. In the theory of holomorphic functions (complex analysis in one or several variables), the stalk of the structure sheaf can be interpreted in terms of convergent power series as follows. Let $X = \mathbb{C}$ (or more generally

an open subset of \mathbb{C}^n , $n \geq 1$, or even more generally any complex manifold), and define the “structure sheaf” \mathcal{O}_X by setting

$$\mathcal{O}_X(U) = \{f: U \rightarrow \mathbb{C} \text{ holomorphic}\}.$$

Then the stalk $\mathcal{O}_{X,x}$ can be identified with the ring of convergent power series at x (i.e., power series in n variables that converge in some open neighborhood of x). The *identity theorem* can be phrased as saying that for every connected open neighborhood U of x , the natural map $\mathcal{O}_X(U) \rightarrow \mathcal{O}_{X,x}$ is injective.

Nov. 26, 2025

Remark 3.23. Recall that for the computation of the limit of a convergent sequence of real numbers, we may pass to a subsequence, i.e., we may replace the index set \mathbb{N} of the limit by any infinite subset of \mathbb{N} . Something similar holds for colimits:

Let (I, \leq) be a partially ordered set. We call a subset $I' \subseteq I$ *cofinal*, if for every $i \in I$ there exists $i' \in I'$ with $i \leq i'$. We equip I' with the induced partial order. Then for every inductive system $(F_i)_{i \in I}$, we have a natural isomorphism

$$\operatorname{colim}_{i \in I'} F_i \cong \operatorname{colim}_{i \in I} F_i.$$

Example 3.24. Let R be a ring, $X = \operatorname{Spec}(R)$. Let $\mathfrak{p} \in \operatorname{Spec}(R)$. Let us compute the stalk of the structure sheaf \mathcal{O}_X at the point \mathfrak{p} . By the previous remark, we may compute the stalk as

$$\mathcal{O}_{X,\mathfrak{p}} = \operatorname{colim}_{f \in R, \mathfrak{p} \in D(f)} \mathcal{O}_X(D(f)) = \operatorname{colim}_{f \in R, \mathfrak{p} \in D(f)} R_f.$$

The latter colimit is isomorphic to the localization $R_{\mathfrak{p}}$ of R with respect to \mathfrak{p} (i.e., the localization with respect to the open subset $R \setminus \mathfrak{p}$). In fact, the universal property of the colimit gives us a ring homomorphism $\operatorname{colim}_{f \in R, \mathfrak{p} \in D(f)} R_f \rightarrow R_{\mathfrak{p}}$ (here we use that $\mathfrak{p} \in D(f)$ by definition is equivalent to $f \notin \mathfrak{p}$, and in this case $\frac{f}{1}$ is a unit in $R_{\mathfrak{p}}$).

It is easy to see that this map is surjective. For the injectivity, we need to show that for all $s, f \in R$, $\mathfrak{p} \in D(f)$ and $i \geq 0$, $\frac{s}{f^i} = 0$ in $R_{\mathfrak{p}}$ implies that $\frac{s}{f^i} = 0$ in some localization R_{f_g} with $\mathfrak{p} \in D(g)$. This also follows immediately from properties of the localization.

The following propositions illustrate in which sense the stalks capture “local information about a sheaf”.

Lemma 3.25. *Let X be a topological space, \mathcal{F} a sheaf on X , $U \subseteq X$ an open subset. Then the natural map*

$$\mathcal{F}(U) \rightarrow \prod_{x \in U} \mathcal{F}_x$$

is injective.

Proof. Let $s \in \mathcal{F}(U)$ be an element which maps to 0 in every stalk \mathcal{F}_x , $x \in U$. By definition of the stalk, thus for every x , there exists an open neighborhood $V_x \subseteq U$ of x such that $s_{V_x} = 0$ (in $\mathcal{F}(V_x)$). But then clearly all the V_x cover U , and the sheaf axioms imply that $s = 0$. \square

Proposition 3.26. *Let X be a topological space, and let $\mathcal{F} \rightarrow \mathcal{G}$ be a morphism of sheaves on X .*

- (1) *The following are equivalent:*
 - (i) *For every open $U \subseteq X$, the map $\mathcal{F}(U) \rightarrow \mathcal{G}(U)$ is injective.*
 - (ii) *For every $x \in X$, the map $\mathcal{F}_x \rightarrow \mathcal{G}_x$ is injective.*
- (2) *The following are equivalent:*
 - (i) *For every open $U \subseteq X$, the map $\mathcal{F}(U) \rightarrow \mathcal{G}(U)$ is bijective.*
 - (ii) *The morphism $\mathcal{F} \rightarrow \mathcal{G}$ is an isomorphism.*
 - (iii) *For every $x \in X$, the map $\mathcal{F}_x \rightarrow \mathcal{G}_x$ is bijective.*

Proof. (1) The implication (ii) \Rightarrow (i) follows from the previous lemma. For the implication (i) \Rightarrow (ii), let $x \in X$, and $s \in \mathcal{F}_x$ mapping to 0 in \mathcal{G}_x . Let $\dot{s} \in \mathcal{F}(V)$ be a representative of s , i.e., an element with image s , where V is a suitable open neighborhood of x . The image of \dot{s} in $\mathcal{G}(V)$ maps to 0 in the stalk at x , hence its restriction to a suitable open neighborhood U of x is 0 (in $\mathcal{G}(U)$). But then the injectivity in (i) implies that $\dot{s}|_U = 0$, and a fortiori $s = 0$.

(2) See Problem sheet 6. \square

Note that the analogous statement to (1) for *surjective* maps is *not true*! (Cf. Problem sheet 7.) It turns out that the stalks provide the correct perspective on these properties, and we make the following definition.

Definition 3.27. *Let $\varphi: \mathcal{F} \rightarrow \mathcal{G}$ be a morphism of sheaves on a topological space X . We call φ injective (surjective, bijective, respectively), if for every $x \in X$ the map $\mathcal{F}_x \rightarrow \mathcal{G}_x$ induced by φ is injective (surjective, bijective, respectively).*

Proposition 3.28. *Let X be a topological space and let $\varphi, \psi: \mathcal{F} \rightarrow \mathcal{G}$ be two morphisms between the sheaves \mathcal{F} and \mathcal{G} on X . The following are equivalent:*

- (i) *The morphisms φ, ψ are equal.*
- (ii) *For every $x \in X$, the induced morphisms $\varphi_x, \psi_x: \mathcal{F}_x \rightarrow \mathcal{G}_x$ between the stalks are equal.*

Proof. It is clear that (i) implies (ii). The converse follows from Lemma 3.25 \square

(3.6) Sheafification.

We now study a “natural way” of attaching to an arbitrary presheaf a *sheaf* that is “as close as possible” to the given presheaf (in particular, both have

the same stalk at each point of the underlying space). This sheaf will be called the *sheafification* (German: *Garbifizierung*) of the given presheaf. We will define it by a universal property, as follows:

Definition/Proposition 3.29. *Let X be a topological space and let \mathcal{F} be a presheaf on X .*

- (1) *A sheaf $\widetilde{\mathcal{F}}$ together with a morphism $\iota_{\mathcal{F}}: \mathcal{F} \rightarrow \widetilde{\mathcal{F}}$ of presheaves is called a sheafification of \mathcal{F} , if for every morphism $\mathcal{F} \rightarrow \mathcal{G}$ from \mathcal{F} to a sheaf \mathcal{G} , there exists a unique morphism $\widetilde{\mathcal{F}} \rightarrow \mathcal{G}$ such that the diagram*

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\quad} & \mathcal{G} \\ & \searrow & \nearrow \\ & \widetilde{\mathcal{F}} & \end{array}$$

commutes.

- (2) *A sheafification of the presheaf \mathcal{F} exists. If \mathcal{F} is a presheaf of groups, abelian groups, rings, ..., then so is the sheafification.*
 (3) *The morphism $\mathcal{F} \rightarrow \widetilde{\mathcal{F}}$ induces an isomorphism on the stalks for each $x \in X$.*
 (4) *For every morphism $\mathcal{F} \rightarrow \mathcal{G}$ we obtain a morphism $\widetilde{\mathcal{F}} \rightarrow \widetilde{\mathcal{G}}$, so that the diagram*

$$\begin{array}{ccc} \mathcal{F} & \longrightarrow & \mathcal{G} \\ \downarrow & & \downarrow \\ \widetilde{\mathcal{F}} & \longrightarrow & \widetilde{\mathcal{G}} \end{array}$$

commutes. Thus sheafification defines a functor from the category of presheaves on X to the category of sheaves on X .

It follows immediately from the definition that the sheafification is uniquely determined up to isomorphism, and that the sheafification of a sheaf \mathcal{F} is simply the identity morphism.

Proof. We need to prove the existence of the sheafification. We may construct it explicitly as follows. For $U \subseteq X$ open, we set

$$\widetilde{\mathcal{F}}(U) = \left\{ (s_x)_x \in \prod_{x \in U} \mathcal{F}_x; \right.$$

$\left. \text{for all } x \text{ there ex. } x \in W \subseteq U \text{ open, } t \in \mathcal{F}(W), \text{ s.t. for all } w \in W : s_w = t_w \right\}.$

(This is a natural candidate in view of Lemma 3.25.) The restriction maps are defined as the obvious projection maps. One checks that this defines a sheaf. From this point, the rest of the proof is not difficult, but doing things in the right order saves some work. We have a morphism $\mathcal{F} \rightarrow \widetilde{\mathcal{F}}$ of presheaves by defining

$$\mathcal{F}(U) \rightarrow \widetilde{\mathcal{F}}(U), \quad s \mapsto (s_x)_x,$$

where s_x denotes the image of s in the stalk \mathcal{F}_x . At this point one checks that this induces an isomorphism on all stalks (thus proving Part (3)); in fact, the projections $\widetilde{\mathcal{F}}(U) \rightarrow \mathcal{F}_x$ for $x \in U$ induce a map $\widetilde{\mathcal{F}} \rightarrow \mathcal{F}$ and it is not hard to check that this map is inverse to the map $\mathcal{F} \rightarrow \widetilde{\mathcal{F}}$ induced by $\iota_{\mathcal{F}}$.

For $\varphi: \mathcal{F} \rightarrow \mathcal{G}$ a morphism of presheaves we obtain a morphism $\widetilde{\mathcal{F}} \rightarrow \widetilde{\mathcal{G}}$ by setting

$$\widetilde{\mathcal{F}}(U) \rightarrow \widetilde{\mathcal{G}}(U), \quad (s_x)_x \mapsto (\varphi_x(s_x))_x.$$

By Part (3) and Proposition 3.28, this is the unique morphism which makes the diagram in (4) commutative. Applying this in the special case where the target \mathcal{G} of the morphism $\mathcal{F} \rightarrow \mathcal{G}$ is a sheaf, shows the universal property, because in that case $\mathcal{G} = \widetilde{\mathcal{G}}$ (more precisely, the morphism $\mathcal{G} \rightarrow \widetilde{\mathcal{G}}$ is an isomorphism, by Proposition 3.26 (alternatively, this follows directly from our construction)). \square

Example 3.30. (constant sheaf) Let X be a topological space, E a set (or abelian group, ...). We define the presheaf \mathcal{F} by setting

$$\mathcal{F}(U) = E, \quad U \subseteq X \text{ open},$$

with the identity maps as restriction maps. The *constant sheaf with value E* is defined as the sheafification of this presheaf. All its stalks are naturally equal to E . (But in general, the sections on an open U of X may be different from E .)

A typical use of the sheafification is to do certain constructions of sheaves that can be naturally carried out for presheaves, but may not themselves yield sheaves (even if one starts with sheaves, so to say), as in the following example.

Example 3.31. Let $f: \mathcal{F} \rightarrow \mathcal{G}$ be a morphism of sheaves. The *image sheaf* $\text{Im}(f)$ is defined as the sheafification of the presheaf

$$U \mapsto \text{Im}(\mathcal{F}(U) \rightarrow \mathcal{G}(U)).$$

(Note that this presheaf usually is not a sheaf!)

The image sheaf comes with a natural injective sheaf morphism $\text{Im}(f) \rightarrow \mathcal{G}$. This is an isomorphism if and only if f is surjective.

Remark 3.32. We can express the universal property of the sheafification by saying that, for every presheaf \mathcal{F} and sheaf \mathcal{G} , there are bijections

$$\text{Hom}(\widetilde{\mathcal{F}}, \mathcal{G}) \xrightarrow{\cong} \text{Hom}(\mathcal{F}, \mathcal{G})$$

(given by composition with the natural map $\mathcal{F} \rightarrow \widetilde{\mathcal{F}}$; these maps are functorial in \mathcal{F} and in \mathcal{G}). On the right, we “view \mathcal{G} as a presheaf” (forgetting that it is a sheaf), and have Hom in the category of presheaves. On the left, we have Hom in the category of sheaves, because source and target are sheaves. (Since morphisms of sheaves by definition are just morphisms of

presheaves, this may sound overly pedantic, but at this point it is useful to distinguish between the two categories.)

We can thus express this by saying that the sheafification functor is left adjoint to the inclusion functor from the category of sheaves into the category of presheaves.

(3.7) Direct and inverse image.

Dec. 3, 2025

Let $f: X \rightarrow Y$ be a continuous map between topological spaces. We want to think about how we could “transport” sheaves from X to Y and vice versa.

Given a presheaf \mathcal{F} on X , it is fairly straightforward to define its “push-forward” or “direct image” in Y .

Definition 3.33. Let $f: X \rightarrow Y$ be a continuous map and let \mathcal{F} be a presheaf on X . We define its direct image (or pushforward) $f_*\mathcal{F}$ by

$$(f_*\mathcal{F})(V) = \mathcal{F}(f^{-1}(V)), \quad V \subseteq Y \text{ open}$$

with the restriction maps induced by the restriction maps of \mathcal{F} .

It is easy to check that for a sheaf \mathcal{F} , the direct image $f_*\mathcal{F}$ is again a sheaf. While this construction is fairly simple, note that it is usually not easy to express the stalks of $f_*\mathcal{F}$ in terms of the stalks of \mathcal{F} .

If $\mathcal{F} \rightarrow \mathcal{F}'$ is a morphism of sheaves on X , then we obtain a morphism $f_*\mathcal{F} \rightarrow f_*\mathcal{F}'$ in the obvious way. It is easy to check that f_* defines a functor from the category of sheaves on X to the category of sheaves on Y . Similarly for sheaves of groups, abelian groups, rings, etc.

If $f: X \rightarrow Y$, $g: Y \rightarrow Z$ are continuous maps, and \mathcal{F} is a presheaf on X , then $(g \circ f)_*\mathcal{F} = g_*f_*\mathcal{F}$.

Going in the other direction is a little more cumbersome, but with the sheafification we have all the necessary tools at our disposal. We will proceed in two steps and first define a presheaf.

