



Syracuse University

# MAT 738: Algebraic Geometry

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## 0 Introduction

### 0.1 Course Description

**MAT 738 Introduction to Algebraic Geometry:** The study of the zeros of polynomials. Classical algebraic varieties in affine and projective space, followed by introduction to modern theory of sheaves, schemes, and cohomology.

### 0.2 Disclaimer

These notes were taken in Spring 2019 in a course taught by Professor Steven Diaz. In some places, notation/material has been changed or added. Any errors in this text should be attributed to the typist – Caleb McWhorter – and not the instructor or any referenced text.

### 0.3 Conventions

Although some results in these notes can be generalized to arbitrary fields, we assume throughout that all fields mentioned are algebraically closed, unless otherwise noted. When arbitrary rings are mentioned, they are assumed to be commutative and possess an identity. All ring homomorphisms  $\phi : R \rightarrow S$  are assumed to have the property that  $\phi(1_R) = 1_S$ . For a ring  $R$ , the whole ring is considered to be an ideal, but not a prime ideal.

# 1 Affine Varieties

## 1.1 Introduction

One could define Algebraic Geometry as the study of solutions to systems of polynomial equations. The early history of Algebraic Geometry was focused on what we will eventually know as affine varieties, especially the simplest cases plane algebraic curves, e.g. lines, circles, parabolas, ellipses, hyperbolas, and cubic curves. The development of Algebraic Geometry was slow, due to cumbersome language, notation, varying approaches, and especially varying or ineffective definitions. However motivated by work in various fields including Complex Analysis, (Algebraic) Topology, Number Theory, and especially Commutative Algebra, Algebraic Geometry developed rapidly. Modern Algebraic Geometry is due largely to the development of the theory of sheaves and schemes by Grothendieck and Serre, but is also due to the contribution of many others such as Zariski, Čech, Leray, Cartan, et al..

## 1.2 Affine Varieties

Let  $k$  be a fixed algebraically closed field.<sup>1</sup> Often, we will focus on the case where  $k = \mathbb{C}$ .

**Definition** (Affine  $n$ -space). Denote by  $k^n$  the set of ordered  $n$ -tuples of elements of  $k$ . Then define  $\mathbb{A}_k^n := k^n$ , called affine  $n$ -space over  $k$ . Note that this is also denoted  $\mathbb{A}^n(k)$  or simply  $\mathbb{A}^n$  when  $k$  is understood.

For ease of notation, we often denote the polynomial ring  $k[x_1, \dots, x_n]$  simply by ' $A$ '. We can think of elements of  $A := k[x_1, \dots, x_n]$  as being functions  $f : \mathbb{A}^n \rightarrow k$  via  $(k_1, \dots, k_n) \mapsto f(k_1, \dots, k_n)$ , i.e. via evaluation; that is, given  $f \in A$  and  $P = (k_1, \dots, k_n)$ , we have  $f(P) = f(k_1, \dots, k_n) \in k$ . This allows us to consider the vanishing set of the polynomial  $f$ .

**Definition** (Zero Set). For  $f \in A := k[x_1, \dots, x_n]$ , define  $Z(f) := \{P \in \mathbb{A}^n \mid f(P) = 0\}$ , called the zero set of  $f$ . For  $T \subseteq A$ , we define the zeros of  $T$ , denoted  $Z(T)$ , by

$$Z(T) := \bigcap_{f \in T} Z(f) = \{P \in \mathbb{A}^n \mid f(P) = 0 \text{ for all } f \in T\}.$$

If  $T = \{f_1, \dots, f_r\}$ , we will often write  $Z(T) = Z(f_1, \dots, f_r)$ .

Note the underlying field  $k$  does matter here. For example,  $Z(x^2 + 1) = \emptyset$  if  $k = \mathbb{R}$  but if  $k = \mathbb{C}$ , then  $Z(x^2 + 1) = \{\pm i\}$ . As another example in  $\mathbb{R}^2$ ,  $Z(y - x^2, x - y^2)$  consists of two points, namely the points  $(0, 0), (1, 1)$  of intersection, see Figure 1. However if  $k = \mathbb{C}^2$ , then  $Z(y - x^2, x - y^2)$  consists of four points:  $(0, 0), (1, 1), (-\zeta_3, \zeta_3^2), (\zeta_3^2, -\zeta_3)$ , where  $\zeta_3$  is a primitive cube root of unity.

<sup>1</sup>Note that much of elementary Algebraic Geometry, the requirement that  $k$  be algebraically closed is unnecessary, and  $k$  being an arbitrary field, or even simply an integral domain would suffice.

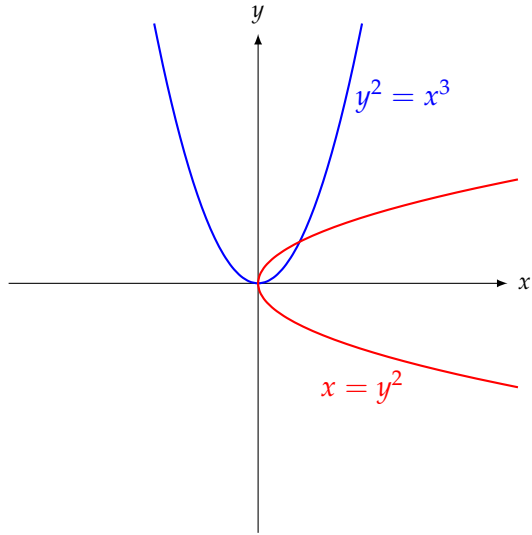


Figure 1: If  $k = \mathbb{R}^2$ , then the set  $Z(y - x^2, x - y^2)$  is the intersection of  $y = x^2$  with  $x = y^2$ .

We now have enough to define the basic building block of Algebraic Geometry.

**Definition** (Algebraic Set). A subset  $Y \subseteq \mathbb{A}^n$  is called an algebraic set if and only if there exists a subset  $T \subseteq A$  such that  $Y = Z(T)$ .

That is, a set of points  $Y$  is an algebraic set if  $Y$  is a set of common zeros for a collection of polynomials  $T$ . This is the start of the bridge between Algebraic Geometry, describing geometric objects using algebraic terms, as some of the following examples shall be to show (though one will have to wait for coordinate rings and much later material to see the deeper connections).

**Example 1.1.**

- (i) The emptyset,  $\emptyset$ , is algebraic since  $\emptyset = Z(1)$ , where  $f = 1$  is the constant polynomial  $f = 1$ . Furthermore,  $\mathbb{A}^n$  is an algebraic set since  $\mathbb{A}^n = Z(0)$ , where  $f = 0$  is the zero polynomial.
- (ii) Any single point  $P = (k_1, \dots, k_n) \in \mathbb{A}^n$  is an algebraic set since  $\{P\} = Z(x_1 - k_1, \dots, x_n - k_n)$ . In fact, any *finite* collection of points is algebraic, c.f. Proposition 1.1. [One should check that you can write down an explicit polynomial to confirm this.]
- (iii) The set  $\{(x, y) : y - f(x) = 0\}$ , where  $f(x)$  is a polynomial, is trivially algebraic. But this is precisely the graph of the function  $y = f(x)$ . For example, the cubic  $y = x^3$  is algebraic (meaning its graph). This easily generalizes to  $y = f(x_1, \dots, x_n)$ , where  $f(x_1, \dots, x_n)$  is a polynomial. Furthermore considering the graph of  $Ax^2 + By^2 +$

$Cz^2 + Dxy + Exz + Fyz + Gx + Hy + Iz + J = 0$ , we see that the graph of every quadratic surface is an algebraic surface, e.g. the cone, ellipsoid, cylinder, hyperboloid, etc..

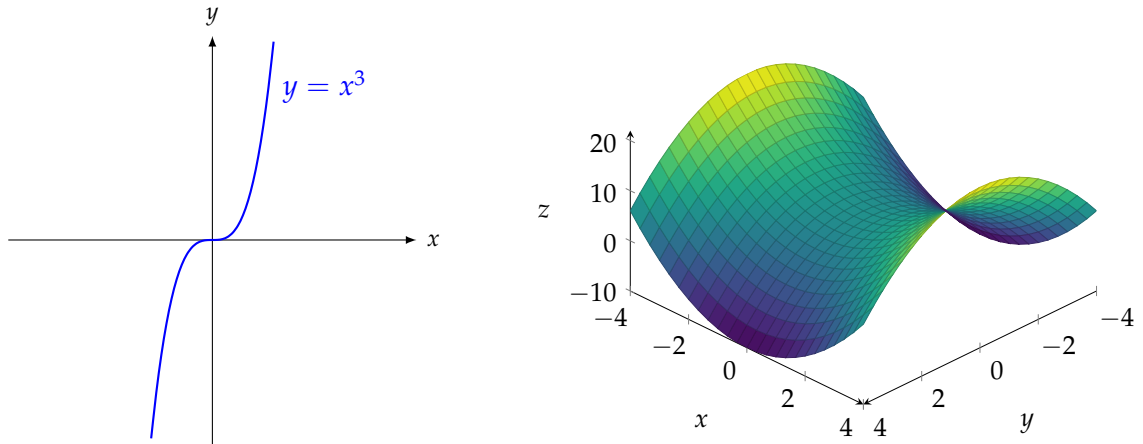


Figure 2: On the left, the algebraic set given by the curve  $y = x^3$  (not including axes). On the right, the algebraic set given by  $z = x^2 - y^2 + 6$  (not including axes).

- (iv) A 'line glued to a circle' is an algebraic set, i.e. the image in Figure 3 (excluding the axes) is an algebraic set since it represents the set  $Z((x^2 + y^2 - 1)(y - 2)) = \{(x, y) : (x^2 + y^2 - 1)(y - 2) = 0\}$ . Why? If  $(x^2 + y^2 - 1)(y - 2) = 0$ , then either  $x^2 + y^2 = 1$ , in which case the point lies on the circle, or  $y - 2 = 0$  in which case the point  $(x, y)$  lies on the line  $y = 2$ . In fact, even the coordinate axes are algebraic sets because together they are  $Z(xy)$ , by a similar reasoning.
- (v) The set of all  $n \times n$  matrices can be identified with the set  $\mathbb{C}^{n^2}$ . This space contains many subsets of interest. For example, the matrices of determinant 1,  $SL_n(\mathbb{C})$ , forms an affine algebraic variety in  $\mathbb{C}^{n^2}$  because it is the vanishing set of the polynomial given by  $\Delta - 1$ , where

$$\Delta(x_{ij}) = \det \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nn} \end{pmatrix}$$

is the determinant. In fact, a determinantal variety is the set of all matrices (considered as a subset of  $\mathbb{C}^{n^2}$ ) of rank at most  $k$ . For  $k \geq n$ , the determinantal variety is the whole space  $\mathbb{C}^{n^2}$ . But for  $k < n$ , the rank of a matrix  $A$  is at most  $k$  if and only if all its  $(k + 1) \times (k + 1)$  subdeterminants vanish. But as these subdeterminants are

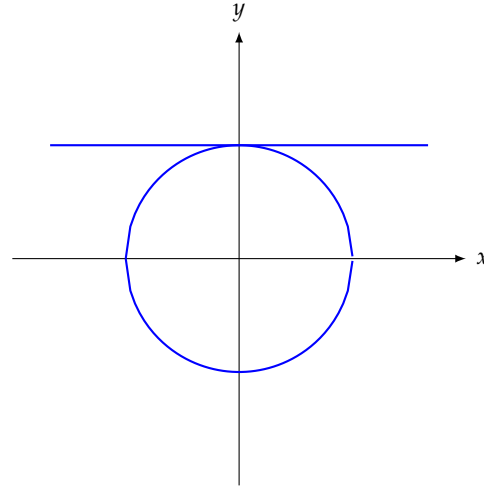


Figure 3: The algebraic set given by a ‘line glued to a circle.’ [Axes not included.]

polynomials in the variables  $x_{ij}$ , the set of matrices of rank at most  $k$  is an affine algebraic variety.  $\triangleleft$

Of course, not all sets are algebraic. Not even all curves in  $\mathbb{R}^2$  are algebraic, as the following exercise demonstrates.

**Exercise.**

- (a) Prove that in  $\mathbb{A}_{\mathbb{R}}^2$ , the graph of  $y = \sin x$  is not an algebraic set, i.e. prove the set  $\{(x, y) : y = \sin x\}$  is not algebraic. [Hint: The graph intersects the  $x$ -axis at infinitely many points, but single variable polynomials have finitely many roots.]
- (b) Prove that in  $\mathbb{A}_{\mathbb{R}}^2$ , the graph of  $y = e^x$  is not an algebraic set, i.e. prove the set  $\{(x, y) : y = e^x\}$  is not an algebraic set. [Hint:  $e^x$  grows ‘faster’ than any polynomial, i.e.  $\lim_{x \rightarrow \infty} \frac{e^x}{x} = \infty$ .]
- (c) Prove that the open ball in the usual Euclidean topology on  $\mathbb{C}^n$  is not an algebraic set by showing that every affine algebraic variety in  $\mathbb{C}^n$  is closed in the Euclidean topology. [Hint: Polynomials are continuous functions from  $\mathbb{C}^n$  to  $\mathbb{C}$ , so their zero sets are closed.] Explain then why the set of invertible matrices,  $\text{GL}_n(\mathbb{C})$  is not an affine algebraic variety.

Note that if  $N \subseteq M$ , then  $Z(M) \subseteq Z(N)$ , since any polynomial which vanishes on all of  $M$  certainly vanishes on all of  $N$ . Combining this with the Hilbert Basis Theorem: if  $R$  is noetherian, then  $R[x_1, \dots, x_n]$  is noetherian, we obtain the following result.



