

Algebraic Geometry I

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Roughly speaking, the goal of algebraic geometry is to study systems of polynomial equations $F_1(X) = \dots = F_n(X) = 0$ for polynomials $F_i \in K[X_1, \dots, X_m]$ over a field (or ring) K . The set of solutions of this system is a geometric object, which we try to understand using algebraic methods, for example considering the ideal $I = (F_1, \dots, F_n)$ in $K[X_1, \dots, X_m]$ or the quotient $K[X_1, \dots, X_m]/I$.

There is a very strong relation between these objects in the case that $K = \overline{K}$ is algebraically closed (e.g. \mathbb{C}). If K is not algebraically closed, or some generic ring, things get more complicated: For example, there are many equations over \mathbb{R} with no solutions, like $x^2 + y^2 + 1 = 0$, which behave differently when considered over \mathbb{C} . The wish to still study these equations geometrically leads to the idea of spectra (the set of all prime ideals of a ring), and later the theory of sheaves and schemes.

1 Algebraic Sets and Affine Varieties

Let K be an algebraically closed field.

Definition 1.1. For $n \in \mathbb{N}$ define *affine n -space* over K as

$$\mathbb{A}^n := \mathbb{A}_K^n := K^n.$$

Definition 1.2. Let $I \subset K[x_1, \dots, x_n]$ be a subset. The associated (*affine*) *algebraic set* is

$$V(I) := \{x \in \mathbb{A}_K^n \mid f(x) = 0 \text{ for all } f \in I\}.$$

A subset $X \subset \mathbb{A}^n$ is called *algebraic* if $X = V(I)$ for some $I \subset K[x_1, \dots, x_n]$.

Remark 1.3. By definition $V(I) = V(\langle I \rangle) = V(f_1, \dots, f_m)$ where $\langle I \rangle = (f_1, \dots, f_m)$ is finitely generated because $K[x_1, \dots, x_n]$ is Noetherian. Therefore, $X \subseteq \mathbb{A}^n$ is algebraic if and only if $X = V(I)$ for some ideal I if and only if $X = V(f_1, \dots, f_m)$ for a finite number of polynomials f_i .

Example 1.4. The following sets are algebraic:

- A parabola $\{(x, x^2) \mid x \in K\} = V(y - x^2)$
- $\emptyset = V(K[x_1, \dots, x_n])$
- $\mathbb{A}^n = V(0)$
- Points: $\{(a_1, \dots, a_n)\} = V(x_1 - a_1, \dots, x_n - a_n)$

Lemma 1.5. Let $I, J \triangleleft K[x_1, \dots, x_n]$ be ideals. Then

- (a) If $I \subseteq J$, then $V(I) \supseteq V(J)$.
- (b) $V(I \cap J) = V(IJ) = V(I) \cup V(J)$
- (c) For any family $(I_t)_{t \in T}$ of ideals, $\bigcap_t V(I_t) = V(\bigcup_t I_t) = V(\sum_t I_t)$

Proof. (a) is clear.

For (b), part (a) yields $V(I \cap J) \subseteq V(IJ)$ and $V(I), V(J) \subseteq V(I \cap J)$, so it remains to show $V(IJ) \subseteq V(I) \cup V(J)$. Let $a \in V(IJ)$. Assume $a \notin V(I)$, i.e. there is $f \in I$ such that $f(a) \neq 0$. Let $g \in J$. Then $fg \in IJ$, so $0 = (fg)(a) = f(a)g(a)$. Since $f(a) \neq 0$, we conclude $g(a) = 0$.

The first equation of (c) is tautological, the second one is remark 1.3, □

Definition 1.6. The *Zariski topology* on \mathbb{A}^n is the topology whose closed subsets are exactly the algebraic sets. That is, $U \subseteq \mathbb{A}^n$ is open iff its complement is algebraic.

Remark 1.7. This is indeed a topology by example 1.4 and lemma 1.5. Note that the Zariski topology induces (via the subspace topology) a topology on any algebraic set $X \subseteq \mathbb{A}^n$, which is also called the Zariski topology.

Recall from general topology that a topological space $X \neq \emptyset$ is called irreducible if $X \neq X_1 \cup X_2$ with $X_i \subsetneq X$ closed. \emptyset is not considered irreducible.

For example, $V(xy) = V(x) \cup V(y)$ (the union of the coordinate axes in \mathbb{A}^2) is not irreducible, while a parabola $V(y - x^2)$ is irreducible (we will see how to check this later).

Definition 1.8. An *affine algebraic variety* is an irreducible closed subset of \mathbb{A}^n .

Definition 1.9. Let $X \subseteq \mathbb{A}^n$ be an arbitrary set. We define the *vanishing ideal* of X as

$$I(X) := \{f \in K[x_1, \dots, x_n] \mid f(x) = 0 \text{ for all } x \in X\}$$

Lemma 1.10. Let $X \subseteq \mathbb{A}^n$ and $S \subseteq K[x_1, \dots, x_n]$. Then

- (a) $X \subseteq V(I(X))$ and $S \subseteq I(V(S))$.
- (b) $V(I(X)) = \overline{X}$ is the closure of X (w.r.t. the Zariski topology).

