# Solutions to the book:
# ***Fulton, Algebraic Curves***

Meng-Gen Tsai
plover@gmail.com

March 16, 2021

## Contents

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

(2) Hence,

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

where $(k) = (i_1 + j_1, \dots, i_n + j_n)$ with $(i_1 + j_1) + \cdots + (i_n + j_n) = r + s$. 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

$$g = g_0 + \cdots + g_r, \qquad h = h_0 + \cdots + h_s$$

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

$$f = gh = g_0 h_0 + \cdots + g_r h_s.$$

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

□

**Problem 1.2.***

*Let $R$ be a UFD, $K$ the quotient field of $R$. Show that every element $z$ of $K$ may be written $z = a/b$, where $a, b \in R$ have no common factors; this representative is unique up to units of $R$.*

*Proof.*

(1) *Show that every element $z$ of $K$ may be written $z = a/b$, where $a$, $b \in R$ have no common factors.* Given any $z = a/b \in K$ where $a, b \in R$. Write

$$\begin{aligned} a &= p_1 \cdots p_n, \\ b &= q_1 \cdots q_m \end{aligned}$$

where all $p_1, \ldots, p_n, q_1, \ldots, q_m$ are irreducible in $R$. (It is possible since $R$ is a UFD.) For each $i$, suppose $p_i \mid q_j$ for some $i, j$. Write $q_j = p_i u$ for some $u \in R$. By the irreducibility of $p_i$ and $q_j$, $u$ is a unit. So

$$z = \frac{a}{b} = \frac{p_1 \cdots \widehat{p_i} \cdots p_n}{q_1 \cdots \widehat{q_j} \cdots q_m} = \frac{p_1 \cdots \widehat{p_i} \cdots p_n}{u q_1 \cdots \widehat{q_j} \cdots q_m}.$$

Continue this method we can write $z = \frac{a'}{b'}$ where $a'$ and $b'$ have no common factors.

(2) Write $z = a/b = a'/b'$ where

(a) $a, b, a', b' \in R$,

(b) $a$ and $b$ have no common factors,

(c) $a'$ and $b'$ have no common factors.

Write

$$\begin{aligned} a &= p_1 \cdots p_n, \\ b &= q_1 \cdots q_m, \\ a' &= p_1' \cdots p_{n'}', \\ b' &= q_1' \cdots q_{m'}' \end{aligned}$$

where all $p_i, q_j, p'_{i'}, q'_{j'}$ are irreducible in $R$. As $z = a/b = a'/b'$, $ab' = a'b$ or

$$p_1 \cdots p_n q'_1 \cdots q'_{m'} = p'_1 \cdots p'_{n'} q_1 \cdots q_m.$$

(3) For $i = 1$, $p_1 = u_1 p'_{i'}$ for some unit $u_1 \in R$ since $a$ and $b$ have no common factors and all $p_1, q_j, p'_{i'}$ are irreducible. Hence

$$u_1 \widehat{p_1} p_2 \cdots p_n q'_1 \cdots q'_{m'} = p'_1 \cdots \widehat{p'_{i'}} \cdots p'_{n'} q_1 \cdots q_m.$$

Continue this method, we have $n \leq n'$ and all $p_1, \ldots, p_n$ are canceled.

(4) Conversely, we can apply the argument in (3) to $i' = 1, \ldots n'$ to conclude that $n' \leq n$. Therefore, $n = n'$ and

$$\underbrace{u_1 \cdots u_n}_{\text{a unit in } R} q'_1 \cdots q'_{m'} = q_1 \cdots q_m.$$

Hence, $b = ub'$ where $u = u_1 \cdots u_n$ is a unit in $R$. Similarly, $a = va'$ where $v$ is a unit in $R$. So the representative of $z \in K$ is unique up to units of $R$.

□

**Problem 1.3.***

*Let $R$ be a PID. Let $\mathfrak{p}$ be a nonzero, proper, prime ideal in $R$.*

(a) *Show that $\mathfrak{p}$ is generated by an irreducible element.*

(b) *Show that $\mathfrak{p}$ is maximal.*

*Proof of (a).*

(1) Let $\mathfrak{p} = (a)$ be a nonzero, proper, prime ideal in $R$. It suffices to show that $a$ is irreducible.

(2) Suppose $a = bc$. By the primality of $\mathfrak{p}$, $b \in \mathfrak{p}$ or $c \in \mathfrak{p}$. Suppose $b \in \mathfrak{p} = (a)$. (The case $c \in \mathfrak{p}$ is similar.) Then there is a $d \in R$ such that $b = ad$. Hence, $a = bc = adc$ or $(1 - dc)a = 0$.

(3) Since $R$ is a domain, $1 = dc$ or $a = 0$. $a = 0$ implies that $\mathfrak{p} = (0)$ is a zero ideal, contrary to the assumption. Therefore, $1 = dc$, or $c$ is a unit, or $a$ is irreducible.

□

*Proof of (b).*

(1) Given any ideal $I = (b)$ of $R$ containing $\mathfrak{p} = (a)$. As the generator $a$ of $\mathfrak{p}$ is in $\mathfrak{p} \subseteq I$, there is some $c \in R$ such that $a = bc$. By the irreducibility of $a$ (in (a)), $b$ is a unit or $c$ is a unit.

(2) $b$ is a unit implies that $I = R$. $c$ is a unit implies that $I = \mathfrak{p}$. In any case, we conclude that $\mathfrak{p}$ is maximal.

□

**Problem 1.4.***

*Let $k$ be an infinite field, $f \in k[x_1, \ldots, x_n]$. Suppose $f(a_1, \ldots, a_n) = 0$ for all $a_1, \ldots, a_n \in k$. Show that $f = 0$. (Hint: Write*

$$f = \sum f_i x_n^i, \qquad f_i \in k[x_1, \ldots, x_{n-1}].$$

*Use induction on $n$, and the fact that $f(a_1, \ldots, a_{n-1}, x_n)$ has only a finite number of roots if any $f_i(a_1, \ldots, a_{n-1}) \neq 0$.)*

*Proof.*

(1) Induction on $n$. The case $n = 1$. (Reductio ad absurdum) If there were a nonzero $f \in k[x_1]$ such that $f(a) = 0$ for all $a \in k$. Note that $f$ has at most $\deg f < \infty$ roots, contrary to the infinity of $k$.

(2) Assume that the conclusion holds for $n - 1$, then for any $f \in k[x_1, \ldots, x_n]$ we can write
$$f = \sum f_i x_n^i, \qquad f_i \in k[x_1, \ldots, x_{n-1}]$$
as $f \in (k[x_1, \ldots, x_{n-1}])[x_n]$. Suppose $f(a_1, \ldots, a_n) = 0$ for all $a_1, \ldots, a_n \in k$. For fixed $a_1, \ldots, a_{n-1}$, the polynomial $f(a_1, \ldots, a_{n-1}, x_n) \in k[x_n]$ has all distinct roots in an infinite field $k$. By (1), $f(a_1, \ldots, a_{n-1}, x_n) = 0 \in k[x_n]$, or each $f_i(a_1, \ldots, a_{n-1}) = 0$. As all $a_1, \ldots, a_{n-1}$ run over $k$, we can apply the induction hypothesis each $f_i(x_1, \ldots, x_{n-1}) = 0 \in k[x_1, \ldots, x_{n-1}]$. Hence, $f = 0 \in k[x_1, \ldots, x_n]$.

