

Solutions to the book: *Fulton, Algebraic Curves*

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Chapter 1: Affine Algebraic Sets

1.1. Algebraic Preliminaries

Problem 1.1.*

Let R be a domain.

- (a) If f, g are forms of degree r, s respectively in $R[x_1, \dots, x_n]$, show that fg is a form of degree $r + s$.
- (b) Show that any factor of a form in $R[x_1, \dots, x_n]$ is also a form.

Proof of (a).

- (1) Write

$$f = \sum_{(i)} a_{(i)} x^{(i)},$$
$$g = \sum_{(j)} b_{(j)} x^{(j)},$$

where $\sum_{(i)}$ is the summation over $(i) = (i_1, \dots, i_n)$ with $i_1 + \dots + i_n = r$ and $\sum_{(j)}$ is the summation over $(j) = (j_1, \dots, j_n)$ with $j_1 + \dots + j_n = s$.

- (2) Hence,

$$fg = \sum_{(i)} \sum_{(j)} a_{(i)} b_{(j)} x^{(i)} x^{(j)}$$
$$= \sum_{(i), (j)} a_{(i)} b_{(j)} x^{(k)}$$

where $(k) = (i_1 + j_1, \dots, i_n + j_n)$ with $(i_1 + j_1) + \dots + (i_n + j_n) = r + s$. Each $x^{(k)}$ is the form of degree $r + s$ and $a_{(i)} b_{(j)} \in R$. Hence fg is a form of degree $r + s$.

□

Proof of (b).

- (1) Given any form $f \in R[x_1, \dots, x_n]$, and write $f = gh$. It suffices to show that g is a form as well. (So does h .)
- (2) Write

$$g = g_0 + \dots + g_r, \quad h = h_0 + \dots + h_s$$

where $g_r \neq 0$ and $h_s \neq 0$. So

$$f = gh = g_0h_0 + \cdots + g_rh_s.$$

Since R is a domain, $R[x_1, \dots, x_n]$ is a domain and thus $g_rh_s \neq 0$. The maximality of r and s implies that $\deg f = r + s$. Therefore, by the maximality of $r + s$, $f = g_rh_s$, or $g = g_r$, or g is a form.

□

Problem 1.5.*

Let k be any field. Show that there are an infinitely number of irreducible monic polynomials in $k[x]$. (Hint: Suppose f_1, \dots, f_n were all of them, and factor $f_1 \cdots f_n + 1$ into irreducible factors.)

Proof (Due to Euclid).

- (1) If f_1, \dots, f_n were all irreducible monic polynomials, then we consider

$$g = f_1 \cdots f_n + 1 \in k[x].$$

So there is an irreducible monic polynomial $f = f_i$ dividing g for some i since

$$\deg g = \deg f_1 + \cdots + \deg f_n \geq 1.$$

- (2) However, f would divide the difference

$$g - f_1 \cdots f_{i-1}f_{i+1} \cdots f_n = 1,$$

contrary to $\deg f_i \geq 1$.

□

Problem 1.6.*

Show that any algebraically closed field is infinite. (Hint: The irreducible monic polynomials are $x - a$, $a \in k$.)

Proof (Due to Euclid).

- (1) Let k be an algebraically closed field. If a_1, \dots, a_n were all elements in k , then we consider a monic polynomials

$$f(x) = (x - a_1) \cdots (x - a_n) + 1 \in k[x].$$

- (2) Since k is algebraically closed, there is an element $a \in k$ such that $f(a) = 0$. By assumption, $a = a_i$ for some $1 \leq i \leq n$, and thus $f(a) = f(a_i) = 1$, contrary to the fact that a field is a commutative ring where $0 \neq 1$ and all nonzero elements are invertible.

□

1.2. Affine Space and Algebraic Sets

Problem 1.8.*

Show that the algebraic subsets of $\mathbf{A}^1(k)$ are just the finite subsets, together with $\mathbf{A}^1(k)$ itself.

Proof.