Proof. (a) is clear, (b) is left as an exercise. □

Proposition 1.11. An affine algebraic set $X \subseteq \mathbb{A}^n$ is a variety if and only if $I(X)$ is a prime ideal.

Proof. Let X be a variety and let $fg \in I(X)$ for $f, g \in K[x_1, \dots, x_n]$. We have $X \subseteq V(fg) \stackrel{1.5}{=} V(f) \cup V(g)$. Hence we can write $X = (X \cap V(f)) \cup (X \cap V(g))$ as the union of two closed subsets. By irreducibility, wlog we have $X = X \cap V(f)$, i.e. $X \subseteq V(f)$, which is equivalent to $f \in I(X)$.

Conversely, suppose that $X = A \cup B$ is not irreducible. Choose points $a \in A \setminus B$ and $b \in B \setminus A$. By Lemma 1.10 and since A, B are closed, we get $V(I(A)) = A$ and $V(I(B)) = B$. Hence there exist $f \in I(A)$ and $g \in I(B)$ with $f(b) \neq 0$ and $g(a) \neq 0$. Thus $fg \in I(X)$, but both $f, g \notin I(X)$ □

Remark 1.12. If $X = V(I)$ is an affine variety, this does not necessarily imply that I is prime: Consider $V((x^2)) \subseteq \mathbb{A}^1$: $V((x^2)) = \{0\}$ is irreducible, but (x^2) is not prime.

Note that \mathbb{A}^n is irreducible since K is infinite. However, this is no longer true if one considers finite fields, since then \mathbb{A}^n is the union of its finitely many points. For example, $I(A_{\mathbb{F}_p}^1) = (X^p - X)$ is not prime.

We use the following result from commutative algebra without proof:

Theorem 1.13 (Hilbert Nullstellensatz). Let $J \triangleleft K[x_1, \dots, x_n]$. Then

- (a) $V(J) = \emptyset$ if and only if $J = K[x_1, \dots, x_n]$.
- (b) $I(V(J)) = \sqrt{J} = \{f \in K[x_1, \dots, x_n] \mid f^n \in J \text{ for some } n\}$
- (c) If J is a maximal ideal, then $J = (x_1 - a_1, \dots, x_n - a_n)$ for some $a_i \in K$.

Corollary 1.14. *There are inclusion-reversing bijections*

$$\begin{aligned} \{\text{affine algebraic sets } X \subseteq \mathbb{A}^n\} &\xleftrightarrow[V]{I} \{\text{radical ideals in } K[x_1, \dots, x_n]\} \\ \{\text{affine algebraic varieties } X \subseteq \mathbb{A}^n\} &\xleftrightarrow[V]{I} \{\text{prime ideals in } K[x_1, \dots, x_n]\} \\ \{\text{points } a \in \mathbb{A}^n\} &\xleftrightarrow[V]{I} \{\text{maximal ideals in } K[x_1, \dots, x_n]\} \end{aligned}$$

Proof. Clear from 1.13, 1.10 and 1.11. \square

Example 1.15. Let f be irreducible in $K[x_1, \dots, x_n]$. Then $V(f)$ is an affine variety. Varieties of this form are called hypersurfaces in \mathbb{A}^n (curves for $n = 2$, surfaces for $n = 3$).

Remark 1.16. If $X \subseteq \mathbb{A}^n$ is a variety, by proposition 1.11 $I(X)$ is prime, and $K[x_1, \dots, x_n]/I$ is an integral domain. We can consider its fraction field $\text{Frac}(K[x_1, \dots, x_n]/I)$.

Theorem 1.17. *Any affine algebraic set can be uniquely written as a finite union of affine varieties.*

For the proof, we need some preparations.

Definition 1.18. A topological space X is called *Noetherian* if any chain of descending closed subsets $X \supseteq X_1 \supseteq X_2 \supseteq \dots$ becomes stationary, i.e. there exists n s.t. $X_m = X_n$ for all $m > n$.

Lemma 1.19. *Affine space \mathbb{A}^n is Noetherian.*

Proof. Let $\mathbb{A}^n \supseteq X_1 \supseteq X_2 \supseteq \dots$ be a chain of closed subsets. Applying $I(-)$ yields an ascending chain $(0) \subseteq I(X_1) \subseteq I(X_2) \subseteq \dots$ of ideals in $K[x_1, \dots, x_n]$. This is a Noetherian ring, so there is some m such that $I(X_n) = I(X_{n+1})$ for all $n \geq m$. By corollary 1.14(a), I is injective on closed subsets, so we are done. \square

More generally,

Corollary 1.20. *Any affine algebraic space $X \subseteq \mathbb{A}^n$ is Noetherian.*

Proof. Any chain in X is also a chain in \mathbb{A}^n . \square

Proposition 1.21. *Let $X \neq \emptyset$ be a Noetherian topological space.*

- (a) *Then X can be written as a finite union of irreducible closed subspaces.*
- (b) *Moreover, if we assume that $X_i \not\subseteq X_j$ for $i \neq j$, then the above decomposition is unique up to permutation. In this case, the X_i are called irreducible components of X .*

Proof. Assume that (a) fails for X . Consider $S = \{Y \subseteq X \mid Y \text{ closed, cannot be written as a finite union of irreducible closed subsets}\}$. Since X is Noetherian, S must have some minimal element Y w.r.t. inclusion. Y is not irreducible, so we can write $Y = Y_1 \cup Y_2$ with $Y_{1,2}$ proper closed subspaces. By minimality, Y_1 and Y_2 can be written as finite unions of irreducible closed subsets, thus so can Y , contradicting $Y \in S$.