□

*Note.* If $k$ is a finite field of order $q = p^k$, then the polynomial $f(x) = x^q - x$ has $q$ distinct roots in $k$.

**Problem 1.5.***

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

*Proof (Due to Euclid).*

(1) If $f_1, \ldots, f_n$ 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

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

and $k[x]$ is a UFD.

(2) However, $f$ would divide the difference

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

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 $a_1, \ldots, a_n$ 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.

□

**Problem 1.7.***

*Let $k$ be a field, $f \in k[x_1, \dots, x_n]$, $a_1, \dots, a_n \in k$.*

(a) *Show that*

$$f = \sum \lambda_{(i)}(x_1 - a_1)^{i_1} \cdots (x_n - a_n)^{i_n}, \qquad \lambda_{(i)} \in k.$$

(b) *If $f(a_1, \dots, a_n) = 0$, show that $f = \sum_{i=1}^{n}(x_i - a_i)g_i$ for some (not unique) $g_i$ in $k[x_1, \dots, x_n]$.*

*Proof of (a).*

(1) Regard $k[x_1, \dots, x_n]$ as $(k[x_1, \dots, x_{n-1}])[x_n]$. Since $(k[x_1, \dots, x_{n-1}])[x_n]$ is a Euclidean domain with a function

$$f \in (k[x_1, \dots, x_{n-1}])[x_n] \mapsto \deg_{x_n} f \in \mathbb{Z}_{\geq 0}$$

satisfying the division-with-remainder property.

(2) Apply the division algorithm for $f$ and nonzero $x_n - a_n$ to produce a quotient $q$ and remainder $r$ with $f = (x_n - a_n)q + r$ and either $r = 0$ or $\deg_{x_n}(r) < \deg_{x_n}(x_n - a_n) = 1$. That is, $r \in k[x_1, \dots, x_{n-1}]$ is a constant in $(k[x_1, \dots, x_{n-1}])[x_n]$. Continue this process to get that $f$ is of the form

$$f = \sum_{i_n} f_{i_n}(x_n - a_n)^{i_n}$$

where $f_{i_n} \in k[x_1, \dots, x_{n-1}]$.

(3) Use the same argument in (2) for each $f_{i_n} \in k[x_1, \dots, x_{n-1}]$, we have

$$\begin{aligned}
f_{i_n} &= \sum_{i_{n-1}} \underbrace{f_{i_n, i_{n-1}}}_{\in k[x_1, \dots, x_{n-2}]} (x_{n-1} - a_{n-1})^{i_{n-1}} \\
f_{i_n, i_{n-1}} &= \sum_{i_{n-2}} \underbrace{f_{i_n, i_{n-1}, i_{n-2}}}_{\in k[x_1, \dots, x_{n-3}]} (x_{n-2} - a_{n-2})^{i_{n-2}}, \\
&\cdots \\
f_{i_n, \dots, i_2} &= \sum_{i_1} \underbrace{f_{i_n, \dots, i_1}}_{\in k} (x_1 - a_1)^{i_1}.
\end{aligned}$$

Note that $f_{i_n, \dots, i_1} \in k$, we can write

$$f = \sum \lambda_{(i)}(x_1 - a_1)^{i_1} \cdots (x_n - a_n)^{i_n}, \qquad \lambda_{(i)} \in k.$$

by replacing all $f_{i_n, \dots, i_k}$ by $f_{i_n, \dots, i_{k-1}}$ for $k = n, n-1, \dots, 2$.

(4) Or use the induction on $n$.

□

*Proof of (b).*

(1) Write
$$f = \sum \lambda_{(i)}(x_1 - a_1)^{i_1} \cdots (x_n - a_n)^{i_n}, \qquad \lambda_{(i)} \in k$$
by (a).

(2) As $f(a_1, \cdots, a_n) = 0$, $\lambda_{(i)} = 0$ if all $i_1, \ldots, i_n$ are zero, that it, there is no nonzero constant term in the representation of $f$. Hence, for each term
$$f_{(i)} := \lambda_{(i)}(x_1 - a_1)^{i_1} \cdots (x_n - a_n)^{i_n}$$
with $\lambda_{(i)} \neq 0$, there exists one $i_k > 0$ for some $1 \leq k \leq n$. So we can write
$$f_{(i)} = (x_k - a_k) \underbrace{(\lambda_{(i)}(x_1 - a_1)^{i_1} \cdots (x_k - a_k)^{i_k - 1} \cdots (x_n - a_n)^{i_n})}_{:= g_{(i)} \in k[x_1, \ldots, x_n]}.$$
Note that the expression of $f_{(i)}$ is not unique since there may exist more than one $i_k > 0$ as $1 \leq k \leq n$.

(3) Now we iterate each nonzero term in $f$, apply the factorization in (2), and then group by each $x_k - a_k$. Therefore, we can write
$$f = \sum_{i=1}^{n} (x_i - a_i) g_i$$
for some $g_1 \in k[x_1, \ldots, x_n]$.

(4) The expression of $f$ is not unique. For example, take $f(x, y) = x^2 + 2xy + y^2 \in k[x, y]$. As $f(0, 0) = 0$, we can write
$$\begin{aligned} f(x,y) &= x \cdot \underbrace{(x + 2y)}_{g_1} + y \cdot \underbrace{y}_{g_2}, \text{ or} \\ &= x \cdot \underbrace{(x + y)}_{g_1} + y \cdot \underbrace{(x + y)}_{g_2}, \text{ or} \\ &= x \cdot \underbrace{x}_{g_1} + y \cdot \underbrace{(2x + y)}_{g_2}. \end{aligned}$$

□

## 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 $\deg r < \deg f$ (as $k[x]$ is a Euclidean domain). 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 $a_1, \ldots, a_m \in k$. Hence,

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

   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 $I = (f_1, \cdots, f_m)$. Note that

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

   Now apply the same argument to get the same conclusion.

(2) Suppose $k = \overline{k}$. $\mathbf{A}^1(k)$ 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 $V(x_1 - a_1, \ldots, x_n - a_n) = \{(a_1, \ldots, a_n)\} \subseteq \mathbf{A}^n(k)$ (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)).

$\square$

**Problem 1.10.**

*Give an example of a countable collection of algebraic sets whose union is not algebraic.*

*Proof.*

(1) Let $k = \mathbb{Q}$ be an infinite field. $V(x - a) = \{a\}$ is an algebraic sets for all $a \in \mathbb{Q}$. In particular, $V(x - a) = \{a\}$ is algebraic for all $a \in \mathbb{Z}$.