Definition 3.34. Let $f: X \rightarrow Y$ be a continuous map and let \mathcal{G} be a presheaf on Y . We define its inverse image presheaf $f^+\mathcal{G}$ by

$$(f^+\mathcal{G})(U) = \operatorname{colim}_{f(U) \subseteq V} \mathcal{G}(V),$$

where the colimit is taken along the restriction maps of \mathcal{G} , and the restriction maps are obtained from the restriction maps of \mathcal{G} and the universal property of the colimit.

Even if \mathcal{G} is a sheaf, the presheaf $f^+\mathcal{G}$ usually is not a sheaf, and we define

Definition 3.35. Let $f: X \rightarrow Y$ be a continuous map and let \mathcal{G} be a presheaf on Y . We define its inverse image sheaf (or pullback) $f^{-1}\mathcal{G}$ to be the sheafification of $f^+\mathcal{G}$.

The construction $\mathcal{G} \mapsto f^+\mathcal{G}$ is functorial in \mathcal{G} . Since sheafification is also functorial in \mathcal{G} , we see that the inverse image f^{-1} is a functor from the

category of presheaves on Y to the category of sheaves on X . If \mathcal{G} is a presheaf of (abelian) groups, rings, etc., then so are $f^+\mathcal{G}$ and $f^{-1}\mathcal{G}$.

Example 3.36. Let X be a topological space, \mathcal{F} a presheaf on X , $x \in X$, and $i: \{x\} \rightarrow X$ the inclusion map. Then $i^{-1}\mathcal{F}$ is the sheaf on the one-point set $\{x\}$ with sections (on the whole space) \mathcal{F}_x .

It is not difficult to compute the stalks of the inverse image presheaf:

Proposition 3.37. Let $f: X \rightarrow Y$ be a continuous map and let \mathcal{G} be a presheaf on Y . Let $x \in X$. There is a natural isomorphism

$$(f^{-1}\mathcal{G})_x \cong \mathcal{G}_{f(x)}.$$

These isomorphisms are functorial in \mathcal{G} .

Proof. We have

$$(f^{-1}\mathcal{G})_x = (f^+\mathcal{G})_x = \operatorname{colim}_{x \in U \subseteq X} \operatorname{colim}_{f(U) \subseteq V \subseteq Y} \mathcal{G}(V) = \mathcal{G}_{f(x)}.$$

For the final equality we use that f is continuous and that therefore every open neighborhood $V \subseteq Y$ of $f(x)$ contains $f(U)$ for some U (e.g., $U = f^{-1}(V)$). \square

From the computation of the stalks, we obtain the compatibility with composition of morphisms in the following sense.

Proposition 3.38. Let $f: X \rightarrow Y$, $g: Y \rightarrow Z$ be continuous maps and let \mathcal{H} be a presheaf on Z . Then there is a natural isomorphism

$$(g \circ f)^{-1}\mathcal{H} \cong f^{-1}(g^{-1}\mathcal{H}).$$

These isomorphisms are functorial in \mathcal{H} .

Proof. One first checks that $(g \circ f)^+\mathcal{H} \cong f^+(g^+\mathcal{H})$. Passing to the sheafification, this implies that $(g \circ f)^{-1}\mathcal{H} \cong f^{-1}(g^+\mathcal{H})$. On the other hand, (the proof of) Proposition 3.37 implies that $f^+(g^+\mathcal{H}) \cong f^{-1}(g^{-1}\mathcal{H})$, because the natural morphism between these sheaves induces isomorphisms on all stalks. \square

Dec. 9, 2025

Example 3.39. If $U \subseteq X$ is an open subset and $j: U \rightarrow X$ denotes the inclusion, then $j^+\mathcal{F} = \mathcal{F}|_U$ for every presheaf \mathcal{F} on X . If \mathcal{F} is a sheaf, then so is $\mathcal{F}|_U$, hence $j^{-1}\mathcal{F} = \mathcal{F}|_U$. In general, $j^{-1}\mathcal{F}$ is the sheafification of $\mathcal{F}|_U$.

In fact, when we compute $f^+\mathcal{F}(W)$, $W \subseteq U$ open, according to the definition in terms of a colimit, then the index set has a largest element (smallest open subset with respect to inclusion), namely W itself, and the colimit “collapses”, i.e., can naturally be identified with $\mathcal{F}(W)$.

Finally we note the following useful relation between the functors f_* and f^{-1} .

Proposition 3.40. *Let $f: X \rightarrow Y$ be a continuous map, and let \mathcal{F} be a sheaf on X , \mathcal{G} a presheaf on Y . Then there is a natural isomorphism*

$$\mathrm{Hom}_{\mathrm{Sh}(X)}(f^{-1}\mathcal{G}, \mathcal{F}) \xrightarrow{\cong} \mathrm{Hom}_{\mathrm{PreSh}(Y)}(\mathcal{G}, f_*\mathcal{F}).$$

These isomorphisms are functorial in \mathcal{F} and in \mathcal{G} . In other words, $f^{-1} \dashv f_$ is a pair of adjoint functors.*

In the situation of the proposition, if \mathcal{F} is a sheaf of abelian groups and \mathcal{G} is a presheaf of abelian groups, then the Hom sets above are abelian groups and the adjunction isomorphisms are group isomorphisms.

Proof. First note that since \mathcal{F} is a sheaf, we may identify $\mathrm{Hom}_{\mathrm{Sh}(X)}(f^{-1}\mathcal{G}, \mathcal{F})$ with $\mathrm{Hom}_{\mathrm{PreSh}(X)}(f^+\mathcal{G}, \mathcal{F})$. It is then not difficult to explicitly construct natural maps in both directions and to check that they are inverse to each other and functorial. \square

Example 3.41. Some more examples of adjoint functors:

- (1) Tensor product and Hom functor. Let R be a ring, let N be a fixed R -module. Let $\mathcal{C} = \mathcal{D} = (R\text{-Mod})$ be the category of R -modules. Then we have isomorphisms

$$\mathrm{Hom}_R(M \otimes_R N, P) \cong \mathrm{Hom}_R(M, \mathrm{Hom}_R(N, P)),$$

i.e., the functor $F(M) = M \otimes_R N$ is left adjoint to the functor $G(P) = \mathrm{Hom}_R(N, P)$.

- (2) Forgetful functors. Let R be a ring, and let $G: (R\text{-Mod}) \rightarrow (\mathrm{Sets})$ be the forgetful functor. Then G has a right adjoint, given by sending each set I to the *free module* $\bigoplus_{i \in I} R$. Similarly, a right adjoint of a forget functor can be considered as a natural notion of *free object* in some category. For the forget functor from R -algebras to sets, we get the polynomial ring (in variables indexed by the set I).
- (3) Sheafification (Remark 3.32).

4. SCHEMES

(4.1) Ringed spaces, locally ringed spaces.

Recall that we have attached to every ring R the topological space $X = \operatorname{Spec}(R)$ and the structure sheaf \mathcal{O}_X . From these data we can recover the ring R as $R = \mathcal{O}_X(X)$, so in some sense we have reached our goal to attach to R a “geometric object” without losing any information. This leads to the following definition.

Definition 4.1. A ringed space is a pair (X, \mathcal{O}_X) where X is a topological space and \mathcal{O}_X is a sheaf of rings on X .

Often one writes X instead of (X, \mathcal{O}_X) . The sheaf \mathcal{O}_X is usually called the *structure sheaf* of X . As we will see soon, however, this is not yet the “good” notion of geometric object that we should use in order to talk about spectra of rings; the problem lies in the notion of morphism. In order to understand this, we first define the natural notion of morphisms of ringed spaces. To define a morphism $(X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ of ringed spaces, it is natural to start with a continuous map $f: X \rightarrow Y$. But in addition, the structure sheaves should also be related. For this, recall that we think of the ring $\mathcal{O}_X(U)$ as the ring of functions defined on U . Then it is natural to expect that for every function defined on $V \subseteq Y$, by “composition with f ” we obtain a function on $f^{-1}(V)$. We need to put this in quotes because there is no reason why the elements of the ring $\mathcal{O}_Y(V)$ should really be function on V , so “composition” does not really make sense. However, we can still ask that the morphism $(X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ comes with maps $\mathcal{O}_Y(V) \rightarrow \mathcal{O}_X(f^{-1}(V))$ for every open $V \subseteq Y$. Clearly, these should be compatible with the restriction maps of these sheaves. Putting everything together, we arrive at the following definition.

Definition 4.2. A morphism $f: (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ of ringed spaces is a pair (f, f^\flat) where $f: X \rightarrow Y$ is a continuous map and $f^\flat: \mathcal{O}_Y \rightarrow f_*\mathcal{O}_X$ is a morphism of sheaves of rings.

There are obvious notions of identity morphisms and composition of morphisms, and we obtain the category $(\operatorname{RingedSpaces})$ of ringed spaces.

By adjunction, the morphism f^\flat corresponds to a morphism $f^\sharp: f^{-1}\mathcal{O}_Y \rightarrow \mathcal{O}_X$ of sheaves of rings on X . In particular, for every $x \in X$, we obtain a ring homomorphism $f_x^\sharp: \mathcal{O}_{Y, f(x)} = (f^{-1}\mathcal{O}_Y)_x \rightarrow \mathcal{O}_{X, x}$ between the stalks. One checks that this ring homomorphism may also be constructed explicitly by using the universal property of the colimit $\mathcal{O}_{Y, f(x)}$ for the maps $\mathcal{O}_Y(V) \rightarrow \mathcal{O}_{X, x}$ (for $V \subseteq Y$ open, $f(x) \in V$) obtained as the composition

$$\mathcal{O}_Y(V) \rightarrow (f_*\mathcal{O}_X)(V) = \mathcal{O}_X(f^{-1}(V)) \rightarrow \mathcal{O}_{X, x}$$

Dec. 10, 2025

where the first map is obtained from f^b , and the final map is the natural map into the stalk, using that $f(x) \in V$ implies $x \in f^{-1}(V)$.

With this definition of the category of ringed spaces, we obtain a functor

$$(\text{Rings})^{\text{opp}} \longrightarrow (\text{RingedSpaces}).$$

In fact, to every ring R we may attach its spectrum $(\text{Spec}(R), \mathcal{O}_{\text{Spec}(R)})$ with the structure sheaf. If $\varphi: R \rightarrow S$ is a ring homomorphism, we have the continuous map ${}^a\varphi: \text{Spec}(S) \rightarrow \text{Spec}(R)$ between the spectra. Furthermore, for every principal open $D(s) \subseteq \text{Spec}(R)$, $s \in R$, we have $({}^a\varphi)^{-1}(D(s)) = D(\varphi(s))$, and thus the natural homomorphism $R_s \rightarrow S_{\varphi(s)}$ is a ring homomorphism $\mathcal{O}_{\text{Spec}(R)}(D(s)) \rightarrow \mathcal{O}_{\text{Spec}(S)}(({}^a\varphi)^{-1}(D(s)))$. Since the $D(s)$ form a basis of the topology, these define the desired sheaf homomorphism $\mathcal{O}_{\text{Spec}(R)} \rightarrow {}^a\varphi_* \mathcal{O}_{\text{Spec}(S)}$. (Cf. Proposition 3.10.)

From now on we usually write $\text{Spec}(R)$ for the ringed space $(\text{Spec}(R), \mathcal{O}_{\text{Spec}(R)})$.

However, it turns out that this functor is not fully faithful. Therefore, passing from rings to ringed spaces remains problematic, because there are morphisms between spectra as ringed spaces that we “do not want to allow”.

In fact, morphisms coming from ring homomorphisms have a special property that we can see by inspecting the stalks.

Proposition 4.3.

- (1) *Let R be a ring, $X = \text{Spec}(R)$ (as a ringed space). For every $x \in X$, the stalk $\mathcal{O}_{X,x}$ is isomorphic to the localization R_x of R with respect to the prime ideal x . In particular, the stalk is a local ring (i.e., it has a unique maximal ideal).*
- (2) *Let $\varphi: R \rightarrow S$ be a ring homomorphism, let $X = \text{Spec}(S)$, $Y = \text{Spec}(R)$ and let $f: X \rightarrow Y$ be the morphism of ringed spaces attached to φ as above. Then for every $x \in X$ the ring homomorphism $\mathcal{O}_{Y,f(x)} \rightarrow \mathcal{O}_{X,x}$ is a local homomorphism of local rings, i.e., it maps the maximal ideal of $\mathcal{O}_{Y,f(x)}$ into the maximal ideal of $\mathcal{O}_{X,x}$.*

Proof. We have already seen the first point. For the second one, note that φ induces a commutative diagram

$$\begin{array}{ccc} \mathcal{O}_Y(Y) & \longrightarrow & \mathcal{O}_X(X) \\ \downarrow & & \downarrow \\ \mathcal{O}_{Y,f(x)} & \longrightarrow & \mathcal{O}_{X,x} \end{array}$$

which we may rewrite as

$$\begin{array}{ccc} R & \xrightarrow{\varphi} & S \\ \downarrow & & \downarrow \\ R_{f(x)} & \longrightarrow & S_x. \end{array}$$

This means that the homomorphism $R_{f(x)} \rightarrow S_x$ is simply the natural homomorphism between localizations induced by φ , i.e., $\frac{a}{s} \mapsto \frac{\varphi(a)}{\varphi(s)}$. In particular, it maps the maximal ideal $f(x)R_{f(x)} = \varphi^{-1}(x)R_{\varphi^{-1}(x)}$ into the maximal ideal xS_x . \square

Definition 4.4.

- (1) A locally ringed space is a ringed space (X, \mathcal{O}_X) such that for every $x \in X$ the stalk $\mathcal{O}_{X,x}$ is a local ring (also called the local ring of X).
- (2) Let X, Y be locally ringed spaces. A morphism $X \rightarrow Y$ of locally ringed spaces is a morphism $X \rightarrow Y$ of ringed spaces such that for every $x \in X$ the induced ring homomorphism $f_x^\sharp: \mathcal{O}_{Y,f(x)} \rightarrow \mathcal{O}_{X,x}$ is a local homomorphism.

The above discussion shows that Spec actually is a contravariant functor from the category of rings to the category of locally ringed spaces.

Theorem 4.5. The contravariant functor $R \mapsto (\text{Spec}(R), \mathcal{O}_{\text{Spec}(R)})$ from the category of rings to the category of locally ringed spaces is fully faithful.

Proof. Let R, S be rings and let $X = \text{Spec}(S), Y = \text{Spec}(R)$ (considered as locally ringed spaces). We have natural maps

$$\text{Spec}: \text{Hom}(R, S) \rightarrow \text{Hom}(X, Y), \quad \Gamma: \text{Hom}(X, Y) \rightarrow \text{Hom}(R, S),$$

and we want to show that they are inverse to each other. It follows directly from the construction of $\text{Spec}(\varphi)$ that $\varphi \mapsto \text{Spec}(\varphi) \mapsto \Gamma(\text{Spec}(\varphi))$ is the identity morphism.