To check uniqueness, assume we have two decompositions $X = X_1 \cup \dots \cup X_r = X'_1 \cup \dots \cup X'_s$ as in (b). Then $X'_1 = \bigcup_i (X_i \cap X'_1)$. Since X'_1 is irreducible, wlog $X'_1 \subseteq X_1$. By the same argument, $X_1 \subseteq X'_i$ for some i . If $i \neq 1$, then $X'_1 \subseteq X'_i$, contradicting our assumption. Hence $i = 1$ and $X_1 = X'_1$. Proceed inductively with $X \setminus X_1 = X_2 \cup \dots \cup X_r = X'_2 \cup \dots \cup X'_s$. \square

Combining 1.20 and 1.21 yields theorem 1.17.

Remark 1.22. The proof strategy for (a) can be summarized as follows: Let X be a Noetherian space and P a property of closed subsets. To show that P holds for all subsets of X (thus in particular for X), it suffices to show that for all $Y \subseteq X$ closed, if P holds for all proper closed subsets of Y , then it also holds for Y . This is called *Noether induction* (a special case of well-founded induction).

Example 1.23. Let $f \in K[x_1, \dots, x_n]$. This is a factorial ring, so we may write $f = g_1^{k_1} \dots g_r^{k_r}$ with g_i irreducible and pairwise different. Then

$$V(f) = V(g_1^{k_1}) \cup \dots \cup V(g_r^{k_r}) = V(g_1) \cup \dots \cup V(g_r)$$

is the decomposition of $V(f)$ into irreducible subsets: $V(g_i)$ is irreducible by proposition 1.11, since $I(V(g_i)) = (g_i)$ is prime.

In general, finding this composition for $V(f_1, \dots, f_r)$ is not easy.

Example 1.24. What is the Zariski topology on \mathbb{A}^1 ? By definition, a closed/algebraic set is of the form $V(I)$ for some ideal $I \subseteq K[x]$. Since $K[x]$ is a PID, $I = (f)$ for some $f = (x - a_1)^{k_1} \dots (x - a_r)^{k_r} \in K[x]$. If f is not constant, we see as in example 1.23 that

$$X = V(f) = \bigcup_i V(x - a_i) = \{a_1, \dots, a_r\}.$$

Hence the closed sets are exactly $V(0) = \mathbb{A}^1$, $V(1) = \emptyset$, and finite unions of points. In other words, the Zariski topology coincides with the cofinite topology on \mathbb{A}^1 . The affine varieties on \mathbb{A}^1 are therefore either \mathbb{A}^1 itself or a single point.

We also see that any two non-empty open subsets have nontrivial intersection, so \mathbb{A}^1 with the Zariski topology is not Hausdorff.

Definition 1.25. Let X be a nonempty topological space. We define the dimension of X as the supremum of all $n \in \mathbb{N}$ such that there is a chain of irreducible subspaces $\emptyset \neq Y_0 \subseteq Y_1 \subseteq \dots \subseteq Y_n \subseteq X$.

Example 1.26. By example 1.24, a maximal chain of affine varieties in \mathbb{A}^1 is $\{0\} \subsetneq \mathbb{A}^1$, hence $\dim \mathbb{A}^1 = 1$.

Definition 1.27. Let R be a (commutative) ring. The Krull dimension of R is the supremum over all l such that there is a chain of prime ideals $\mathfrak{p}_l \subsetneq \mathfrak{p}_{l-1} \subsetneq \dots \subsetneq \mathfrak{p}_0 \subsetneq R$.

Recall from corollary 1.14 that there is an inclusion-reversing correspondence between prime ideals of $K[x_1, \dots, x_n]$ and affine algebraic varieties in \mathbb{A}^n . Fixing some variety X , it follows that subvarieties correspond bijectively to prime ideals that contain $I(X)$, i.e. prime ideals of $K[x_1, \dots, x_n]/I(X)$. Hence

Proposition 1.28. If X is an affine algebraic variety, then $\dim X = \dim K[x_1, \dots, x_n]/I(X)$.

2 Morphisms of Affine Varieties

2.1 Regular Morphisms

Definition 2.1. Let $X \subseteq \mathbb{A}_K^n$ be an algebraic set. A function $f : X \rightarrow K$ is *regular* if there is a polynomial $F \in K[x_1, \dots, x_n]$ such that $f = F|_X$, i.e. $f(x) = F(x)$ for all $x \in X$. Write $A(X)$ for the set of regular functions on X .

Remark 2.2. $A(X)$ is a ring (and even a K -algebra) in a natural way, with addition and multiplication defined pointwise. Moreover, there is a homomorphism of K -algebras

$$K[x_1, \dots, x_n] \twoheadrightarrow A(X), \quad F \mapsto F|_X.$$

The kernel of this morphism is exactly $I(X)$, so that $A(X) \cong K[x_1, \dots, x_n]/I(X)$ canonically.