(2) Note that

$$Y := \bigcup_{a \in \mathbb{Z}} V(x - a) = \mathbb{Z}$$

is a countable union of algebraic sets. Since $Y$ is a proper subset of $k = \mathbb{Q}$, it cannot be algebraic by Problem 1.8.

$\square$

**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 $(r, \theta)$ 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 1.12.**

*Suppose $C$ is an affine plane curve, and $L$ is a line in $\mathbb{A}^2(k)$, $L \not\subseteq C$. Suppose $C = V(f)$, $f \in k[x, y]$ a polynomial of degree $n$. Show that $L \cap C$ is a finite set of no more than $n$ points. (Hint: Suppose $L = V(y - (ax + b))$, and consider $f(x, ax + b) \in k[x]$.)*

*Proof.*

(1) Say $L = V(y - (ax + b))$ be a line in $\mathbb{A}^2(k)$. (The case $L = V(x - (ay + b))$ is similar.)

(2) Note that $L \not\subseteq C$ implies that $(y - (ax + b)) \nmid f$. Hence, the polynomial

$$g : x \mapsto f(x, ax + b) \in k[x]$$

is nonzero and $\deg g \leq n$. Therefore, the number of roots of $g$ in $k$ is no more than $n$.

(3) Hence,

$$\begin{aligned} L \cap C &= V(y-(ax+b)) \cap V(f) \\ &= \{(x,y) \in \mathbb{A}^2(k) : y = ax+b \text{ and } f(x,y)=0\} \\ &= \{(x,y) \in \mathbb{A}^2(k) : f(x,ax+b)=0\} \end{aligned}$$

is finite of no more than $n$ points.

□

**Problem 1.13.**

*Show that each of the following sets is not algebraic:*

(a) $\{(x,y) \in \mathbf{A}^2(\mathbb{R}) : y = \sin(x)\}$.

(b) $\{(z,w) \in \mathbf{A}^2(\mathbb{C}) : |z|^2 + |w|^2 = 1\}$, *where* $|x+iy|^2 = x^2+y^2$ *for* $x, y \in \mathbb{R}$.

(c) $\{(\cos(t), \sin(t), t) \in \mathbf{A}^3(\mathbb{R}) : t \in \mathbb{R}\}$.

*Proof of (a).*

(1) (Reductio ad absurdum) If

$$Y := \{(x,y) \in \mathbf{A}^2(\mathbb{R}) : y = \sin(x)\}$$

were algebraic, then there is a subset $S$ of $\mathbb{R}[x,y]$ such that

$$Y = V(S) = \bigcap_{f \in S} V(f).$$

(2) $S \neq \varnothing$ since $Y \neq \mathbf{A}^2(\mathbb{R})$. ($(89,64) \in \mathbf{A}^2(\mathbb{R}) - Y$.)

(3) Take a fixed line $L = V(y)$ in $\mathbf{A}^2(\mathbb{R})$. For each affine curve $f \in S$, we have

$$V(f) \cap L \supseteq \bigcap_{f \in S} V(f) \cap L = Y \cap L = \{(n\pi, 0) \in \mathbf{A}^2(\mathbb{R}) : n \in \mathbb{Z}\},$$

which is infinite. By problem 1.12, $y \mid f$. As $f$ runs over $S$, $Y \subseteq V(y) = L$, contradicts that $\left(0, \frac{\pi}{2}\right) \in L - Y$.

□

*Proof of (b).*

(1) Similar to (a). (Reductio ad absurdum) If

$$Y := \{(x,y) \in \mathbf{A}^2(\mathbb{C}) : |x|^2 + |y|^2 = 1\}$$

were algebraic, then there is a subset $S$ of $\mathbb{C}[x,y]$ such that

$$Y = V(S) = \bigcap_{f \in S} V(f).$$

(2) $S \neq \varnothing$ since $Y \neq \mathbf{A}^2(\mathbb{C})$. ($(89,64) \in \mathbf{A}^2(\mathbb{C}) - Y$.)

(3) Take a fixed line $L = V(x)$ in $\mathbf{A}^2(\mathbb{C})$. For each affine curve $f \in S$, we have

$$V(f) \cap L \supseteq \bigcap_{f \in S} V(f) \cap L = Y \cap L = \{(0,y) \in \mathbf{A}^2(\mathbb{C}) : |y| = 1\},$$

which is infinite (since $Y$ contains a unit circle in the complex plane). By problem 1.12, $x \mid f$. As $f$ runs over $S$, $Y \subseteq V(x) = L$, contradicts that the origin $(0,0) \in L - Y$.

$\square$

*Proof of (c).*

(1) Similar to (a) and (b).

(2) *Suppose $C$ is an affine plane curve, and $L$ is a line in $\mathbb{A}^3(k)$, $L \not\subseteq C$. Suppose $C = V(f)$, $f \in k[x,y,z]$ a polynomial of degree $n$. Show that $L \cap C$ is a finite set of no more than $n$ points.* The proof is similar to Problem 1.12.

  (a) Say $L = V(y - (ax+b), z - (cx+d))$ be a line in $\mathbb{A}^3(k)$.

  (b) Note that $L \not\subseteq C$ implies that $(y-(ax+b)) \nmid f$ and $(z-(cx+d)) \nmid f$. Hence, the polynomial

  $$g : x \mapsto f(x, ax+b, cx+d) \in k[x]$$

  is nonzero and $\deg g \leq n$. Therefore, the number of roots of $g$ in $k$ is no more than $n$.

  (c) Hence,

  $$\begin{aligned} L \cap C &= V(y-(ax+b), z-(cx+d)) \cap V(f) \\ &= \{(x,y) \in \mathbb{A}^2(k) : y = ax+b, z = cx+d \text{ and } f(x,y) = 0\} \\ &= \{(x,y) \in \mathbb{A}^2(k) : f(x, ax+b, cx+d) = 0\} \end{aligned}$$

  is finite of no more than $n$ points.

(3) (Reductio ad absurdum) If

$$Y := \{(\cos(t), \sin(t), t) \in \mathbf{A}^3(\mathbb{R}) : t \in \mathbb{R}\}$$

were algebraic, then there is a subset $S$ of $\mathbb{R}[x, y, z]$ such that

$$Y = V(S) = \bigcap_{f \in S} V(f).$$

(4) $S \neq \varnothing$ since $Y \neq \mathbf{A}^3(\mathbb{R})$. ($(1989, 6, 4) \in \mathbf{A}^3(\mathbb{R}) - Y$.)