- (1) Show that $k[x]$ is a PID if k is a field.
- (a) Let I be an ideal of $k[x]$.
 - (b) If $I = \{0\}$ then $I = (0)$ and I is principal.
 - (c) If $I \neq \{0\}$, then take f to be a polynomial of minimal degree in I . It suffices to show that $I = (f)$. Clearly, $(f) \subseteq I$ since I is an ideal. Conversely, for any $g \in I$,

$$g(x) = f(x)h(x) + r(x)$$

for some $h, r \in k[x]$ with $r = 0$ or $\deg r < \deg f$. Now as

$$r = g - fh \in I,$$

$r = 0$ (otherwise contrary to the minimality of f), we have $g = fh \in (f)$ for all $g \in I$.

- (2) Let Y be an algebraic subset of $\mathbf{A}^1(k)$, say $Y = V(I)$ for some ideal I of $k[x]$. Since $k[x]$ is a PID, $I = (f)$ for some $f \in k[x]$.
- (a) If $f = 0$, then $I = (0)$ and $Y = V(0) = \mathbf{A}^1(k)$.
 - (b) If $f \neq 0$, then $f(x) = 0$ has finitely many roots in k , say $a_1, \dots, a_m \in k$. Hence,

$$Y = V(I) = V(f) = \{f(a) = 0 : a \in k\} = \{a_1, \dots, a_m\}$$

is a finite subsets of $\mathbf{A}^1(k)$.

By (a)(b), the result is established.

□

Notes.

- (1) By the Hilbert basis theorem, $k[x]$ is Noetherian as k is Noetherian. Hence, for any algebraic subset $Y = V(I)$ of $\mathbf{A}^1(k)$, we can write $I = (f_1, \dots, f_m)$. Note that

$$Y = V(I) = V(f_1) \cap \dots \cap V(f_m).$$

Now apply the same argument to get the same conclusion.

- (2) Suppose $k = \bar{k}$. $\mathbf{A}^1(k)$ is irreducible, because its only proper closed subsets are finite, yet it is infinite (because k is algebraically closed, hence infinite).

Problem 1.9.

If k is a finite field, show that every subset of $\mathbf{A}^n(k)$ is algebraic.

Proof.

- (1) Every subset of $\mathbf{A}^n(k)$ is finite since $|\mathbf{A}^n(k)| = |k|^n$ is finite.
- (2) Note that $V(x_1 - a_1, \dots, x_n - a_n) = \{(a_1, \dots, a_n)\} \subseteq \mathbf{A}^n(k)$ (property (5) in this section) and any finite union of algebraic sets is algebraic (property (4) in this section). Thus, every subset of $\mathbf{A}^n(k)$ is algebraic (by (1)).

□

Problem 1.11.

Show that the following are algebraic sets:

- (a) $\{(t, t^2, t^3) \in \mathbf{A}^3(k) : t \in k\}$;
- (b) $\{(\cos(t), \sin(t)) \in \mathbf{A}^2(\mathbb{R}) : t \in \mathbb{R}\}$;
- (c) *the set of points in $\mathbf{A}^2(\mathbb{R})$ whose polar coordinates (r, θ) satisfy the equation $r = \sin(\theta)$.*

Proof of (a).

- (1) The twisted cubic curve

$$Y = \{(t, t^2, t^3) \in \mathbf{A}^3(k) : t \in k\} = V(x^2 - y) \cap V(x^3 - z)$$

is algebraic. We say that Y is given by the parametric representation $x = t, y = t^2, z = t^3$.

- (2) The generators for the ideal $I(Y)$ are $x^2 - y$ and $x^3 - z$.
- (3) Y is an affine variety of dimension 1.
- (4) The affine coordinate ring $A(Y)$ is isomorphic to a polynomial ring in one variable over k .

□

Proof of (b). The circle

$$\{(\cos(t), \sin(t)) \in \mathbf{A}^2(\mathbb{R}) : t \in \mathbb{R}\} = V(x^2 - y^2 - 1)$$

is algebraic. □

Proof of (c). The circle

$$\{(r, \theta) : r = \sin(\theta)\} = V(x^2 + y^2 - y)$$

is algebraic again. □

Problem 1.15.*

Let $V \subseteq \mathbf{A}^n(k)$, $W \subseteq \mathbf{A}^m(k)$ be algebraic sets. Show that

$$V \times W = \{(a_1, \dots, a_n, b_1, \dots, b_m) : (a_1, \dots, a_n) \in V, (b_1, \dots, b_m) \in W\}$$

is an algebraic set in $\mathbf{A}^{n+m}(k)$. It is called the **product** of V and W .

