

M4P33 Algebraic Geometry

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0 Introduction

I will not follow a particular book, but everything I am going to say will be contained in one of the following books.

Lecture 1
Friday
11/01/19

- I Shafarevich, Basic algebraic geometry, 1974
- R Hartshorne, Algebraic geometry, 1977
- J Harris, Algebraic geometry: a first course, 1992

1 Affine varieties

Notation 1.1.

- R is a commutative ring with unity.
- K is a field.
- $K[x_1, \dots, x_n]$ is the ring of polynomials in n variables.
- \mathbb{A}^n is K^n as a set.

Definition 1.2. Let $S \subseteq K[x_1, \dots, x_n]$ then

$$Z(S) = \{x \in \mathbb{A}^n \mid \forall f \in S, f(x) = 0\}$$

is called the **zero locus** of S . Subsets of \mathbb{A}^n that are of this form are called **affine varieties**.

Remark 1.3. Some authors call **algebraic set** the object $Z(S)$. We will not follow this notation.

Example 1.4.

- Single points $p = (p_1, \dots, p_n)$. $p = Z(S)$ where

$$S = \{x_1 - p_1, \dots, x_n - p_n\}.$$

- $\mathbb{A}^n = Z(0)$.
- $\emptyset = Z(1)$.
- Subspaces of $\mathbb{A}^n = K^n$.
- If $X = Z(f_1, \dots, f_n) \subseteq \mathbb{A}^n$ and $Y = Z(g_1, \dots, g_m) \subseteq \mathbb{A}^n$ are affine varieties then

$$X \times Y = Z(f_1, \dots, f_n, g_1, \dots, g_m) \subseteq \mathbb{A}^{n+m}$$

is a variety.

Remark 1.5. If $S \subseteq K[x_1, \dots, x_n]$ and $I = \langle S \rangle$ then $Z(S) = Z(I)$.

Theorem 1.6 (Hilbert's basis theorem). *If R is Noetherian then $R[x]$ is Noetherian.*

Corollary 1.7. *Every ideal in $K[x_1, \dots, x_n]$ is finitely generated.*

Definition 1.8. Let $X \subseteq \mathbb{A}^n$ then

$$I(X) = \{f \in K[x_1, \dots, x_n] \mid \forall x \in X, f(x) = 0\}.$$

Example 1.9. $I(p) = I((p_1, \dots, p_n)) = \langle x_1 - p_1, \dots, x_n - p_n \rangle$.

Goal is

$$\begin{array}{ccc} \{\text{affine varieties in } \mathbb{A}^n\} & \leftrightarrow & \{\text{ideals of } K[x_1, \dots, x_n]\} \\ X & \mapsto & I(X) \\ Z(J) & \leftarrow & J \end{array}.$$

$$Z(I(X)) = X \text{ but } I(Z(J)) \supseteq J.$$

Example 1.10. $J = \langle x^2 + 1 \rangle \subseteq \mathbb{R}[x] = I(\emptyset) = I(Z(x^2 + 1))$.

Proposition 1.11.

- If $X \subseteq Y$ then $I(Y) \subseteq I(X)$. If $I \subseteq J$ then $Z(J) \subseteq Z(I)$.
- $X \subseteq Z(I(X))$ and $S \subseteq I(Z(S))$.

- If X is affine then $Z(J(X)) = X$. If $X = Z(S)$ then take Z of $S \subseteq I(Z(S))$.

Example 1.12. Let $J \subseteq \mathbb{C}[x]$. $J = \langle f \rangle$, where $f = (x - x_1)^{k_1} \dots (x - x_n)^{k_n}$.

Definition 1.13. Let $I \subseteq K[x_1, \dots, x_n]$ be an ideal.

$$I \subseteq \sqrt{I} = \{f \in K[x_1, \dots, x_n] \mid \exists n \in \mathbb{N}, f^n \in I\}.$$

If $\sqrt{I} = I$, we say I is a **radical ideal**.

(Exercise: \sqrt{I} is an ideal, $I \subseteq \sqrt{I}$, and $\sqrt{I} = \bigcap_{p \text{ prime}} p$)

Theorem 1.14 (Hilbert's Nullstellensatz). $I(Z(J)) = \sqrt{J}$. If $\sqrt{J} = J$ then

$$\begin{array}{ccc} \{\text{affine varieties}\} & \leftrightarrow & \{\text{radical ideals}\} \\ X & \mapsto & I(X) \\ Z(J) & \leftarrow & J \end{array}.$$

Proposition 1.15.