(5) Take a fixed line $L = V(x-1, y)$ in $\mathbf{A}^3(\mathbb{R})$. For each affine curve $f \in S$, we have

$$V(f) \cap L \supseteq \bigcap_{f \in S} V(f) \cap L = Y \cap L = \{(1, 0, 2n\pi) \in \mathbf{A}^3(\mathbb{R}) : n \in \mathbb{Z}\},$$

which is infinite. By (2), $(x-1) \mid f$ and $y \mid f$. As $f$ runs over $S$, $Y \subseteq V(x-1, y) = L$, contradicts that $(1, 0, \pi) \in L - Y$.

□

**Supplement.** *A circular disk of radius* 1 *in the plane* $xy$ *rolls without slipping along the* $x$ *axis. The figure described by a point of the circumference of of the disk is called a* ***cycloid****. The parametrized curve* $\alpha : \mathbb{R} \to \mathbb{R}^2$ *is*

$$\begin{cases} x = t - \sin t \\ y = 1 - \cos t. \end{cases}$$

*The cycloid is not algebraic (as (a)).*

**Problem 1.14.***

*Let* $f$ *be a nonconstant polynomial in* $k[x_1, \ldots, x_n]$*,* $k$ *algebraically closed. Show that* $\mathbf{A}^n(k) - V(f)$ *is infinite if* $n \geq 1$*, and* $V(f)$ *is infinite if* $n \geq 2$*. Conclude that the complement of any proper algebraic set is infinite. (Hint: See Problem 1.4.)*

*Proof.*

(1) *Show that* $\mathbf{A}^n(k) - V(f)$ *is infinite if* $n \geq 1$. Since $f$ is a nonconstant polynomial in $k[x_1, \ldots, x_n]$, we may assume that $\deg_{x_n}(f) > 0$. Hence

$$x_n \mapsto f(1, \ldots, 1, x_n)$$

is a nonconstant polynomial of degree $\deg_{x_n}(f) > 0$ in $k[x_n]$. So $f$ has finitely many roots in $k$, say $\xi_1, \ldots, \xi_m$ ($m \geq 0$). Hence,

$$(1, \ldots, 1, x_n) \neq 0$$

whenever $x_n \neq \xi_m$. Such subset in $\mathbf{A}^1(k)$ is infinite since $k = \overline{k}$ (Problem 1.6). Therefore,

$$\begin{aligned}\mathbf{A}^n(k) - V(f) &= \{(a_1, \dots, a_n) \in \mathbf{A}^n(k) : f(a_1, \dots, a_n) \neq 0\} \\ &\supseteq \{a_n \in \mathbf{A}^1(k) : f(1, \dots, 1, x_n) \neq 0\}\end{aligned}$$

is infinite.

(2) *Show that $V(f)$ is infinite if $n \geq 2$.*

(a) Similar to (1). Since $f$ is a nonconstant polynomial in $k[x_1, \dots, x_n]$, we may assume that $m := \deg_{x_n}(f) > 0$. Write

$$f = \sum_{i=0}^{m} f_i(x_1, \dots, x_{n-1}) x_n^i.$$

Note that each $f_i$ is well-defined since $n \geq 2$.

(b) If $f_n$ is constant in $k[x_1, \dots, x_{n-1}]$, then $f_n$ is nonzero (since $m > 0$) or $V(f_n) = \varnothing$. If $f_n$ is nonconstant in $k[x_1, \dots, x_{n-1}]$, then the set $\mathbf{A}^{n-1}(k) - V(f_n)$ is infinite by (1). In any case,

$$\mathbf{A}^{n-1}(k) - V(f_n)$$

is infinite.

(c) For each $P = (a_1, \dots, a_{n-1}) \in \mathbf{A}^{n-1}(k) - V(f_n)$,

$$g_P : x_n \mapsto f(P, x_n) = f(a_1, \dots, a_{n-1}, x_n)$$

defines a polynomial in $k[x_n]$ of degree $m > 0$. Since $k = \overline{k}$, $g_P$ has at least one root $Q \in k$. Hence

$$V(f) \supseteq \{(P, Q) \in \mathbf{A}^n(k) : P \in \mathbf{A}^{n-1}(k) - V(f_n), g_P(Q) = 0\}$$

is infinite since the set $\mathbf{A}^{n-1}(k) - V(f_n)$ is infinite.

*Note.* It is not true if $k \neq \overline{k}$. For example, $V(x^2 + y^2 + 1) = \varnothing$ in $\mathbf{A}^2(\mathbb{R})$.

(3) Note that

$$\mathbf{A}^n(k) - V(S) = \mathbf{A}^n(k) - \bigcap_{f \in S} V(f) = \bigcup_{f \in S} (\mathbf{A}^n(k) - V(f)).$$

Thus the complement of any proper algebraic set is infinite by (1).

□

**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

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

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 $(P, Q) \in V(S) \subseteq \mathbf{A}^{n+m}(k)$, we have $h(P, Q) = 0$ for all $h \in S = S_V \cup S_W$ (by (2)). By construction, $f(P) = 0$ for all $f \in S_V$ since $f$ only involve $x_1, \dots, x_n$. Hence, $P \in V$. Similarly, $Q \in W$. Therefore, $(P, Q) \in V \times W$.

□

## 1.3. The Ideal of a Set of Points

**Problem 1.16.***

*Let $V, W$ be algebraic sets in $\mathbf{A}^n(k)$. Show that $V = W$ if and only if $I(V) = I(W)$.*

*Proof.*

(1) (Proof of Equation (6) in this section.) *Show that if $X \subseteq Y$, then $I(X) \supseteq I(Y)$.* If $f \in I(Y)$ then $f(P) = 0$ for all $P \in Y$. So $f(P) = 0$ for all $P \in X \subseteq Y$ or $f \in I(X)$.

(2) (Proof of Equation (8) in this section.) *$I(V(S)) \supseteq S$ for any set $S$ of polynomials; $V(I(X)) \supseteq X$ for any set $X$ of points.*

   (a) If $f \in S$ then $f$ vanishes on $V(S)$, hence $f \in IV(S)$.

   (b) If $P \in X$ then every polynomial in $I(X)$ vanishes at $P$, so $P$ belongs to the zero set of $I(X)$.

(3) (Proof of Equation (9) in this section.) *$V(I(V(S))) = V(S)$ for any set $S$ of polynomials, and $I(V(I(X))) = I(X)$ for any set $X$ of points. So if $V$ is an algebraic set, $V = V(I(V))$, and if $I$ is the ideal of an algebraic set, $I = I(V(I))$.*

   (a) In each case, it suffices to show that the left side is a subset of the right side. (by Equations (6)(8) in this section).

   (b) If $P \in V(S)$ then $f(P) = 0$ for all $f \in I(V(S))$, so $P \in V(I(V(S)))$.

   (c) If $f \in I(X)$ then $f(P) = 0$ for all $P \in V(I(X))$. Thus $f$ vanishes on $V(I(X))$, so $f \in I(V(I(X)))$.