Proof.

- (1) Write

$$\begin{aligned} V &= V(S_V) = \{a \in \mathbf{A}^n(k) : f(a) = 0 \forall f \in S_V\} \\ W &= V(S_W) = \{b \in \mathbf{A}^m(k) : g(b) = 0 \forall g \in S_W\}, \end{aligned}$$

where $S_V \subseteq k[x_1, \dots, x_n]$ and $S_W \subseteq k[y_1, \dots, y_m]$. It suffices to show that

$$V \times W = V(S),$$

where $S \subseteq k[x_1, \dots, x_n, y_1, \dots, y_m]$ is the union of S_V and S_W .

- (2) Here we can identify S_V with the subset of $k[x_1, \dots, x_n, y_1, \dots, y_m]$ by noting that

$$k[x_1, \dots, x_n] \hookrightarrow (k[y_1, \dots, y_m])[x_1, \dots, x_n] = k[x_1, \dots, x_n, y_1, \dots, y_m].$$

Here we regard k as a subring of $k[y_1, \dots, y_m]$. Similar treatment to S_W .

- (3) By construction, $V \times W \subseteq V(S)$. Conversely, given any $(a, b) \in V(S)$, we have $h(a, b) = 0$ for all $h \in S = S_V \cup S_W$ (by (2)). By construction, $f(a) = 0$ for all $f \in S_V$ since f only involve x_1, \dots, x_n . Hence, $a \in V$. Similarly, $b \in W$. Therefore, $(a, b) \in V \times W$.

□

1.3. The Ideal of a Set of Points

Problem 1.18.*

Let I be an ideal in a ring R . If $a^n \in I$, $b^m \in I$, show that $(a + b)^{n+m} \in I$. Show that $\text{rad}(I)$ is an ideal, in fact a radical ideal. Show that any prime ideal is radical.

Proof.

- (1) Show that $(a + b)^{n+m} \in I$ if $a^n \in I$, $b^m \in I$. By the binomial theorem,

$$(a + b)^{n+m} = \sum_{i=0}^{n+m} a^i b^{n+m-i}.$$

For each term $a^i b^{n+m-i}$, either $i \geq n$ holds or $n + m - i \geq m$ holds, and thus $a^i b^{n+m-i} \in I$ (since $a^n \in I$, $b^m \in I$ and I is an ideal). Hence, the result is established.

- (2) Show that $\text{rad}(I)$ is an ideal.

- (a) $0 \in \text{rad}(I)$ since $0 = 0^1 \in I$ for any ideal in R .
- (b) $(a + b)^{n+m} \in I$ if $a^n \in I$, $b^m \in I$ by (1).
- (c) $(-a)^{2n} = (a^n)^2 \in I$ if $a^n \in I$ (since I is an ideal).
- (d) $(ra)^n = r^n a^n \in I$ if $a^n \in I$ and $r \in R$ (since I is an ideal and R is commutative).

- (3) Show that $\text{rad}(\text{rad}(I)) = \text{rad}(I)$. It suffices to show $\text{rad}(\text{rad}(I)) \subseteq \text{rad}(I)$. Given any $a \in \text{rad}(\text{rad}(I))$. By definition $a^n \in \text{rad}(I)$ for some positive integer n . Again by definition $(a^n)^m = a^{nm} \in I$ for some positive integer m . As nm is a positive integer, $a \in \text{rad}(I)$.

- (4) Show that every prime ideal \mathfrak{p} is radical. Given any $a \in \text{rad}(\mathfrak{p})$, that is, $a^n \in \mathfrak{p}$ for some positive integer. Write $a^n = aa^{n-1}$ if $n > 1$. By the primality of \mathfrak{p} , $a \in \mathfrak{p}$ or $a^{n-1} \in \mathfrak{p}$. If $a \in \mathfrak{p}$, we are done. If $a^{n-1} \in \mathfrak{p}$, we continue this descending argument (or the mathematical induction) until the power of a is equal to 1. Hence \mathfrak{p} is radical.