Remark 2.3. By corollary 1.14, $A(X)$ is always reduced, $A(X)$ is integral iff X is a variety, and $A(X)$ is a field iff X is a point (in which case $A(X) \cong K$).

Definition 2.4. Let $X \subseteq \mathbb{A}^n$, $Y \subseteq \mathbb{A}^m$ be affine algebraic sets. A map $\varphi : X \rightarrow Y$ is called *regular* if $\varphi = (f_1, \dots, f_m)$ for some regular $f_1, \dots, f_m \in A(X)$. A regular map φ is an isomorphism if it has an inverse which is also regular.

Example 2.5. (i) $f : \mathbb{A}^1 \rightarrow V(y - x^2) \subseteq \mathbb{A}^2$, $t \mapsto (t, t^2)$ is a regular map. It has inverse $(x, y) \mapsto x$, which is also regular, hence $\mathbb{A}^1 \cong V(y - x^2)$.

(ii) $\varphi : \mathbb{A}^1 \rightarrow V(y^2 - x^3) \subseteq \mathbb{A}^2$, $t \mapsto (t^2, t^3)$ is regular and bijective as well, but its inverse $(x, y) \mapsto \frac{y}{x}$ is not regular, so φ is not an isomorphism.

Proposition 2.6. Let $X \subseteq \mathbb{A}^n$ and $Y \subseteq \mathbb{A}^m$ be algebraic sets, and let $\varphi : X \rightarrow Y$ be a regular map. Then φ is continuous (w.r.t. the Zariski topology on X and Y).

Proof. Let $\varphi = (f_1, \dots, f_m)$ and $J = \langle F_1, \dots, F_k \rangle \subseteq K[x_1, \dots, x_m]$ with $V(J) \subseteq Y$. Then

$$\varphi^{-1}(V(J)) = \varphi^{-1}(V(F_1, \dots, F_k)) = \{x \in X \mid F_j(f_1(x), \dots, f_m(x)) = 0, j = 1, \dots, k\}$$

Now $F_j(f_1(x), \dots, f_m(x))$ is a composition of polynomials, hence a polynomial, call it \tilde{F}_j . We conclude $\varphi^{-1}(V(J)) = X \cap V(\tilde{F}_1, \dots, \tilde{F}_k)$ as desired. \square

Remark 2.7. The converse is false. For example, one easily concludes from example 1.24 that every bijective map $\mathbb{A}^1 \rightarrow \mathbb{A}^1$ is continuous, but there are way more bijections than polynomials (say because polynomials are defined by their values on any infinite subset). On the other hand, if K is finite (loosing algebraic closedness), then every function $\mathbb{A}^1 \rightarrow \mathbb{A}^1$ is regular.

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Remark 2.8. Let X be an algebraic set, and let $f : X \rightarrow \mathbb{A}^1$. Then f is a regular map if and only if f is a regular function. Note that the composition of regular maps is regular, since compositions of polynomials are polynomials.

Definition 2.9. Let X, Y be algebraic sets and $F : X \rightarrow Y$ be regular. Then we set $F^* : A(Y) \rightarrow A(X)$, $g \mapsto g \circ F$. This is well-defined by remark 2.8, and F^* clearly preserves addition and multiplication, so it is a morphism of K -algebras.

Remark 2.10. Let $F = (f_1, \dots, f_m) : X \rightarrow Y$, $f_i \in K[x_1, \dots, x_n]$, then F^* is given by the K -algebra homomorphism $A(Y) \cong K[y_1, \dots, y_m]/I(Y) \rightarrow K[x_1, \dots, x_n]/I(X) \cong A(X)$ (see remark 2.2) defined by $y_i \mapsto f_i$. Hence $F(x) = (F_1^*(y_1), \dots, F_m^*(y_m))$.

Theorem 2.11. (i) *There is a bijection $\text{Mor}(X, Y) \rightarrow \text{Hom}_{K\text{-Alg}}(A(Y), A(X))$ given by $F \mapsto F^*$.*

(ii) *If $F : X \rightarrow Y$ and $H : Y \rightarrow Z$ are regular, then $(H \circ F)^* = F^* \circ H^*$. Further, $\text{id}_X^* = \text{id}_{A(X)}$.*

(iii) *Let $F : X \rightarrow Y$ be regular. Then F is an isomorphism of affine sets if and only if F^* is an isomorphism of K -algebras*

Proof. Injectivity in (i) follows from remark 2.10. For surjectivity, let $\varphi : A(Y) \rightarrow A(X)$ be a K -algebra homomorphism and define $F : X \rightarrow Y$ by $F = (\varphi(y_1), \dots, \varphi(y_m))$. We need to check that this is well-defined, i.e. that the image of F lies in Y . Then it is clear that F is regular and that $F^* = \varphi$, again by remark 2.10.

So let $g \in I(Y)$, we need to show $g \circ F = 0$. But this is exactly the statement $\varphi([g]) = \varphi(0) = 0$.