(4) *Show that $V = W$ if and only if $I(V) = I(W)$.*

   (a) By Equation (6) in this section, $I(V) \supseteq I(W)$ if $V \subseteq W$ and $I(V) \subseteq I(W)$ if $V \supseteq W$. Thus, $I(V) = I(W)$ if $V = W$.

   (b) Conversely, $I(V) = I(W)$ implies that $V(I(V)) = V(I(W))$ by Equation (3) in the previous section and similar argument in (a). By Equation (9) in this section, $V(I(V)) = V$ and $V(I(W)) = W$. Thus, $V = W$.

□

**Problem 1.17.***

(a) *Let $V$ be an algebraic set in $\mathbf{A}^n(k)$, $P \in \mathbf{A}^n(k)$ a point not in $V$. Show that there is a polynomial $f \in k[x_1, \dots, x_n]$ such that $f(Q) = 0$ for all $Q \in V$, but $f(P) = 1$. (Hint: $I(V) \neq I(V \cup \{P\})$.)*

(b) *Let $P_1, \dots, P_r$ be distinct points in $\mathbf{A}^n(k)$, not in an algebraic set $V$. Show that there are polynomials $f_1, \dots, f_r \in I(V)$ such that $f_i(P_j) = 0$ if $i \neq j$, and $f_i(P_i) = 1$. (Hint: Apply (a) to the union of $V$ and all but one point.)*

(c) *With $P_1, \dots, P_r$ and $V$ as in (b), and $a_{ij} \in k$ for $1 \leq i, j \leq r$, show that there are $g_i \in I(V)$ with $g_i(P_j) = a_{ij}$ for all $i$ and $j$. (Hint: Consider $\sum_j a_{ij} f_j$.)*

*Proof of (a).*

(1) Since $I(V) \supsetneq I(V \cup \{P\})$ (by Problem 1.16), there is a polynomial $f \in k[x_1, \ldots, x_n]$ such that $f(Q) = 0$ for all $Q \in V$, but $f(P) \neq 0$.

(2) Since $k$ is a field, $(f(P))^{-1} \in k$. Consider the polynomial $(f(P))^{-1} f \in k[x_1, \ldots, x_n]$. It is well-defined. Also, $((f(P))^{-1} f)(Q) = (f(P))^{-1} f(Q) = 0$ for all $Q \in V$, but $(f(P))^{-1} f)(P) = (f(P))^{-1} f(P) = 1$.

□

*Proof of (b).*

(1) For $1 \leq i \leq$, define

$$W = V \cup \{P_1, \ldots, P_r\}$$
$$W_i = V \cup \{P_1, \ldots, \widehat{P_i}, \ldots, P_r\}.$$

Here $W = W_i \cup \{P_i\} \neq W_i$.

(2) By (a), there is a polynomial $f_i \in k[x_1, \ldots, x_n]$ such that $f_i(Q) = 0$ for all $Q \in W_i$, but $f_i(P_i) = 1$. Here $f_i \in I(V)$ and $f_i(P_j) = \delta_{ij}$ where $\delta_{ij}$ is the Kronecker delta.

□

*Proof of (c).*

(1) For each $1 \leq i \leq r$, define

$$g_i = \sum_j a_{ij} f_j \in k[x_1, \ldots, x_n].$$

(2) $g_i \in I(V)$ since $g_i$ is a linear combination of $f_j$ and $I(V)$ is an ideal.

(3) Also,

$$g_i(P_j) = \sum_{j'} a_{ij'} f_{j'}(P_j) = \sum_{j'} a_{ij'} \delta_{j'j} = a_{ij}.$$

□

**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* $\mathrm{rad}(I)$ *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* $\mathrm{rad}(I)$ *is an ideal.*

(a) $0 \in \mathrm{rad}(I)$ 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* $\mathrm{rad}(\mathrm{rad}(I)) = \mathrm{rad}(I)$. It suffices to show $\mathrm{rad}(\mathrm{rad}(I)) \subseteq \mathrm{rad}(I)$. Given any $a \in \mathrm{rad}(\mathrm{rad}(I))$. By definition $a^n \in \mathrm{rad}(I)$ for some positive integer $n$. Again by definition $(a^n)^m = a^{nm} \in I$ for some positive integer $m$. As $nm$ is a postive integer, $a \in \mathrm{rad}(I)$.

(4) *Show that every prime ideal* $\mathfrak{p}$ *is radical.* Given any $a \in \mathrm{rad}(\mathfrak{p})$, 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 1.19**

*Show that* $I = (x^2+1) \subseteq \mathbb{R}[x]$ *is a radical (even a prime) ideal, but* $I$ *is not the ideal of any set in* $\mathbf{A}^1(\mathbb{R})$*.*

*Proof.*

(1) *Show that* $I = (x^2+1)$ *is a prime ideal in* $\mathbb{R}[x]$. Given any $fg \in I$. It suffices to show that $f \in I$ or $g \in I$. By definition of $I$, there is a polynomial $h \in \mathbb{R}[x]$ such that $fg = (x^2+1)h$. So $(x^2+1) \mid f$ or $(x^2+1) \mid g$ since $x^2+1$ is irreducible in a unique factorization domain $\mathbb{R}[x]$. Therefore, $f \in I$ or $g \in I$.

(2) *Show that* $I$ *is not the ideal of any set in* $\mathbf{A}^1(\mathbb{R})$. Since $x^2+1$ has no roots in $\mathbb{R}$, $I$ cannot be the ideal of any nonempty set in $\mathbf{A}^1(\mathbb{R})$. Besides, $I(\varnothing) = (1) \neq (x^2+1)$.

□

**Problem 1.20.***

*Show that for any ideal $I$ in $k[x_1, \dots, x_n]$, $V(I) = V(\mathrm{rad}(I))$, and $\mathrm{rad}(I) \subseteq I(V(I))$.*

*Proof.*

(1) *Show that $V(I) = V(\mathrm{rad}(I))$.* Since $I \subseteq \mathrm{rad}(I)$, it suffices to show that $V(I) \subseteq V(\mathrm{rad}(I))$. Given any $P \in V(I)$. For any $f \in \mathrm{rad}(I)$, $f^n \in I$ for some positive integer $n > 0$. Note that

$$0 = (f^n)(P) = f(P)^n$$

since $f^n \in I$ and $P \in V(I)$. As $k$ is a domain, $f(P)^n = 0$ implies $f(P) = 0$. So $P \in V(\mathrm{rad}(I))$.

(2) By Equations (6) and (8) in this section,

$$I(V(I)) = I(V(\mathrm{rad}(I))) \supseteq \mathrm{rad}(I).$$

□

*Note.*

(1) By the Hilbert's Nullstellensatz, $I(V(I)) = \mathrm{rad}(I)$ if $k = \overline{k}$.

(2) Take $I = (x^2 + 1)$ as an ideal in $\mathbb{R}[x]$. Note that $I(V(I)) = I(\varnothing) = (1)$ and $\mathrm{rad}(I) = I = (x^2 + 1)$. So the equality in $\mathrm{rad}(I) \subsetneq I(V(I))$ might not hold if $k \neq \overline{k}$. (See Problem 1.19.)