Now consider the composition $f \mapsto \Gamma(f) \mapsto \text{Spec}(\Gamma(f))$. We write $f = (f, f^\flat)$ and $\text{Spec}(\Gamma(f)) = (g, g^\flat)$. For every $x \in X$, we have the commutative diagram

$$\begin{array}{ccc} \mathcal{O}_Y(Y) & \longrightarrow & (f_* \mathcal{O}_X)(Y) = \mathcal{O}_X(X) \\ \downarrow & & \downarrow \\ \mathcal{O}_{Y,f(x)} & \longrightarrow & \mathcal{O}_{X,x}. \end{array}$$

In terms of the rings R, S this diagram may be written as

$$\begin{array}{ccc} R & \xrightarrow{\Gamma(f)} & S \\ \downarrow & & \downarrow \\ R_{f(x)} & \longrightarrow & S_x. \end{array}$$

Now f is a morphism of *locally* ringed spaces, so the ring homomorphism in the lower row of this diagram is local. This implies that the preimage of the maximal ideal of S_x is the maximal ideal of $R_{f(x)}$. It follows that $f(x) = \Gamma(f)^{-1}(x)$. In other words, as continuous maps we have $f = g$. It then follows from the above diagram that the sheaf morphisms f^\flat and g^\flat

induce the same maps between the stalks $R_{f(x)}$ and S_x for all x . Therefore they coincide by Proposition 3.28. \square

(4.2) Schemes.

Dec. 16, 2025

References: [GW1] Sections (2.9) – (2.12), Chapter 3; [Ha] Chapter II.2.

In view of the previous discussion, we arrive at the following definition.

Definition 4.6. *An affine scheme is a locally ringed space that is isomorphic to a locally ringed space of the form $(\mathrm{Spec}(R), \mathcal{O}_{\mathrm{Spec}(R)})$ for a ring R .*

Rephrasing Theorem 4.5, we can say that the functor Spec is a contravariant equivalence between the category of rings and the category of affine schemes. Therefore, we have succeeded in attaching to each ring a “geometric object” (namely a locally ringed space), and this construction preserves the information of the ring, and also of ring homomorphisms.

From this point, it is easy to extend the definition to include many more geometric objects that are interesting from the point of algebraic geometry, and accessible to the methods of commutative algebra. We start with the following simple remark.

Remark 4.7. Let $X = (X, \mathcal{O}_X)$ be a locally ringed space, and let $U \subseteq X$ be an open subset. Then $(U, \mathcal{O}_{X|U})$ is a locally ringed space (which we often just denote by U). The natural morphism $U \rightarrow X$ of locally ringed spaces is called an *open immersion*.

As an example, let $X = \mathrm{Spec}(R)$ be an affine scheme, and let $s \in R$. Then $D(s)$ (in the sense of the above construction) is a locally ringed space, and as a locally ringed space is isomorphic to $\mathrm{Spec}(R_s)$, i.e., it is again an affine scheme.

We can now give Grothendieck’s definition of a *scheme*. (In the beginning, what we call a *scheme* was called a *prescheme* (e.g. in the first edition of [Mu] and in [Diedonné, Grothendieck: Éléments de Géométrie Algébrique]), but the terminology has changed later.)

Definition 4.8. *A scheme is a locally ringed space X such that there exists an open cover $X = \bigcup_i U_i$, such that for every i , $(U_i, \mathcal{O}_{X|U_i})$ is an affine scheme. A morphism of schemes is a morphism of the underlying locally ringed spaces.*

Proposition/Definition 4.9. *Let X be a scheme, and let $U \subseteq X$ be an open subset, seen as a locally ringed space as above. Then U is a scheme. We call U an open subscheme of X .*

Proof. We need to show that we can cover U by affine schemes. To do so, cover $X = \bigcup_i U_i$ by affine schemes. Then $U \cap U_i$ is open in U_i , and hence can be covered by principal open subsets of U_i . But every principal open of an affine scheme is itself an affine scheme, as remarked above. \square

Example 4.10.

- (1) (affine space) Let R be a ring. Then we call $\mathbb{A}_R^n := \text{Spec}(R[T_1, \dots, T_n])$ *affine space of relative dimension n over R* . The inclusion $R \rightarrow R[T_\bullet]$ gives us a morphism $\mathbb{A}_R^n \rightarrow \text{Spec}(R)$ of affine schemes.
- (2) Let k be a field. By 0 we denote the “origin” in \mathbb{A}_k^n , i.e., the closed point corresponding to the maximal ideal (T_1, \dots, T_n) .
For $n \geq 2$, the open subscheme $U = \mathbb{A}_k^n \setminus \{0\}$ is not affine (cf. Problem Sheet 9). In particular, open subschemes of affine schemes need not be affine.
- (3) (spectrum of a domain) Let R be a domain. Then $\eta = (0)$ is the unique minimal prime ideal, and hence the generic point of $\text{Spec}(R)$. The stalk $\mathcal{O}_{\text{Spec}(R), \eta}$ is the field of fractions $K := \text{Frac}(R)$. For every non-empty open $U \subseteq X := \text{Spec}(R)$, the natural map $\mathcal{O}_X(U) \rightarrow \mathcal{O}_{\text{Spec}(R), \eta} = K$ is injective, thus all the rings $\mathcal{O}_X(U)$ ($U \neq \emptyset$) and hence also all the stalks $\mathcal{O}_{X, x}$ may be considered as subrings of K in a natural way. Furthermore, for every non-empty open U we have

$$\mathcal{O}_X(U) = \bigcap_{x \in U} \mathcal{O}_{X, x}$$

as subrings of K .

Dec. 17, 2025

- (4) (closed subschemes of affine schemes) Let R be a ring and $\mathfrak{a} \subseteq R$ an ideal. We have seen that the continuous map $i: \text{Spec}(R/\mathfrak{a}) \rightarrow \text{Spec}(R)$ induced by the canonical projection $R \rightarrow R/\mathfrak{a}$ is a homeomorphism onto its image $V(\mathfrak{a})$. From now on we write $V(\mathfrak{a})$ for the affine scheme obtained in this way, i.e., the topological space is $V(\mathfrak{a})$, and the structure sheaf is $i_* \mathcal{O}_{\text{Spec}(R/\mathfrak{a})}$. Then $V(\mathfrak{a}) \cong \text{Spec}(R/\mathfrak{a})$ as schemes.
- (5) Let k be a field. For every $n \geq 1$, the scheme $\text{Spec}(k[T]/(T^n))$ has the form of the previous example. Each of these schemes topologically is just one point, however, they are pairwise non-isomorphic. We think of the scheme structure of $\text{Spec}(k[T]/(T^n))$ for $n > 1$ as giving us an “infinitesimal neighborhood” of this point, which is larger when n is large, because the image of a polynomial in the ring $k[T]/(T^n)$ gives us not only the information about the value of the polynomial at $T = 0$, but also the first, ..., $(n - 1)$ -th derivative of the polynomial at 0.
- (6) (schematic intersection of closed subscheme of affine scheme) Let R be a ring, $\mathfrak{a}, \mathfrak{b} \subseteq R$ ideals. We define the *schematic intersection*

$$V(\mathfrak{a}) \cap V(\mathfrak{b}) = V(\mathfrak{a} + \mathfrak{b})$$

as a “closed subscheme” of $\text{Spec}(R)$ in the sense of Part (5). The scheme structure allows us to see, in addition to the set (and topological space) $V(\mathfrak{a}) \cap V(\mathfrak{b})$, also the “type of intersection”. For instance, if k is an algebraically closed field and $R = k[X, Y]$ the polynomial ring in two variables, then for $\mathfrak{a} = (Y)$ and $\mathfrak{b} = (Y - f(X))$, $f \in k[X]$, the scheme $V(\mathfrak{a}) \cap V(\mathfrak{b})$ sees the zeros of f with their multiplicities.

However, there are also schemes (e.g., “projective space” as constructed below) that are not isomorphic to an open subscheme of an affine scheme. Understanding how to construct these is one of the main next steps.

(4.3) Morphisms into affine schemes.

Jan. 6, 2026

References: [GW1] Section (3.3).

We have shown that morphisms between affine schemes correspond to ring homomorphisms between the rings of global sections of their structure sheaves. This result generalizes as follows. Recall the notation $\Gamma(U, \mathcal{F}) = \mathcal{F}(U)$ (for a presheaf \mathcal{F}).

Theorem 4.11. *Let X be a locally ringed space, R a ring and $Y = \operatorname{Spec}(R)$. The map*

$$\operatorname{Hom}_{\operatorname{locRS}}(X, Y) \longrightarrow \operatorname{Hom}_{\operatorname{Ring}}(R, \Gamma(X, \mathcal{O}_X)),$$

$$f \mapsto (R = \Gamma(Y, \mathcal{O}_Y) \xrightarrow{f^b(Y)} \Gamma(f^{-1}(Y), f_*\mathcal{O}_X) = \Gamma(X, \mathcal{O}_X)),$$

is a bijection.

Proof. It is not too hard to prove the theorem along the same lines as Theorem 4.5 (see [GW1] Proposition 3.4).

We give a simpler proof in the case that X is a scheme in order to illustrate the principle of *gluing of morphisms*. \square

Proposition 4.12. (Gluing of morphisms) *Let X, Y be schemes (or: topological spaces, (locally) ringed spaces), and let $X = \bigcup_i U_i$ be a cover by open subsets. Let $f_i: U_i \rightarrow Y$ be morphisms such that $f_i|_{U_i \cap U_j} = f_j|_{U_i \cap U_j}$ for all i, j . Then there exists a unique morphism $f: X \rightarrow Y$ such that $f|_{U_i} = f_i$ for all i .*

Proof. On sets, define $f(x) = f_i(x)$ where i is chosen such that $x \in U_i$. This is independent of i and thus defines a map $f: X \rightarrow Y$ of sets such that $f|_{U_i} = f_i$ for all i . Continuity can be checked locally on X , hence f is continuous, because all the f_i are.

It remains to define a sheaf homomorphism $\mathcal{O}_Y \rightarrow f_*\mathcal{O}_X$. For $V \subseteq Y$ open, combining the data of the f_i gives us a homomorphism

$$\Gamma(V, \mathcal{O}_Y) \longrightarrow \prod_i \Gamma(f^{-1}(V) \cap U_i, \mathcal{O}_X).$$

Applying the sheaf axioms for the sheaf \mathcal{O}_X and the cover $f^{-1}(V) = \bigcup_i (f^{-1}(V) \cap U_i)$ one checks that this homomorphism factors through $\Gamma(f^{-1}(V), \mathcal{O}_X)$. This defines the desired homomorphism $\mathcal{O}_Y \rightarrow f_*\mathcal{O}_X$. \square

Proof of Theorem 4.11. Let $X = \bigcup_i U_i$ be a cover by affine open subschemes. We also chose covers $U_i \cap U_j = \bigcup U_{ijk}$ by affine open subschemes. Consider the diagram

$$\begin{array}{ccccc}
\mathrm{Hom}(X, Y) & \longrightarrow & \prod_i \mathrm{Hom}(U_i, Y) & \xrightarrow{\quad\quad\quad} & \prod_{i,j,k} \mathrm{Hom}(U_{ijk}, Y) \\
\downarrow & & \downarrow & & \downarrow \\
\mathrm{Hom}(R, \Gamma(X, \mathcal{O}_X)) & \longrightarrow & \prod_i \mathrm{Hom}(R, \Gamma(U_i, \mathcal{O}_X)) & \xrightarrow{\quad\quad\quad} & \prod_{i,j,k} \mathrm{Hom}(R, \Gamma(U_{ijk}, \mathcal{O}_X))
\end{array}$$

where the vertical maps are as in the statement of the theorem, the top horizontal morphisms are given by restriction of morphisms to open subspaces, and the bottom horizontal row is given by restriction of sections (this is basically $\mathrm{Hom}(R, -)$ of the “sheaf sequence” for \mathcal{O}_X).

The top row is exact by “gluing of morphisms”, the bottom row is exact because \mathcal{O}_X is a sheaf and the Hom functor is left exact. By Theorem 4.5, $\mathrm{Hom}(U_i, Y) = \mathrm{Hom}(R, \Gamma(U_i, \mathcal{O}_X))$, the vertical morphisms in the middle and on the right hand side are isomorphisms. It follows that the vertical morphism on the left is an isomorphism as well. This is what we had to show. \square

Example 4.13.

- (1) Let X be a scheme. There is a unique morphism $X \rightarrow \mathrm{Spec}(\mathbb{Z})$ of schemes.
- (2) Let k be a field (or any ring), and let X be a scheme. A morphism $X \rightarrow \mathrm{Spec}(k)$ is the same as a k -algebra structure on $\Gamma(X, \mathcal{O}_X)$ (which is by definition a ring homomorphism $k \rightarrow \Gamma(X, \mathcal{O}_X)$).

Often, a k -algebra structure (for some field or ring k) on a scheme X is given (e.g., on $\mathrm{Spec}(k[T_\bullet]/\mathfrak{a})$, one of our examples of interesting schemes), and in this case, similarly as for k -algebras, it is usually useful to consider only morphisms which are compatible with this structure. This leads to the following notion of “relative schemes”, or “schemes over a fixed base scheme S ”.

Definition 4.14. Let S be a scheme. The category (Sch/S) of S -schemes is defined as follows. The objects are morphisms $X \rightarrow S$ of schemes. The morphisms between S -schemes $X \rightarrow S$ and $Y \rightarrow S$ are scheme morphisms $X \rightarrow Y$ such that the triangle

$$\begin{array}{ccc}
X & \xrightarrow{\quad\quad\quad} & Y \\
& \searrow & \swarrow \\
& S &
\end{array}$$

is commutative. Composition of morphisms is the usual composition of morphisms of schemes.

If $f: X \rightarrow S$ is an S -scheme, we call f its structure morphism. Usually we omit it from the notation and simply speak of X as an S -scheme. The

Hom-sets in the category of S -schemes are usually denoted as $\mathrm{Hom}_S(X, Y)$. If $S = \mathrm{Spec}(R)$ is affine, we also speak of R -schemes instead.

The scheme S is also called the *base scheme*.

By 4.13 (1), we have $(\mathrm{Sch}) = (\mathrm{Sch}/S)$.

Remark 4.15. Let R be a ring. If X is an R -scheme, then the rings $\Gamma(U, \mathcal{O}_X)$ for $U \subseteq X$ open, and the local rings $\mathcal{O}_{X,x}$ for $x \in X$ as well as their residue class fields $\kappa(x) = \mathcal{O}_{X,x}/\mathfrak{m}_x$ all are equipped with the structure of an R -algebra, since the R -algebra $\Gamma(X, \mathcal{O}_X)$ naturally maps to all of them, and all the natural homomorphisms between these rings are homomorphisms of R -algebras.