For (ii), $\text{id}_X^* = \text{id}_{A(X)}$ is clear, and for $f \in A(Z)$ one has

$$(H \circ F)^*(f) = f \circ H \circ F = H^*(f) \circ F = (F^* \circ H^*)(f),$$

so $(H \circ F)^* = F^* \circ H^*$. Then (iii) follows from (i) and (ii). \square

Example 2.12. Looking again at the maps from example 2.5, we see that $f : \mathbb{A}^1 \rightarrow V(y-x^2), t \mapsto (t, t^2)$ is an isomorphism, because $f^* : K[x, y]/(y-x^2) \rightarrow K[t], x \mapsto t, y \mapsto t^2$ clearly is. On the other hand, let $\varphi : \mathbb{A}^1 \rightarrow V(y^2-x^3), t \mapsto (t^2, t^3)$. We saw that this is a bijective regular map and gave intuitive reasoning for why this map isn't an isomorphism. But now we can prove it: We have

$$f^* : K[x, y]/(y^2-x^3) \rightarrow K[t], \quad x \mapsto t^2, y \mapsto t^3$$

is not surjective, for the image does not contain t .

Remark 2.13. In categorical terms, theorem 2.11 says that

$$\begin{array}{c} \left\{ \begin{array}{l} \text{algebraic sets} \\ \text{regular maps} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{finitely generated reduced } K\text{-algebras} \\ K\text{-algebra homomorphisms} \end{array} \right\} \\ X \mapsto A(X) \\ F \mapsto F^* \end{array}$$

is a contravariant functor, and even an equivalence of categories: For essential surjectivity, note that every finitely generated K -algebra can be written as a quotient $K[x_1, \dots, x_n]/I$ by choosing generators. Then consider $X = V(I)$.

Proposition 2.14. *Let X, Y be algebraic sets, and let $f : X \rightarrow Y$ be a regular map. Then*

(i) *$f^* : A(Y) \rightarrow A(X)$ is surjective if and only if $\overline{f(X)} = Y$, i.e. if the image of f is dense in Y .*

(ii) *f^* is injective if and only if $f(X) \subseteq Y$ is closed and $f : X \rightarrow f(X)$ is an isomorphism.*

Proof. Exercise. \square

2.2 Rational Maps of Varieties

Let $X \subseteq \mathbb{A}^n$ be an affine algebraic variety. Then $I(X)$ is prime, so $A(X) \cong K[x_1, \dots, x_n]/I(X)$ is an integral domain. Hence we can define its field of fractions $K(X) := \text{Frac } A(X)$.

Definition 2.15. An element $\varphi \in K(X)$ is called regular at $x \in X$ if there exist $f, g \in A(X)$ with $\varphi = \frac{f}{g}$ and $g(x) \neq 0$.

Example 2.16. Let $X = V(x^2 - yz) \subseteq \mathbb{A}^3$ and $x = (0, 0, 1)$. Consider $\varphi = \frac{y}{x} \in K(X)$. Even though it may look like φ might not be regular at x , one can note that $\frac{y}{x} = \frac{x}{z}$ in $K(X)$, so actually $\varphi(x)$ can be defined and φ is regular at x .

Proposition 2.17. Let $\varphi \in K(X)$. Then φ is regular at every $x \in X$ if and only if $\varphi \in A(X)$.

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Remark 2.18. If $X \subseteq \mathbb{A}^n$ is an affine algebraic variety, the closed sets are exactly of the form $V_X(I) := \{x \in X \mid f(x) = 0 \text{ for all } f \in I\}$ for ideals $I \subseteq A(X)$, and V_X is still an inclusion-reversing bijection between radical ideals and closed subsets, compare exercises.

Proof. Assume $\varphi \in K(X)$ is regular at every point $x \in X$. Consider $I := \{f \in A(X) \mid f\varphi \in A(X)\}$. Then the claim is equivalent to $I = A(X)$, hence to $V_X(I) = \emptyset$ by remark 2.18. Assume there exists $x \in V_X(I)$. Since φ is regular at x , we can write $\varphi = \frac{g}{h}$ with $g, h \in A(X)$ and $h(x) \neq 0$. Hence $h \in I$, and $h(x) = 0$ by choice of x , contradiction. \square

Definition 2.19. Let $X \subseteq \mathbb{A}^n$ be an affine variety and $U \subseteq X$ be open. Denote $\mathcal{O}_X(U) := \{\varphi \in K(X) \mid \varphi \text{ regular at all } x \in U\}$. For $\varphi \in K(X)$, its domain is $\text{dom}(\varphi) := \{a \in X \mid \varphi \text{ is regular at } a\}$. In other words, $\mathcal{O}_X(U) = \{\varphi \in K(X) \mid U \subseteq \text{dom}(\varphi)\}$.

By proposition 2.17, $\mathcal{O}_X(X) = A(X)$.

Example. (i) $\varphi = \frac{y}{x}$ on $X = V(y - x^2)$ is regular, since $\varphi = x$. Hence $\text{dom}(\varphi) = X$.

(ii) $\varphi = \frac{y}{x}$ on $X = V(y^2 - x^3)$ has $\text{dom}(\varphi) = X \setminus \{(0, 0)\}$.

Proposition 2.20. Let $\varphi \in K(X)$. Then $\text{dom}(\varphi)$ is an open non-empty set in X .