**Proposition 1.1.**

- (a) Let  $T \subseteq A$  and  $J$  be the ideal generated by  $T$ , then  $Z(T) = Z(J)$ . In particular, every algebraic set in  $\mathbb{A}^n$  is of the form  $Z(J)$  for some ideal  $J$  of  $A$ .
- (b) Every algebraic set in  $\mathbb{A}^n$  is of the form  $Z(T)$  for some finite set  $T \subseteq A$ .

*Proof.*

- (a) Since  $T$  generates  $J$ , we know that  $T \subseteq J$  which immediately implies  $Z(J) \subseteq Z(T)$ . For the reverse inclusion, let  $P \in Z(T)$  so that for all  $f \in T$ ,  $f(P) = 0$ . If  $g \in J$ , we have  $g = \sum_{i=1}^m a_i f_i$ , where  $a_i \in A$ ,  $f_i \in T$ . But then we have

$$g(P) = \sum_{i=1}^m a_i(P) f_i(P) = \sum_{i=1}^m a_i(P) \cdot 0 = 0.$$

Therefore,  $Z(T) = Z(J)$ . By definition,  $Y \subseteq \mathbb{A}^n$  is algebraic if and only if there is  $T \subseteq A$  with  $Y = Z(T)$ . Taking  $J := \langle T \rangle$ , the second claim follows.

- (b) Since  $k$  is a field, we know that  $A = k[x_1, \dots, x_n]$  is noetherian by the Hilbert Basis Theorem. Recall that every ideal in a noetherian ring is finitely generated (in fact this is equivalent to the definition). By (a), we know that  $Y \subseteq \mathbb{A}^n$  is algebraic if and only if  $Y = Z(J)$  for some ideal  $J$  of  $A$ . But as  $A$  is noetherian, we can find a finite number of generators, say  $T := \{f_1, \dots, f_r\}$ , for  $J$ . Therefore,  $Y = Z(J) = Z(\langle T \rangle) = Z(T) = Z(f_1, \dots, f_r)$ , as desired.  $\square$

Our goal is to build an underlying topological structure with which to work. This will form the basis for much of what is to come later. But first, we will need a proposition.

**Proposition 1.2.**

- (a) The empty set and whole space are algebraic sets.
- (b) The finite union of algebraic sets is algebraic.
- (c) The intersection of any algebraic sets is algebraic.

*Proof.*

- (a) Recall from Example 1.1 that  $\emptyset = Z(1)$  and  $\mathbb{A}^n = Z(0)$  are algebraic sets.
- (b) By induction, it suffices to prove that the union of two algebraic sets is algebraic. Suppose that  $S_1, S_2$  are algebraic sets. Then by Proposition 1.1, we know that  $S_1 = Z(T_1)$  and  $S_2 = Z(T_2)$  for some  $T_1, T_2 \subseteq A$ . We need show that  $S_1 \cup S_2 = Z(T_1) \cup Z(T_2) = Z(T)$  for some set  $T$ . We shall show that  $Z(T_1) \cup Z(T_2) = Z(T_1 T_2)$ , i.e.

$T = T_1 T_2 = \{t_1 t_2 : t_1 \in T_1, t_2 \in T_2\}$  works, so that again by Proposition 1.1,  $S_1 \cup S_2$  is algebraic.

To see that  $Z(T_1) \cup Z(T_2) \subseteq Z(T_1 T_2)$ , let  $P \in Z(T_1) \cup Z(T_2)$ . But then  $P \in Z(T_1)$  or  $Z(T_2)$ . Without loss of generality, suppose  $P \in Z(T_1)$ . Any element of  $T_1 T_2$  is of form  $fg$ , where  $f \in T_1, g \in T_2$ . But then  $P \in Z(T_1 T_2)$ .

To see that  $Z(T_1 T_2) \subseteq Z(T_1) \cup Z(T_2)$ , choose  $P \in Z(T_1 T_2)$ . We will show that if  $P \notin Z(T_1)$  then  $P \in Z(T_2)$ . So suppose  $P \notin Z(T_1)$ . Then there is  $f \in T_1$  with  $f(P) \neq 0$ . Choose any  $g \in T_2$ . Now  $fg \in T_1 T_2$  so  $(fg)(P) = 0$ . But  $0 = (fg)(P) = f(P)g(P)$ . We know  $f(P) \neq 0$  whenever  $k$  is an integral domain, so that we must have  $g(P) = 0$ . As  $g \in T_2$  was arbitrary, then  $P \in Z(T_2)$ .

- (c) Suppose  $\{S_i\}_{i \in \mathcal{I}}$  is a collection of algebraic sets. Then for each  $i \in \mathcal{I}$ , we know that  $S_i = Z(T_i)$  for some  $T_i \subseteq A$ . But then we have

$$\bigcap_{i \in \mathcal{I}} S_i = \bigcap_{i \in \mathcal{I}} Z(T_i) = Z\left(\bigcup_{i \in \mathcal{I}} T_i\right),$$

where the last equality follows since  $P \in Z(\bigcup_{i \in \mathcal{I}} T_i)$  if and only if every polynomial in every  $T_i$  vanishes at  $P$ , i.e.  $P \in \bigcap_{i \in \mathcal{I}} Z(T_i)$ .  $\square$

Notice that Proposition 1.2 shows that the algebraic sets are precisely the closed sets in some topology, called the Zariski topology on  $\mathbb{A}^n$ .

**Definition** (Zariski Topology). The Zariski topology on  $\mathbb{A}^n$  is defined by taking the open sets to be the complements of algebraic sets.

**Example 1.2.** What is the Zariski topology on  $\mathbb{A}^1$ ? Since  $k$  is a field,  $A = k[x]$  is a PID, so every ideal in  $A$  is principal. But by Proposition 1.1, every algebraic set  $Y$  is of the form  $Y = Z(J)$  for some ideal  $J$ . But then  $Y = Z(f)$  for some polynomial. Since  $k$  is algebraically closed, we can factor  $f(x)$  as  $f(x) = c(x - a_1) \cdots (x - a_n)$ , where  $c, a_1, \dots, a_n \in k$ . Therefore,  $Z(f) = \{a_1, \dots, a_n\}$ . We know also from Example 1.1 that any finite set in  $\mathbb{A}^n$  is algebraic. The closed sets in the Zariski topology are then  $\emptyset$ ,  $\mathbb{A}^1$ , and all finite subsets. Therefore, the Zariski topology on  $\mathbb{A}^1$  consists of  $\emptyset$ ,  $\mathbb{A}^1$ , and the complements of finite subsets. But then every set which is not the whole set or  $\emptyset$  contain all but finitely many elements of  $k$ . In particular, every two open sets intersect so that the Zariski topology on  $\mathbb{A}^1$  is (extremely) not Hausdorff. Note that one did not need the fact that  $k[x]$  a PID. Any algebraic set is of the form  $\bigcap_{i \in \mathcal{I}} Z(f_i)$ , where  $f_i \in k[x]$ . However,  $f_i$  can only be 0, in which case  $Z(f_i) = \mathbb{A}^1$ , a nonzero constant, in which case  $Z(f_i) = \emptyset$ , or a nonconstant polynomial in which case  $Z(f_i)$  consists on finitely many points. In particular, the intersection consists of finitely many points.  $\triangleleft$

When studying objects geometrically, one breaks them into their constituent pieces and studies them individually, as well as how they fit together. So when studying geometric objects from an algebraic or topological structure, we will also want to break pieces into smaller structures.

**Definition (Irreducible).** A nonempty subset  $Y$  of a topological space  $X$  is irreducible if and only if it cannot be expressed as the union  $Y = Y_1 \cup Y_2$  of two proper subsets each of which is closed in  $Y$  (in the induced topology). The empty set is not considered to be irreducible. A set which is not irreducible is reducible.

**Example 1.3.** Whenever  $k$  is infinite, e.g. when  $k$  is algebraically closed,  $\mathbb{A}^1$  is irreducible as the only proper closed subsets are finite, so  $\mathbb{A}^1$  could not be written as a finite union of closed sets.  $\triangleleft$

**Example 1.4.** In  $\mathbb{A}^2$ , the set  $Z(xy)$  is reducible as we can write  $Z(xy) = Z(x) \cup Z(y)$ , i.e. for  $xy$  to vanish either  $x$  must vanish or  $y$  must vanish. This should be expected since the coordinate axes can be broken up into the  $x$ -axis and  $y$ -axis individually, c.f. Example 1.1(iv).  $\triangleleft$

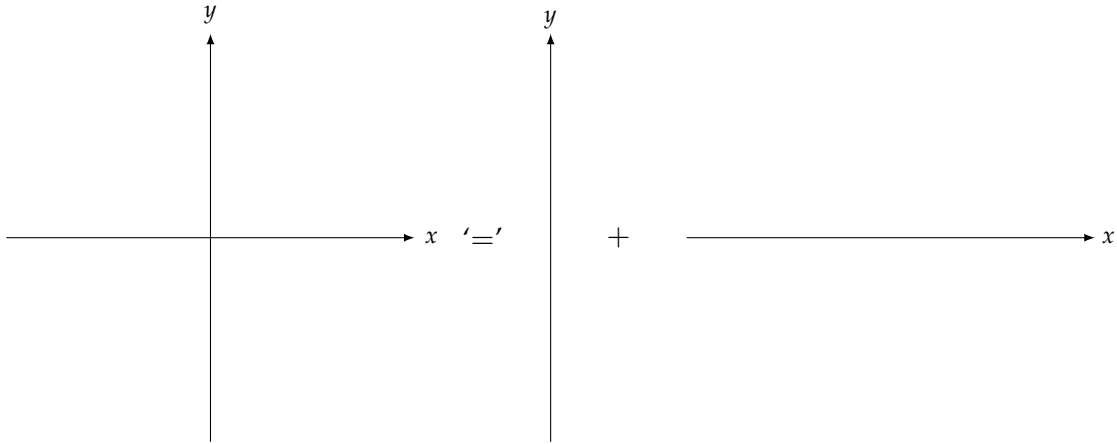


Figure 4: The decomposition  $Z(xy) = Z(x) \cup Z(y)$ .

**Example 1.5.**

- (i) Any nonempty open subset of an irreducible space is irreducible and dense. This confirms our intuition that Zariski open sets are very 'big'.
- (ii) If  $Y$  is an irreducible subset of  $X$ , then its closure  $\bar{Y}$  in  $X$  is also irreducible.
- (iii) If  $Y$  is irreducible and  $U_1, U_2$  are nonempty open subsets of  $Y$ , then  $U_1 \cap U_2 \neq \emptyset$ . Why? If the intersection were not empty, then  $Y \setminus U$  would be a closed proper subset of  $Y$  containing  $U_2$ , which contradicts the fact that  $Y_2$  is dense.

- (iv) If  $Y$  is irreducible and  $U$  is nonempty and open in  $Y$ , then  $U$  is both dense and irreducible. Why? If  $\overline{U} \subsetneq Y$ , then  $Y \setminus U \subsetneq Y$  so that  $Y = \overline{U} \cup (Y \setminus U)$ , contradicting the irreducibility of  $Y$ . Now if  $U$  were reducible, then there would be closed subsets  $Y_1, Y_2$  of  $Y$  with  $U = (U \cap Y_1) \cup (U \cap Y_2)$ . Each  $U \cap Y_i$  is a proper subset of  $U$  and  $U \subsetneq Y_i$ .

**Definition (Affine Algebraic Variety).** An affine algebraic variety is an irreducible closed subset of  $\mathbb{A}^n$  (with the induced topology). This is also sometimes referred to as simply an affine variety. An open subset of an affine variety is a quasi-affine variety.

Notice all the proceeding definitions and examples connected subsets of  $\mathbb{A}^n$  and ideals in  $A$ . Before moving forward, we first need to examine this correspondence more closely. Notice before one began with a collection of polynomials and then obtained a collection of points. One can go in the other direction as well, which gives the following definition.

**Definition ( $I(Y)$ ).** Let  $Y \subseteq \mathbb{A}^n$  be a subset. Define the ideal of  $Y$ , denoted  $I(Y)$ , by  $I(Y) := \{f \in A : f(P) = 0 \text{ for all } P \in Y\}$ .

Of course, one should actually check that this is an ideal.

**Proposition 1.3.** Let  $Y \subseteq \mathbb{A}^n$  be any subset. Then  $I(Y)$  is an ideal.

*Proof.* We know that  $0 \in I(Y)$  since 0 vanishes everywhere. Now suppose that  $f, g \in I(Y)$  and  $h \in A$ . For any  $P \in Y$ ,

$$\begin{aligned}(f + g)(P) &= f(P) + g(P) = 0 + 0 = 0 \\ (hf)(P) &= h(P)f(P) = h(P)(0) = 0\end{aligned}$$

so that  $f + g, hf \in I(Y)$ . □

We then have two functions between two different important sets, namely

$$\left\{ \begin{array}{c} \text{Subsets of } \mathbb{A}^n \end{array} \right\} \begin{array}{c} \xrightarrow{I(-)} \\ \xleftarrow{Z(-)} \end{array} \left\{ \begin{array}{c} \text{subsets of} \\ k[x_1, \dots, x_n] \end{array} \right\}$$

To find the relationship between this connection, we will need the following result.