**Problem 1.21.***

*Show that $I = (x_1 - a_1, \dots, x_n - a_n) \subseteq k[x_1, \dots, x_n]$ is a maximal ideal, and that the natural homomorphism from $k$ to $k[x_1, \dots, x_n]/I$ is an isomorphism.*

*Proof.*

(1) *Show that $I$ is a maximal ideal.* Suppose that $J$ is an ideal such that $J \supsetneq I$. Take any $f \in J - I$. By Problem 1.7(a),

$$f = \sum \lambda_{(i)} (x_1 - a_1)^{i_1} \cdots (x_n - a_n)^{i_n}.$$

As $f \notin I$, there is a nonzero constant term in $f$, say $\lambda \in k - \{0\}$. Note that $f - \lambda \in I \subsetneq J$. Hence,

$$\lambda = f - (f - \lambda) \in J$$

since $J$ is an ideal. As $\lambda \neq 0$, $J = k[x_1, \ldots, x_n]$ is not a proper ideal containing $I$.

(2) Let $\varphi : k \to k[x_1, \ldots, x_n]/I$ be the natural homomorphism. (That is, $\varphi : \lambda \to \lambda + I \in k[x_1, \ldots, x_n]/I$.)

(3) *Show that $\varphi$ is surjective.* Given any $f + I \in k[x_1, \ldots, x_n]/I$. By Problem 1.7(a),

$$f = \sum \lambda_{(i)}(x_1 - a_1)^{i_1} \cdots (x_n - a_n)^{i_n}.$$

So

$$\begin{aligned} f + I &= \sum \lambda_{(i)}(x_1 - a_1)^{i_1} \cdots (x_n - a_n)^{i_n} + I \\ &= \left( f(a_1, \ldots, a_n) + \sum_{\text{nonconstant}} \lambda_{(i)}(x_1 - a_1)^{i_1} \cdots (x_n - a_n)^{i_n} \right) + I \\ &= f(a_1, \ldots, a_n) + I. \end{aligned}$$

(Here the summation over all nonconstant terms is in $I$.) Hence

$$\varphi : f(a_1, \ldots, a_n) \in k \mapsto f + I.$$

(4) *Show that $\varphi$ is injective.* $\ker(\varphi) = \{\lambda \in k : \lambda \in I\} = k \cap I = \{0\}$ since $I$ is a proper ideal.

(5) By (2)(3)(4), $\varphi : k \to k[x_1, \ldots, x_n]/(x_1 - a_1, \ldots, x_n - a_n)$ is an isomorphism.

$\square$

## 1.4. The Hilbert Basis Theorem

**Problem 1.22.***

*Let $I$ be an ideal in a ring $R$, $\pi : R \to R/I$ the natural homomorphism.*

(a) *Show that for every ideal $J'$ of $R/I$, $\pi^{-1}(J') = J$ is an ideal of $R$ containing $I$, and for every ideal $J$ of $R$ containing $I$, $\pi(J) = J'$ is an ideal of $R/I$. This sets up a natural one-to-one correspondence between $\{$ideals of $R/I\}$ and $\{$ideals of $R$ that contain $I\}$.*

(b) *Show that $J'$ is a radical ideal if and only if $J$ is radical. Similarly for prime and maximal ideals.*

(c) *Show that $J'$ is finitely generated if $J$ is. Conclude that $R/I$ is Noetherian if $R$ is Noetherian. Any ring of the form $k[x_1, \dots, x_n]/I$ is Noetherian.*

*Proof of (a).*

(1) *Show that for every ideal $J'$ of $R/I$, $\pi^{-1}(J') = J$ is an ideal of $R$ containing $I$.*

   (a) *Show that $J$ contains $I$.* Note that $\pi^{-1}(0) = I \subseteq \pi^{-1}(J') = J$. So $J$ contains $I$. In particular, $J \neq \varnothing$ since $I \neq \varnothing$.

   (b) *Show that $J$ is a additive subgroup of $R$.* It suffices to show that $a - b \in J$ for any $a \in J$ and $b \in J$. Actually,

$$\pi(a - b) = \pi(a) - \pi(b) \in J'$$

   implies $a - b \in \pi^{-1}(J') = J$.

   (c) *Show that for every $r \in R$ and every $a \in J$, the product $ra \in J$.* In fact,

$$\pi(ra) = \pi(r)\pi(a) \in J'$$

   implies $ra \in \pi^{-1}(J') = J$.

(2) *Show that for every ideal $J$ of $R$ containing $I$, $\pi(J) = J'$ is an ideal of $R/I$.*

   (a) *Show that $J'$ is nonempty.* Note that $\pi(a) = 0 \in \pi(I) \subseteq \pi(J) = J'$ for any $a \in I$. So $J'$ is nonempty since $J$ is nonempty.

   (b) *Show that $J'$ is a additive subgroup of $R/I$.* It suffices to show that $\pi(a) - \pi(b) \in J'$ for any $\pi(a) \in J'$, $\pi(b) \in J'$, $a \in J$ and $b \in J$. It is trivial since

$$\pi(a) - \pi(b) = \pi(a - b) \in \pi(J) = J',$$

   $\pi$ is a ring homomorphism and $J$ is an ideal.

   (c) *Show that for every $\pi(r) \in R/I$ ($r \in R$) and every $\pi(a) \in J'$ ($a \in J$), the product $\pi(r)\pi(a) \in J'$.* It is trivial since

$$\pi(r)\pi(a) = \pi(ra) \in \pi(J) = J',$$

   $\pi$ is a ring homomorphism and $J$ is an ideal.

(3) By (1)(2), we setup the correspondence between

$$\{\text{ideals of } R/I\} \longleftrightarrow \{\text{ideals of } R \text{ that contain } I\}.$$

Note that this correspondence preserves the subset relation, and thus this correspondence is one-to-one.

□

*Proof of (b).*

(1) *Show that $J'$ is radical if $J$ is radical.* It suffices to show that $(a+I)^n = a^n + I \in J'$ implies that $a + I \in J'$. Note that

$$(a+I)^n = a^n + I \in J'$$

implies that $a^n \in J$ or $a \in J$ since $J$ is radical. Hence $a + I \in J/I = J'$.

(2) *Show that $J$ is radical if $J'$ is radical.* It suffices to show that $a^n \in J$ implies that $a \in J$. Note that

$$\pi(a^n) = \pi(a)^n \in J'$$

implies that $\pi(a) \in J'$ since $J'$ is radical. $a \in \pi^{-1}(J') = J$.