Proof. Define $I := \{f \in A(X) \mid f\varphi \in A(X)\}$. As before, we have φ is regular at x if and only if $x \notin V_X(I)$, so $\text{dom } \varphi = X \setminus V_X(I)$ is open. \square

Remark 2.21. Let X be an irreducible topological space. Then

- (i) Every non-empty open subset $U \subseteq X$ is dense in X .
- (ii) If $U_1, U_2 \subseteq X$ are open and non-empty, then $U_1 \cap U_2 \neq \emptyset$.

Hence, if X is an affine variety and $f \in A(X)$ evaluates to zero on some non-empty open, then already $f = 0$.

Remark 2.22. Let $U \subseteq X$ be a non-empty open. Any regular $\varphi \in \mathcal{O}_X(U) \subseteq K(X)$ defines a set-theoretical function $\varphi : U \rightarrow K$, by sending $a \in U$ to $\frac{f(a)}{g(a)}$, where $\varphi = \frac{f}{g}$ with $f, g \in A(X)$ and $g(a) \neq 0$. This is well-defined, for if $\varphi = \frac{f_1}{g_1}$ with $g_1(a) \neq 0$, then $f g_1 - f_1 g = 0$ in $A(X)$.

Conversely, let $\varphi : U \rightarrow K$ be a (set-theoretical) function. Then φ defines a regular function on U if for every $a \in U$ there is an open neighbourhood $a \in V \subseteq U$ such that $\varphi(b) = \frac{f(b)}{g(b)}$ for all $b \in V$, where $f, g \in K[x_1, \dots, x_n]$ and $g(b) \neq 0$ for all $b \in V$.

These assignments $(\varphi \in \mathcal{O}_X(U)) \mapsto (\varphi : U \rightarrow K)$ and $(\varphi : U \rightarrow K) \mapsto [\frac{f}{g}]$ are clearly well-defined and mutually inverse, so this is an equivalent view on regular functions on U .

One sees easily that the composition of regular maps is again regular.

Remark 2.23. Let $\varphi_1, \varphi_2 \in \mathcal{O}_X(V)$ be two regular functions, and let $U \subseteq V$ be nonempty open. If $\varphi_1|_U = \varphi_2|_U$ then $\varphi_1 = \varphi_2$.

Definition 2.24. (i) A *quasi-affine variety* is an open subset of an affine algebraic variety.

(ii) A regular map between quasi-affine varieties $U \subseteq \mathbb{A}^n, V \subseteq \mathbb{A}^m$ is a map $\varphi : U \rightarrow V$ given by $\varphi = (\varphi_1, \dots, \varphi_m)$ with φ_i regular on U . φ is an isomorphism if there is a regular inverse.

Remark 2.25. For affine varieties, by remark 2.13 all information on regular maps $f : X \rightarrow Y$ could be obtained from their induced coordinate maps $f^* : A(Y) \rightarrow A(X)$. This is no longer true for quasi-affine varieties: for example, $\mathbb{A}^2 \setminus 0 \hookrightarrow \mathbb{A}^2$ induces an isomorphism of coordinate rings

Definition 2.26. Let X be an affine variety and $f \in A(X)$. Then $D(f) := X \setminus V_X(f)$ is called the *distinguished open subset* of f in X .

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Remark 2.27. Since $D(f) \cap D(g) = D(fg)$, finite intersections of distinguished opens are again distinguished open. Any open $U \subseteq X$ is a finite union of distinguished open subsets. Indeed, $U = X \setminus V_X(f_1, \dots, f_n) = \bigcup_i D(f_i)$.

Proposition 2.28. Let X be an affine variety and $0 \neq f \in A(X)$. Then $\mathcal{O}_X(D(f)) = A(X)_f = \{ \frac{g}{f^n} \mid g \in A(X), n \in \mathbb{N} \} \subseteq K(X)$. In particular, on a distinguished open subset a regular function is always globally the quotient of two elements from $A(X)$.

Proof. \supseteq is clear. So let $\varphi \in \mathcal{O}_X(D(f))$ and consider

$$I = \{h \in A(X) \mid h\varphi \in A(X)\} \subseteq A(X).$$

This is an ideal which clearly satisfies $V_X(I) \cap D(f) = \emptyset$. Hence $V_X(I) \subseteq V_X(f)$, and by the Nullstellensatz 1.13 we see that $f \in \sqrt{I}$, i.e. $f^n \in I$ for some n . \square

Example 2.29. Consider $D(x) = \mathbb{A}^1 \setminus 0 \rightarrow V(xy-1) \subseteq \mathbb{A}^2, x \mapsto (x, \frac{1}{x})$. This is an isomorphism (with inverse $(x, y) \mapsto x$ between the quasi-affine $\mathbb{A}^1 \setminus 0$ and the affine variety $V(xy-1)$). Note that this is not true in general: not every quasi-affine variety is isomorphic to an affine variety. For example, $\mathbb{A}^2 \setminus 0$ isn't isomorphic to any affine variety. However, we have

Proposition 2.30. Let X be an affine variety and $f \in A(X)$. Then $D(f)$ is isomorphic to an affine variety Y with $A(Y) \cong A(X)_f$.