Jan. 7, 2026

Remark 4.16. Theorem 4.11 has the following variant for S -schemes. If $S = \mathrm{Spec}(R)$ and $X = \mathrm{Spec}(A)$ are affine schemes, where A is an R -algebra, so that X is an S -scheme, then for every S -scheme T the natural map

$$\mathrm{Hom}_S(T, X) \longrightarrow \mathrm{Hom}_R(A, \Gamma(T, \mathcal{O}_T))$$

is bijective. Here on the left we have morphisms of S -schemes and on the right we have homomorphisms of R -algebras.

(4.4) Morphisms from spectrum of a field into scheme X .

References: [GW1] Section (3.4).

Let X be a scheme. To study X , it is often essential to understand the sets of morphisms $\mathrm{Hom}(T, X)$ for varying schemes T . Even though these sets are often hard to understand, their importance justifies introducing a shorter symbol for them.

Definition 4.17.

(1) Let X be a scheme. For every scheme T we write

$$X(T) := \mathrm{Hom}(T, X)$$

and call this the set of T -valued points of X .

(2) If X, T are S -schemes for some scheme S , then we usually (by abuse of notation) write

$$X(T) = \mathrm{Hom}_S(T, X)$$

for the set of morphisms $T \rightarrow X$ of S -schemes and call this the set of T -valued points of the S -scheme X . (If it is necessary to distinguish between the two sets, we could also write $X_S(T)$.)

(3) If $T = \mathrm{Spec}(R)$ is affine, we also write $X(R) = X(\mathrm{Spec}(R))$ and speak of R -valued points.

Example 4.18. Let R be a ring.

(1) For the affine space \mathbb{A}_R^n over R we have

$$\mathbb{A}_R^n(T) = \mathrm{Hom}_{\mathrm{Spec}(R)}(T, \mathbb{A}_R^n) = \mathrm{Hom}_R(R[T_1, \dots, T_n], \Gamma(T, \mathcal{O}_T)) = \Gamma(T, \mathcal{O}_T)^n.$$

Note that here it is important that we take only morphisms of R -schemes on the right (and correspondingly, of R -algebras on the left).

- (2) More generally, if $X = V(\mathfrak{a})$ for an ideal $\mathfrak{a} \subseteq R[T_1, \dots, T_n]$, then for every R -algebra A we can identify

$$X(A) = \{(x_i)_i \in A^n; \forall f \in \mathfrak{a} : f(x_1, \dots, x_n) = 0\},$$

where we again take morphisms of R -schemes on the left hand side. (And similarly for $X(T)$ where T is any R -scheme, not necessarily affine.)

Remark 4.19. There is another, more formal but also very useful justification why the T -valued points of a scheme are important. We will take this up again later in more detail, and hence at this point give only a brief sketch.

The argument applies to any (locally small) category \mathcal{C} (for us, it would be the category of schemes, or the category of S -schemes for some scheme S). To each object X of \mathcal{C} we may attach the functor

$$h_X : \mathcal{C}^{\text{opp}} \rightarrow (\text{Sets}), \quad X \mapsto \text{Hom}_{\mathcal{C}}(T, X),$$

(on morphisms, h_X is given by composition).

In this way, we obtain a functor $\mathcal{C} \rightarrow \text{Fun}(\mathcal{C}^{\text{opp}}, (\text{Sets}))$ from \mathcal{C} to the category of (contravariant) functors from \mathcal{C} to the category of sets (with morphisms of functors as morphisms). The Yoneda lemma states that this functor is fully faithful. In particular, given objects X, Y of \mathcal{C} , we have $X \cong Y$, if and only if the functors h_X and h_Y are isomorphic. (Proving this result is not difficult, you should try it! Or see, e.g., [GW1] Section (4.2).)

Note however that it is (almost always) a very special property of a functor $\mathcal{C}^{\text{opp}} \rightarrow (\text{Sets})$ to be of the form h_X for some X ; for most functors this is not true.

For schemes, with our terminology of T -valued points, this means that a scheme X is determined by the collection of all of its T -valued points together with the maps $X(T) \rightarrow X(T')$ induced by scheme morphisms $T \rightarrow T'$.

While in general it is difficult to make the set $X(T)$ explicit, we can give a useful description at least in the case where T is the spectrum of a field, see Proposition 4.21 below. To prepare for this, we start with the following remarks.

Let X be a scheme and let $x \in X$.

Definition 4.20. *Let X be a scheme and let $x \in X$. We call the stalk $\mathcal{O}_{X,x}$ the local ring of X (or \mathcal{O}_X) at x and usually denote its (unique) maximal ideal by \mathfrak{m}_x . The quotient $\kappa(x) := \mathcal{O}_{X,x}/\mathfrak{m}_x$ is called the residue class field of X at x .*

By definition of the notion of morphism of scheme (i.e., of morphism of locally ringed space), the residue class field behaves functorially in the following sense. For a morphism $f : X \rightarrow Y$ of schemes and a point $x \in X$, we have the ring homomorphism $f_x^\# : \mathcal{O}_{Y,f(x)} \rightarrow \mathcal{O}_{X,x}$, a *local* homomorphism

between local rings. This induces a ring homomorphism $\kappa(f(x)) \rightarrow \kappa(\overline{f(x)})$ between the residue class fields, which in this section we will denote by $\overline{f_x^\#}$.

If $U \subseteq X$ is an affine open neighborhood of x (i.e., $U \subseteq X$ is open and the scheme U is affine), say $U = \text{Spec}(A)$, then x corresponds to a prime ideal $\mathfrak{p}_x \subset A$ and we obtain a ring homomorphism

$$\mathcal{O}_{X,x} \cong \mathcal{O}_{U,x} = A_{\mathfrak{p}_x} \longleftarrow A.$$

Passing to the spectra, we obtain a morphism

$$j_x: \text{Spec}(\mathcal{O}_{X,x}) \rightarrow U \rightarrow X,$$

where the morphism $U \rightarrow X$ is the inclusion of the open subscheme U . This morphism is independent of the choice of U . (It is easy to see that the morphism is not changed if U is replaced by a principal open subscheme of U . From this, one may deduce the independence of U .) It maps the closed point of $\text{Spec}(\mathcal{O}_{X,x})$ to x (because the inverse image of the maximal ideal of $A_{\mathfrak{p}_x}$ in A is \mathfrak{p}_x).

Furthermore, the projection $\mathcal{O}_{X,x} \rightarrow \kappa(x)$ induces a morphism $\text{Spec}(\kappa(x)) \rightarrow \text{Spec}(\mathcal{O}_{X,x})$ and composing this with j_x we obtain a morphism

$$i_x: \text{Spec}(\kappa(x)) \rightarrow X$$

which maps the unique point of $\text{Spec}(\kappa(x))$ to x .

Proposition 4.21. *Let X be a scheme, and let K be a field. The maps*

$$X(K) \xrightleftharpoons{\quad} \{(x, \alpha); x \in X, \alpha: \kappa(x) \rightarrow K\}$$

$$f \longmapsto (\text{Im}(f), \overline{f^\#})$$

$$i_x \circ \text{Spec}(\alpha) \longleftarrow (x, \alpha)$$

are inverse to each other and in particular are bijective.

Here by abuse of notation we denote by $\text{Im}(f)$ the unique point in the image of f .

Proof. It follows from the above discussion that the given maps are inverse to each other. \square

Similarly, if k is a field, we have the following version for k -schemes.

Proposition 4.22. *Let k be a field, X a k -scheme, and let K be an extension field of k (so that $\text{Spec}(K)$ also is a k -scheme). The maps of Proposition 4.21 restrict to bijections*

$$X(K) \xrightleftharpoons{\quad} \{(x, \alpha); x \in X, \alpha: \kappa(x) \rightarrow K \text{ } k\text{-homom.}\}.$$

Here $X(K)$ denotes the set $\text{Hom}_k(\text{Spec}(K), X)$ of K -valued points of X as a k -scheme.

5. PROJECTIVE SPACE

(5.1) Gluing of schemes.

References: [GW1] Section (3.5).

Jan. 13, 2026

Definition 5.1. A gluing datum consists of

- a family $(U_i)_{i \in I}$ of schemes,
- for all $i, j \in I$, an open subscheme $U_{ij} \subseteq U_i$,
- for all $i, j \in I$, an isomorphism $\varphi_{ji}: U_{ij} \rightarrow U_{ji}$,

such that

- (a) for all i , $U_{ii} = U_i$ (and $\varphi_{ii} = \text{id}_{U_i}$),
- (b) for all i, j, k ,

$$\varphi_{ij} \circ \varphi_{jk} = \varphi_{ik} \quad \text{on } U_{kj} \cap U_{ki}$$

(part of this condition is that $\varphi_{jk}(U_{kj} \cap U_{ki}) \subseteq U_{ji}$).

Note that the “cocycle condition” (b) implies in particular that $\varphi_{ii} = \text{id}_{U_i}$ (i.e., we could omit this condition from (a)), and that the isomorphisms φ_{ij} and φ_{ji} are inverse to each other.

Proposition 5.2. Let $((U_i)_i, (U_{ij})_{i,j}, (\varphi_{ij})_{i,j})$ be a gluing datum. There exists a scheme X together with open immersions $\psi_i: U_i \rightarrow X$, $i \in I$, such that $X = \bigcap_i \psi(U_i)$, and for all i, j , the restriction $\psi_i|_{U_{ij}}$ is an isomorphism $U_{ij} \xrightarrow{\cong} \psi_i(U_i) \cap \psi_j(U_j)$, and the composition $\psi_i^{-1}|_{U_{ij}} \circ \psi_j|_{U_{ji}}$ equals the isomorphism φ_{ij} .

The scheme X together with the ψ_i is uniquely determined up to unique isomorphism.

If all the U_i , $U_{i,j}$ are S -schemes and the φ_{ij} are morphisms of S -schemes for some scheme S , then X carries a (unique) S -scheme structure so that all the ψ_i are morphisms of S -schemes.

Proof. Construct the topological space X as in Problem 28, and the structure sheaf \mathcal{O}_X using Proposition 3.10, applied to the basis of the topology of X consisting of all those open subsets that are contained in (at least) one of the $\psi_i(U_i)$. See [GW1] Proposition 3.10 for a few more details.

The uniqueness and the final statement follow from gluing of morphisms (Proposition 4.12). \square

Example 5.3.

- (1) (Disjoint union) For any family $(U_i)_{i \in I}$ of schemes we may set $U_{ij} = \emptyset$ for all i, j . This gives a gluing datum (with the uniquely determined φ_{ij}), and the scheme obtained by gluing is called the *disjoint union* of the U_i , and denoted by $\bigsqcup_{i \in I} U_i$.
- (2) (Gluing of two schemes) Let U_1, U_2 be schemes, and let $U_{12} \subseteq U_1$, $U_{21} \subseteq U_2$ be open subschemes with an isomorphism $U_{12} \cong U_{21}$. There is

a unique way to extend this to a gluing datum. The cocycle condition is automatically satisfied.

- (3) (Affine line with doubled origin) Let k be a field, $U_1 = \mathbb{A}_k^1$, $U_2 = \mathbb{A}_k^1$, $U_{12} = U_1 \setminus \{0\}$, $U_{21} = U_2 \setminus \{0\}$, and $U_{12} \cong U_{21}$ the identity. This defines a gluing datum, and the resulting scheme is called the “affine line with doubled origin”. One can show that this (somewhat “pathological”, because we applied the gluing in a “stupid” way (in the above situation the isomorphism φ_{ij} extends to an isomorphism $U_1 \cong U_2$); more precisely, it is a non-separated scheme, see below) scheme is not affine.
- (4) (Projective line) Let k be a field, $U_1 = \mathbb{A}_k^1$, $U_2 = \mathbb{A}_k^1$, $U_{12} = U_1 \setminus \{0\}$, $U_{21} = U_2 \setminus \{0\}$, and $U_{12} \cong U_{21}$ the morphism $x \mapsto x^{-1}$ (i.e., on affine coordinate rings, it is given by $k[T, T^{-1}] \rightarrow k[T, T^{-1}]$, $T \mapsto T^{-1}$). This defines a gluing datum, and the resulting scheme is called the “projective line over k ”, cf. also the next section.

(5.2) Projective space.

References: [GW1] Sections (3.6), (3.7); for a slightly different approach see [Ha] II.2 and/or [GW1] Chapter 13.

Jan. 14, 2026

Let R be a ring. Consider the following gluing datum which mimics the covering of $\mathbb{P}^n(k)$ (from the introduction) by the open subsets $\{(x_0 : \cdots : x_n); x_i \neq 0\}$, $i = 0, \dots, n$. (Note that each of these has a natural bijection with k^n by $(x_0 : \cdots : x_n) \mapsto \left(\frac{x_0}{x_i}, \dots, \frac{\widehat{x_i}}{x_i}, \dots, \frac{x_n}{x_i}\right)$.)

Let

- $U_i = \operatorname{Spec} R \left[\frac{X_0}{X_i}, \dots, \frac{\widehat{X_i}}{X_i}, \dots, \frac{X_n}{X_i} \right]$ (where we view all these rings as subrings of $R[X_0, \dots, X_n, X_0^{-1}, \dots, X_n^{-1}]$),
- $U_{ij} = D \left(\frac{X_j}{X_i} \right) \subseteq U_i$,
- $\varphi_{ij} : U_{ji} \rightarrow U_{ij}$ is the identity (note that the localizations $\Gamma(U_i, \mathcal{O}_{U_i})_{\frac{X_j}{X_i}}$ and $\Gamma(U_j, \mathcal{O}_{U_j})_{\frac{X_i}{X_j}}$ are *equal* as subrings of $R[X_0, \dots, X_n, X_0^{-1}, \dots, X_n^{-1}]$).

Because the maps φ_{ij} are defined as the identity of subrings of the ring $R[X_0, \dots, X_n, X_0^{-1}, \dots, X_n^{-1}]$, it is immediate that the cocycle condition is satisfied.

Note that for every i , the ring $R \left[\frac{X_0}{X_i}, \dots, \frac{\widehat{X_i}}{X_i}, \dots, \frac{X_n}{X_i} \right]$ is isomorphic to a polynomial ring over R in n variables, i.e., $U_i \cong \mathbb{A}_R^n$.

Definition 5.4. *The R -scheme attached to this gluing datum by Proposition 5.2 is called projective space of relative dimension n over R and denoted by \mathbb{P}_R^n .*

The open subschemes $U_i \cong \mathbb{A}_R^n$ are also called the *standard charts* of \mathbb{P}_R^n .