**Proposition 1.4.**

- (i) If  $T_1 \subseteq T_2$  are subsets of  $A$ , then  $Z(T_1) \supseteq Z(T_2)$ .
- (ii) If  $Y_1 \subseteq Y_2$  are subsets of  $\mathbb{A}^n$ , then  $I(Y_1) \supseteq I(Y_2)$ .
- (iii) For any two subsets  $Y_1, Y_2$  of  $\mathbb{A}_1^2$ , we have  $I(Y_1 \cup Y_2) = I(Y_1) \cap I(Y_2)$ .

- (iv) For any ideal  $J \subseteq A$ ,  $I(Z(J)) = \sqrt{J}$ , where  $\sqrt{J} := \{f \in A : f^r \in J \text{ for some } r > 0\}$  is the radical of  $J$ .
- (v) For any subset  $Y \subseteq \mathbb{A}^n$ ,  $Z(I(Y)) = \overline{Y}$ , the closure of  $Y$  in the Zariski topology.

*Proof.*

- (i) If  $P \in Z(T_2)$ , then  $f(P) = 0$  for all  $f \in T_2$ . But then  $f(P) = 0$  for all  $f \in T_1$ , showing that  $P \in Z(T_1)$ .
- (ii) If  $f \in I(Y_2)$ , then  $f(P) = 0$  for all  $P \in Y_2$ . But then  $f(P) = 0$  for all  $P \in Y_1$ , showing that  $f \in I(Y_1)$ .
- (iii) We know that  $f \in I(Y_1 \cup Y_2)$  if and only if  $f(P) = 0$  for all  $P \in Y_1 \cup Y_2$  if and only if  $f(P) = 0$  for all  $P \in Y_1$  and  $f(P) = 0$  for all  $P \in Y_2$  if and only if  $f \in I(Y_1)$  and  $f \in I(Y_2)$  if and only if  $f \in I(Y_1) \cap I(Y_2)$ .
- (iv) This follows immediately from Hilbert's Nullstellensatz, c.f. Theorem 1.1:  $f \in \sqrt{J}$  if and only if  $f^r \in J$  for some  $r > 0$  if and only if  $f^r(P) = 0$  for all  $P \in Z(J)$ , where the last "if and only if" follows from the definition of  $Z(-)$  and the Nullstellensatz.
- (v) We know that  $Z(I(Y))$  is closed because it is algebraic. We know also that  $Z(I(Y)) \supseteq Y$  because if  $P \in Y$ , then  $f(P) = 0$  for all  $f \in I(Y)$ , showing  $P \in Z(I(Y))$ . Now if  $W$  is any closed set, say  $W = Z(J)$ , then  $I(W) \supseteq J$  because if  $f \in J$ , then  $f(P) = 0$  for all  $P \in Z(J) = W$ , showing  $f \in I(W)$ . Thus,  $Z(I(W)) \subseteq Z(J) = W$ . We know that  $Y = W$  and  $Z(I(W)) \supseteq W$ . But then  $W = Z(I(W))$ .

Now suppose  $W$  is any closed subset containing  $Y$ . From (ii), we have  $I(W) \subseteq I(Y)$ . But then from (i), we know that  $Z(I(W)) \supseteq Z(I(Y))$ . Then from (iii), we know  $W = Z(I(W))$  so that  $W \supseteq Z(I(Y))$ . Therefore,  $Z(I(Y))$  is a closed set containing  $Y$  and contained in any closed set containing  $Y$ . Therefore,  $Z(I(Y)) = \overline{Y}$ .  $\square$

As a reminder for the reader,

**Theorem 1.1** (Hilbert's Nullstellensatz). *Let  $k$  be an algebraically closed field,  $J$  be an ideal in  $A = k[x_1, \dots, x_n]$ , and  $f \in A$  be a polynomial vanishing at all points of  $Z(J)$ . Then  $f^r \in J$  for some  $r > 0$ .*

*Proof.* See any 'standard' introductory text on Commutative Algebra.  $\square$

Note for Hilbert's Nullstellensatz, one does need  $k$  to be algebraically closed, as the following examples show:

**Example 1.6.**

- (i) If  $k = \mathbb{R}$  and  $J = (x^2 + x + 1) \subseteq \mathbb{R}[x]$ , then  $Z(J) = \emptyset$ . Now 1 vanishes at all points of  $\emptyset = Z(J)$ , but no power of 1 is in  $(x^2 + x + 1)$ .
- (ii) If  $k = \mathbb{R}$  and  $J = (x^2 + y^2) \subseteq \mathbb{R}[x, y]$ , then  $Z(J) = \{(0, 0)\}$ . Now  $x$  vanishes at  $(0, 0)$  but no power of  $x$  is in  $(x^2 + y^2)$ .  $\triangleleft$

As a result, we can now see the connection between the subsets of  $\mathbb{A}^n$  and the subsets of  $k[x_1, \dots, x_n]$  that we had discussed earlier.

$$\begin{array}{ccc}
 \left\{ \begin{array}{c} \text{Subsets of } \mathbb{A}^n \end{array} \right\} & \begin{array}{c} \xrightarrow{I(-)} \\ \xleftarrow{Z(-)} \end{array} & \left\{ \begin{array}{c} \text{subsets of} \\ k[x_1, \dots, x_n] \end{array} \right\} \\
 \text{IU} & & \text{IU} \\
 \left\{ \begin{array}{c} \text{Closed subsets} \\ \text{of } \mathbb{A}^n \end{array} \right\} & \begin{array}{c} \xrightarrow[\sim]{I(-)} \\ \xleftarrow{Z(-)} \end{array} & \left\{ \begin{array}{c} \text{Radical ideals} \\ \text{of } k[x_1, \dots, x_n] \end{array} \right\}
 \end{array}$$

**Corollary 1.1.** *There is a one-to-one (inclusion-reversing) correspondence between algebraic sets in  $\mathbb{A}^n$  and radical ideals in  $A$  given by  $Y \mapsto I(Y)$  and  $\mathfrak{a} \mapsto Z(\mathfrak{a})$ . Furthermore, an algebraic set is irreducible if and only if its ideal is a prime ideal.*

*Proof.* All of this was shown in Proposition 1.4 with the exception of the final statement. Now suppose that  $Y$  is irreducible. We need show  $I(Y)$  is prime. Suppose that  $fg \in I(Y)$ . Then  $Y \subseteq Z(fg) = Z(f) \cup Z(g)$ . But then  $Y = Y \cap Z(fg) = (Y \cap Z(f)) \cup (Y \cap Z(g))$ , both of which are closed subsets of  $Y$  (in the subspace topology). Since  $Y$  is irreducible,  $Y$  must be one of the sets in this union. Without loss of generality, assume  $Y = Y \cap Z(f)$ . But then  $f \in I(Y)$ , as desired. Now suppose that  $\mathfrak{p}$  is a prime ideal, and  $Z(\mathfrak{p}) = Y_1 \cup Y_2$ . Then we must have  $\mathfrak{p} = I(Y_1) \cap I(Y_2)$ . But then  $\mathfrak{p} = I(Y_1)$  or  $\mathfrak{p} = I(Y_2)$ . Without loss of generality, assume  $\mathfrak{p} = I(Y_1)$ . Then we have  $Z(\mathfrak{p}) = Z(I(Y_1)) = Y_1$ . Therefore,  $Z(\mathfrak{p})$  is irreducible.  $\square$

This gives the most complete diagram as

$$\begin{array}{ccc}
 \left\{ \begin{array}{c} \text{Subsets of } \mathbb{A}^n \end{array} \right\} & \begin{array}{c} \xrightarrow{I(-)} \\ \xleftarrow{Z(-)} \end{array} & \left\{ \begin{array}{c} \text{subsets of} \\ k[x_1, \dots, x_n] \end{array} \right\} \\
 \text{IU} & & \text{IU} \\
 \left\{ \begin{array}{c} \text{Closed subsets} \\ \text{of } \mathbb{A}^n \end{array} \right\} & \begin{array}{c} \xrightarrow[\sim]{I(-)} \\ \xleftarrow{Z(-)} \end{array} & \left\{ \begin{array}{c} \text{Radical ideals} \\ \text{of } k[x_1, \dots, x_n] \end{array} \right\} \\
 \text{IU} & & \text{IU} \\
 \left\{ \begin{array}{c} \text{Subvarieties} \\ \text{of } \mathbb{A}^n \end{array} \right\} & \begin{array}{c} \xrightarrow[\sim]{I(-)} \\ \xleftarrow{Z(-)} \end{array} & \left\{ \begin{array}{c} \text{Prime ideals} \\ \text{of } k[x_1, \dots, x_n] \end{array} \right\}
 \end{array}$$

**Example 1.7.**

- (i)  $\mathbb{A}^n$  is irreducible because it corresponds to the zero ideal in  $A$ , which is prime.
- (ii) If  $f$  is an irreducible polynomial in  $A = k[x, y]$  (a UFD), then  $f$  generates a prime ideal (irreducibles are primes in a UFD). Then it must be that  $Y = Z(f)$  is irreducible. This is called the affine curve defined by the equation  $f(x, y) = 0$ . If the degree of  $f$  is  $d$ , we say that  $Y$  is a curve of degree  $d$ . Generally, if  $f$  is an irreducible polynomial in  $A = k[x_1, \dots, x_n]$ , the affine variety  $Y = Z(f)$  is called a hypersurface for  $n > 3$  (or simply a surface if  $n = 3$ ).
- (iii) A maximal ideal  $\mathfrak{m}$  of  $A = k[x_1, \dots, x_n]$  corresponds to a minimal irreducible set (by ‘inclusion-reversingness’) of  $\mathbb{A}^n$ , which must be a point, say  $P = (a_1, \dots, a_n)$ . Then every maximal ideal of  $A$  is of the form  $\mathfrak{m} = (x_1 - a_1, \dots, x_n - a_n)$  for some  $a_1, \dots, a_n \in k$ . Note that we can express  $\{P\} = Z(\langle x_1 - a_1, \dots, x_n - a_n \rangle)$ ,  $\langle x_1 - a_1, \dots, x_n - a_n \rangle$  is maximal as  $k[x_1, \dots, x_n] / \langle x_1 - a_1, \dots, x_n - a_n \rangle \cong k$  is a field, and that this result requires that  $k$  be algebraically closed.  $\triangleleft$

Note that polynomials in more than one variable can have infinitely many roots. For example,  $f(x, y) = xy$  has zeros whenever  $x = 0$  or  $y = 0$ . Clearly,  $Z(xy) = \{(x, 0) \mid x \in \mathbb{R}\} \cup \{(0, y) \mid y \in \mathbb{R}\}$ , the coordinate axes. In fact in the finite field case, there are nonzero polynomials which are everywhere zero, the trivial example being  $f(x) = \prod_{i=1}^{p^n} (x - k_i)$ , where  $k = \{k_1, \dots, k_{p^n}\}$ . But in the case where  $k$  is infinite, there will always exist a point where the polynomial does not have a root.

**Proposition 1.5.** *Let  $k$  be an infinite field and  $0 \neq f \in k[x_1, \dots, x_n]$ . Then there exists a point  $P \in \mathbb{A}^n$  such that  $f(P) \neq 0$ .*

*Proof.* We proceed by induction on  $n$ . The case where  $n = 1$  is routine since any polynomial in a single variable has finitely many roots by degree considerations. Assume then that the result is true for  $n$ , and let  $f \in k[x_1, \dots, x_{n+1}]$ . Write  $f$  as  $a_m x_{n+1}^m + a_{m-1} x_{n+1}^{m-1} + \dots + a_1 x_{n+1} + a_0$ , where  $a_i \in k[x_1, \dots, x_n]$ . Since  $f$  is nonzero, some  $a_i \neq 0$ . Recalling  $k[x_1, \dots, x_{n+1}] = k[x_1, \dots, x_n][x_{n+1}]$  and using the induction hypothesis, there exists  $Q = (b_1, \dots, b_n)$ , where  $b_i \in k$ , such that  $a_i(Q) \neq 0$ . Now  $f(b_1, \dots, b_n, x_{n+1})$  is a nonzero polynomial in a single variable, which can have only finitely many roots. Because  $k$  is infinite, there must then be  $b_{n+1} \in k$  so that  $f(b_1, \dots, b_n, b_{n+1}) \neq 0$ , as desired.  $\square$

**Definition ((Affine) Coordinate Ring).** If  $Y \subseteq \mathbb{A}^n$  is an algebraic set, we define the affine coordinate ring, denoted  $A(Y)$ , to be  $A/I(Y)$ .

One can think of elements of  $A(Y)$  to be functions from  $Y \rightarrow k$ : if  $Y \subseteq \mathbb{A}^n$ ,  $f \in A = k[x_1, \dots, x_n]$ , then  $f$  certainly gives a function  $f : \mathbb{A}^n \rightarrow k$  via restriction. Note that  $f, g \in k[x_1, \dots, x_n]$  induce the same function from  $Y \rightarrow k$  if and only if  $f - g \in I(Y)$ . Hence,  $A(Y)$  is the ring of all functions  $f : Y \rightarrow k$  that are restrictions of polynomials.