Proof. Set

$$Y := \{(x, t) \in X \times \mathbb{A}^1 \mid tf(x) = 1\} \subseteq X \times \mathbb{A}^1 \subseteq \mathbb{A}^{n+1}.$$

Then as in example 2.29, $D(f) \rightarrow Y, x \mapsto (x, \frac{1}{f(x)})$ is an isomorphism with inverse $(x, y) \mapsto x$, so $D(f) \cong Y$ and $A(Y) \cong \mathcal{O}_X(D(f)) \cong A(X)_f$. \square

We have seen that for X an algebraic set and $f \in A(X)$ regular, $V_X(f)$ is closed in X . The same is true for quasi-affine varieties:

Lemma 2.31. Let X be an affine variety and $U \subseteq X$ open. Let $\varphi \in \mathcal{O}_X(U)$. Then $V_U(\varphi) := V(\varphi) \cap U = \{x \in U \mid \varphi(x) = 0\}$ is closed in U .

Proof. Let $a \in U$. Then there exists an open neighbourhood $a \in U_a \subseteq U$ and $f, g \in A(X)$ such that $\varphi = \frac{f_a}{g_a}$ on U_a . Then

$$U_a \setminus V(\varphi) = \{x \in U_a \mid \varphi(x) \neq 0\} = \{x \in U_a \mid f_a(x) \neq 0\} = U_a \setminus V(f_a)$$

is open in X , hence $U \setminus V(\varphi) = \bigcup_a U_a \setminus V(\varphi)$ is open. \square

Proposition 2.32. *Let X be a quasi-affine variety and $U \subseteq X$ be open. Let φ, ψ be two regular functions on X such that $\varphi|_U = \psi|_U$. Then $\varphi = \psi$ on X .*

Proof. $V_X(\varphi - \psi)$ contains the open, hence dense by 2.21, set U . \square

Proposition 2.33. *Let X, Y be algebraic sets and $U \subseteq X$ be open. Then any regular map $\varphi : U \rightarrow Y$ is continuous (w.r.t. the Zariski topology). In particular, $\varphi \in \mathcal{O}_X(U)$ is a continuous map $U \rightarrow \mathbb{A}^1$.*

Proof. Let $\varphi = (\varphi_1, \dots, \varphi_m)$ and let $Z = V_Y(g_1, \dots, g_m) \subseteq Y$ be a closed subset. Then $\varphi^{-1}(Z) = \{x \in U \mid g_i(\varphi_1(x), \dots, \varphi_m(x)) = 0 \text{ for all } i\}$, which is closed by lemma 2.31. \square

Let $\varphi : U \rightarrow V$ be regular. For any regular map $f \in \mathcal{O}(V)$, the composition $f \circ \varphi \in \mathcal{O}(U)$ is well-defined, hence we get as before a K -algebra homomorphism

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$$\varphi^* : \mathcal{O}(V) \rightarrow \mathcal{O}(U), \quad f \mapsto f \circ \varphi.$$

The assignment $U \mapsto \mathcal{O}(U)$, $\varphi \mapsto \varphi^*$ is a contravariant functor as before, but no longer an equivalence of categories, see exercises.

Let X, Y be affine algebraic subsets. We know that regular maps $X \rightarrow Y$ are given by polynomial functions. It may happen that we do not have any "interesting" polynomial maps. For example, over $K = \mathbb{C}$ consider $X = \mathbb{A}^1$ and $Y = V(x^2 + y^2 - 1) \subseteq \mathbb{A}^2$. Then the only regular maps $X \rightarrow Y$ are constant. However, the nontrivial map $t \mapsto (\frac{t^2-1}{t^2+1}, \frac{2t}{t^2+1})$ induces an isomorphism $\mathbb{A}^1 \setminus \{\pm i\} \rightarrow Y \setminus \{(1, 0)\}$.

Let X be an affine algebraic variety. Then $\varphi \in K(X)$ is a regular function on $\text{dom } \varphi$. Moreover, given $\varphi_1, \dots, \varphi_m \in K(X)$, we get a regular map on the open set $\bigcap_i \text{dom } \varphi_i \rightarrow \mathbb{A}^m$.

Definition 2.34. Let X be an affine algebraic variety and Y an affine algebraic set. A *rational map* $\varphi : X \dashrightarrow Y \subseteq \mathbb{A}^m$ is given by $\varphi = (\varphi_1, \dots, \varphi_m)$ with $\varphi_i \in K(X)$ such that $\varphi(x) \in Y$ for every $x \in \text{dom } \varphi := \bigcap_i \text{dom } \varphi_i$. A rational map $\varphi : X \dashrightarrow Y$ is called *dominant* if the image of φ is dense in Y , i.e. if $\overline{\varphi(\text{dom } \varphi)} = Y$.

A rational map $\varphi : X \dashrightarrow Y$ induces a regular map $\text{dom } \varphi \rightarrow Y$. Let $\varphi : X \dashrightarrow Y$ and $\psi : Y \dashrightarrow Z$ be rational maps. Then ψ might not be defined on $\text{im } \varphi$. But if φ is dominant, then $\psi \circ \varphi$ is well-defined on the non-empty open $\varphi^{-1}(\text{dom } \psi)$.

Definition 2.35. Let X be an affine algebraic variety and Y an affine algebraic set. A rational map $\varphi : X \dashrightarrow Y$ is an equivalence class of pairs (U, φ_U) , where $U \subseteq X$ is nonempty open, $\varphi_U : U \rightarrow Y$ is regular, and $(U, \varphi_U) \sim (V, \varphi_V)$ if and only if $\varphi_U|_{U \cap V} = \varphi_V|_{U \cap V}$. The rational map is dominant if for some (and therefore all) (U, φ_U) one has $\overline{\varphi_U(U)} = Y$.