1. $Z(S) \cup Z(T) = Z(ST)$.
2. $\bigcap_i Z(S_i) = Z(\bigcup_i S_i)$.
3. $Z(0) = \mathbb{A}^n$ and $Z(1) = \emptyset$.

Proof.

1. If $p \in Z(S) \cup Z(T)$, then $f(p) = 0$ for $f \in S$ or $f \in T$, so $f(p) = 0$ for $f \in ST$, where

$$ST = \left\{ \sum_{i \in I, I \text{ finite}} s_i t_i \right\} \subseteq S \cap T,$$

with equality if $S + T = R$. If $p \in Z(ST)$, there exists f such that $f(p) = 0$ for $f \in S$ or $f(p) = 0$ for $f \in T$, so $p \in Z(S) \cup Z(T)$.

□

Definition 1.16. The **Zariski topology** on \mathbb{A}^n is the topology generated by closed sets of the form $Z(S)$. By the above proposition this is a topology.

Example 1.17. \mathbb{A}^1 is not Hausdorff.

Definition 1.18. A topological space X is **irreducible** if it cannot be expressed as a union $X = A \cup B$, where A and B are proper and closed subsets. \emptyset is not considered irreducible.

Example 1.19. \mathbb{A}^1 .

Example 1.20. Any non-empty open set of irreducible X is dense and irreducible. Suppose A is open then $X = A^c \cup \overline{A}$. Since X is irreducible then $A^c = X$, a contradiction, or $\overline{A} = X$. Suppose A is reducible. Let $A = (A \cap B) \cup (A \cap C)$, where B and C are closed. Then $X = A^c \cup (B \cup C)$. $A^c = X$ or $B \cup C = X$, which are contradictions.

Example 1.21. If A is irreducible then \overline{A} is also irreducible. Suppose \overline{A} is not irreducible. $\overline{A} = (\overline{A} \cap B) \cup (\overline{A} \cap C)$. Take $\bigcap A$, $A = (A \cap B) \cup (A \cap C)$, a contradiction.

Definition 1.22. An affine variety is **irreducible** if it is irreducible as a topological space.

Remark 1.23. A **quasi-affine variety** is an open set of an affine variety.

Proposition 1.24.

1. $I(X \cup Y) = I(X) \cap I(Y)$.
2. $Z(I(X)) = \overline{X}$ for any $X \subseteq \mathbb{A}^n$.

Proof.

1. If $f \in I(X \cup Y)$ then $f(p) = 0$ for all $p \in X \cup Y$, so $f \in I(X)$ and $f \in I(Y)$.
2. We know that $X \subseteq Z(I(X))$ hence $\overline{X} \subseteq Z(I(X))$. Now, let Y be a closed set containing X , that is $X \subseteq Y$. Then

$$I(Y) \subset I(X) \implies Z(I(X)) \subset Z(I(X)) = Y,$$
 so any closed set containing Y contains $Z(I(X))$.

□

Proposition 1.25. X is irreducible if and only if $I(X)$ is prime.

Proof.

\implies Let $f, g \in I(X)$.

$$X \subseteq Z(fg) = Z(f) \cup Z(g) \implies X = (X \cap Z(f)) \cup (X \cap Z(g)).$$

$Z(f) \subseteq X$, so $f \in I(X)$, or $Z(g) \subseteq X$, so $g \in I(X)$.

\Leftarrow Exercise.

□

Example 1.26. \mathbb{A}^n .

Definition 1.27. If $X \subseteq \mathbb{A}^n$, the **coordinate ring** of X is

$$A(X) = \frac{K[x_1, \dots, x_n]}{I(X)}.$$

Example 1.28. Let $f \in K[x_1, \dots, x_n]$ be irreducible. If $n = 3$, $Z(f)$ is a surface. If $n = 2$, $Z(f)$ is a curve.

Example 1.29. Let $y - x^2 \in K[x, y]$. Then

$$\begin{aligned} A(X) &= \frac{K[x, y]}{\langle y - x^2 \rangle} \cong K[x, x^2] \rightarrow K[x] \\ \sum_{i,j} a_{ij} x^i x^{2j} &= \sum_{i,j} a_{ij} x^{2j+i} \mapsto \sum_n b_n x^n \end{aligned}$$

Example 1.30. Let $xy - 1 \in K[x, y]$. Then

$$A(X) = \frac{K[x, y]}{\langle xy - 1 \rangle} \cong K\left[x, \frac{1}{x}\right].$$

$A(X)$ cannot be $K[x]$.