**Example 1.8.** Let  $Y \subseteq \mathbb{A}^2$  be the set given by  $xy = 1$ , i.e.  $Z(xy - 1)$ . It is routine to verify that  $\sqrt{\langle xy - 1 \rangle} = \langle xy - 1 \rangle$ . But then we have

$$k[x, y] / (xy - 1) \cong k[x, x^{-1}],$$

the ring of Laurent polynomials. The isomorphism is easy to prove when one realizes the relation  $xy - 1 = 0$  implies that  $xy = 1$  so that we can take  $y = x^{-1}$ .  $\triangleleft$

**Remark.** We know that  $A(Y)$  is an integral domain if and only if  $I(Y)$  is prime if and only if  $Y$  is irreducible. Now  $A(Y)$  is finitely generated as a  $k$ -algebra because it is a quotient of  $k[x_1, \dots, x_n]$ , which is finitely generated as a  $k$ -algebra (one can take the image of the generators to be a generating set). On the other hand, any finitely generated  $k$ -algebra, say  $B$ , which is a domain is the affine coordinate ring of some variety. Why? Consider a map  $\psi : k[x_1, \dots, x_n] \rightarrow B$  is a surjection with kernel  $I$ . Then taking  $Y = Z(I)$ , we have  $A(Y) = B$ .

To study the topology of the affine varieties we have defined, we will need to introduce an important class of topological spaces, which is just the topological variant of its algebraic cousin.

**Definition** (Noetherian). A topological space  $X$  is called noetherian if it satisfies the ascending chain condition on open subsets (every chain of open subsets stabilizes), i.e. for any chain of open subsets  $U_1 \subseteq U_2 \subseteq \dots \subseteq U_r \subseteq \dots$ , there exists an  $n$  such that  $U_n = U_{n+1} = \dots$ . Equivalently, a topological space  $X$  is noetherian if it satisfies the descending chain condition on closed subsets.

**Example 1.9.** The topological space  $\mathbb{A}^n$ , with the Zariski topology, is noetherian as given a set of closed subsets  $Y_1 \supseteq Y_2 \supseteq \dots$ , applying  $Y(-)$  (noting it is inclusion-reversing), we have  $I(Y_1) \subseteq I(Y_2) \subseteq \dots$ . But this is an ascending chain of ideals in  $A = k[x_1, \dots, x_n]$ . As  $A$  is noetherian (by the Hilbert Basis Theorem), the chain of ideals must stabilize, say at  $n$ . Finally as  $Y_i = Z(I(Y_i))$ , so too must the chain  $Y_1 \supseteq Y_2 \supseteq \dots$  stabilize at  $n$ .  $\triangleleft$

**Example 1.10.** The topological space  $\mathbb{R}^n$ , with the usual Euclidean topology, is not noetherian. Let  $\{a_n\}$  be a strictly monotone decreasing set with  $a_n \rightarrow 0$ . Letting  $Y_i$  be the closed sphere centered at the origin with radius  $a_i$ , we see that  $\{Y_i\}$  is a chain of closed subsets that does not stabilize.  $\triangleleft$

**Proposition 1.6.** *In a noetherian topological space, every nonempty set of closed subsets has a minimal element.*

*Proof.* Let  $S$  be a nonempty collection of closed subsets. Choose  $Y_1 \in S$ . If  $Y_1$  is minimal, we are done. If not, choose  $Y_2 \subsetneq Y_1$ . If  $Y_2$  is minimal, we are done. If not, choose  $Y_3$  such that  $Y_3 \subsetneq Y_2$ . Continuing in this process, we construct a chain  $Y_1 \supsetneq Y_2 \supsetneq Y_3 \supsetneq \dots$ . Since the space is noetherian, this chain must stabilize, say at  $n$ . But then  $Y_n$  must be a minimal



element of  $S$ . □

This is equivalent to the algebraic property that every collection of submodules (or ideals) must contain a maximal element.

**Proposition 1.7.** *In a noetherian topological space  $X$ , every nonempty closed subset  $Y$  can be expressed as a finite union  $Y = Y_1 \cup \cdots \cup Y_r$  of irreducible closed subsets of  $Y$ . If requires  $Y_i \supsetneq Y_j$  for  $i \neq j$  (which is possible), the  $Y_i$  are uniquely determined up to reordering. In this case, the  $Y_i$  are called the irreducible components of  $Y$ .*

*Proof.* Let  $S$  be the set of all nonempty closed subsets of  $X$  that cannot be expressed as a finite union of irreducible closed sets. We wish to show that  $S = \emptyset$ . Suppose that  $S \neq \emptyset$ . Because  $X$  is noetherian,  $S$  must have a minimal element, say  $Y$ . Because  $Y \in S$ ,  $Y$  cannot be irreducible. Thus, we can write  $Y = A \cup B$ , where  $A, B \subsetneq Y$  are nonempty and closed in  $Y$ . But by the minimality of  $Y$ ,  $A, B$  must be the finite union of irreducibles. Suppose  $A = A_1 \cup \cdots \cup A_s$  and  $B = B_1 \cup \cdots \cup B_t$  irreducible, where the  $A_i$  and  $B_j$  are irreducible closed subsets of  $A, B$ , respectively. But then the  $A_i, B_j$  are closed in  $Y$ , and we have  $Y = A_1 \cup \cdots \cup A_s \cup B_1 \cup \cdots \cup B_t$ , which contradicts the fact that  $Y \in S$ . Therefore, every nonempty closed subset  $Y$  of  $X$  has such a decomposition. Suppose  $Y = Y_1 \cup \cdots \cup Y_s$ , where the  $Y_i$  are irreducible. If  $Y_i \supseteq Y_j$  for  $i \neq j$ , you could drop  $Y_j$  from the expression. If so, then do just that. We can then assume that  $Y_i \not\supseteq Y_j$  for  $i \neq j$ .

It remains to show that this expression is unique. Assume  $Y = Y_1 \cup \cdots \cup Y_s = Y'_1 \cup \cdots \cup Y'_t$  as expressions as in the theorem. If  $i = j$ ,  $Y_i \not\supseteq Y_j$  and  $Y'_i \not\supseteq Y'_j$ . Then  $Y_1 = Y_1 \cap Y = Y_1 \cap (Y'_1 \cup \cdots \cup Y'_t) = (Y_1 \cap Y'_1) \cup \cdots \cup (Y_1 \cap Y'_t)$ . But  $Y_1$  is irreducible, so these cannot all be closed proper subsets of  $Y_1$ . Therefore,  $Y_1 = Y_1 \cap Y'_i$  for some  $i$ , i.e.  $Y_1 \subseteq Y'_i$ . Mutatis mutandis,  $Y'_i \subseteq Y_j$  for some  $j$ . Then  $Y_1 \subseteq Y'_i \subseteq Y_j$ . Then  $j = 1$  and  $Y_1 = Y'_i$ . One then reindexes so that  $Y_1 = Y'_1$ .

We claim that  $\overline{Y \setminus Y_1} = Y_2 \cup \cdots \cup Y_s$  and  $\overline{Y \setminus Y'_1} = Y'_2 \cup \cdots \cup Y'_t$ . Now  $Y_2 \cup \cdots \cup Y_s$  is a closed set containing  $Y \setminus Y_1$ . Let  $W$  be any closed set containing  $Y \setminus Y_1$ . Fix any  $i \geq 2$ , then  $W \supseteq Y_i \setminus Y_1$ . Then  $Y_i = (Y_i \cap W) \cup (Y_i \cap Y_1)$ . But as  $Y_i$  is irreducible, either  $Y_i = Y_i \cap W$  or  $Y_i = Y_i \cap Y_1$ . If  $Y_i = Y_i \cap Y_1$  then  $Y_i \subseteq Y_1$ , a contradiction. It must then be that  $Y_i = Y_i \cap W$  so that  $Y_i \subseteq W$ . But then  $Y_2 \cup \cdots \cup Y_s \subseteq W$ .

Therefore, we have shown  $Y_2 \cup \cdots \cup Y_s = Y'_2 \cup \cdots \cup Y'_t$ . Clearly, this process must terminate: without loss of generality assume  $s \leq t$ . We then have  $Y'_{s+1} \cup \cdots \cup Y'_t = \emptyset$  and  $Y_i = Y'_i$  for all  $i$ , as desired. □

**Corollary 1.2.** *Every algebraic set in  $\mathbb{A}^n$  can be uniquely expressed as a union of varieties, no one containing another.*

**Definition (Dimension).** If  $X$  is a topological space, we say that the dimension of  $X$ , denoted  $\dim X$ , is the supremum of all integers  $n$  such that there exists a chain  $Z_0 \subset Z_1 \subset$

$\cdots \subset Z_n$  of distinct irreducible closed subsets of  $X$ . We define the dimension of an affine or quasi-affine variety to be the its dimension as a topological space.

**Example 1.11.** The dimension of  $\mathbb{A}^1$  is 1 because the only irreducible closed subsets of  $\mathbb{A}^1$  are single points or the whole space.  $\triangleleft$

**Remark.** In general, it is not a simple feat to compute the dimension of a space directly from its definition. One can find lower bounds by finding an example of a chain of length  $n$ . However, it is difficult to prove that there is no longest chain or that even a given chain is *the* longest. This approach generally only works if one has a strong description of what the irreducible closed sets in the space are. Note that a maximal chain does not have to be a maximum chain. Meaning that just because a chain cannot be refined to a longer chain does not mean there does not exist some other longer chain of sets.

There is also the notion of dimension for rings.

**Definition ((Krull) Dimension).** If  $A$  is a ring, the height of a prime ideal  $\mathfrak{p}$  is the supremum of all  $n$  such that there exists a chain  $\mathfrak{p}_0 \subset \mathfrak{p}_1 \subset \cdots \subset \mathfrak{p}_n = \mathfrak{p}$  of distinct prime ideals. We define the (Krull) dimension of  $A$  to be the supremum of all the heights of all prime ideals.

In special cases, the relationship between this ring theoretic definition of dimension and the topological definition gives us a much more practical method of computing the dimension of a space.

**Proposition 1.8.** *If  $Y$  is an affine algebraic set, then the dimension of  $Y$  is the dimension of its affine coordinate ring  $A(Y)$ .*

*Proof.* If  $Y \subseteq \mathbb{A}^n$  is an affine algebraic set, then the irreducible closed subsets of  $Y$  correspond to prime ideals of  $A = k[x_1, \dots, x_n]$  containing  $I(Y)$ . But these correspond to prime ideals in  $A(Y)$ . Therefore,  $\dim Y$  is the length of the longest chain of prime ideals in  $A(Y)$ , which is precisely its dimension as a ring.  $\square$

Generally, tools from Commutative Algebra are the typical approach to computing the dimension of a space.

**Theorem 1.2.** *Let  $k$  be a field, and let  $B$  be an integral domain which is a finitely generated  $k$ -algebra. Then*

- (i) *the dimension of  $B$  is equal to the transcendence degree of the quotient field  $K(B)$  of  $B$  over  $k$*
- (ii) *for any prime ideal  $\mathfrak{p}$  in  $B$ , we have*

$$\dim B = \text{height } \mathfrak{p} + \dim B/\mathfrak{p}$$

*Proof.* See Matsumura [Mat70, Chapter 5 §14], or in the case where  $k$  is algebraically closed, Atiyah-Macdonald [AM69, Chapter 11].  $\square$

**Proposition 1.9.** *The dimension of  $\mathbb{A}^n$  is  $n$ .*

*Proof.* By Proposition 1.8, the dimension of the polynomial ring  $k[x_1, \dots, x_n]$  is  $n$ . But then the result follows from (i) in Theorem 1.2 because  $k(x_1, \dots, x_n)$  has transcendence degree  $n$ .  $\square$

**Remark.** If  $Y \subseteq X$  is a closed subset, we know that  $\dim Y \leq \dim X$ . But in the cases where  $\dim X < \infty$ , this gives another approach to computing  $\dim Y$  by trying the following: find lower bounds on the  $\dim Y$  by finding chains in  $Y$ . Find upper bounds on the  $\dim Y$  by using the fact that you know  $\dim X$  and can find chains in  $X$  starting at  $Y$ . Then one tries to ‘squeeze’ these chains together.

**Proposition 1.10.** *If  $Y$  is a quasi-affine variety, then  $\dim Y = \dim \bar{Y}$ .*

*Proof.* If  $Z_0 \subset \dots \subset Z_n$  is a sequence of distinct closed irreducible subsets of  $Y$ , then  $\bar{Z}_0 \subset \dots \subset \bar{Z}_n$  is a sequence of distinct closed irreducible subsets of  $\bar{Y}$ . Thus, we must have  $\dim Y \leq \dim \bar{Y}$ . In particular, the dimension of  $Y$  must be finite. Therefore, there exists a maximal chain in  $Y$ , say  $Z_0 \subset \dots \subset Z_n$ , where  $n = \dim Y$ . Since the chain is maximal,  $Z_0 = \{P\}$ , where  $P$  is a point, because if  $Z_0$  contained at least two points, say  $P, Q$  then  $\{P\} \subset Z_0$  would contradict the maximality of the chain. The point  $P$  corresponds to some maximal ideal  $\mathfrak{m}$  of the affine coordinate ring  $A(\bar{Y})$ . Each  $\bar{Z}_i$  corresponds to a prime ideal contained in  $\mathfrak{m}$ , so that the height  $\mathfrak{m} = n$ . On the other hand as  $P$  is a point in affine space,  $A(\bar{Y})/\mathfrak{m} \cong k$ . But then  $n = \dim A(\bar{Y}) = \dim \bar{Y}$ . Therefore,  $\dim Y = \dim \bar{Y}$ .  $\square$

Note this is something special about varieties because, generally, there are topological spaces  $X$  and dense open sets  $U$  with  $\dim U < \dim X$ , c.f. [Har77, Exercise 1.10].