Proposition 5.5. *Let R be a ring, $n \geq 0$. Then $\Gamma(\mathbb{P}_R^n, \mathcal{O}_{\mathbb{P}_R^n}) = R$.*

Proof. See Problem sheet 11. \square

Corollary 5.6. *Let R be a ring, $n \geq 1$. Then the scheme \mathbb{P}_R^n is not affine.*

Proof. Otherwise the structure morphism $\mathbb{P}_R^n \rightarrow \operatorname{Spec}(R)$ would be an isomorphism because of Proposition 5.5 and Theorem 4.5. But (the underlying continuous map of) this morphism clearly is not injective (e.g., because even the composition $\mathbb{A}_R^n \rightarrow \mathbb{P}_R^n \rightarrow \operatorname{Spec}(R)$ with one of the standard charts is not injective). \square

Proposition 5.7. *Let R be a ring, and let $R \rightarrow k$ be a ring homomorphism to a field k . Then*

$$\mathbb{P}_R^n(k) = \mathbb{P}^n(k),$$

where the left hand side is the set of k -valued points of the R -scheme \mathbb{P}_R^n , and the right hand side is the “classical” projective space over k as in the introduction.

Proof. We have corresponding identifications for the standard charts, and they are compatible with the gluing datum. \square

Recall how we defined the Zariski topology on $\mathbb{P}^n(k)$ in the first chapter, by defining closed subsets $V_+(I)$ for ideals $I \subset k[X_\bullet]$ generated by homogeneous polynomials. We can transfer this definition to the context of schemes by once more using gluing of schemes. For a homogeneous polynomial $f(X_0, \dots, X_n)$ we write $\Phi_i(f) = f\left(\frac{X_0}{X_i}, \dots, \frac{X_n}{X_i}\right) \in R\left[\frac{X_0}{X_i}, \dots, \frac{X_n}{X_i}\right] \subseteq R[X_0, \dots, X_n, X_0^{-1}, \dots, X_n^{-1}]$ for its *dehomogenization* with respect to X_i .

Let R be a ring and let $I \subseteq R[X_0, \dots, X_n]$ be a *homogeneous* ideal, i.e., an ideal generated by homogeneous polynomials. For each i , let V_i be the closed subscheme of $U_i = \operatorname{Spec} R\left[\frac{X_0}{X_i}, \dots, \frac{X_n}{X_i}\right]$ defined by the polynomials $\Phi_i(f)$, where f ranges over all homogeneous polynomials in I , i.e.,

$$V_i = V(\Phi_i(f); f \in I \text{ homogeneous}).$$

We extend this to a gluing datum by setting

$$V_{ij} = V_i \cap U_{ij}.$$

One checks that the isomorphisms $\varphi_{ij}: U_{ji} \rightarrow U_{ij}$ above induce isomorphisms $\varphi_{ij}: V_{ji} \rightarrow V_{ij}$. In this way we obtain a gluing datum.

Definition 5.8. *The scheme attached to this gluing datum is denoted by $V_+(I)$.*

Topologically, $V_+(I)$ is a closed subset of \mathbb{P}_R^n (since we can check this by intersecting with each U_i). The k -valued points of $V_+(I)$ coincide with the set $V_+(I)$ defined in the first chapter (as a subset of \mathbb{P}_k^n , cf. Proposition 5.7).

Definition 5.9. For a homogeneous polynomial $f \in R[X_0, \dots, X_n]$ we write

$$D_+(f) = \mathbb{P}_R^n \setminus V_+(f),$$

an open subscheme of \mathbb{P}_R^n .

As a special case, $D_+(X_i) = U_i$. For a homogeneous polynomial f we have

$$D_+(f) \cap U_i = D_+(f) \cap D_+(X_i) = D_+(X_i f),$$

and under the identification $D_+(X_i) = U_i$, this set is identified with $D(\Phi_i(f))$ (as follows from the definition and the construction of $V_+(f)$).

It follows that the sets $D_+(f)$ for varying homogeneous f form a basis of the topology of \mathbb{P}_R^n .

Proposition 5.10. Let R be a ring, and let $f_1, \dots, f_m \in R[X_0, \dots, X_n]$ be homogeneous polynomials of the same degree d . Let I be the homogeneous ideal generated by the f_j . Then there is a morphism of R -schemes

$$f: \mathbb{P}_R^n \setminus V_+(I) \longrightarrow \mathbb{P}_R^m$$

which for any ring homomorphism $R \rightarrow k$ to a field k induces on k -valued points the map

$$\mathbb{P}^n(k) \setminus V_+(I) \longrightarrow \mathbb{P}^m(k), \quad (x_0 : \dots : x_n) \mapsto (f_0(x_\bullet) : \dots : f_m(x_\bullet)).$$

Here in the description of the map on k -valued points we fix a representative $x_\bullet = (x_0, \dots, x_n) \in k^{n+1}$. Note that while the value $f_j(x_0, \dots, x_n)$ of an individual f_j is not well-defined, the points $(f_0(x_\bullet) : \dots : f_m(x_\bullet))$ is well-defined, because of our assumption that all f_j are homogeneous of the same degree.

One can show moreover that the morphism f is uniquely characterized by the behavior on k -valued points whenever R is a reduced ring (i.e., has no non-trivial nilpotent elements).

Proof. We use $R[X_0, \dots, X_n]$ as “the polynomial ring of \mathbb{P}_R^n ”, and $R[Y_0, \dots, Y_m]$ as “the polynomial ring of \mathbb{P}_R^m ”, in order to distinguish between the two sides. So, for instance, $D_+(X_i) \subset \mathbb{P}_R^n$ and $D_+(Y_j) \subset \mathbb{P}_R^m$ are the standard charts.

Now we first construct a morphism

$$D_+(f_j) \longrightarrow D_+(Y_j)$$

which on k -valued points induces the desired morphism.

To do so,

$$D_+(f_j) = \bigcup_i (D_+(X_i) \cap D_+(f_j)) = \bigcup_i D_+(X_i f_j).$$

(Using the same cover, one can show that $D_+(f_j)$ is affine and compute its coordinate ring, and use this to specify the morphism f_j directly, but we proceed slightly differently.)

We have $D_+(X_i f_j) = \text{Spec}(R[\frac{X_0}{X_i}, \dots, \frac{X_n}{X_i}, \frac{X_i^d}{f_j}])$, because $\frac{f_j}{X_i^d}$ is the dehomogenization of f_j with respect to X_i (denoted by $\Phi_i(f_j)$ above), and

$D_+(X_i f_j)$ is the principal open inside $D_+(X_i) \cong \mathbb{A}_R^n$ defined by this element. We then have a morphism $D_+(X_i f_j) \rightarrow D_+(Y_j)$ attached to the ring homomorphism

$$R \left[\frac{X_0}{X_j}, \dots, \frac{X_m}{X_j} \right] \rightarrow R \left[\frac{X_0}{X_i}, \dots, \frac{X_n}{X_i}, \frac{X_i^d}{f_j} \right], \quad \frac{X_\ell}{X_j} \mapsto \frac{f_\ell}{f_j}.$$

Note that

$$\frac{f_\ell}{f_j} = \frac{X_i^d}{f_j} \cdot \frac{f_\ell}{X_i^d}$$

is really an element of the left hand side.

It is then easy to check that these morphisms by gluing of morphisms give rise to a morphism $D_+(f_j) \rightarrow D_+(Y_j)$ with the desired behavior on k -valued points.

Finally, one uses gluing of morphisms again, now applied to the compositions $D_+(f_j) \rightarrow D_+(Y_j) \subset \mathbb{P}_R^m$ in order to obtain a morphism

$$\mathbb{P}_R^n \setminus V_+(I) = \bigcup_j D_+(f_j) \longrightarrow \mathbb{P}_R^m.$$

□

6. FIBER PRODUCTS OF SCHEMES

References: [GW1] Sections (4.4) – (4.8)

In this section we will discuss the notion of (fiber) product of schemes, which turns out to be useful in many respects. One motivation is this: It is a natural question whether we can define products in the setting of schemes, or k -schemes, say, where k is a field. For example, the bijection

$$\begin{aligned} \mathbb{P}^1(k) \times \mathbb{P}^1(k) &\rightarrow V_+(X_0X_3 - X_1X_2) \subset \mathbb{P}^3(k), \\ ((x : y), (x' : y')) &\mapsto (xx' : xy' : yx' : yy'), \end{aligned}$$

leads us to expect that there is an isomorphism $\mathbb{P}_k^1 \times \mathbb{P}_k^1 \rightarrow V_+(X_0X_3 - X_1X_2)$ of k -schemes — only that the symbol $\mathbb{P}_k^1 \times \mathbb{P}_k^1$ is undefined at this point! Note that one has to be a bit careful here: It is not hard to check that the above map is bijective, but it is not a homeomorphism if we equip $\mathbb{P}^1(k) \times \mathbb{P}^1(k)$ with the product topology; rather, the suitable topology is a different one (cf. also Problem 4).

(6.1) Fiber products in a category.

We take a categorical approach and define the product (and the more general notion of *fiber product*) by a universal category as follows.

Definition 6.1. *Let \mathcal{C} be a category, and let $f: X \rightarrow S$, $g: Y \rightarrow S$ be morphisms in \mathcal{C} . An object P of \mathcal{C} together with morphisms $p: P \rightarrow X$ and $q: P \rightarrow Y$ with $f \circ p = g \circ q$ is called a fiber product of X and Y over S , if the following universal property holds:*

For every scheme T together with morphisms $\varphi: T \rightarrow X$ and $\psi: T \rightarrow Y$ with $f \circ \varphi = g \circ \psi$ there exists a unique morphism $\xi: T \rightarrow P$ such that the following diagram commutes:

$$\begin{array}{ccccc} T & & & & \\ & \searrow \xi & & \searrow \varphi & \\ & & P & \xrightarrow{p} & X \\ & \searrow \psi & \downarrow q & & \downarrow f \\ & & Y & \xrightarrow{g} & S \end{array}$$

In view of the universal property, a fiber product (i.e., the object P together with the morphisms $P \rightarrow X$, $P \rightarrow Y$) is uniquely determined up to unique isomorphism, if it exists. We therefore speak of “the” fiber product of X and Y over S and denote it by $X \times_S Y$. The morphisms $X \times_S Y \rightarrow X$, $X \times_S Y \rightarrow Y$ are called the *projections* from the fiber product to its factors.

Terminology: Saying that the (commutative) diagram

$$\begin{array}{ccc} P & \longrightarrow & X \\ \downarrow & & \downarrow \\ Y & \longrightarrow & S \end{array}$$

is a *fiber product diagram* or is *cartesian* is equivalent to saying that P together with the given morphisms to X and Y is a fiber product of X and Y over S . One also speaks of a *pullback diagram*, or calls P the pullback of X along $Y \rightarrow S$ (or of Y along $X \rightarrow S$).

Remarks and Examples 6.2.

- (1) Let \mathcal{C} be the category of sets and let $f: X \rightarrow S$, $g: Y \rightarrow S$ be maps of sets. Then the fiber product $X \times_S Y$ exists and is given by (as always, up to unique isomorphism)

$$X \times_S Y = \{(x, y) \in X \times Y; f(x) = g(y)\},$$

where the maps $X \times_S Y \rightarrow X$ and $X \times_S Y \rightarrow Y$ are the restrictions of the usual projections from the cartesian product $X \times Y$ to its factors.

As a subset of $X \times Y$, we can rewrite this as

$$X \times_S Y = \bigsqcup_{s \in S} f^{-1}(s) \times g^{-1}(s).$$

This explains the terminology *fiber product*.

- (2) Let \mathcal{C} be the category of topological spaces and let $f: X \rightarrow S$, $g: Y \rightarrow S$ be continuous maps. Then the fiber product $X \times_S Y$ exists and is given by (as always, up to unique isomorphism)

$$X \times_S Y = \{(x, y) \in X \times Y; f(x) = g(y)\},$$

where the maps $X \times_S Y \rightarrow X$ and $X \times_S Y \rightarrow Y$ are the restrictions of the usual projections from the cartesian product $X \times Y$ to its factors. The topology is defined as the coarsest topology for which both projections are continuous. Equivalently, if we equip the product $X \times Y$ with the product topology, then $X \times_S Y$ carries the subspace topology. More explicitly, the open subsets of $X \times_S Y$ are those that can be written as unions of sets of the form $U \times_S V$, where $U \subseteq X$ and $V \subseteq Y$ are open.

- (3) If pt is a terminal object in \mathcal{C} (i.e., every object of \mathcal{C} admits a unique morphism to pt), then the universal property of $X \times_{\text{pt}} Y$ (with respect to the unique maps $X \rightarrow \text{pt}$, $Y \rightarrow \text{pt}$) is precisely the universal property of the product of X and Y .

This applies, for example, the category of sets (with pt a set with one element), to the category of schemes (with terminal object $\text{Spec}(\mathbb{Z})$) and to the category of S -schemes (with terminal object S , or more precisely $\text{id}_S: S \rightarrow S$).

- (4) If \mathcal{C} is the category of sets or the category of topological spaces, $f: X \rightarrow S$ is a morphism and $s \in S$, then the inclusion $\{s\} \rightarrow S$ is a morphism and there is a natural identification of $X \times_S \{s\}$ with the fiber $f^{-1}(s)$ (in

the case of topological spaces, we equip the fiber $f^{-1}(s) \subseteq X$ with the subspace topology.

Dually to the notion of fiber product we have the notion of *algamated sum* or *pushout*. The corresponding commutative diagrams are called *cocartesian*. An example is the tensor product of rings.

(6.2) Fiber products of schemes.

Jan. 21, 2026

Theorem 6.3. *All fiber products in the category of schemes exist.*

Moreover, for scheme morphisms $X \rightarrow S$, $Y \rightarrow S$, the fiber product $X \times_S Y$ also satisfies the universal property of the fiber product in the category of locally ringed spaces.

With more work, one can show that also in the category of locally ringed spaces all fiber products exist; we will not need to use this.