Definition 1.31. A **Noetherian** topological space X is a topological space such that if

$$C_1 \supseteq C_2 \supseteq \dots$$

is a decreasing chain of closed sets then there is a k such that $C_k = C_{k+1} = \dots$

Example 1.32. \mathbb{A}^n . Recall that if $A \subset B$ then $I(B) \subset I(A)$. So using the definition above,

$$I(C_1) \subseteq I(C_2) \subseteq \dots$$

Since $K[x_1, \dots, x_n]$ is Noetherian then $I(C_i)$ stabilises. So $I(C_k) = I(C_{k+1}) = \dots$, but taking Z , we recover C_k so C_k stabilises as well.

Lecture 3
Tuesday
15/01/19

Theorem 1.33. *If X is Noetherian then any non-empty closed subset can be expressed as a finite union of irreducible closed sets $X = Y_1 \cup \dots \cup Y_n$. Moreover, if we require that $Y_i \subseteq Y_j$ then this expression is unique.*

Proof. Let C be the collection of closed sets that do not satisfy that property. Let Y be a minimum closed inside C , in particular Y is reducible, so $Y = Y' \cup Y''$, for Y', Y'' closed. Hence $Y', Y'' \notin C$, so they can be expressed as a finite union of irreducibles, a contradiction. If $Y_i \not\subseteq Y_j$, then suppose

$$Y_1 \cup \dots \cup Y_n = X_1 \cup \dots \cup X_n.$$

Then $Y_1 \subset X_1 \cup X_n$, in particular $Y_1 = \bigcup_j (Y_1 \cap X_j)$, so there is a j such that $Y_1 \cap X_j = Y_1$, so $Y_1 \subset X_j$. We can assume $j = 1$ and repeat the same argument to find that $Y_1 = X_1$, so consider $\overline{Y \setminus Y_1} = Y_2 \cup \dots \cup Y_n$. But

$$Y_2 \cup \dots \cup Y_n = X_2 \cup \dots \cup X_n,$$

and the result follows by induction. \square

Corollary 1.34. *Any affine variety in \mathbb{A}^n can be expressed equally as a union of irreducible algebraic varieties.*

Definition 1.35. The **dimension** of a topological space is the supremum of n where

$$Y_0 \subset \dots \subset Y_n$$

is a sequence of irreducible closed sets.

Example 1.36. Dimension of \mathbb{A}^1 is one.

Definition 1.37. Let A be a ring and \mathfrak{p} be a prime ideal, then the **height** of \mathfrak{p} is the supremum of n where

$$\mathfrak{p}_1 \subset \dots \subset \mathfrak{p}_n \subset \mathfrak{p},$$

where \mathfrak{p}_i are prime. The **Krull dimension** of A is

$$\sup_{\mathfrak{p} \text{ prime}} \text{height}(\mathfrak{p}).$$

Proposition 1.38. *If Y is affine then $\dim(Y) = \dim(A(Y))$.*

Proof. Let C be a closed and irreducible set $C \subset Y$, then $I(C) \supset I(Y)$, then $I(C)$ is prime. \square

Proposition 1.39. *Let K be a field and B be an integral domain which is a finitely generated algebra, then*

- $\dim(B)$ is the transcendence degree of $K(B)$ over K , and
- if $\mathfrak{p} \subseteq B$ is prime, then

$$\text{height}(\mathfrak{p}) + \dim\left(\frac{B}{\mathfrak{p}}\right) = \dim(B).$$

Proof. Atiyah Macdonald chapter 11. \square

Proposition 1.40 (Krull Hauptidealsatz). *Let A be a Noetherian ring and $f \in A$ not a zero divisor and not a unit. Then every prime ideal containing f has height one.*

Proof. Atiyah Macdonald page 122. \square

Proposition 1.41. *A Noetherian integral domain A is a UFD if and only if every prime ideal I of height one is principal.*

Theorem 1.42. *An irreducible variety $Y \subseteq \mathbb{A}^n$ has dimension $n - 1$ if and only if $Y = Z(f)$ where f is an irreducible polynomial in $K[x_1, \dots, x_n]$.*

Proof.