**Example 1.12.** Any nonempty open subset of an irreducible space is irreducible and dense. Suppose  $U \subseteq Y$  is an open set, where  $Y$  is irreducible. To prove density, note that (assuming  $U$  was nonempty) if  $\bar{U} \neq Y$ , then we could write  $Y = \bar{U} \cup U^c$ , contradicting the irreducibility of  $Y$ . To see the irreducibility of  $U$ , suppose that  $U = A \cup B$  with  $A, B$  closed in  $Y$ . Because  $U$  is dense in  $Y$ , we know  $Y = \bar{U} = \overline{A \cup B} = \bar{A} \cup \bar{B}$ . As  $Y$  is irreducible, we must have  $Y = \bar{A}$  or  $Y = \bar{B}$ . Without loss of generality, assume that  $Y = \bar{A}$ . Therefore,  $A = \bar{A} \cap U = Y \cap U = U$ . But then  $U$  is irreducible.  $\triangleleft$

**Proposition 1.11.** *If  $Y$  is an irreducible subsets of  $X$ , then its closure in  $X$ ,  $\bar{Y}$ , is irreducible.*

*Proof.* Assume  $\bar{Y}$  is not irreducible. There exist closed subsets  $Y_1, Y_2$  of  $X$  with  $\bar{Y} \not\subseteq Y_1$ ,  $\bar{Y} \not\subseteq Y_2$ , and  $\bar{Y} = (\bar{Y} \cap Y_1) \cup (\bar{Y} \cap Y_2)$ . As  $Y \subseteq \bar{Y}$ , we have  $Y = (Y \cap Y_1) \cup (Y \cap Y_2)$ . But  $Y$

irreducible, so  $Y = Y \cap Y_1$  or  $Y = Y \cap Y_2$ . Without loss of generality, suppose  $Y = Y \cap Y_1$ . But then  $Y \subseteq Y_1$ , which as  $Y_1$  closed,  $\bar{Y} \subseteq Y_1$ , a contradiction.  $\square$

**Theorem 1.3** (Krull Hauptidealsatz). *Let  $A$  be a noetherian ring, and let  $f \in A$  be an element which is neither a zero divisor nor a unit. Then every minimal prime ideal  $\mathfrak{p}$  containing  $f$  has height 1.*

*Proof.* See Atiyah-Macdonald [AM69, p.122].  $\square$

**Proposition 1.12.** *A noetherian integral domain  $A$  is a UFD if and only if every ideal of height one is principal.*

*Proof.* See Matsumura [Mat70, p.141] or Bourbaki [Bou65, Chapter 7 §3].  $\square$

**Proposition 1.13.** *A variety  $Y \subseteq \mathbb{A}^n$  has dimension  $n - 1$  if and only if it is the zero set,  $Z(f)$ , for some irreducible polynomial  $f \in k[x_1, \dots, x_n]$ .*

*Proof.* Suppose that  $Y = Z(f)$ . If  $f$  is irreducible, we know that  $Z(f)$  is a variety. Now  $\mathfrak{p} = (f)$  is certainly the minimal prime of  $f$ . Then by Theorem 1.2,  $Z(f)$  has dimension 1. But again by Theorem 1.2,  $\text{height } \mathfrak{p} + \dim k[x_1, \dots, x_n] = \dim k[x_1, \dots, n]$ . Then by Proposition 1.8,  $\dim Y = \dim A(Y) = n - 1$ .

Now suppose  $Y$  has dimension  $n - 1$ . Observe  $\dim k[x_1, \dots, x_n] = n - 1$ , and  $\dim A = n$ . Then  $Y$  corresponds to a prime ideal of height 1, say  $\mathfrak{p}$ . Now the polynomial ring  $A$  is a UFD, so by Proposition 1.12,  $\mathfrak{p}$  is necessarily generated by an irreducible polynomial, say  $f$ . But then we have shown  $Y = Z(f)$ , as desired.  $\square$

## 2 Projective Varieties

### 2.1 Introduction

Graded rings first.

**Definition** (Grading). Let  $R$  be a ring. A grading of  $R$  is an expression of the additive group  $(R, +)$  as an internal direct sum  $R = \bigoplus_{i=1}^{\infty} R_i$  with the property that if  $a \in R_d, b \in R_e$ , then  $ab \in R_{e+d}$ , written  $R_e \cdot R_d \subseteq R_{de}$ . A graded ring is a ring together with a given grading. An element of  $R_d$  is said to be homogeneous of degree  $d$ .

**Example 2.1.** Let  $R = k[x_1, \dots, x_n]$ .  $R_i = \{f \in R: \text{all monomials of } f \text{ having } \deg i\} \cup \{0\}$ , is homogenous of every degree.  $\mathbb{C}[x, y]$ ,  $x^2 + 4xy - 17y^2$  is homogeneous of degree 2.  $x^3 - xy$  is not homogeneous.  $\triangleleft$

**Remark.** You can replace  $\bigoplus_{i=0}^{\infty} R_i$  with  $\bigoplus_{i \in M} R_i$ , where  $M$  is any monoid. We say the case of  $\mathbb{Z}$  is  $\mathbb{Z}$ -grading.

Let  $R$  be a graded ring. Each  $f \in R$  has a unique expression  $f = f_0 + \dots + f_d$ , where  $f_i$  is homogeneous of degree  $i$ —simply the definition of a direct sum.

Definition and prop (homogeneous graded ideal)

**Proposition 2.1.** Let  $R$  be a graded ring and  $I \subseteq R$  be an ideal. The following are equivalent:

- (i)  $I$  can be generated by homogeneous elements
- (ii)  $I = \bigoplus_{i=0}^{\infty} (I \cap R_i)$  as a group
- (iii) given  $f \in R$ , write  $f = f_0 + \dots + f_d$ , where  $f_i$  is homogeneous of degree  $i$ . Then  $f \in I$  if and only if all  $f_i \in I$ .

*Proof.* (b) if and only if (c) definition of direct sum. In (c), note that all  $f_i \in I$  certainly  $f \in I$ . The only things to check is  $f \in I$ , then  $f_i \in I$ . (c) to (a): write every  $f \in I$  as  $f = f_0 + \dots + f_d$ , where  $f_i$  is homogeneous of degree  $i$ . Certainly,  $I$  is generated by all the  $f_i$  that appear as  $f$  varies over all  $f \in I$ . (a) to (c): Say  $I$  is generated by  $\{f_{\alpha}\}, \alpha \in A$ , where  $f_{\alpha}$  is homogenous of degree  $d_{\alpha}$ . Choose  $F \in I$ , then  $F = \sum_{i=1}^n a_i f_{\alpha_i}$ . Write  $F = F_0 + \dots + F_d$ , where  $F_j$  is homogeneous of degree  $j$ . What is  $F_j$  in terms of the expression?

$$F_j = \sum_{i=1}^n ((\deg j - \deg(f_{\alpha_i})) \text{ piece of } a_i) f_{\alpha_i} \in I.$$

□

**Proposition 2.2.** Let  $R$  be a graded ring.

- (i) if  $I, J$  are homogeneous ideals, then so are  $I + J$ ,  $IJ$ ,  $I \cap J$ , and  $\sqrt{I}$
- (ii) let  $I$  be a homogeneous ideal. Then  $I$  is prime if and only if for any two homogeneous elements  $f, g \in R$ , if  $fg \in I$  then either  $f \in I$  or  $g \in I$ .
- (iii) if  $f, g \in R$ , and integral domain, with  $f, g$  nonzero, then  $fg$  is homogeneous if and only if  $f, g$  are homogeneous.

*Proof.*

$f = f_0 + \cdots + f_d$ ,  $g = g_0 + \cdots + g_e$   $fg = (f_d g_e) + (f_{d-1} g_e + f_d g_{e-1}) + \cdots$ . If all  $f_i \in I$ , then  $f \in I$  and we are done. If all  $g_i \in I$ , then  $g \in I$  and we are done. So assume that  $f_i \notin I$  and some  $g_j \notin I$ . Let  $s$  be the largest number such that  $f_s \notin I$  and let  $t$  be the largest number such that  $g_t \notin I$ . We examine the degree  $s + t$  piece of  $fg$  as  $fg \in I$  and  $I$  is homogeneous, it is in  $I$ . It will have the form  $f_s g_t +$  terms of the form  $f_i g_j$  with either  $i > s$  or  $j > t$ . All of these extra terms are in  $I$ , the whole sum is in the ideal. Thus,  $f_s g_t \in I$  then either  $f_s \in I$  or  $g_t \in I$ , a contradiction.  $\square$

For a homogeneous ideal  $I$  of  $R$ , we often denote  $I \cap R_i$  by  $I_i$ . It then follows that

$$R/I \cong \frac{\bigoplus R_i}{\bigoplus I_i} \cong \bigoplus_{i=0}^{\infty} R_i/I_i.$$

Thus,  $R/I$  is naturally a graded ring with  $(R/I)_i = R_i/I_i$ . Now suppose  $R$  is a noetherian graded ring and  $I \subset R$  is a homogeneous ideal. We know  $I$  can be generated by homogeneous ideal because it is homogeneous. Because  $R$  is noetherian,  $I$  can be generated by finitely many elements. Can it be generated by finitely many homogeneous elements? Indeed, this is the case. If you set up the proof of the ACC then every ideal is f.g., you can prove ACC then every set of generators for an ideal has a finite subset that generates.

Now for projective space, you may have heard ‘parallel lines meet at infinity’.

The basic idea is to ‘compactify’  $\mathbb{A}^n$  by adding ‘points at infinity’. This is similar to the way  $\mathbb{R}^1$  is compactified to  $S^1$  or  $\mathbb{R}^2$  to  $S^2$ . This is not at all apparent from the initial definition of projective space, but will eventually become clear.

Consider  $\mathbb{A}^{n+1}$  with coordinates  $x_0, x_1, \dots, x_n$ . On  $\mathbb{A}^{n+1} \setminus \{(0, \dots, 0)\}$ , we define the following equivalence relation:  $(a_0, \dots, a_n) \sim (b_0, \dots, b_n)$  if and only if there exists  $\lambda \in k^\times$  such that  $(a_0, \dots, a_n) = (\lambda b_0, \dots, \lambda b_n)$ . The equivalence class of  $(a_0, \dots, a_n)$  is the one-dimensional subspace of  $\mathbb{A}^{n+1}$  spanned by  $(a_0, \dots, a_n)$ —minus the origin, which is the line through the origin and  $(a_0, \dots, a_n)$  minus the origin.

**Definition.** Projective  $n$ -space over  $k$ , denoted  $\mathbb{P}_k^n$  or  $\mathbb{P}^n(k)$  or  $\mathbb{P} = \mathbb{A}_k^{n+1} \setminus \{(0, \dots, 0)\} / \sim$ . A point  $P \in \mathbb{P}$  is an equivalence class of some point  $(a_0, \dots, a_n) \in \mathbb{A}^{n+1} \setminus \{(0, \dots, 0)\}$  and is denoted  $[a_0, \dots, a_n]$ . The  $a_i$  are called the homogeneous coordinates of the point  $P$ . They are well defined up to a nonzero constant multiple.  $\mathbb{P}$  is also the set of lines through the origin in  $k^{n+1}$ , the set of one-dimensional subspaces of  $k^{n+1}$ .

Denote the polynomial ring  $k[x_0, \dots, x_n]$  by  $S$ . For  $f \in S$  and  $O \in \mathbb{P}^n$ ,  $f(P)$  is not well defined because the coordinates of  $P$  are not well defined. But suppose  $f \in S$  is homogeneous:  $f(\lambda a_0, \dots, \lambda a_n) = \lambda^{\deg f} f(a_0, \dots, a_n)$ .  $f(P)$  still not well defined since  $\lambda \in k^\times$ , whether  $f(P) = 0$  is well defined. So we define for a homogeneous  $f \in S$ , we define the zeros of  $f$ , denoted  $Z(f)$  by  $Z(f) = \{P \in \mathbb{P}^n : f(P) = 0\}$ . For a set of homogeneous elements  $T \subseteq S$ , we define the zeros of  $T$ , denoted  $Z(T)$  by  $Z(T) = \cap_{f \in T} Z(f) = \{P \in \mathbb{P}^n : f(P) = 0 \text{ for all } f \in T\}$ . A set  $Y \subseteq \mathbb{P}^n$  is called algebraic if and only if  $Y = Z(T)$  for some subset  $T \subseteq S$  of homogeneous elements. If  $I \subseteq S$  is a homogeneous ideal, we define  $Z(I) = \{P \in \mathbb{P}^n : f(P) = 0 \text{ for all homogeneous } f \in I\} = \cap_{f \in I, f \text{ homog}} Z(f)$ .

**Proposition 2.3.** *Let  $T \subseteq S$  be a set of homogeneous elements, and let  $I \subseteq S$  be the homogenous ideal generated by  $T$ . Then  $Z(T) = Z(I)$ . Thus, every algebraic set in  $\mathbb{P}^n$  is of the form  $Z(I)$  for a homogeneous ideal and  $Z(\{f_1, \dots, f_r\})$  for finitely many homogeneous  $f_i$ ,  $Z(f_1, \dots, f_r)$ .*

The algebraic subsets of  $\mathbb{P}^n$  satisfy the properties needed to be the closed subsets of a topology on  $\mathbb{P}^n$ , it is the Zariski topology.

**Definition.** A projective algebraic variety (or simply projective variety) is an irreducible algebraic set in  $\mathbb{P}^n$ , with the induced topology. An open subset of a projective variety is a quasi-projective variety. The dimension of a variety or quasi-projective variety is its dimension as a topological space. If  $Y$  is any subset of  $\mathbb{P}^n$ , we define the homogeneous ideal of  $Y$  in  $S$ , denoted  $I(Y)$ , generated by  $\{f \in S : f \text{ homogeneous and } f(P) = 0 \text{ for all } P \in Y\}$ . If  $Y$  is an algebraic set, we define the set of homogeneous coordinate ring of  $Y$  to be  $S(Y) := S/I(Y)$ .