Proof. We first consider the case that $X = \operatorname{Spec}(A)$, $Y = \operatorname{Spec}(B)$ and $S = \operatorname{Spec}(R)$ are all affine. In this case, we claim that the (affine) scheme $\operatorname{Spec}(A \otimes_R B)$ satisfies the universal property of the fiber product in the category of locally ringed spaces. (Note that it follows formally from the universal property of the tensor product (it is the pushout of A and B with respect to the homomorphisms $R \rightarrow A$ and $R \rightarrow B$) and the antiequivalence of the categories of rings and of affine schemes, that $\operatorname{Spec}(A \otimes_R B)$ is the fiber product in the category of affine schemes.) This claim follows easily from Theorem 4.11, in fact for every locally ringed space T we have

$$\begin{aligned} & \operatorname{Hom}_{\operatorname{locRS}}(T, \operatorname{Spec}(A \otimes_R B)) \\ &= \operatorname{Hom}_{\operatorname{Ring}}(A \otimes_R B, \Gamma(T, \mathcal{O}_T)) \\ &= \operatorname{Hom}_{\operatorname{Ring}}(A, \Gamma(T, \mathcal{O}_T)) \times_{\operatorname{Hom}_{\operatorname{Ring}}(R, \Gamma(T, \mathcal{O}_T))} \operatorname{Hom}_{\operatorname{Ring}}(B, \Gamma(T, \mathcal{O}_T)) \\ &= \operatorname{Hom}_{\operatorname{locRS}}(T, X) \times_{\operatorname{Hom}_{\operatorname{locRS}}(T, S)} \operatorname{Hom}_{\operatorname{locRS}}(T, Y). \end{aligned}$$

The composition is the map $\xi \mapsto (p \circ \xi, q \circ \xi)$, and the statement that this map is a bijection is precisely the universal property of the fiber product.

In the general case, the fiber product may be constructed by gluing of schemes. We give a rough sketch and refer to [GW1] Theorem 4.18 and the references given there for more details.

Choose affine open covers

$$S = \bigcup_i W_i, \quad f^{-1}(W_i) = \bigcup_j U_{ij}, \quad g^{-1}(W_i) = \bigcup_k V_{ik}.$$

Then one constructs a gluing datum for the family

$$U_{ij} \times_{W_i} V_{ik}.$$

For a pair of indices $(i, j, k), (i', j', k')$, one shows that, denoting by p_1, p_2 the projections from $U_{ij} \times_{W_i} V_{ik}$ to its two factors,

$$p_1^{-1}(U_{ij} \cap U_{i'j'}) \cap p_2^{-1}(V_{ik} \cap V_{i'k'})$$

is an open subscheme of $U_{ij} \times_{W_i} V_{ik}$ which satisfies the universal property of the fiber product

$$(U_{ij} \cap U_{i'j'}) \times_{W_i \cap W_{i'}} (V_{ik} \cap V_{i'k'}).$$

This open subschemes will be, in the scheme obtained by gluing, the intersection of (the images of) $U_{ij} \times_{W_i} V_{ik}$ and $U_{i'j'} \times_{W_{i'}} V_{i'k'}$. The identification morphisms are chosen as the unique isomorphisms obtained from the characterization by the universal property of a fiber product. This also ensures that the cocycle condition is satisfied. \square

Notation: For schemes X, Y, S , and rings R, A , we sometimes write $X \otimes_R A := X \times_{\text{Spec}(R)} \text{Spec}(A)$, $X \otimes_S A := X \times_S \text{Spec}(A)$ and $X \times_R Y := X \times_{\text{Spec}(R)} Y$ (provided that we are given the scheme morphisms required to define these fiber products).

Example 6.4. As the following example shows, the topological space of a fiber product of schemes is different, in general, from the fiber product (in the category of topological spaces) of the underlying spaces. Since

$$\mathbb{C} \otimes_{\mathbb{R}} \mathbb{C} = \mathbb{R}[X]/(X^2+1) \otimes_{\mathbb{R}} \mathbb{C} \cong \mathbb{C}[X]/(X^2+1) = \mathbb{C}[X]/(X-i)(X+i) \cong \mathbb{C} \times \mathbb{C},$$

where the final isomorphism uses the Chinese Remainder Theorem and the natural isomorphisms $\mathbb{C}[X]/(X-a) \cong \mathbb{C}$, $a \in \mathbb{C}$, we have that

$$\text{Spec}(\mathbb{C}) \times_{\text{Spec}(\mathbb{R})} \text{Spec}(\mathbb{C}) \cong \text{Spec}(\mathbb{C} \times \mathbb{C}) = \text{Spec}(\mathbb{C}) \sqcup \text{Spec}(\mathbb{C})$$

consists of *two* points (both are closed and have residue class field \mathbb{C} ; this scheme is the disjoint union of two copies of $\text{Spec}(\mathbb{C})$).

Remarks 6.5.

- (1) For any ring homomorphism $R \rightarrow R'$, we have $\mathbb{A}_R^n \otimes_R R' = \mathbb{A}_{R'}^n$. In particular, for any ring R , we have $\mathbb{A}_R^n = \mathbb{A}_{\mathbb{Z}}^n \otimes_{\mathbb{Z}} R$. In view of this, we define, for an arbitrary scheme S , $\mathbb{A}_S^n = \mathbb{A}_{\mathbb{Z}}^n \times_{\text{Spec}(\mathbb{Z})} S$. Via the second projection, this is an S -scheme, called the *affine space of relative dimension n over S* .

(6.3) Base change.

Let $S' \rightarrow S$ be a morphism of schemes. We obtain a functor

$$(\text{Sch}/S) \longrightarrow (\text{Sch}/S'), \quad X \rightarrow X \times_S S',$$

where $X \times_S S'$ is an S' -scheme via the second projection.

On morphisms, the functor is defined as follows. Given a morphism $X \rightarrow Y$ of S -schemes, we need to define a morphism $X \times_S S' \rightarrow Y \times_S S'$. To do so, by the universal property of $Y \times_S S'$, it is enough to specify morphisms

$X \times_S S' \rightarrow Y$ and $X \times_S S' \rightarrow S'$ (compatible with the morphisms to S). For the first one, we take the composition $X \times_S S' \rightarrow X \rightarrow Y$, for the second one the projection to the second factor.

(6.4) Fibers of morphisms.

In view of Example 6.2 (4), we define fibers of morphisms of schemes as follows:

Definition 6.6. *Let $f: X \rightarrow S$ be a morphism of schemes, and let $s \in S$ (i.e., s is a point of the underlying topological space of S). Denote by $i_s: \text{Spec}(\kappa(s)) \rightarrow S$ the canonical map (Section (4.4)). Then the scheme*

$$f^{-1}(s) := X \times_S \text{Spec}(\kappa(s))$$

is called the (schematic) fiber of f over s .

In the case of the schematic fiber, the fiber product behaves well regarding the underlying topological space.

Proposition 6.7. *Let $f: X \rightarrow S$ be a morphism of schemes, $s \in S$, and let $f^{-1}(s) = X \otimes_S \kappa(s)$ be the schematic fiber. Then the projection*

$$f^{-1}(s) \rightarrow X$$

on topological spaces is a homeomorphism onto the fiber of the underlying continuous map $f: X \rightarrow S$.

Proof. It is clear that we may assume that S is affine. Furthermore, covering X by affine open subschemes, it is easy to reduce to the case that X is affine. So assume $S = \text{Spec}(R)$, $X = \text{Spec}(A)$, and f corresponds to the ring homomorphism $\varphi: R \rightarrow A$. Let $\mathfrak{p} \subset R$ be the prime ideal corresponding to s , and denote by $\kappa(\mathfrak{p})$ the residue class field of \mathfrak{p} . We may describe $\kappa(\mathfrak{p})$ equivalently as $R_{\mathfrak{p}}/\mathfrak{p}R_{\mathfrak{p}}$ or as $\text{Frac}(R/\mathfrak{p})$.

Then the definition of the schematic fiber amounts to

$$f^{-1}(s) = \text{Spec}(A \otimes_R \kappa(\mathfrak{p})).$$

We may compute the tensor product as

$$A \otimes_R \kappa(\mathfrak{p}) = A \otimes_R S^{-1}R \otimes_{S^{-1}R} S^{-1}R/\mathfrak{p}S^{-1}R = S^{-1}A/\mathfrak{p}S^{-1}A,$$

where $S = R \setminus \mathfrak{p}$. (In the term on the right, by abuse of notation we write S instead of $\varphi(S)$ and \mathfrak{p} instead of $\varphi(\mathfrak{p})$.) This gives us a bijection between $\text{Spec}(A \otimes_R \kappa(\mathfrak{p}))$ and the set of prime ideals \mathfrak{q} in A which satisfy

$$\varphi(\mathfrak{p}) \subseteq \mathfrak{q}, \quad \varphi(S) \cap \mathfrak{q} = \emptyset,$$

or equivalently,

$$\varphi^{-1}(\mathfrak{q}) = \mathfrak{p}.$$

This is the desired statement on sets. To finish the proof, one checks that the resulting bijective map is a homeomorphism (similarly as in Proposition 2.8, Proposition 2.13). \square

Remark 6.8. Let S be a scheme. Let X be an S -scheme (i.e., we are given a scheme morphism $f: X \rightarrow S$). With the construction of the schematic fiber, the morphism f gives rise to a family $(X_s)_{s \in S}$, where each $X_s := X \otimes_S \kappa(s)$ is a scheme over a field (namely over the residue class field $\kappa(s)$), and hence an object that is closer to classical algebraic geometry. Properties of the morphism f may often be viewed as properties of this family.

7. PROPERTIES OF SCHEMES AND OF MORPHISMS OF SCHEMES

We introduce some further notions, giving names to important properties of schemes and scheme morphisms. One of the goals is to obtain a better understanding of the connection between the theory of schemes and the more classical point of view taken in the first chapter. Along the way, we will illustrate how fiber products of schemes are useful to “translate” notions from topology to scheme theory.

(7.1) Reduced, irreducible, integral schemes.

In class, I did things in a slightly different order. In particular the part on irreducible schemes was not yet discussed (as of January 28).

Recall the definition of a reduced ring:

Definition 7.1. Let R be a ring. An element $x \in R$ is called nilpotent, if there exists $n \geq 0$ such that $x^n = 0$. The ring R is called reduced, if it has no nilpotent elements $\neq 0$.

Definition/Proposition 7.2. A scheme X is called reduced, if the following equivalent conditions are satisfied:

- (i) For every open $U \subseteq X$, the ring $\Gamma(U, \mathcal{O}_X)$ is reduced.
- (ii) For every affine open $U \subseteq X$, the ring $\Gamma(U, \mathcal{O}_X)$ is reduced.
- (iii) There exists an affine open cover $X = \bigcup_i U_i$ such that for every i the ring $\Gamma(U_i, \mathcal{O}_X)$ is reduced.
- (iv) For every $x \in X$, the ring $\mathcal{O}_{X,x}$ is reduced.

Proof. See Problem 33. □

Every domain is reduced, but not conversely. More precisely, a reduced ring R is a domain if and only if it has a *unique* minimal prime ideal (necessarily the zero ideal), if and only if $\text{Spec}(R)$ is irreducible. This leads to the notion of *integral* scheme, see below. Before we come to it, we discuss irreducibility and generic points in the context of schemes; cf. Section (2.3).

Definition 7.3. A scheme X is called irreducible, if its underlying topological space is irreducible (i.e., is $\neq \emptyset$ and cannot be written as a union of two proper closed subsets).

From the corresponding result for affine schemes, we obtain the existence and uniqueness of generic points.

Proposition 7.4. *Let X be a scheme, and let $Z \subseteq X$ be an irreducible closed subset of (the underlying topological space of) X . Then Z has a unique generic point, i.e., there exists a unique $\eta \in Z$ such that $Z = \{\eta\}$.*

Definition/Proposition 7.5. *A scheme X is called integral, $X \neq \emptyset$ and if the following equivalent conditions are satisfied:*

- (i) *The scheme X is reduced and irreducible.*
- (ii) *For every non-empty open $U \subseteq X$, the ring $\Gamma(U, \mathcal{O}_X)$ is a domain.*
- (iii) *For every non-empty affine open $U \subseteq X$, the ring $\Gamma(U, \mathcal{O}_X)$ is a domain.*

Proof. By the above discussion, an affine scheme $\text{Spec}(R)$ is reduced and irreducible if and only if R is a domain. If X is a reduced (or irreducible, respectively) scheme, then so is every non-empty open subscheme. Together we obtain (i) \Rightarrow (ii). The implication (ii) \Rightarrow (iii) is trivial. Regarding (iii) \Rightarrow (i), we have already seen that (iii) implies that X is reduced.

It remains to show that (iii) implies that X is irreducible. Otherwise, there exist non-empty open subsets $U, U' \subseteq X$ with empty intersection. By shrinking U and U' , if necessary, we may assume that U and U' are affine open subschemes. Then $U \cup U'$ is a non-irreducible affine open subscheme, so $\Gamma(U \cup U', \mathcal{O}_X)$ is not a domain. \square

If X is an integral scheme, then all the local rings $\mathcal{O}_{X,x}$ are domains (note that the converse does not hold, though). Since X is irreducible, it has a (unique) generic point $\eta \in X$. The local ring $K(X) := \mathcal{O}_{X,\eta}$ is a domain with only one prime ideal, and hence a field, called the *field of rational functions of X* .

(7.2) Subschemes.

Recall that we have defined the notion of *open subscheme*: If X is a scheme and $U \subseteq X$ an open subset of (the topological space) X , restricting the structure sheaf of X to U equips U with the structure of a scheme, and schemes of this form are called *open subschemes*. The inclusion $U \rightarrow X$ naturally is a scheme morphism. A scheme morphism $j: U \rightarrow X$ is called an *open immersion*, if the continuous map j is a homeomorphism onto an open subset of X , and under this homeomorphism the structure sheaf of U is identified with the restriction $\mathcal{O}_{X|j(U)}$. Equivalently, j factors through an isomorphism with an open subscheme of X and the natural inclusion of that open subscheme into X . (The difference between *open subschemes* and *open immersions* is similar to the difference (in the context of sets) between *subsets* and *injective maps*.)

There is also a notion of closed subscheme which is, however, slightly more involved. The main reason is that unlike open subschemes, closed subschemes are not determined by the underlying closed subset of X .

For the definition, recall that a morphism of sheaves is called surjective, if the induced maps on stalks are surjective at all points of the underlying

topological space. If $f: \mathcal{F} \rightarrow \mathcal{G}$ is a morphism of sheaves, we have the notion of the image sheaf $\text{im}(f)$ (the sheafification of the presheaf $U \mapsto \text{im}(\mathcal{F}(U) \rightarrow \mathcal{G}(U))$), and f is surjective, if and only if $\text{im}(f) = \mathcal{G}$. For a surjective homomorphism $f: \mathcal{F} \rightarrow \mathcal{G}$ of rings, the kernel sheaf $\text{Ker}(f)$ (defined by $U \mapsto \text{Ker}(\mathcal{F}(U) \rightarrow \mathcal{G}(U))$) is an ideal sheaf in \mathcal{F} (i.e., for every open U , the subset $\text{Ker}(f)(U) \subseteq \mathcal{F}(U)$ is an ideal), and there is an isomorphism $\mathcal{G} \cong \mathcal{F} / \text{Ker}(f)$, where the quotient sheaf is defined as the sheafification of the presheaf $U \mapsto \mathcal{F}(U) / \text{Ker}(f)(U)$.