□

Problem PLACEHOLDER

PLACEHOLDER

Proof.

- (1) PLACEHOLDER

1.4. The Hilbert Basis Theorem

1.5. Irreducible Components of an Algebraic Set

1.6. Algebraic Subsets of the Plane

1.7. Hilbert's Nullstellensatz

1.8. Modules; Finiteness Conditions

Problem 1.41.*

If S is module-finite over R , then S is ring-finite over R .

Proof.

- (1) $S = \sum R s_i$ for some $s_1, \dots, s_n \in S$ since S is module-finite over R .
(2) Let I be the minimal subset of $\{s_1, \dots, s_n\}$ which also spans S , say $\{t_1, \dots, t_m\}$ with $m \leq n$. Clearly we can write

$$S = R[t_1, \dots, t_m],$$

that is, S is ring-finite over R .

- (3) The converse is not true (Problem 1.42).

□

Problem 1.42.

Show that $S = R[x]$ (the ring of polynomials in one variable) is ring-finite over R , but not module-finite.

Proof.

- (1) $S = R[x]$ is ring-finite over R by definition (as $x \in S$).
- (2) (Reductio ad absurdum) If $S = \sum Rs_i$ for some $s_1, \dots, s_n \in S$ were module-finite over R . Any element $s \in \sum Rs_i$ is of degree

$$\deg s \leq \max_{1 \leq i \leq n} \deg s_i := m.$$

So that $x^{m+1} \in S = R[x]$ but not in $\sum Rs_i$, which is absurd.

□

Problem 1.43.* (WIP)

If L is ring-finite over K (K, L fields) then L is a finitely generated field extension of K .

Proof.

- (1) $L = K[v_1, \dots, v_n]$ for some $v_i \in L$. To show $L = K[v_1, \dots, v_n] = K(v_1, \dots, v_n)$, it suffices to show that all v_i are algebraic over L .
- (2)

□

1.9. Integral Elements**1.10. Field Extensions**

Chapter 2: Affine Varieties

2.1. Coordinate Rings

Problem 2.1.*

Show that the map which associates to each $f \in k[x_1, \dots, x_n]$ a polynomial function in $\mathcal{F}(V, k)$ is a ring homomorphism whose kernel is $I(V)$.

Proof.

- (1) Define a map $\alpha : k[x_1, \dots, x_n] \rightarrow \mathcal{F}(V, k)$. Every polynomial $f \in k[x_1, \dots, x_n]$ defines a function from V to k by

$$\alpha(f)(a_1, \dots, a_n) = f(a_1, \dots, a_n)$$

for all $(a_1, \dots, a_n) \in V$.

- (2) α is a ring homomorphism by construction in (1).
(3) Show that $\ker(\alpha) = I(V)$. In fact, given any $f \in k[x_1, \dots, x_n]$, we have $\alpha(f) = 0$ (sending all $a \in V$ to $0 \in k$) if and only if $f(a) = 0$ for all $a \in V$ if and only if $f \in I(V)$.
(4) Hence $k[x_1, \dots, x_n]/I(V) = \Gamma(V) \hookrightarrow \mathcal{F}(V, k)$ is an injective homomorphism.

□

Problem PLACEHOLDER

PLACEHOLDER

Proof.

- (1) PLACEHOLDER

2.2. Polynomial Maps

2.3. Coordinate Changes

2.4. Rational Functions and Local Rings

2.5. Discrete Valuation Rings

2.6. Forms

2.7. Direct Products of Rings

2.8. Operations with Ideals

Problem 2.39.*

Prove the following relations among ideals I_i , J in a ring R :

(a) $(I_1 + I_2)J = I_1J + I_2J$.

(b) $(I_1 \cdots I_N)^n = I_1^n \cdots I_N^n$.

Proof of (a).

(1) Note that $(I_1 + I_2)J$ and $I_1J + I_2J$ are ideals.