\implies If Y has dimension $n - 1$ then $I(Y)$ has height one, by the above proposition $I(Y) = \langle f \rangle$, so $Y = Z(f)$.

\impliedby Let $I = I(Y)$ then I is prime, by the Krull Hauptidealsatz we have that I has height one, so $\dim(Y) = n - 1$. \square

2 Projective varieties

Definition 2.1. The **projective space** \mathbb{P}^n is defined as

$$\mathbb{P}^n = \frac{\mathbb{A}^{n+1} \setminus \{0\}}{\{x \sim \lambda x \mid \lambda \in K^*\}}.$$

A point in \mathbb{P}^n is written as $[a_0 : \dots : a_n] = \overline{(a_0, \dots, a_n)}$.

Definition 2.2. A **graded ring** R is a ring together with a decomposition

$$R = \bigoplus_{d \geq 0} R_d,$$

where R_d are abelian groups and $R_k \cdot R_t \subseteq R_{k+t}$.

Example 2.3. $K[x_0, \dots, x_n]$ is a graded ring, where R_d are monomials of degree d .

Notation 2.4. Let A be $K[x_0, \dots, x_n]$ without the grading and S be $K[x_0, \dots, x_n]$ as a graded ring.

Definition 2.5. An ideal $I \subseteq S$ is **homogeneous** if

$$I = \bigoplus_{d \geq 0} (I \cap S_d).$$

If $f = f_0 + \dots + f_d$, then $f_i \in I$.

Remark 2.6. I is homogeneous if and only if $I = \langle f_0, \dots, f_n \rangle$, where f_i are homogeneous.

Lemma 2.7. If I, J are homogeneous then

1. $I + J$ is homogeneous,
2. IJ is homogeneous,
3. $I \cap J$ is homogeneous, and
4. \sqrt{I} is homogeneous.

Proof.

4. Let $f = f_0 + \dots + f_d \in \sqrt{I}$ then

$$f^n = (f_0 + \dots + f_d)^n = f_d^n + \dots \in I \quad \implies \quad f_d^n \in I \quad \implies \quad f_d \in \sqrt{I},$$

so $f - f_d \in \sqrt{I}$, by induction $f_i \in \sqrt{I}$.

□

Definition 2.8. If f is homogeneous of degree k then $f(\lambda \cdot x) = \lambda^k \cdot f(x)$, in particular $f(x) = 0$ if and only if $f(\lambda \cdot x) = 0$, so it makes sense to define

$$Z(f) = \{x \in \mathbb{P}^n \mid f(x) = 0\}.$$

More generally, if $I \subseteq S$ is a homogeneous ideal then

$$Z(I) = \{x \in \mathbb{P}^n \mid f \in I \text{ homogeneous, } f(x) = 0\}.$$

Definition 2.9. A subset $X \subseteq \mathbb{P}^n$ is called a **projective variety** if $X = Z(T)$ for some homogeneous ideal T .

Proposition 2.10.

- $Z(S) \cup Z(T) = Z(ST)$.
- $\bigcap_{\alpha} Z(S_{\alpha}) = Z(\bigcup_{\alpha} S_{\alpha})$.
- $Z(0) = \mathbb{P}^n$ and $Z(1) = \emptyset$.

Definition 2.11. We define the **Zariski topology** on \mathbb{P}^n by taking closed sets to be $Z(T)$ for some T .

Definition 2.12.

- A projective variety is **irreducible** if it is an irreducible topological space.
- An open subset of a projective variety is called a **quasi-projective variety**.
- The **dimension** of a projective variety is its dimension as a topological space.
- If $T \subseteq S$ then

$$I(T) = \langle f \in S \mid f \text{ homogeneous, } \forall p \in T, f(p) = 0 \rangle.$$

Definition 2.13. If X is a projective variety the **homogeneous coordinate ring** is

$$S(X) = \frac{S}{I(X)}.$$

Definition 2.14. If $f \in S$ is linear and homogeneous, we call $Z(f)$ a **hyperplane**.

Let

$$\begin{aligned} \phi_i : \quad U_i &\rightarrow \mathbb{A}^n \\ [a_0 : \cdots : a_n] &\mapsto \left(\frac{a_0}{a_i}, \dots, \frac{a_n}{a_i} \right). \end{aligned}$$

Proposition 2.15. ϕ_i is a homeomorphism in the Zariski topology.