Note that  $I(Y)$  is a homogeneous ideal so  $S(Y)$  is a graded ring. These are similar to old algebraic sets with one funny difference.  $S$  is clearly a homogeneous ideal of  $S$ .  $Z(S) = \emptyset$ ,  $S = k[x_0, \dots, x_n]$  ( $x_0, \dots, x_n$ ) is also clearly a homogeneous ideal of  $S$ . It is often called  $S_+$  because it contains all homogeneous elements of positive degree  $Z(S_+) = \emptyset$ . This is the only thing which goes awry.  $S_+$  is sometimes called the irrelevant maximal ideal since it removed from the correspondence we saw in the affine case.

We now work on showing  $\mathbb{P}^n$  is  $\mathbb{A}^{n+1}$  with points added at  $\infty$ . In  $\mathbb{P}^n$ , consider closed sets of the form  $Z(f)$  with  $f$  a nonconstant polynomial. These are called hypersurfaces. When  $f$  is linear, it is called a hyperplane. Of particular interest is when  $f = x_i$  for some  $i$ . Set  $H_i = Z(x_i) = \{[a_0, \dots, a_n] \mid a_i = 0\}$  and  $U_i = \mathbb{P}^n \setminus H_i$ ,  $i = 0, \dots, n$ ,  $U_i$  open. The  $U_i$  are an open cover of  $\mathbb{P}^n$

$$(\cup_i^n U_i)^c = \cap_0^n U_i^c = \cap_0^n H_i = \{[a_0, \dots, a_n] : a_i = 0 \text{ all } i\} = \emptyset.$$

$P = [a_0, \dots, a_n] \in U_i$  if and only if  $P = [a_0/a_i, \dots, a_{i-1}/a_i, 1, a_{i+1}/a_i, \dots, a_n/a_i]$ . Each point in  $U_i$  has a unique set of homogeneous coordinates such that the  $i$ th coordinate is 1. Define a map  $\phi_i : \mathbb{A}^n \rightarrow U_i$  by  $\phi_i(a_1, \dots, a_n) = [a_1, a_2, \dots, 1, \dots, a_n]$ . Moreover, this is clearly a bijection.

**Proposition 2.4.** *The map  $\phi_i$  is a homeomorphism of  $U_i$  with its induced topology to  $\mathbb{A}^n$  with its Zariski topology.*

The proof is based on homogenization and dehomogenization of polynomials. To make notation simpler, we assume  $i = 0$ . Let  $S = k[x_0, \dots, x_n]$ ,  $A = k[x_1, \dots, x_n]$ , and  $S^h$  denote the homogeneous elements of  $S$ . There is a ring homomorphism  $\alpha : S \rightarrow A$ , defined as evaluation at  $x_0 = 1$ :  $\alpha(f(x_0, \dots, x_n)) = f(1, x_1, \dots, x_n)$ . Since  $\alpha$  is a ring homomorphism

$$\begin{aligned}\alpha(f + g) &= \alpha(f) + \alpha(g) \\ \alpha(fg) &= \alpha(f)\alpha(g),\end{aligned}$$

called dehomogenization because even if  $f$  is homogeneous,  $\alpha(f)$  may not be:  $\alpha(x_0^2 + x_0x_1) = 1 + x_1$ .

Homogenization:  $\beta : A \rightarrow S^h$ :  $\beta(f(x_1, \dots, x_n)) = x_0^{\deg f} f(x_1/x_0, \dots, x_n/x_0)$ ,  $\beta(f)$  is homogeneous of degree  $\deg f$ . Look at a monomial of  $f$ :  $x_1^{i_1} x_2^{i_2} \dots x_n^{i_n}$ ,  $i_1 + \dots + i_n \leq \deg f$ .

$$x_0^{\deg f} (x_1/x_0)^{i_1} \dots (x_n/x_0)^{i_n} = x_0^{\deg f - (i_1 + \dots + i_n)} x_1^{i_1} \dots x_n^{i_n}$$

has degree  $\deg f$ .

$\beta(fg) = \beta(f)\beta(g)$ .  $\beta(fg) = x_0^{\deg f + \deg g} f(x_1/x_0, \dots, x_n/x_0)g(x_1/x_0, \dots, x_n/x_0) = x_0^{\deg f} f(x_1/x_0, \dots, x_n/x_0) x_0^{\deg g} g(x_1/x_0, \dots, x_n/x_0) = \beta(f)\beta(g)$ .  $\beta(f + g)$  might not equal  $\beta(f) + \beta(g)$ .

If  $\deg f \neq \deg g$ ,  $\beta(f) + \beta(g)$  will not even be homogeneous.

If  $\deg f = \deg g = \deg(f + g)$ , then  $\beta(f + g) = \beta(f) + \beta(g)$ .

$$\alpha(\beta(f)) = \alpha(x_0^{\deg f} f(x_1/x_0, \dots, x_n/x_0)) = 1^{\deg f} f(x_1/x_0, \dots, x_n/x_0) = f$$

$\beta(\alpha(f)) = \beta(\alpha(x_0^l f))$ . Assume you have a homogeneous  $F$  that is not divisible by  $x_0$ .

$$F = \sum a_{i_0 \dots i_n} x_0^{i_0} \dots x_n^{i_n}$$

where  $i_0 + \dots + i_n = d$ .

$\alpha(F) = \sum a_{i_0 \dots i_n} x_1^{i_0} \dots x_n^{i_n}$  and in at least one case  $i_1 + \dots + i_n = d$ .

$\beta(\alpha(F)) = x_0^d a_{i_0 \dots i_n} ((x_1/x_0)^{i_0} \dots (x_n/x_0)^{i_n}) = F$ . Consider a point  $(a_1, \dots, a_n) \in \mathbb{A}^n$ .  $\phi_0(a_1, \dots, a_n) = [1, a_1, \dots, a_n] \in U_0 \subseteq \mathbb{P}^n$ .

$f \in k[x_1, \dots, x_n]$   $F \in k[x_0, \dots, x_n]$   $F$  homogeneous  $f(a_1, \dots, a_n) = 1^{\deg f} f(a_1/1, \dots, a_n/1) = \beta(f)(1, a_1, \dots, a_n)$ .  $F(1, a_1, \dots, a_n) = \alpha(F)(a_1, \dots, a_n)$ .  $f$  vanishes at  $P \in \mathbb{A}^n$  if and only if  $\beta(f)$  vanishes on  $\phi_0(P) \in U_0$   $F$  vanishes at  $\phi_0(P) \in U_0$  if and only if  $\alpha(F)$  vanishes at  $P \in \mathbb{A}^n$ .

It is now easy to see that  $\phi_0 : \mathbb{A}^n \rightarrow U_0 \subseteq \mathbb{P}^n$  is a homeomorphism.

Suppose  $Y \subseteq \mathbb{A}^n$  is closed.  $Y = Z(T)$ ,  $T \subseteq k[x_1, \dots, x_n]$ . Set  $\beta(T) = \{\beta(f) \mid f \in T\}$ ,  $\phi_0(Y) = Z(\beta(T)) \cap U_0$ .  $W \subseteq U_0$  closed in  $U_0$   $W = U_0 \cap \overline{W}$ ,  $\overline{W}$  closed in  $\mathbb{P}^n$   $\overline{W} = Z(T)$ ,  $T \subseteq S^h$   $\alpha(T) = \{\alpha(F) \mid F \in T\}$   $\phi_0^{-1}(W) = Z(\alpha(T))$



**Corollary 2.1.** *If  $Y$  is a projective (respectively quasi-projective) variety, then  $Y$  is covered by the open sets  $U_i \cap Y$ ,  $i = 0, \dots, n$ , which are homeomorphic to affine (respectively quasi-affine) varieties with the map  $\phi_i$ .*

$\mathbb{A}^n \cong U_i \subseteq \mathbb{P}^n$ ,  $U_i = \mathbb{P}^n \setminus H_i$ ,  $H_i = Z(x_i) = \{[a_0, \dots, 0, \dots, a_n \mid \text{not all } a_i = 0\} \cong \mathbb{P}^{n-1}$ ,  $\mathbb{P}^n = \mathbb{A}^n \cup \mathbb{P}^{n-1}$ . Parallel lines meet at infinity.

$\mathbb{A}^2$  coordinates  $x, y$   $Ax + By + C = 0$  at least one of  $A, B \neq 0$ .  $AB + Cy + D = 0$ ,  $C \neq D$ .

Homogenize  $Z(A(X/Z) + B(Y/Z) + C = 0)$   $Ax + By + CZ = 0 - Ax + BY + DZ = 0$  so  $(C - D)Z = 0$  so  $Z = 0$ . If  $Z = 0$ , still have  $Ax + By = 0$ .

$x = \lambda B$ ,  $y = -\lambda A$ ,  $[\lambda B, -\lambda A, 0]$  for  $\lambda \neq 0$ . One point in  $\mathbb{P}^2$ .  $[B, -A, 0]$  it is in  $H_2$ .  
 $x_0 \iff x, x_1 \iff y, x_2 \iff z$ .

Slope of  $Ax + By + C = 0$  is the ratio  $-A/B$ . So each slope determines what point at infinity the line goes to.

Looking at a curve in different patches and seeing how they fit together. Hyperbola:  $xy - 1 = 0$  homogenize that  $xy - z^2 = 0$   $z = 1$ ,  $xy - 1 = 0$   $y = 1$   $x - z^2 = 0$   $x = 1$   $y - z^2 = 0$

$B(1/2, 2), [1/2, 2, 1]$   $C[-1, -1, 1], (-1, -1)$   $D[-1/2, -2, 1], (-1/2, -2)$   $A[1, 1, 1], (1, 1)$   
 $y - z^2$  (plot)  $E[1, 0, 0](0, 0)$   $A(1, 1)[1, 1, 1]$   $B(4, 2)[1/2, 2, 1] = [1, 4, 2]$   $C[-1, -1, 1] =$   
 $[1, 1, -1]$   $D[-1/2, -2, 1] = [1, 4, -2]$   
 $x - z^2 = 0$  (plot)  $F(0, 0)$   $A(1, 1)[1, 1, 1]$   $B(1/4, 1/2), [1/2, 2, 1] = [1/4, 1, 1/2]$   $C(1, -1)[-1, -1, 1] =$   
 $[1, 1, -1]$   $D(1/4, -1/2)[-1/2, -2, 1] = [1/4, 1, -1/2]$

$\rho_d(P) = [M_0(P), M_1(P), \dots, M_N(P)]$  First note that the map is well defined.  $\rho_d([\lambda a_0, \dots, \lambda a_n]) = \lambda^d \rho_d([a_0, \dots, a_n])$  because all of the  $M_i$  are homogeneous of degree  $d$ .

$f : \mathbb{P}^2 \rightarrow \mathbb{P}^2$   $f[(x_0, x_1, x_2)] = [x_0 x_1 x_0 x_2, x_0^2] [0, 0, 1] \rightarrow [0, 0, 0]$ , bad

But not a problem above since one of  $a_i$  is nonzero. The exercise asks you to check various things.  $\rho_d$  is one-to-one,  $\rho_d(\mathbb{P}^n)$  is a closed subset of  $\mathbb{P}^N$ , if we give  $\rho_d(\mathbb{P}^n)$  its induced topology as a subset of  $\mathbb{P}^N$  then  $\rho_d : \mathbb{P}^n \rightarrow \rho_d(\mathbb{P}^n)$  is a homeomorphism. It seems reasonable to call it an embedding.

**Example 2.2.**  $n = 1, d = 2$   $[a_0, a_1] \mapsto [a_0^2, a_0 a_1, a_1^2]$ , labeled  $X, Y, Z$ . The image is contained in  $Z(XZ - Y^2)$ . In fact,....  $\triangleleft$

**Example 2.3** (Segre Embedding). Let  $\psi : \mathbb{P}^r \times \mathbb{P}^s \rightarrow \mathbb{P}^n$  be the map defined by sending the ordered pair  $[a_0, \dots, a_r] \times [b_0, \dots, b_s] \mapsto [\dots, a_i b_j, \dots]$  all  $a_i b_j$ .  $N = rs + r + s = (r + 1)(s + 1) - 1$ . This is well defined.  $[\lambda a_0, \dots, \lambda a_r] \times [\mu b_0, \dots, \mu b_s] = \lambda \mu [\dots a_i b_j \dots]$ .  $\triangleleft$

**Example 2.4.**  $\psi : \mathbb{P}^1 \times \mathbb{P}^1 \rightarrow \mathbb{P}^3$   $[a_0, a_1] \times [b_0, b_1] \mapsto [a_0 b_0, a_0 b_1, a_1 b_0, a_1 b_1]$  labeled  $WXYZ$ . image lies on  $WZ - XY = 0$  in fact =. Book asks you to show  $\psi$  is one-to-one and image is closed.  $\triangleleft$

The book does not ask you to show that  $\psi$  is a homeomorphism onto its image when you give the image the induced topology. Why? We have not defined the Zariski topology on  $\mathbb{P}^r \times \mathbb{P}^s$ .