Definition 7.6. *Let X be a scheme. A closed subscheme of X is given by a closed subset Z together with an ideal sheaf $\mathcal{I} \subseteq \mathcal{O}_X$ such that*

$$Z = \{x \in X; (\mathcal{O}_X / \mathcal{I})_x \neq 0\}$$

and such that $(Z, \mathcal{O}_X / \mathcal{I})$ is a scheme.

Note that Z is defined by \mathcal{I} . One can show that for any ideal sheaf $\mathcal{I} \subseteq \mathcal{O}_X$ the set $\text{supp}(\mathcal{O}_X / \mathcal{I}) := \{x \in X; (\mathcal{O}_X / \mathcal{I})_x \neq 0\}$ (the *support* of $\mathcal{O}_X / \mathcal{I}$) is closed in X . Thus a closed subscheme “is” really the same as an ideal sheaf \mathcal{I} such that $(\text{supp}(\mathcal{O}_X / \mathcal{I}), \mathcal{O}_X / \mathcal{I})$ is a scheme. (This latter property is not automatic; there are ideal sheaves for which it is not satisfied.)

If $Z \subseteq X$ is a closed subscheme with corresponding ideal sheaf \mathcal{I} , we have a natural scheme morphism $Z \rightarrow X$ which on topological spaces is the inclusion map i and on sheaves is given by $\mathcal{O}_X \rightarrow \mathcal{O}_X / \mathcal{I} = i_* \mathcal{O}_Z$. Thus, if Z is a closed subscheme, we can recover \mathcal{I} from the structure sheaf of Z and the natural inclusion $i: Z \rightarrow X$ as $\mathcal{I} = \text{Ker}(\mathcal{O}_X \rightarrow i_* \mathcal{O}_Z)$.

Example 7.7.

- (1) Let R be a ring, $\mathfrak{a} \subseteq R$ an ideal. Then $V(\mathfrak{a}) \subseteq \text{Spec}(R)$ is a closed subscheme. We will prove below that all closed subschemes of an affine scheme have this form.
- (2) Let R be a ring, and let $I \subseteq R[X_0, \dots, X_n]$ be a homogeneous ideal. Then $V_+(I) \subseteq \mathbb{P}_R^n$ is a closed subscheme. (We have seen that $V_+(I)$ topologically is a closed subset. The sheaf homomorphism $\mathcal{O}_{\mathbb{P}_R^n} \rightarrow \mathcal{O}_{V_+(I)}$ is surjective; this can be checked on the standard open charts, thus reducing to the affine case.) One can show that every closed subscheme of \mathbb{P}_R^n has this form.

Jan. 28, 2026

Definition 7.8. *A morphism $i: Z \rightarrow X$ is called a closed immersion, if the continuous map i is a homeomorphism onto a closed subset of X and the sheaf homomorphism $\mathcal{O}_X \rightarrow i_* \mathcal{O}_Z$ is surjective. Equivalently, i factors as an isomorphism from Z onto a closed subscheme of X and the natural morphism from that closed subscheme to X .*

Theorem 7.9. *Let R be a ring, $X = \text{Spec}(R)$, and let $Z \subseteq X$ be a closed subscheme. Then there exists a unique ideal $\mathfrak{a} \subseteq R$ such that $Z = V(\mathfrak{a})$ (i.e., Z and $V(\mathfrak{a})$ are defined by the same ideal sheaf in \mathcal{O}_X).*

The ideal \mathfrak{a} is given as

$$\mathfrak{a} = I_Z := \text{Ker}(R = \Gamma(X, \mathcal{O}_X) \longrightarrow \Gamma(Z, \mathcal{O}_Z)).$$

In particular, every closed subscheme of an affine scheme is itself affine.

Proof. Because of a lack of time we skipped this proof in class. It is easy to check that $I_{V(\mathfrak{a})} = \mathfrak{a}$. Therefore it is enough to show that for every closed subscheme Z , we have $Z = V(I_Z)$.

The ring homomorphism $A \rightarrow \Gamma(Z, \mathcal{O}_Z)$ factors through A/I_Z , and we want to show that the natural morphism $Z \rightarrow \text{Spec}(A/I_Z)$ is an isomorphism. Replacing A by A/\mathcal{I} , we may assume that $\varphi: A \rightarrow \Gamma(Z, \mathcal{O}_Z)$ is injective (and then want to show that $Z \cong \text{Spec}(A)$).

(I) Let us show that the map $Z \rightarrow \text{Spec}(A)$ is a homeomorphism. We know already that it is injective and closed; it remains to show its surjectivity. We will show that Z is not contained in a proper closed subset of $\text{Spec}(A)$. Let $s \in A$ with $Z \subseteq V(s)$; we will show that then necessarily s is nilpotent, i.e., $V(s) = \text{Spec}(A)$.

In view of the injectivity of φ , it is enough to check that $\varphi(s)$ is nilpotent. Let $Z = \bigcup_i V_i$ be a finite affine open cover (Z is quasi-compact since it is closed in the quasi-compact affine scheme $\text{Spec}(A)$). Then $\Gamma(Z, \mathcal{O}_Z)$ injects into the product $\prod_i \Gamma(V_i, \mathcal{O}_Z)$, so it is enough to show that all restrictions $s|_{V_i}$ are nilpotent. But $V_i \subseteq Z \subseteq V(s)$ implies $V_i = V_{V_i}(s|_{V_i})$, so $s|_{V_i} \in \Gamma(V_i, \mathcal{O}_Z)$ is indeed nilpotent.

(II) To conclude the proof, we show that $Z = \text{Spec}(R) = X$ as schemes, i.e., the sheaf homomorphism $\mathcal{O}_X \rightarrow \mathcal{O}_Z$ is an isomorphism (we identify $Z = X$ as topological spaces in view of Step (I)). This sheaf homomorphism is surjective by assumption, and it remains to show the injectivity. We check this on the stalks.

So let $\mathfrak{p} \subset R$ be a prime ideal (i.e., a point of X), and consider the ring homomorphism $R_{\mathfrak{p}} = \mathcal{O}_{X,\mathfrak{p}} \rightarrow \mathcal{O}_{Z,\mathfrak{p}}$. It is then enough to show that for all $g \in A$ with $\frac{g}{1} \mapsto 0 \in \mathcal{O}_{Z,\mathfrak{p}}$ we have $g = 0$.

So fix g with this property. Let $V \subseteq Z$ be an affine open neighborhood of \mathfrak{p} such that $\varphi(g)|_V = 0$. Choose an affine open cover $Z = \bigcup_{i=1}^n V_i$ with $V_1 = V$.

Let $s \in A$ with $D(s) \subseteq V$.

Claim. There exists $N \geq 0$ such that $\varphi(s^N g) = 0 \in \Gamma(Z, \mathcal{O}_Z)$.

We can check this on each V_i separately. By assumption $\varphi(g|_V) = 0$; it remains to handle the case $i > 1$. Since $D_{V_i}(\varphi(s)|_{V_i}) = D(s) \cap V_i \subseteq V \cap V_i$, we have $g|_{D_{V_i}(\varphi(s)|_{V_i})} = 0$, i.e., the image of $\varphi(g)$ in the localization $\Gamma(V_i, \mathcal{O}_Z)_{\varphi(s)|_{V_i}}$ is 0. Thus $(\varphi(s)|_{V_i})^{N_i} \varphi(g)|_{V_i} = 0$ for some N_i .

The claim is proved. Since φ is injective, it follows that $s^N g = 0$, so the image of g in A_s is 0. A fortiori, g maps to 0 in $A_{\mathfrak{p}}$. This is what remained to show. \square

Proposition 7.10. *Let X be a scheme, and let $Z \subseteq X$ be a closed subset of the topological space X . Then there exists a unique reduced closed subscheme of X with underlying topological space Z .*

Proof. If $X = \operatorname{Spec}(R)$ is affine and $Z = V(\mathfrak{a})$ as a set, for an ideal $\mathfrak{a} \subseteq R$, then the scheme $V(\sqrt{\mathfrak{a}})$ is the unique reduced closed subscheme of X with underlying set Z (recall, cf. Proposition 2.9, that $V(\mathfrak{a})$ and $V(\mathfrak{b})$ have the same underlying closed subset, if and only if the radicals of \mathfrak{a} and \mathfrak{b} are equal; the quotient of a ring by an ideal is reduced if and only if the ideal is a radical ideal).

In the general case, in view of the uniqueness statement, we may obtain the desired closed subscheme by using gluing of schemes. \square

Combining the notions of open and closed subscheme, we obtain the following notion. Recall that a subset of a topological space is called *locally closed*, if it can be written as the intersection of an open and of a closed subset.

Corollary 7.11. *Let X be a scheme. Then there is a unique reduced closed subscheme $X_{\text{red}} \subseteq X$ with the same topological space as X , called the underlying reduced scheme of X . Every morphism $T \rightarrow X$ from a reduced scheme T to X factors through the natural inclusion $X_{\text{red}} \rightarrow X$. In particular the construction of the underlying reduced scheme is functorial, i.e., every morphism $X \rightarrow Y$ induces a morphism $X_{\text{red}} \rightarrow Y_{\text{red}}$, and this is compatible with composition and identity morphisms.*

Proof. Everything is clear by the above except for the claim about morphisms $T \rightarrow X$ from reduced schemes to X which can be reduced to the case where $X = \operatorname{Spec}(R)$ is affine. In that case, $X_{\text{red}} = \operatorname{Spec}(R/\operatorname{nil}(R))$ is the affine scheme attached to the quotient of R by its nil radical, and the claim is checked easily. \square

Definition 7.12. *Let X be a scheme. If Y is a closed subscheme of an open subscheme of X , then Y is called a subscheme of X . Correspondingly, we call a morphism $i: Y \rightarrow X$ of schemes an immersion, if the continuous map is a homeomorphism onto a locally closed subset, and for every $y \in Y$ the homomorphism $i_y^\sharp: \mathcal{O}_{X,i(y)} \rightarrow \mathcal{O}_{Y,y}$ is surjective. Equivalently, i is an immersion, if it factors as a closed immersion $Y \rightarrow U$ and an open immersion $U \rightarrow X$.*

If $Y \subseteq X$ is a subscheme, then the topological space of Y is a locally closed subset of X . We have a natural scheme morphism $Y \rightarrow X$ (which may be obtained as the composition $Y \rightarrow U \rightarrow X$ with $U \subseteq X$ open as in the definition), and the sheaf homomorphism $\mathcal{O}_X \rightarrow i_*\mathcal{O}_Y$ (where $i: Y \rightarrow X$ is the inclusion) induces a surjection $\mathcal{O}_{X,i(y)} \rightarrow (i_*\mathcal{O}_Y)_{i(y)}$ for every $y \in Y$, i.e., $Y \rightarrow X$ is an immersion.

Proposition 7.13. *The properties of a morphism of being a closed immersion (or an open immersion) are stable under base change, i.e., given scheme morphisms $f: X \rightarrow S$ and $S' \rightarrow S$, and denoting by $f': X \times_S S' \rightarrow S'$ the base change of f , we have*

- (1) *If f is a closed immersion, then f' is a closed immersion.*
- (2) *If f is an open immersion, then f' is an open immersion.*

Clearly, both these properties are also stable under composition of morphisms, i.e., the composition of two closed (or: two open) immersions is a closed (open) immersion.

(7.3) Separated morphisms.

Let X be a topological space. The space X is called *Hausdorff*, if for any pair of points $x, y \in X$, $x \neq y$, there exist open neighborhoods U of x and V of y such that $U \cap V = \emptyset$. We may reformulate this as follows: The diagonal map $\Delta: X \rightarrow X \times X$, $x \mapsto (x, x)$, has *closed* image $\Delta(X) \subseteq X \times X$. The latter formulation can easily be translated to the world of schemes, and actually leads to a useful notion (which in fact in some sense reflects the Hausdorff property as we know it from the category of topological spaces (see, e.g., Proposition 7.20); even though, as we know, the underlying topological space of a scheme is rarely Hausdorff, and therefore we use a different term for this property in the context of schemes).

Definition 7.14. *Let S be a scheme. An S -scheme Y is called separated, if the diagonal morphism*

$$\Delta_{Y/S}: Y \rightarrow Y \times_S Y$$

defined by the identity morphism $Y \rightarrow Y$ (for each of the two factors) is a closed immersion.

We also say that Y is separated over S , or that the morphism $Y \rightarrow S$ is separated. A scheme X is called separated, if X is separated over $\text{Spec}(\mathbb{Z})$.

Remark 7.15. In the “ancient” literature of modern algebraic geometry (e.g., the original edition of Dieudonné’s and Grothendieck’s *Éléments de géométrie algébrique*) the terminology was slightly different. There, what we call a scheme was called a prescheme. What we call a separated scheme was called a scheme.

Proposition 7.16. *Every morphism between affine schemes is separated. In particular, every affine scheme is separated.*

Proof. Let $\varphi: A \rightarrow B$ be a ring homomorphism. Then the natural homomorphism $B \otimes_A B \rightarrow B$, $b \otimes b' \mapsto bb'$, is surjective. This implies the proposition. \square

Example 7.17. Let k be a field. The affine line with doubled origin X (cf. Example 5.3 (3)) is not separated over k . It is not difficult to show

directly that in this case the diagonal has non-closed image. But it also follows immediately from the following proposition (use the obvious two different morphisms from \mathbb{A}_k^1 to X).

Feb. 3, 2026

Sometimes it is useful to know that the diagonal morphism always is an immersion.

Proposition 7.18. *Let $f: X \rightarrow S$ be a morphism of schemes. Then the diagonal $\Delta: X \rightarrow X \times_X S$ is an immersion.*

Proof. The question is local on the target, so we may assume that S is affine. Let $X = \bigcup_i U_i$ be an affine open cover. Then Δ factors as $X \rightarrow \bigcup_i (U_i \times_S U_i) \rightarrow X \times_S X$, and the second morphism is an open immersion. Thus it is enough to check that the first morphism is a closed immersion. This can be checked locally on the target, i.e., it remains to observe that (by Proposition 7.16) for every i , $U_i \rightarrow U_i \times_S U_i$ is a closed immersion. \square

We record (without proof) the following properties that are not difficult to show (use properties of fiber products and of closed immersions that we have already discussed).

Lemma 7.19.