(2) *Show that $(I_1 + I_2)J \subseteq I_1J + I_2J$.* Given any

$$\alpha = (a_1 + a_2)b \in (I_1 + I_2)J$$

where $a_i \in I_i$ and $b \in J$. It suffices to show that $\alpha \in I_1J + I_2J$ (by (1)).

In fact,

$$\alpha = (a_1 + a_2)b = a_1b + a_2b \in I_1J + I_2J.$$

(3) *Show that $(I_1 + I_2)J \supseteq I_1J + I_2J$.* Given any

$$\alpha = a_1b_1 + a_2b_2 \in I_1J + I_2J$$

where $a_i \in I_i$ and $b_i \in J$. It suffices to show that $\alpha \in (I_1 + I_2)J$ (by (1)).

In fact,

$$\alpha = a_1b_1 + a_2b_2 = (a_1 + \underbrace{0}_{\in I_2})b_1 + (\underbrace{0}_{\in I_1} + a_2)b_2 \in (I_1 + I_2)J$$

since $(I_1 + I_2)J$ is an ideal.

□

Proof of (b).

- (1) Note that $(I_1 \cdots I_N)^n$ and $I_1^n \cdots I_N^n$ are ideals.
(2) Show that $(I_1 \cdots I_N)^n \subseteq I_1^n \cdots I_N^n$. Given any

$$\alpha = \alpha_1 \cdots \alpha_n$$

where $\alpha_i \in I_1 \cdots I_N$. It suffices to show that $\alpha \in I_1^n \cdots I_N^n$ (by (1)). For each $\alpha_i \in I_1 \cdots I_N$, write

$$\alpha_i = \sum_{j(i)} \alpha_{j(i),1} \cdots \alpha_{j(i),N}$$

where $\alpha_{j(i),k} \in I_k$ for $1 \leq k \leq N$. Hence

$$\begin{aligned} \alpha &= \alpha_1 \cdots \alpha_n \\ &= \left(\sum_{j(1)} \alpha_{j(1),1} \cdots \alpha_{j(1),N} \right) \cdots \left(\sum_{j(n)} \alpha_{j(n),1} \cdots \alpha_{j(n),N} \right) \\ &= \sum_{j(1), \dots, j(n)} (\alpha_{j(1),1} \cdots \alpha_{j(1),N}) \cdots (\alpha_{j(n),1} \cdots \alpha_{j(n),N}) \\ &= \sum_{j(1), \dots, j(n)} \underbrace{(\alpha_{j(1),1} \cdots \alpha_{j(n),1})}_{\in I_1^n} \cdots \underbrace{(\alpha_{j(1),N} \cdots \alpha_{j(n),N})}_{\in I_N^n} \\ &\in I_1^n \cdots I_N^n. \end{aligned}$$

- (3) Show that $(I_1 \cdots I_N)^n \supseteq I_1^n \cdots I_N^n$. Given any

$$\alpha = \alpha_1 \cdots \alpha_N \in I_1^n \cdots I_N^n$$

where $\alpha_i \in I_i^n$ ($1 \leq i \leq N$). It suffices to show that $\alpha \in (I_1 \cdots I_N)^n$ (by (1)). For each $\alpha_i \in I_i^n$, write

$$\alpha_i = \sum_{j(i)} \alpha_{j(i),1} \cdots \alpha_{j(i),n}$$

where $\alpha_{j(i),k} \in I_i$ for $1 \leq k \leq n$. Hence

$$\begin{aligned}
\alpha &= \alpha_1 \cdots \alpha_N \\
&= \left(\sum_{j(1)} \alpha_{j(1),1} \cdots \alpha_{j(1),n} \right) \cdots \left(\sum_{j(N)} \alpha_{j(N),1} \cdots \alpha_{j(N),n} \right) \\
&= \sum_{j(1), \dots, j(N)} (\alpha_{j(1),1} \cdots \alpha_{j(1),n}) \cdots (\alpha_{j(N),1} \cdots \alpha_{j(N),n}) \\
&= \sum_{j(1), \dots, j(N)} \underbrace{(\alpha_{j(1),1} \cdots \alpha_{j(N),1})}_{\in I_1 \cdots I_N} \cdots \underbrace{(\alpha_{j(1),n} \cdots \alpha_{j(N),n})}_{\in I_1 \cdots I_N} \\
&\in (I_1 \cdots I_N)^n.
\end{aligned}$$

□

2.9. Ideals with a Finite Number of Zeros

2.10. Quotient Modules and Exact Sequences

Problem 2.51.