It is an exercise to show that if we identify  $\mathbb{A}^2$  with  $\mathbb{A}^1 \times \mathbb{A}^1$  in the natural way that the Zariski topology on  $\mathbb{A}^2$  is not the product topology of the Zariski topologies on the two  $\mathbb{A}^1$ 's. Hint: In  $\mathbb{A}^2$  with coordinates  $x, y$ ,  $Z(x - y)$  is closed in  $\mathbb{A}^2$  with the Zariski topology, but not the product topology.

There are three ways to define the Zariski topology on  $\mathbb{P}^r \times \mathbb{P}^s$ .

1)  $\mathbb{P}^r$  is covered by  $U_i$ 's with the  $U_i$  homeomorphic to  $\mathbb{A}^r$ .  $\mathbb{P}^s$  is covered by  $U_j$ 's with each  $U_j$  homeomorphic to  $\mathbb{A}^s$ .  $\mathbb{P}^r \times \mathbb{P}^s$  will be covered by  $U_i \times U_j$ 's.  $\mathbb{P}^s$  is covered by  $U_j$ 's with each  $U_j$  homeomorphic to  $\mathbb{A}^s$ .  $\mathbb{P}^r \times \mathbb{P}^s$  will be covered by  $U_i \times U_j$ 's. Give  $U_i \times U_j$  the Zariski topology of  $\mathbb{A}^{r+s}$ ,  $U_i \times U_k \cap U_k \times U_l$ . The topology induced from  $U_i \times U_j$  is the same as the topology induced from  $U_k \times U_l$ . So you can glue to get a topology on  $\mathbb{P}^r \times \mathbb{P}^s$ .  $X \subseteq \mathbb{P}^r \times \mathbb{P}^s$  closed if and only if  $X \cap U_i \times U_j$  closed all  $i, j$ .

2) on  $\mathbb{P}^r$  take homogeneous coordinates  $x_0, \dots, x_r$  and on  $\mathbb{P}^s$  take homogeneous coordinates  $y_0, \dots, y_s$ . A polynomial  $f \in k[x_0, \dots, x_r, y_0, \dots, y_s]$  is said to be bihomogeneous of bidegree  $d, e$  if and only if every monomial of  $f$  has degree  $d$  in the  $x_i$ 's and degree  $e$  in the  $y_j$ 's. In this case,  $f(\lambda a_0, \dots, \lambda a_r, \mu b_0, \dots, \mu b_s) = \lambda^d \mu^e f(a_0, \dots, a_r, b_0, \dots, b_s)$  whether  $f$  vanishes on  $(P, Q) \in \mathbb{P}^r \times \mathbb{P}^s$  is well defined. Define  $Y \subseteq \mathbb{P}^r \times \mathbb{P}^s$  is closed if and only if  $Y = Z(T)$  for some subset  $T \subseteq k[x_0, \dots, y_s]$  of bihomogeneous polynomials.

3) Give  $\mathbb{P}^r \times \mathbb{P}^s$  the unique topology it must have for the Segre map  $\psi : \mathbb{P}^r \times \mathbb{P}^s \rightarrow \psi(\mathbb{P}^r \times \mathbb{P}^s) \subseteq \mathbb{P}^N$  to be a homeomorphism when  $\psi(\mathbb{P}^r \times \mathbb{P}^s)$  is given the induced topology as a subset of  $\mathbb{P}^N$ .

All three give the same topology.

3 morphisms:

Note: any affine variety is also a quasi-affine variety. Same thing holds for projective and quasi-projective.

def: let  $Y$  be a quasi-affine variety in  $\mathbb{A}^n$ . A function  $f : Y \rightarrow k$  is regular at a point  $P \in Y$  if and only if there is an open neighborhood  $U$  with  $P \in U \subseteq Y$  and polynomials  $g, h \in A = k[x_1, \dots, x_n]$  such that  $h$  is nowhere zero on  $U$  and  $f = g/h$  on  $U$ . We say that  $f$  is regular on  $Y$  if and only if it is regular at every point of  $Y$ .

"A function is regular if and only if it is locally a rational function."

Note: It is important to remember this is not iff continuous does not imply regular.  $f : \mathbb{A}^1 \rightarrow \mathbb{A}^1$  every bijection is continuous.

Lemma 3.1: A regular function is continuous when  $k$  is identified with  $\mathbb{A}_k^1$  with its Zariski topology.

*Proof.* It is enough to show that  $f^{-1}$  of closed is closed.  $f^{-1}(\emptyset) = \emptyset$ . Need  $f^{-1}$  of finite sets closed. Since finite unions of closed are closed just need to show  $f^{-1}$  of a point is closed. This can be checked locally: a subset  $Z$  of a topological space  $Y$  is closed if there exists an open cover of  $Y$  such that  $Z \cap U$  is closed in  $U$  for every  $U$  in cover.

Let  $U$  be an open set on which  $f$  can be represented  $f = g/h$ ,  $g, h$  polynomials on  $U$ ,  $h \neq 0$ . Such  $U$  form open cover.  $f^{-1}(a) \cap U = \{P \in U : g(P)/h(P) = a\}$

$g(P)/h(P) = a$  if and only if  $(g - ah)(P) = 0$ . that is closed.

Functions on projective spaces are more tricky.  $P \in \mathbb{P}^n$ ,  $f \in k[x_0, \dots, x_n]$ .  $f(P)$  is not well defined even if  $f$  is homogeneous.  $f, g \in k[x_0, \dots, x_n]$  both homogeneous of the same degree  $d$ . also assume  $g(P) \neq 0$ .  $P = [a_0, \dots, a_n]$

$$\frac{f(\lambda a_0, \dots, \lambda a_n)}{g(\lambda a_0, \dots, \lambda a_n)} = \frac{\lambda^d f(a_0, \dots, a_n)}{\lambda^d g(a_0, \dots, a_n)} = \frac{f(a_0, \dots, a_n)}{g(a_0, \dots, a_n)}.$$

Therefore,  $f/g(P)$  is well defined.

**Def:** Let  $Y$  be a quasi projective variety in  $\mathbb{P}^n$ . A function  $f : Y \rightarrow k$  is regular at a point  $P \in Y$  iff there is an open neighborhood  $U$  with  $P \in U \subseteq Y$  and homogeneous polynomials  $g, h \in S = k[x_0, \dots, x_n]$  of the same degree such that  $h$  is nowhere zero on  $U$  and  $f = g/h$  on  $U$ . We say  $f$  is regular iff it is regular at every point.

**Proposition 2.5.** Let  $Y \subseteq \mathbb{P}^n$  be a quasi-projective variety.  $f : Y \rightarrow k$  a function.  $P \in Y$  and assume  $P \in U_i = \mathbb{P}^n \setminus Z(x_i)$ . Then when we think of  $U_i$  as  $\mathbb{A}^n$ ,  $Y \cap U_i$  is a quasi-affine variety and by restriction we get a function  $f|_{Y \cap U_i} : Y \cap U_i \rightarrow k$ . Then  $f$  is regular at  $P$  under the projective definition iff  $f|_{Y \cap U_i}$  is regular at  $P$  under the affine definition.

*Proof.* Assume  $f$  is regular at  $P$  under the projective definition. Thus, we have an open set  $U$  with  $P \in U \subseteq Y$  and homogeneous polynomials  $g, h \in S = k[x_0, \dots, x_n]$  of the same degree such that  $h$  is nowhere zero on  $U$  and  $f = g/h$  on  $U$ . On  $U_0 \cap U$ , which is open in  $U_0 \cap Y$

$$\frac{g(a_0, \dots, a_n)}{h(a_0, \dots, a_n)} = \frac{g(1, a_1/a_0, \dots, a_n/a_0)}{h(1, a_1/a_0, \dots, a_n/a_0)}.$$

But  $g(1, x_1, \dots, x_n)h(1, x_1, \dots, x_n) \in k[x_1, \dots, x_n]$ ,  $h \neq 0$  on  $U_0 \cap Y$  so  $f|_{U_0 \cap Y}$  is regular at  $P$  under the affine definition.

Assume  $f|_{U_0 \cap Y}$  is regular at  $P$  under the affine definition. There is an open neighborhood  $U$  with  $P \in U \subseteq U_0 \cap Y$  and polynomials  $g, h \in k[x_1, \dots, x_n]$  such that  $h$  is nowhere zero on  $U$  and  $f = g/h$  on  $U$ . Note that  $U$  is open in  $Y$  not just  $U_0 \cap Y$ . Let  $G$  and  $H$  be the homogenizations of  $g$  and  $h$ . If they do not have the same degree multiply the one of lower degree by an appropriate power of  $x_0$  to make them both have the same degree. Now call them  $\bar{G}, \bar{H}$ . For any point  $P = [1, a_1, \dots, a_n] \in U$ ,

$$f(P) = \frac{g(P)}{h(P)} = \frac{\bar{G}(1, a_1, \dots, a_n)}{\bar{H}(1, a_1, \dots, a_n)} = \frac{\bar{G}(\lambda, \lambda a_1, \dots, \lambda a_n)}{\bar{H}(\lambda, \lambda a_1, \dots, \lambda a_n)}$$

**Fact:**  $X$  a variety  $f, g$  regular functions on  $X$ . Suppose  $f = g$  on some nonempty open  $U \subseteq X$ . Then  $f = g$  on all  $X$ . **Proof**  $Z(f - g)$  is closed in  $X$  and since in an irreducible space nonempty opens are dense it is also dense.  $Z(f - g) = X$ .  $\square$

**Definition.** Let  $k$  be a fixed algebraically closed field. A variety over  $k$  is an affine, quasi-affine, projective, or quasi-projective variety. If  $X$  and  $Y$  are two varieties, a morphism

$\phi : X \rightarrow Y$  is a continuous map such that for every open  $V \subseteq Y$  and for every regular function  $f : V \rightarrow k$ , the function  $f \circ \phi : \phi^{-1}(V) \rightarrow k$  is regular. A morphism  $\phi : X \rightarrow Y$  is an isomorphism if and only if there exists a morphism  $\psi : Y \rightarrow X$  such that  $\phi \circ \psi = 1_Y$  and  $\psi \circ \phi = 1_X$ .

Note that an isomorphism is bijective and bicontinuous (hence a homeomorphism). The converse does not hold. There exists bijective bicontinuous functions that are morphisms in one direction but not in the other.

**Example 2.5.**  $X = \mathbb{A}_t^1, Y = Z(Y^2 - X^3) \subseteq \mathbb{A}_{X,Y}^2$   $\phi : X \rightarrow Y, \phi(t) = (t^2, t^3)$  One can check that  $\phi$  is a morphism, one-to-one, onto,  $\phi^{-1}$  exists. Check that it is continuous.  $\phi^{-1}$  is not a morphism. There exists a regular function  $f : X \rightarrow k$  such that  $f \circ \phi^{-1} : ? \rightarrow ?$  is not regular.  $f$  is locally a rational function but  $f \circ \phi^{-1}$  is not. Problem at the cusp.

Alternate definition of a morphism:

**Proposition 2.6.** Let  $X \subseteq \mathbb{P}^n$  and  $Y \subseteq \mathbb{P}^m$  be quasi-projective varieties and  $f : X \rightarrow Y$  a function. Then  $f$  is a morphism if and only if the following condition is satisfied: given any  $P \in X$ , there exists a neighborhood  $U$  of  $P, P \in U \subseteq X$ , such that  $f(U)$  is contained in one of the affine opens  $U_i \subseteq \mathbb{P}^m$ .

Denote this set by  $U_0$ . Now think of  $f : U \rightarrow \mathbb{A}^m$ . We require further that there exist  $m$  regular functions  $g_i : U \rightarrow k$  such that for all  $Q \in U$

$$f(Q) = (g_1(Q), \dots, g_m(Q))$$

Further since regular functions are locally rational by shrinking  $U$ , you may assume each  $g_i$  is a rational function.

A morphism is a function locally given by tuples of rational functions. We have shown polynomials are continuous in the Zariski topology. Easily follows rational functions are continuous where defined. A composition of rational functions is rational.

**Example 2.6.** Consider the Veronese  $\nu : \mathbb{P}^2 \rightarrow \mathbb{P}^2$  given by  $\nu([x_0, x_1]) = [x_0^2, x_0x_1, x_1^2]$ . It is a morphism.  $y \mapsto (y, y^2)$ . On  $U_0 \subseteq \mathbb{P}^1, \nu(U_0) \subseteq U'_0$

$$U(1, x_1/x_0) = [1, x_1/x_0, (x_1/x_0)^2]$$

$$U_1 \subseteq \mathbb{P}^1, \nu(U_1) \subseteq U'_2 \quad \nu(x_0/x_1, 1) = [(x_0/x_1)^2, x_0/x_1, 1] \quad \nu(y) = [y^2, y].$$

Let  $X \subseteq \mathbb{P}^n$  and  $Y \subseteq \mathbb{P}^m$  be quasi-projective varieties and  $f : X \rightarrow Y$  be a function. Then  $f$  is a morphism if and only if the following condition is satisfied: given any  $P \in X$ , there is an open neighborhood  $U$  of  $P, P \in U \subseteq X$  and  $m$  polynomials.  $F_0, \dots, F_m \in k[x_0, \dots, x_n]$  all homogeneous of the same degree such that for all  $Q \in U$ ,  $f(Q) = [F_0(Q), F_1(Q), \dots, F_m(Q)]$ .