Remark 2.36. The relation in definition 2.35 is an equivalence relation. Indeed, if $(U, \varphi_U) \sim (V, \varphi_V) \sim (W, \varphi_W)$, then $\varphi_U|_{U \cap W}$ and $\varphi_W|_{U \cap W}$ are regular maps that agree on the non-empty open $U \cap V \cap W$, hence they are equal by proposition 2.32.

The two above definitions are equivalent: If φ is regular in the sense of 2.34, then $[(\text{dom } \varphi, \varphi)]$ defines a regular map as in 2.35. Conversely, if an equivalence class $\{(U_i, \varphi_i)\}_i$ is given, then the map $\bigcup_i U_i, x \mapsto \varphi_i(x)$ for any i with $x \in U_i$ is regular, i.e. a rational map as in 2.34. Clearly, the notion of dominance is preserved by these identifications.

One can compose dominant rational maps $\varphi : X \dashrightarrow Y, \psi : Y \dashrightarrow Z$ by setting

$$[(U, \varphi_U)] \circ [(V, \varphi_V)] := [(\varphi_U^{-1}(V), \psi_V \circ \varphi_U|_{\varphi_U^{-1}(V)})]$$

Write $\text{Mor}_{\text{rat}}(X, Y)$ for the set of rational morphisms $X \dashrightarrow Y$.

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Definition 2.37. Let $\varphi : X \dashrightarrow Y$ be dominant. In the same way as for regular maps, we define

$$\varphi^* : \text{Mor}_{\text{rat}}(Y, \mathbb{A}^1) \rightarrow \text{Mor}_{\text{rat}}(X, \mathbb{A}^1), \quad f \mapsto f \circ \varphi.$$

Proposition 2.38. *Let X be an affine algebraic variety. Then $\text{Mor}_{\text{rat}}(X, \mathbb{A}^1)$ is a field with the operations $(U, f) * (V, g) := (U \cap V, f|_{U \cap V} + g|_{U \cap V})$ for $*$ $\in \{+, -, \cdot\}$ and $(U, f)^{-1} = (U \setminus V(f), \frac{1}{f})$. Moreover, $\text{Mor}_{\text{rat}}(X, \mathbb{A}^1) \cong K(X)$ as fields.*

Proof. It is clear that the given operations are well-defined and make $\text{Mor}_{\text{rat}}(X, \mathbb{A}^1)$ a field. The equivalence of definitions 2.34 and 2.35 provides a field isomorphism $K(X) \rightarrow \text{Mor}_{\text{rat}}(X, \mathbb{A}^1)$, $f \mapsto (\text{dom } f, f)$. \square

Corollary 2.39. *If $\varphi : X \dashrightarrow Y$ is a dominant rational map between affine varieties, we get a K -homomorphism of fields $\varphi^* : K(Y) \rightarrow K(X)$, $f \mapsto f \circ \varphi$.*

Recall that for regular maps, we had in 2.13 an equivalence between algebraic sets + regular maps, and reduced f.g. K -algebras + K -algebra homomorphisms. In the case of rational maps, we get similarly

Theorem 2.40. $\varphi \mapsto \varphi^*$ is a bijection $\{\varphi \in \text{Mor}_{\text{rat}}(X, Y) \mid \varphi \text{ dominant}\}$ to $\text{Hom}_K(K(Y), K(X))$. This assignment is functorial, and induces an equivalence of categories

$$\begin{array}{ccc} \left\{ \begin{array}{l} \text{affine algebraic varieties} + \\ \text{dominant rational maps} \end{array} \right\} & \longleftrightarrow & \left\{ \begin{array}{l} \text{field extensions } L/K \text{ of finite transcendence degree} + \\ K\text{-linear homomorphisms} \end{array} \right\} \\ X & \mapsto & K(X) \\ \varphi & \mapsto & \varphi^* \end{array}$$

Proof. To show that $\varphi \mapsto \varphi^*$ is a bijection, define an inverse by assigning to $f : K(Y) \rightarrow K(X)$ the morphism $(f(y_1), \dots, f(y_m))$. Everything else is clear. \square

Definition 2.41. A dominant rational map $\varphi : X \dashrightarrow Y$ is called a *birational equivalence* (and X and Y are called *birational* or *rationally equivalent*) if there exists a rational dominant map $\psi : Y \dashrightarrow X$ such that $\varphi \circ \psi = \text{id}_Y$ and $\psi \circ \varphi = \text{id}_X$ as rational maps.

Proposition 2.42. *Let X, Y be affine algebraic varieties. The following statements are equivalent:*

- (i) X and Y are birational.
- (ii) $K(X) \cong K(Y)$.
- (iii) There exist non-empty open subsets $U \subseteq X$ and $V \subseteq Y$ such that $U \cong V$ are isomorphic (in the sense of regular maps).

Proof. (i) \Leftrightarrow (ii) follows from 2.40, (i) \Leftrightarrow (iii) from the definition of rational function as regular functions on some open. \square