(3) *Show that $J'$ is prime if $J$ is prime.* It suffices to show that $(a+I)(b+I) = ab + I \in J'$ implies that $a + I \in J'$ or $b + I \in J'$. Note that

$$(a+I)(b+I) = ab + I \in J'$$

implies that $ab \in J$. So $a \in J$ or $b \in J$ by the primality of $J$. Hence $a + I \in J'$ or $b + I \in J'$.

(4) *Show that $J$ is prime if $J'$ is prime.* It suffices to show that $ab \in J$ implies that $a \in J$ or $b \in J$. Note that

$$\pi(ab) = \pi(a)\pi(b) \in J'$$

implies that $\pi(a) \in J'$ or $\pi(b) \in J'$ by the primality of $J'$. So $a \in \pi^{-1}(J') = J$ or $b \in \pi^{-1}(J') = J$.

(5) *Show that $J'$ is maximal if $J$ is maximal.* Suppose $\mathfrak{m}$ is an ideal containing $J'$. By (a), $\pi^{-1}(\mathfrak{m})$ is an ideal containing $J$. So $\pi^{-1}(\mathfrak{m}) = J$ or $\pi^{-1}(\mathfrak{m}) = R$ by the maximality of $J$. Hence, $\mathfrak{m} = \pi(J) = J'$ or $\mathfrak{m} = \pi(R) = R/I$.

(6) *Show that $J$ is maximal if $J'$ is maximal.* Suppose $\mathfrak{m}$ is an ideal containing $J$. By (a), $\pi(\mathfrak{m})$ is an ideal containing $J'$. So $\pi(\mathfrak{m}) = J'$ or $\pi(\mathfrak{m}) = R/I$ by the maximality of $J'$. Hence, $\mathfrak{m} = \pi^{-1}(J') = J$ or $\mathfrak{m} = \pi^{-1}(R/I) = R$.

□

*Note.*

(1) Note that

$$R/J \cong (R/I)/(J/I)$$

if $J$ is an ideal of $R$ such that $I \subseteq J$.

(2) Hence, $J$ is prime iff $R/J \cong (R/I)/(J/I)$ is a domain iff $J/I$ is prime.

(3) Also, $J$ is maximal iff $R/J \cong (R/I)/(J/I)$ is a field iff $J/I$ is maximal.

*Proof of (c).*

(1) *Show that $J'$ is finitely generated if $J$ is.* Suppose $J$ is generated by $a_1, \ldots, a_m$. It suffices to show that $J'$ is generated by

$$a_1 + I, \ldots, a_m + I \in J/I.$$

Given any $a + I \in J'$ where $a \in J$. Write $a = \sum_{1 \leq i \leq m} r_i a_i$ for some $r_i \in R$. Then

$$a + I = \sum r_i a_i + I = \sum (r_i + I)(a_i + I)$$

is generated by $a_1 + I, \ldots, a_m + I$.

(2) *Show that that $R/I$ is Noetherian if $R$ is Noetherian.* Note that $R$ is an ideal of itself.

(3) *Show that any ring of the form $k[x_1, \ldots, x_n]/I$ is Noetherian.* By the corollary to the Hilbert basis theorem, $k[x_1, \ldots, x_n]$ is Noetherian. By (2), the ring $k[x_1, \ldots, x_n]/I$ is Noetherian.

□

## 1.5. Irreducible Components of an Algebraic Set

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

## 1.6. Algebraic Subsets of the Plane

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

## 1.7. Hilbert's Nullstellensatz

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

## 1.8. Modules; Finiteness Conditions

**Problem 1.41.***

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

*Proof.*

(1) $S = \sum Rs_i$ for some $s_1, \ldots, s_n \in S$ since $S$ is module-finite over $R$.

(2) Let $I$ be the minimal subset of $\{s_1, \ldots, s_n\}$ which also spans $S$, say $\{t_1, \ldots, t_m\}$ with $m \leq n$. Clearly we can write

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

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 $s_1, \ldots, s_n \in S$ 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) $L = K[v_1, \cdots, v_n]$ for some $v_i \in L$. To show $L = K[v_1, \cdots, v_n] = K(v_1, \cdots, v_n)$, it suffices to show that all $v_i$ are algebraic over $L$.

(2)

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

## 1.9. Integral Elements

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

## 1.10. Field Extensions

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

**Problem PLACEHOLDER**

*PLACEHOLDER*

*Proof.*

(1) PLACEHOLDER

□

# Chapter 2: Affine Varieties

## 2.1. Coordinate Rings

### Problem 2.1.*

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

*Proof.*

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

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

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

(2) $\alpha$ is a ring homomorphism by construction in (1).

(3) *Show that* $\ker(\alpha) = I(V)$. In fact, given any $f \in k[x_1, \ldots, x_n]$, 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 $k[x_1, \ldots, x_n]/I(V) = \Gamma(V) \hookrightarrow \mathscr{F}(V, k)$ is an injective homomorphism.

$\square$

### 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

$$(x_1 + x_2)y \in (I_1 + I_2)J$$

where $x_i \in I_i$ and $y \in J$. It suffices to show that $(x_1 + x_2)y \in I_1J + I_2J$ (by (1)). In fact,

$$(x_1 + x_2)y = x_1y + x_2y \in I_1J + I_2J.$$

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

$$x_1y_1 + x_2y_2 \in I_1J + I_2J$$

where $x_i \in I_i$ and $y_i \in J$. It suffices to show that $x_1y_1 + x_2y_2 \in (I_1 + I_2)J$ (by (1)). In fact,

$$x_1y_1 + x_2y_2 = (x_1 + \underbrace{0}_{\in I_2})y_1 + (\underbrace{0}_{\in I_1} + x_2)y_2 \in (I_1 + I_2)J$$

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

$\square$

*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

$$x = x_1 \cdots x_n$$

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

$$x_i = \sum_{j(i)} x_{j(i),1} \cdots x_{j(i),N}$$

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

$$\begin{aligned}
x &= x_1 \cdots x_n \\
&= \left( \sum_{j(1)} x_{j(1),1} \cdots x_{j(1),N} \right) \cdots \left( \sum_{j(n)} x_{j(n),1} \cdots x_{j(n),N} \right) \\
&= \sum_{j(1),\dots,j(n)} (x_{j(1),1} \cdots x_{j(1),N}) \cdots (x_{j(n),1} \cdots x_{j(n),N}) \\
&= \sum_{j(1),\dots,j(n)} \underbrace{(x_{j(1),1} \cdots x_{j(n),1})}_{\in I_1^n} \cdots \underbrace{(x_{j(1),N} \cdots x_{j(n),N})}_{\in I_N^n} \\
&\in I_1^n \cdots I_N^n.
\end{aligned}$$