Let

$$0 \longrightarrow V_1 \longrightarrow \cdots \longrightarrow V_n \longrightarrow 0$$

be an exact sequence of finite-dimensional vector spaces. Show that $\sum (-1)^i \dim(V_i) = 0$.

Proof (Proposition 7 in this section).

- (1) For $i = 0, \dots, n$, by the rank-nullity theorem for a linear transformation $\varphi_i : V_i \rightarrow V_{i+1}$, we have

$$\dim V_i = \dim \operatorname{im}(\varphi_i) + \dim \ker(\varphi_i).$$

(Here $V_0 = V_{n+1} := 0$ by convention.)

- (2) By the exactness of the sequence, we have

(a) $\operatorname{im}(\varphi_i) = \ker(\varphi_{i+1})$ for $i = 0, \dots, n-1$. In particular, $\ker(\varphi_1) = \operatorname{im}(\varphi_0) = 0$.

(b) $\ker(\varphi_n) = V_n$.

Hence,

$$\begin{aligned}
\sum_{i=1}^{n-1} (-1)^i \dim(V_i) &= \sum_{i=1}^{n-1} (-1)^i \dim \operatorname{im}(\varphi_i) + \sum_{i=1}^{n-1} (-1)^i \dim \operatorname{ker}(\varphi_i) \\
&= \sum_{i=1}^{n-1} (-1)^i \dim \operatorname{ker}(\varphi_{i+1}) + \sum_{i=1}^{n-1} (-1)^i \dim \operatorname{ker}(\varphi_i) \\
&= (-1)^{n-1} \underbrace{\dim \operatorname{ker}(\varphi_n)}_{=V_n} + (-1)^1 \underbrace{\dim \operatorname{ker}(\varphi_1)}_{=0} \\
&= -(-1)^n \dim V_n,
\end{aligned}$$

or $\sum (-1)^i \dim(V_i) = 0$.

□

2.11. Free Modules

Chapter 3: Local Properties of Plane Curves

3.1. Multiple Points and Tangent Lines

Problem PLACEHOLDER

PLACEHOLDER

Proof.

(1) PLACEHOLDER

□

3.2. Multiplicities and Local Rings

3.3. Intersection Numbers

Chapter 4: Projective Varieties

4.1. Projective Space

Problem PLACEHOLDER

PLACEHOLDER

Proof.

(1) PLACEHOLDER

□

4.2. Projective Algebraic Sets

4.3. Affine and Projective Varieties

4.4. Multiprojective Space

Chapter 5: Projective Plane Curves

5.1. Definitions

Problem PLACEHOLDER

PLACEHOLDER

Proof.

(1) PLACEHOLDER

□

5.2. Linear Systems of Curves

5.3. Bézout's Theorem

5.4. Multiple Points

5.5. Max Noether's Fundamental Theorem

5.6. Applications of Noether's Theorem

Chapter 6: Varieties, Morphisms, and Rational Maps

6.1. The Zariski Topology

6.2. Varieties

6.3. Morphisms of Varieties

6.4. Products and Graphs

6.5. Algebraic Function Fields and Dimension of Varieties

6.6. Rational Maps

Chapter 7: Resolution of Singularities

7.1. Rational Maps of Curves

Problem PLACEHOLDER

PLACEHOLDER

Proof.

(1) PLACEHOLDER

□

7.2. Blowing up a Point in A^2

7.3. Blowing up a Point in P^2

7.4. Quadratic Transformations

7.5. Nonsingular Models of Curves

Chapter 8: Riemann-Roch Theorem

8.1. Divisors

Problem PLACEHOLDER

PLACEHOLDER

Proof.

(1) PLACEHOLDER

□

8.2. The Vector Spaces $L(D)$

8.3. Riemann's Theorem

8.4. Derivations and Differentials

8.5. Canonical Divisors

8.6. Riemann-Roch Theorem