- (1) *The composition of separated morphisms is separated.*
- (2) *The property of being separated is stable under base change.*
- (3) *The property of being separated can be checked locally on the target.*
- (4) *Every immersion is separated.*

Proposition 7.20. *Let S be a scheme. Let X, Y be S -schemes, such that X is reduced and that Y is separated over S . Let $U \subseteq X$ be a dense open subscheme. If $f, g: X \rightarrow Y$ are morphisms with $f|_U = g|_U$, then $f = g$.*

Proof. Let $E = \text{Eq}(f, g)$ be the equalizer of f and g , i.e., the scheme defined by the following fiber product diagram

$$\begin{array}{ccc} E & \longrightarrow & Y \\ \downarrow & & \downarrow \Delta \\ X & \xrightarrow{(f,g)} & Y \times_S Y. \end{array}$$

The morphism in the lower row is the morphism $X \rightarrow Y \times_S Y$ obtained by using the universal property of the fiber product $Y \times_S Y$ for the two morphisms f and g . (Since Δ is always an immersion, the same is true for the morphism $E \rightarrow X$; here we use that the property of being an immersion is stable under base change.)

The universal property of this particular fiber product translates into the following universal property for the scheme E . A morphism $h: T \rightarrow X$ factors through the projection $E \rightarrow X$ if and only if the compositions $f \circ h$ and $g \circ h$ are equal.

This shows that the inclusion $U \rightarrow X$ factors through E . We want to show that the identity morphism $X \rightarrow X$ also factors through E (i.e., that $E = X$). Since Y/S is separated by assumption, in the situation at hand Δ and hence the morphism $E \rightarrow X$ are closed immersions. Since $U \subseteq E$ and U is dense in X , the underlying topological space of E is equal to X . Since X is reduced, this implies that $E = X$, as desired. \square

Proposition 7.21. *Let S be an affine scheme, let X be a separated S -scheme, and let $U, V \subseteq X$ be affine open subschemes. Then $U \cap V$ is also an affine open subscheme of X .*

Proof. We have a cartesian diagram

$$\begin{array}{ccc} U \cap V & \longrightarrow & U \times_S V \\ \downarrow & & \downarrow \\ X & \longrightarrow & X \times_S X \end{array}$$

Since the lower horizontal arrow is a closed immersion by assumption, so is the upper one. Now $U \times_S V$ is affine, and every closed subscheme of an affine scheme is itself affine by Theorem 7.9. \square

More precisely, there is the following characterization of separated morphisms:

Proposition 7.22. *Let $S = \operatorname{Spec}(R)$ be an affine scheme. Let $f: X \rightarrow S$ be a morphism of schemes. The following are equivalent.*

- (i) *The morphism f is separated.*
- (ii) *For any two affine open subschemes $U, V \subseteq X$, the intersection $U \cap V$ is affine and the natural ring homomorphism*

$$\Gamma(U, \mathcal{O}_X) \otimes_R \Gamma(V, \mathcal{O}_X) \rightarrow \Gamma(U \cap V, \mathcal{O}_X)$$

is surjective.

- (iii) *There exists an affine open cover $X = \bigcup_i U_i$ such that for any i, j , the intersection $U_i \cap U_j$ is affine and the natural ring homomorphism*

$$\Gamma(U_i, \mathcal{O}_X) \otimes_R \Gamma(U_j, \mathcal{O}_X) \rightarrow \Gamma(U_i \cap U_j, \mathcal{O}_X)$$

is surjective.

Proof. The implications (i) \Rightarrow (ii) \Rightarrow (iii) follow from what we have already shown. It remains to show (iii) \Rightarrow (i), so assume that $X = \bigcup_i U_i$ is an affine open cover as in (iii). To show that $\Delta: X \rightarrow X \times_S X$ is a closed immersion, we may work locally on the target. We have $X \times_S X = \bigcup_{i,j} U_i \times_S U_j$. Since $\Delta^{-1}(U_i \times_S U_j) = U_i \cap U_j$, and the morphisms

$$U_i \cap U_j \longrightarrow U_i \times_S U_j$$

are closed immersions by the assumptions in (iii), the result follows. \square

Note that (of course) the argument of the proof does not show that being separated can be checked locally on the source (which is not true ...) – working locally on X we would only look at the morphisms $U_i \rightarrow U_i \times_S U_i$, and this is not enough.

Corollary 7.23. *Let S be a scheme, $n \geq 1$. Then the morphism $\mathbb{P}_S^n \rightarrow S$ is separated.*

Proof. Since being separated is stable under base change, it is enough to consider the case $S = \operatorname{Spec}(\mathbb{Z})$. In this case, the result follows from the previous proposition, applied to the standard cover $\mathbb{P}_{\mathbb{Z}}^n = \bigcup_i D_+(X_i)$. \square

8. SCHEMES LOCALLY OF FINITE TYPE OVER A FIELD

(8.1) Morphisms locally of finite type.

Definition 8.1. A morphism $f: X \rightarrow S$ is called *locally of finite type*, if the following equivalent conditions are satisfied:

- (i) For every affine open $V \subseteq S$ and every affine open $U \subseteq f^{-1}(V)$, the $\Gamma(V, \mathcal{O}_S)$ -algebra $\Gamma(U, \mathcal{O}_X)$ is of finite type.
- (ii) There exists an affine open cover $S = \bigcup_j V_j$ and for every j an affine open cover $f^{-1}(V_j) = \bigcup_i U_{ij}$, such that for all j and i the $\Gamma(V_j, \mathcal{O}_S)$ -algebra $\Gamma(U_{ij}, \mathcal{O}_X)$ is of finite type.

Proof of the equivalence. See [GW1] Proposition/Definition 10.5. □

Often this property is combined with the following one:

Definition 8.2. A morphism $f: X \rightarrow S$ of schemes is called *quasi-compact*, if the following equivalent conditions are satisfied:

- (i) For every quasi-compact open $V \subseteq S$, the inverse image $f^{-1}(V)$ is quasi-compact.
- (ii) For every affine open $V \subseteq S$, the inverse image $f^{-1}(V)$ is quasi-compact.
- (iii) There exists an affine open cover $S = \bigcup_j V_j$ such that for every j the preimage $f^{-1}(V_j)$ is quasi-compact.

Proof. For the interesting implication (iii) \Rightarrow (i), use that an open subset of a scheme is quasi-compact if and only if it can be covered by finitely many affine open subschemes. Indeed, take a cover $S = \bigcup_j V_j$ as in (iii) and let $V \subseteq S$ be any quasi-compact open. Cover it by finitely many principal opens of the V_j . It is then enough to show that these principal opens have quasi-compact inverse image. But by assumption $f^{-1}(V_j)$ can be covered by finitely many affine opens in X ; thus the inverse image of a principal open therein can be covered by one principal open in each of these affine schemes. □

Note that it is not enough to check the condition on an arbitrary open cover (i.e., by not-necessarily-affine open subschemes).

Definition 8.3. A morphism of schemes is called *of finite type*, if it is locally of finite type and quasi-compact.

These properties satisfy the “usual” permanence properties.

Lemma 8.4. The properties of being locally of finite type, quasi-compact, of finite type

- (1) are stable under composition and
- (2) are stable under base change.

Every immersion is locally of finite type. Every closed immersion is of finite type.

Proof. Omitted (See [GW1] Sections (10.1), (10.2).) \square

Examples 8.5.

- (1) Let S be a scheme. For every $n \geq 1$, \mathbb{A}_S^n , \mathbb{P}_S^n and all closed subschemes of these schemes are of finite type over S .
- (2) Every morphism between affine schemes is quasi-compact.
- (3) Let R be a ring and let $A = R[X_i; i \in I]$ be a polynomial ring in *infinitely many* variables. Then $\text{Spec}(A) \rightarrow \text{Spec}(R)$ is not locally of finite type.

(8.2) Schemes locally of finite type over a field.

Let k be a field. Let us explain why (or rather in which sense) reduced schemes that can be embedded as subschemes of \mathbb{P}_k^n are “fairly close” to the vanishing sets of homogeneous polynomials that we considered in the first chapter. The crucial properties hold more generally for (reduced) schemes locally of finite type over k , so we will start by studying schemes of this form.

Theorem 8.6. *Let k be a field and let X be a scheme locally of finite type over $\text{Spec}(k)$. Let $x \in X$. The following are equivalent.*

- (i) *The point x is a closed point.*
- (ii) *The field extension $\kappa(x)/k$ is finite.*
- (iii) *The field extension $\kappa(x)/k$ is algebraic.*

Proof. This is a version of Hilbert’s Nullstellensatz: Namely, this theorem says that for a k -algebra A of finite type and maximal ideal $\mathfrak{m} \subset A$, the field A/\mathfrak{m} is a *finite* extension of k . This shows (i) \Rightarrow (ii). Furthermore, the implication (ii) \Rightarrow (iii) is obvious.

Now assume (iii), and let $U \subseteq X$ be an affine open neighborhood of x , say $U = \text{Spec}(A)$, and x corresponds to the prime ideal $\mathfrak{p} \subset A$. Then $A/\mathfrak{p} \subseteq \kappa(x)$ and the assumption implies that the ring homomorphism

$$k \rightarrow A \rightarrow A/\mathfrak{p}$$

is an injective *integral* homomorphism between domains. Since the source is a field, so is the target. Hence x is closed in U . Since this holds for all affine open neighborhoods of x in X , it follows that x is closed in X . \square

Corollary 8.7. *Let $f: X \rightarrow Y$ be a morphism between schemes that are locally of finite type over a field k . (As usual this means that f is a morphism of k -schemes.) Then f maps closed points of X to closed points of Y .*

Proof. Let x be a closed point of X . We obtain an inclusion $\kappa(f(x)) \subseteq \kappa(x)$ between the residue class fields (which is a k -homomorphism). Since $\kappa(x)$ is algebraic over k by Theorem 8.6, so is $\kappa(f(x))$, and invoking the theorem again, we obtain the desired conclusion. \square

Corollary 8.8. *Let k be an algebraically closed field, and let X be a k -scheme locally of finite type. Then the set $X(k)$ can naturally be identified with the set of closed points of X .*

Proof. By the theorem, and since algebraically closed fields have no non-trivial algebraic extensions, the set of closed points in X equals the set of points with residue class field k . By Proposition 4.22, this set can be identified with the set $X(k)$ of k -valued points of X . \square

Definition/Proposition 8.9. *Let X be a topological space. A subset $Z \subseteq X$ is called very dense, if the following equivalent conditions are satisfied.*

- (i) *The map $U \rightarrow U \cap Z$ induces a bijection between the set of open subsets of X and the set of open subsets of Z .*
- (ii) *The map $F \rightarrow F \cap Z$ induces a bijection between the set of closed subsets of X and the set of closed subsets of Z .*
- (iii) *The map $L \rightarrow L \cap Z$ induces a bijection between the set of locally closed subsets of X and the set of locally closed subsets of Z .*
- (iv) *For every closed subset $F \subseteq X$, we have $F = \overline{F \cap Z}$.*
- (v) *Every non-empty locally closed subset of X contains a point of Z .*

Proof. The following implications are easy:

$$(iv) \iff (ii) \iff (i) \iff (iii) \implies (v)$$

Let us show that (iv) implies (v). Let $\emptyset \neq L \subseteq X$ be locally closed, say $L = F \setminus F'$ for $F' \subsetneq F \subseteq X$ closed. Then $F' \cap Z \neq F \cap Z$, and this implies $L \cap Z \neq \emptyset$. Next we show that (v) implies (ii). Take $F, F' \subseteq X$ closed with $F \cap Z = F' \cap Z$, equivalently $((F \cup F') \setminus (F' \cap F)) \cap Z = \emptyset$. But $(F \cup F') \setminus (F' \cap F)$ is locally closed, so (v) implies that this set is empty, whence $F = F'$. At this point we have seen that (i), (ii), (iv) and (v) are all equivalent.

It remains to show that these properties also imply (iii). For this, first note that for any locally closed subset $L \subseteq X$,

$$\overline{L \cap Z} = \overline{L}.$$

(Clearly, we have \subseteq . Furthermore, the set

$$(\overline{L} \setminus \overline{L \cap Z}) \cap L$$

is open in \overline{L} , hence locally closed in X , but has empty intersection with Z , and thus is empty in view of (v). But L is dense in \overline{L} , so it intersects every non-empty open subset, so $\overline{L} \setminus \overline{L \cap Z} = \emptyset$.) This shows, that for locally closed subsets L, L' in X with $L \cap Z = L' \cap Z$ we have $\overline{L} = \overline{L'}$; call this closed set F .

It follows easily from the characterization (ii) that $Z \cap F$ is very dense in F . Since L and L' are open in F , and have same intersection with $Z \cap F$, this implies $L = L'$ in view of the characterization (i). \square

Proposition 8.10. *Let k be a field and let X be a k -scheme locally of finite type. Then the subset of closed points is very dense in X .*

Proof. We check that every non-empty locally closed subset Z of X contains a closed point. Shrinking Z , if necessary, we may assume that it is closed in an affine open subscheme $U = \operatorname{Spec}(A)$ of X . We may view Z as a closed subscheme of the form $\operatorname{Spec}(A/\mathfrak{a})$ for some ideal \mathfrak{a} . But then A/\mathfrak{a} is non-zero, because the subset is non-empty, hence contains a maximal ideal, and this corresponds to a closed point of $\operatorname{Spec}(A/\mathfrak{a})$, hence also of U .

Since U and X are locally of finite type over k , Theorem 8.6 implies that this closed point of U is also closed in X . \square

Example 8.11. Let R be a discrete valuation ring, and let π be a generator of the maximal ideal of R . Then $\operatorname{Spec}(R) = \{(0), (\pi)\}$ consists of two points, the closed point (π) and the generic point (0) . Then $U := D(\pi) = \operatorname{Spec}(\operatorname{Frac}(R))$, and (0) is a closed point of U , but not of $\operatorname{Spec}(R)$.

Remark 8.12. In combination with Proposition 7.4, Proposition 8.10 means that for a scheme locally of finite type over an algebraically closed field k , we can recover the space X from the space $X(k)$ by defining X to be the set of irreducible closed subsets of $X(k)$, with the topology given by calling a set closed if it consists of all irreducible closed subsets of some closed subset of $X(k)$; this is called the *sobrification* of $X(k)$, see [GW1] Remark 3.38. We did not define morphisms of the objects (“classical algebraic varieties”) in Chapter 1, but if one does, one can extend this remark to an equivalence of categories between reduced (irreducible) schemes of finite type over k and classical algebraic varieties over k , cf. [GW1] Theorem 3.37.

Corollary 8.13. *Let k be an algebraically closed field and let $f, g: X \rightarrow Y$ be morphisms between k -schemes locally of finite type which induce the same map $X(k) \rightarrow Y(k)$. Assume that X is reduced. Then $f = g$.*

Proof. We need to show that the equalizer $\operatorname{Eq}(f, g)$ (cf. the proof of Proposition 7.20) equals X . But $\operatorname{Eq}(f, g)$ is a subscheme of X and by assumption $\operatorname{Eq}(f, g)(k) = X(k)$. By the proposition this implies that this subscheme has the same underlying topological space as X . In particular, it is a closed subscheme. Because X is reduced, it has to be equal to X . \square

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