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

$$x = x_1 \cdots x_N \in I_1^n \cdots I_N^n$$

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

$$x_i = \sum_{j(i)} x_{j(i),1} \cdots x_{j(i),n}$$

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

$$\begin{aligned}
x &= x_1 \cdots x_N \\
&= \left( \sum_{j(1)} x_{j(1),1} \cdots x_{j(1),n} \right) \cdots \left( \sum_{j(N)} x_{j(N),1} \cdots x_{j(N),n} \right) \\
&= \sum_{j(1),\dots,j(N)} (x_{j(1),1} \cdots x_{j(1),n}) \cdots (x_{j(N),1} \cdots x_{j(N),n}) \\
&= \sum_{j(1),\dots,j(N)} (\underbrace{x_{j(1),1} \cdots x_{j(N),1}}_{\in I_1 \cdots I_N}) \cdots (\underbrace{x_{j(1),n} \cdots x_{j(N),n}}_{\in I_1 \cdots I_N}) \\
&\in (I_1 \cdots I_N)^n.
\end{aligned}$$

□

**Problem 2.41.***

*Let $I$, $J$ be ideals in $R$. Suppose $I$ is finitely generated and $I \subseteq \operatorname{rad}(J)$. Show that $I^n \subseteq J$ for some $n$.*

*Proof.*

(1) Let $I$ be generated by $x_1, \dots, x_m \in I$. As $I \subseteq \operatorname{rad}(J)$, there are integers $n_i > 0$ such that $x_i^{n_i} \in J$.

(2) Let $N = n_1 + \cdots + n_m$. Given any $x = \sum_{i=1}^m r_i x_i \in I$, so

$$\begin{aligned}
x^N &= \left( \sum_{i=1}^m r_i x_i \right)^N \\
&= \sum_{k_1 + \cdots + k_m = N} \binom{N}{k_1, \dots, k_m} r_1^{k_1} x_1^{k_1} \cdots r_m^{k_m} x_m^{k_m}.
\end{aligned}$$

(3) Note that for each term there is some $j$ such that $k_j \geq n_j$. Hence,

$$\begin{aligned}
& x_j^{k_j} = x_j^{k_j - n_j} x_j^{n_j} \in J && (J \text{ is an ideal}) \\
\Longrightarrow\ & r_1^{k_1} x_1^{k_1} \cdots r_m^{k_m} x_m^{k_m} \in J \text{ for each term} && (J \text{ is an ideal}) \\
\Longrightarrow\ & x^N \in J. && (J \text{ is an ideal}) \\
\Longrightarrow\ & I^N \subseteq J.
\end{aligned}$$

□

**Supplement.** *(Exercise 1.13 in the textbook: Eisenbud, Commutative Algebra with a View Toward Algebraic Geometry.) Suppose that $I$ is an ideal in a commutative ring. Show that if* $\mathrm{rad}(I)$ *is finitely generated, then for some integer $N$ we have* $(\mathrm{rad}(I))^N \subseteq I$*. Conclude that in a Noetherian ring the ideals $I$ and $J$ have the same radical iff there is some integer $N$ such that $I^N \subseteq J$ and $J^N \subseteq I$. Use the Nullstellensatz to deduce that if $I, J \subseteq S = k[x_1, \dots, x_n]$ are ideals and $k$ is algebraically closed, then $Z(I) = Z(J)$ iff $I^N \subseteq J$ and $J^N \subseteq I$ for some $N$.*

*Proof.*

(1) *Show that if* $\mathrm{rad}(I)$ *is finitely generated, then for some integer $N$ we have* $(\mathrm{rad}(I))^N \subseteq I$. Say $x_1, \dots, x_m \in \mathrm{rad}(I)$ generate $\mathrm{rad}(I)$.

(a) For each $i$, there exists an integer $n_i > 0$ such that $x_i^{n_i} \in I$ (since $\mathrm{rad}(I)$ is radical).

(b) Let $N = n_1 + \cdots + n_m$. Given any $x = \sum_{i=1}^m r_i x_i \in \mathrm{rad}(I)$, so

$$\begin{aligned} x^N &= \left(\sum_{i=1}^m r_i x_i\right)^N \\ &= \sum_{k_1+\cdots+k_m=N} \binom{N}{k_1, \dots, k_m} r_1^{k_1} x_1^{k_1} \cdots r_m^{k_m} x_m^{k_m}. \end{aligned}$$

(c) Note that for each term there is some $j$ such that $k_j \geq n_j$. Hence,

$$\begin{aligned} & x_j^{k_j} = x_j^{k_j - n_j} x_j^{n_j} \in I && (I \text{ is an ideal}) \\ \Longrightarrow\ & r_1^{k_1} x_1^{k_1} \cdots r_m^{k_m} x_m^{k_m} \in I \text{ for each term} && (I \text{ is an ideal}) \\ \Longrightarrow\ & x^N \in I. && (I \text{ is an ideal}) \\ \Longrightarrow\ & (\mathrm{rad}(I))^N \subseteq I. \end{aligned}$$

(2) *Show that in a Noetherian ring the ideals $I$ and $J$ have the same radical iff there is some integer $N$ such that $I^N \subseteq J$ and $J^N \subseteq I$.*

(a) ($\Longrightarrow$) Since in a Noetherian ring every ideal is finitely generated, $\mathrm{rad}(I)$ and $\mathrm{rad}(J)$ are finitely generated. By (1), there is a common integer $N$ such that

$$(\mathrm{rad}(I))^N \subseteq I \quad \text{and} \quad (\mathrm{rad}(J))^N \subseteq J.$$

Note that $I^N \subseteq (\mathrm{rad}(I))^N$ and $J^N \subseteq (\mathrm{rad}(J))^N$. Since $\mathrm{rad}(I) = \mathrm{rad}(J)$ by assumption,

$$\begin{aligned} I^N &\subseteq (\mathrm{rad}(I))^N = (\mathrm{rad}(J))^N \subseteq J, \\ J^N &\subseteq (\mathrm{rad}(J))^N = (\mathrm{rad}(I))^N \subseteq I. \end{aligned}$$

(b) ($\Longleftarrow$) It suffices to show that $\operatorname{rad}(I) \subseteq \operatorname{rad}(J)$. $\operatorname{rad}(J) \subseteq \operatorname{rad}(I)$ is similar. Given any $x \in \operatorname{rad}(I)$, there is an integer $M > 0$ such that $x^M \in I$. Hence $x^{MN} \in I^N \subseteq J$, or $x \in \operatorname{rad}(J)$.

(3) *Show that if $I, J \subseteq S = k[x_1, \dots, x_n]$ are ideals and $k$ is algebraically closed, then $Z(I) = Z(J)$ iff $I^N \subseteq J$ and $J^N \subseteq I$ for some $N$.* Note that $S$ is Noetherian and we can apply part (2). By the Nullstellensatz, $Z(I) = Z(J)$ iff $\operatorname{rad}(I) = \operatorname{rad}(J)$ iff $I^N \subseteq J$ and $J^N \subseteq I$ for some $N$.

□

## 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 $\varphi_i : V_i \to V_{i+1}$, 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,

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

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 $\mathbf{A}^2$

## 7.3. Blowing up a Point in $\mathbf{P}^2$

## 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