**Example 2.7.** We can find the inverse of the Veronese embedding.  $\nu : \mathbb{P}^1 \rightarrow \mathbb{P}^2$   $\nu([x_0, x_1]) = [x_0^2, x_0x_1, x_1^2]$  labeled  $(Y_0, Y_1, Y_2)$  On  $U_0 \subseteq \mathbb{P}^2$ ,  $\nu^{-1}[Y_0, Y_1, Y_2] = [Y_0, Y_1]$  On  $U_2 \cap \nu(\mathbb{P}^1) \subseteq \mathbb{P}^2$   $\nu^{-1}[Y_0, Y_1, Y_2] = [Y_1, Y_2]$   $U_0$  and  $U_2$  cover  $\nu(\mathbb{P}^1)$

$U_0: [x_0, x_1] \mapsto [x_0, x_0x_1, x_1^2] \mapsto [x_0^2, x_0x_1] = [x_0, x_1]$  since  $x_0 \neq 0$ .

$U_1: [x_0, x_1] \mapsto [x_0, x_0x_1, x_1^2] \mapsto [x_0x_1, x_1^2] = [x_0, x_1]$  since  $x_1 \neq 0$ .

No the other way:

$U_0: [Y_0, Y_1, Y_2] \mapsto [Y_0, Y_1] \mapsto [Y_0^2, Y_0Y_1, Y_1^2]$  only working on  $\nu(\mathbb{P}^1)$ ,  $Y_0Y_2 = Y_1^2$   $[Y_0^2, Y_0Y_1, Y_0Y_2] = [Y_0, Y_1, Y_2]$

$U_1: [Y_0, Y_1, Y_2] \mapsto [Y_1, Y_2] \mapsto [Y_1^2, Y_1Y_2, Y_2^2] = [Y_0Y_2, Y_1Y_2, Y_2^2] = [Y_0, Y_1, Y_2]$  since  $Y_2 \neq 0$ .

$\nu(\mathbb{P}^1) \cap U_0 \cap U_2$  on  $\mathbb{P}^2$   $[Y_0, Y_1, Y_2] \mapsto [Y_0, Y_1] = [Y_0Y_2, Y_1, Y_2] = [Y_1^2, Y_1Y_2] = [Y_1, Y_2]$  using  $Y_0Y_2 = Y_1^2$ .

**Definition.** Let  $Y$  be a variety. We denote by  $\mathcal{O}(Y)$  the ring of all regular functions on  $Y$ . If  $P$  is a point of  $Y$ , we define the local ring of  $P$  on  $Y$ ,  $\mathcal{O}_{P,Y}$  (or simply  $\mathcal{O}_P$ ) to be the ring of germs of regular functions on  $Y$  near  $P$ : equivalence classes of pairs  $\langle U, f \rangle$ , where  $U$  is an open neighborhood of  $P$  in  $Y$  and  $f$  is a regular function on  $U$  with the equivalence relation  $\langle U, f \rangle \sim \langle V, g \rangle \Leftrightarrow f = g$  on  $U \cap V$ .

$$\begin{aligned}\langle U, f \rangle + \langle V, g \rangle &= \langle U \cap V, f + g \rangle \\ \langle U, f \rangle \langle V, g \rangle &= \langle U \cap V, fg \rangle\end{aligned}$$

Of course, there much to check here. Use the fact that  $Y$  is a variety (hence irreducible)

Notice that for  $\langle U, f \rangle \in \mathcal{O}_{P,Y}$ ,  $f(P)$  is well defined because  $P$  is contained in every  $U$ . The evaluation map  $\text{ev} : \mathcal{O}_{P,Y} \rightarrow k$  given by  $\langle U, f \rangle \mapsto f(P)$  is easily seen to be a ring homomorphism. For surjectivity, observe that  $\langle Y, a \rangle \mathcal{O}_{P,Y}$  is the constant function  $a$  for  $a \in k$ . The kernel is a maximal ideal,  $\mathfrak{m}_{P,Y} = \{\langle U, f \rangle : f(P) = 0\}$ . Moreover,  $\mathcal{O}_{P,Y}/\mathfrak{m}_{P,Y} \cong k$ .

**Remark.** For any commutative noetherian ring  $R$ , we say that  $R$  is a local ring if and only if it has a unique maximal ideal,  $\mathfrak{m}$ . We say that  $R/\mathfrak{m}$  is the residue field of  $R$ .

**Proposition 2.7.**  $\mathcal{O}_{P,Y}$  is a local ring, i.e.  $\mathfrak{m}_{P,Y}$  the unique maximal ideal.

*Proof.* Recall that a ring is local if and only if it has a unique maximal ideal if and only if the only proper maximal ideal consists of all non-units of the ring. Suppose that  $\langle U, f \rangle \notin \mathfrak{m}_{P,Y}$ . Then  $f(P) \neq 0$ . By possibly restricting to a smaller open subset,  $P \in U_1 \subseteq U$ , we may write  $f = g/h$ , where  $g, h \in k[x_1, \dots, x_n]$ ,  $h \neq 0$  on  $U_1$ , and  $g(P) \neq 0$ . Let  $U_2 = U_1 \setminus Z(g)$ . We know that  $P \in U_2$  and  $h/g$  is regular on  $U_2$ . But then  $\langle U_2, h/g \rangle \in \mathcal{O}_{P,Y}$ . But

$$\langle U_2, h/g \rangle \cdot \langle U, f \rangle = \langle U_2, h/g \rangle \langle U_2, g/h \rangle = \langle U_2, 1 \rangle,$$

so that  $\langle U, f \rangle$  is invertible in  $\mathcal{O}_{P,Y}$ . Therefore,  $\langle U, f \rangle$  is not contained in any proper ideal. This shows that  $\mathfrak{m}_{P,Y}$  is the unique maximal ideal.  $\square$

Note that the above proof did not show that  $\mathcal{O}_{P,Y}$  was indeed noetherian, but we shall see this later. In fact, one does not need commutative or noetherian to define local, merely the unique maximal ideal. However, commutative algebraists typically, when using the term ‘local ring’, intend for this to mean commutative, noetherian, and with unique maximal ideal.

**Definition.** If  $Y$  is a variety, we define the function field of  $K(Y)$  of  $Y$  as follows: an element of  $K(Y)$  is an equivalence class of pairs  $\langle U, f \rangle$ , where  $U$  is a nonempty open subset of  $Y$ ,  $f$  is a regular function on  $U$ , and we define  $\langle U, f \rangle \sim \langle V, g \rangle$  if and only if  $f = g$  on  $U \cap V$ . We define

$$\begin{aligned}\langle U, f \rangle + \langle V, g \rangle &= \langle U \cap V, f + g \rangle \\ \langle U, f \rangle \langle V, g \rangle &= \langle U \cap V, fg \rangle.\end{aligned}$$

The elements of  $K(Y)$  are called rational functions on  $Y$ .

One should check that  $K(Y)$  is indeed a field. Note that one needs  $Y$  to be irreducible so that any two open sets intersect. Otherwise, the addition and multiplication described above might not make sense. We have natural ring homomorphisms

$$k \hookrightarrow \mathcal{O}(Y) \hookrightarrow \mathcal{O}_{P,Y} \hookrightarrow K(Y),$$

with maps  $a \mapsto$  constant function  $a$ ,  $f \mapsto \langle U, f \rangle$ , and  $\langle U, f \rangle \langle U, f \rangle$ , respectively. It is routine to verify that these are injective ring homomorphisms. Furthermore,  $\mathcal{O}(Y)$ ,  $\mathcal{O}_{P,Y}$ , and  $K(Y)$  are all  $k$ -algebras. We often think of them as subrings.

Now let  $f : X \rightarrow Y$  be a morphism of varieties. Since by definition under a morphism, regular functions pull back to regular functions, it is easy to see we get the following ring homomorphism:  $f^* : \mathcal{O}(Y) \rightarrow \mathcal{O}(X)$ . If  $P \in X$ ,  $f(P) \in Y$ . Now  $f^* : \mathcal{O}_{f(P),Y} \rightarrow \mathcal{O}_{P,X}$  is given by  $\langle U, g \rangle \mapsto \langle f^{-1}(U), f^*(g) \rangle$  and is a  $k$ -algebra homomorphism. When  $f$  is an isomorphism, these are both isomorphisms. Furthermore,  $(f^{-1})^* = (f^*)^{-1}$ , and  $\mathcal{O}(Y), \mathcal{O}_{P,Y}$  are isomorphic invariants. What about the map  $f^* : K(Y) \rightarrow K(X)$ ? This is not always defined: if  $f(X)$  is contained in a proper closed subset of  $Y$ , there will be some open  $U \subseteq Y$  such that  $f^{-1}(U) = \emptyset$ .

We now give a brief review of localization in commutative rings.

**Definition.** Let  $R$  be a ring and  $S \subseteq R$ . We say  $S$  is multiplicatively closed if and only if  $1 \in S$  and if  $a, b \in S$ , then  $ab \in S$ .

Given a ring  $R$  and a multiplicatively closed set  $S \subseteq R$ , we define the localization of  $R$  (with respect to  $S$ ), denoted  $S^{-1}R$  or  $R_S$  as follows: as a set  $S^{-1}R$  is the set of equivalence classes of elements  $r/s$ , where  $r \in R, s \in S$ , under the equivalence relation

$$\frac{r}{s} \sim \frac{a}{t} \Leftrightarrow \exists w \in S (\text{SUCH THAT}) w(rt - sa) = 0.$$

We make  $S^{-1}R$  into a ring by defining

$$\begin{aligned}\frac{r}{s} + \frac{a}{t} &= \frac{rt + as}{st} \\ \frac{r}{s} \cdot \frac{a}{t} &= \frac{ra}{st}.\end{aligned}$$

One of the most common examples of such an  $S$  and a ring is when  $R$  is an integral domain and  $S$  is the prime ideal  $S = R \setminus \{0\}$ . In this case  $S^{-1}R$  is the fraction field of  $R$ . More generally for any integral domain  $R$ , if  $\mathfrak{p}$  is a prime ideal, then  $S := R \setminus \mathfrak{p}$  is a multiplicatively closed subset (as one easily verifies). In this special case,  $S^{-1}R$  is denoted  $R_{\mathfrak{p}}$  instead of  $R_S = R_{R \setminus \mathfrak{p}}$ , called the localization of  $R$  at  $\mathfrak{p}$ . As another typical example, if  $f \in R$  is not nilpotent, then  $S = \{1, f, f^2, \dots\}$  is a multiplicatively closed subset of  $R$ . In this case,  $S^{-1}R$  is denoted  $R_f$ , called the localization of  $R$  at  $f$ .

**Remark.** If  $f$  is prime, then  $(f)$  is prime. However,  $R_f \neq R_{(f)}$ .

**Theorem 2.1.** *Let  $Y \subseteq \mathbb{A}^n$  be an affine variety with affine coordinate ring  $A(Y)$ . Then*

1.  $\mathcal{O}(Y) \cong A(Y)$
2. *for each point  $P \in Y$ , let  $\mathfrak{m}_P \subseteq A(Y)$  be the ideal of functions vanishing at  $P$ . Then  $P \mapsto \mathfrak{m}_P$  gives a one-to-one correspondence between the points of  $Y$  and the maximal ideals of  $A(Y)$*
3. *for each  $P$ ,  $\mathcal{O}_{P,Y} \cong A(Y)_{\mathfrak{m}_P}$  and  $\dim \mathcal{O}_{P,Y} = \dim Y$*
4.  *$K(Y)$  is isomorphic to the quotient field of  $A(Y)$ , and hence  $K(Y)$  is a finitely generated field extension of  $k$  with transcendence degree  $\dim Y$ .*

*Proof.*

- (a) We have an injective homomorphism  $\alpha : A(Y) \rightarrow \mathcal{O}(Y)$ . Start with the homomorphism  $f : k[x_1, \dots, x_n] \rightarrow \mathcal{O}(Y)$ . A regular function need to be locally rational (but polynomials are globally rational). The kernel of the map is  $I(Y)$ . Now

$$\alpha' : A(Y) = k[x_1, \dots, x_n] / I(Y) \longrightarrow \mathcal{O}(Y)$$

is injective. We prove surjectivity later.

- (b) The points of  $\mathbb{A}^n$  are in bijective correspondence with the maximal ideals of  $k[x_1, \dots, x_n]$ . [We know that the maximal ideals are points  $P = (a_1, \dots, a_n)$  and  $I(P) = (x_1 - a_1, \dots, x_n - a_n)$ , the polynomials vanishing at  $P$ .] Now  $P \in Y$  if and only if  $I(P) \supseteq I(Y)$ . But  $I(P)$  is maximal. The points of  $Y$  are then in bijective correspondence with the maximal ideals of  $k[x_1, \dots, x_n]$  containing  $I(Y)$  which are in correspondence with the maximal ideals of  $A(Y)$ , which are  $k[x_1, \dots, x_n] / I(Y)$ .

(c) For each point  $P$ , there is a natural map  $A(Y)_{\mathfrak{m}_P} \rightarrow \mathcal{O}_{P,Y}$

$a/b \in A(Y)_{\mathfrak{m}_P}$ , where  $a, b \in A(Y)$  and  $b(P) \neq 0$ . Replace  $a, b$  by polynomials that represent them. Now  $Y \setminus Z(b)$  is an open neighborhood of  $P$  in  $Y$ .

$a/b \mapsto \langle Y \setminus Z(b), a/b \rangle \in \mathcal{O}_{P,Y}$  is injective as  $\alpha$  is injective.

For surjective,  $\langle U, f \rangle \in \mathcal{O}_{P,Y}$  represented by  $\langle V, g/h \rangle$ ,  $g, h$  polynomials,  $h \neq 0$  on  $V$ ,  $g/h \in A(Y)$ .

This gives  $\mathcal{O}_{P,Y} \cong A(Y)_{\mathfrak{m}_P}$ .



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