Introduction

Oh hey, it's another one of these independent studies. Me and a friend are going to be going through William Fulton's *Algebraic Curves*. It will be hard, it will be long, and it might not work out for me, but who cares.

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We will assume all rings are commutative with unity, where $\mathbb{Z}$ is the integers, $\mathbb{Q}$ is the rationals, $\mathbb{R}$ is the reals, and $\mathbb{C}$ is the complex numbers.

Any integral domain R has a quotient field K, which contains R as a subring, and any element in K may be written as a not necessarily unique ratio of two elements of R. Any one-to-one ring homomorphism from R to a field L extends uniquely to a ring homomorphism from K to L.

If R is a ring, then $R[x]$ is the ring of polynomials with coefficients in R. The degree of a nonzero polynomial $\sum a_ix^i$ is the largest integer d such that $a_d \neq 0$. The polynomial is monic if $a_d = 1$.

The ring of polynomials in n variables over R is $R[x_1, \dots, x_n]$. We write $R[x, y]$ and $R[x, y, z]$ if $n = 2$ and 3 respectively. Monomials in $R[x_1, \dots, x_n]$ are of the form $x^{(i)} := x_1^{i_1}x_2^{i_2}\cdots x_n^{i_n}$, where i_j are nonnegative integers, and the degree of the monomial is $i_1 + \cdots i_n$. Every $F \in R[x_1, \dots, x_n]$ has a unique expression $F = \sum a_{(i)}x^{(i)}$, where $x^{(i)}$ are monomials, and $a_{(i)} \in R$. We say F is homogeneous of degree d if all $a_{(i)}$ are zero except for monomials of degree d. The polynomial F is written as $F = F_0 + F_1 + \cdots F_d$, where F_i is a form of degree i, and $d = \deg(F)$ for $F_d \neq 0$.

The ring R is a subring of $R[x_1, \dots, x_n]$, and the ring $R[x_1, \dots, x_n]$ is characterized by the following: if $\varphi\colon R \rightarrow S$ is a ring homomorphism, and $s_1, \dots, x_n$ are elements in S, then there is a unique extension of φ to a ring homomorphism $\overline{\varphi}\colon R[x_1, \dots, x_n] \rightarrow S$ such that $\overline{\varphi}(x_i) = s_i$. The image of F under $\overline{\varphi}$ is written $F(s_1, \dots, s_n)$. The ring $R[x_1, \dots, x_n]$ is canonically isomorphic to $R[x_1, \dots, x_{n-1}][x_n]$.

An element $a \in R$ is called irreducible if it is not a unit or zero, and any factorization $a = bc$ with $b, c \in R$ is such that either b or c is a unit. A domain R is a unique factorization domain (UFD) if every nonzero element in R can be factored uniquely up to units and ordering.

If R is a UFD with quotient field K, then any irreducible element $F \in R[x]$ remains irreducible when considered in $K[x]$.

Theorem (Gauss's Lemma for $\mathbb{Z}$)**:** If $F \in \mathbb{Z}[x]$ is a monic polynomial that is irreducible, then F is irreducible in $\mathbb{Q}[x]$.

If F and G are polynomials in $R[x]$ with no common factors in $R[x]$, then they have no common factors in $K[x]$.

If R is a UFD, then $R[x]$ is also a UFD, and consequently $k[x_1, \dots, x_n]$ is a UFD for any field k. The quotient field of $k[x_1, \dots, x_n]$ is written $k(x_1, \dots, x_n)$ is called the field of rational functions in n variables over k.

If $\varphi\colon R \to S$ is a ring homomorphism, $\ker(\varphi) := \varphi^{-1}(0)$. The kernel is an ideal in R. An ideal in R is proper if $I \neq R$, and a proper ideal is known as maximal if it is not contained in any larger proper ideal.[I] An ideal $\mathfrak{p}$ is prime if, whenever $ab \in \mathfrak{p}$, then $a \in \mathfrak{p}$ or $b \in \mathfrak{p}$.[II]

Let k be a field and I a proper ideal in $k[x_1, \dots, x_n]$. The canonical homomorphism π from $k[x_1, \dots, x_n]$ to $k[x_1, \dots, x_n]/I$ restricts to a ring homomorphism from k to $k[x_1, \dots, x_n]/I$. We regard k as a subring of $k[x_1, \dots, x_n]/I$, which is a vector space over k.

If R is an integral domain, then $\text{char}(R)$, the characteristic of R, is the smallest integer p such that

$$\underbrace{1 + 1 \cdots + 1}_{p \text{ times}} = 0.$$

If p exists, we say $\text{char}(R) = p$, else 0.

Note that if $\varphi\colon \mathbb{Z} \rightarrow R$ is the unique ring homomorphism from $\mathbb{Z}$ to R,[III] then $\ker(\varphi) = \langle p \rangle$, so $\text{char}(R)$ is prime or 0.

If R is a ring, and $F \in R[x]$, and a is a root of F, then $F = (x - a)G$ for some unique polynomial $G \in R[x]$. A field k is algebraically closed if any nonconstant $F \in k[x]$ has a root.

Exercise (Exercise 1.1)**:** Let R be an integral domain.

(a) If F and G are forms of degree r and 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.

Solution:

(a) Let $H = FG$, where F is a form of degree r and G is a form of degree s. Note that since F and G are forms, we know that $F = F_r$, where F_r is the form with degree r, and $G = G_s$, where G_s is the form with degree s.

[I]Alternatively, an ideal I is maximal if the quotient ring R/M is a field.

[II]Alternatively, an ideal $\mathfrak{p}$ is prime if $R/\mathfrak{p}$ is an integral domain.

[III]This is because $\mathbb{Z}$ is initial in the category of rings. See Aluffi.

Exercise (Exercise 1.2)**:** Let R be a UFD and K the quotient field of R. Show that every element $z \in K$ may be written as $z = a/b$, where $a, b \in R$ have no common factors. This representative is unique up to units of R.

Solution: Since $K = \text{Frac}(R)$, we know that every $z \in K$ is of the form $z = \frac{a}{b}$. Since R a unique factorization domain, $\gcd(a, b)$ is unique and well-defined. Set $c \cdot \gcd(a, b) = a$ and $d \cdot \gcd(a, b) = b$. Then,

$$\begin{aligned} z &= \frac{a}{b} \\ &= \frac{c \cdot \gcd(a,b)}{d \cdot \gcd(a,b)} \\ &= \frac{c}{d}. \end{aligned}$$

We show that this is unique up to units. Suppose

$$\begin{aligned} z &= \frac{c}{d} \\ &= \frac{c'}{d'}. \end{aligned}$$

Then, by the properties of the field of fractions, we know that

$$c'd = cd',$$

and since R is a UFD, we know that $\gcd(c, d) = \gcd(c', d') = 1$, so $c = u_1c'$ and $d = u_2d'$.

Exercise (Exercise 1.3)**:** Let R be a principal ideal domain, and let P be a nonzero proper prime ideal in R.

(a) Show that P is generated by an irreducible element.

(b) Show that P is maximal.

Solution:

(a) Since P is principal, we know that $P = \langle a \rangle$ for some $a \in R$. We know that a cannot be a unit, as otherwise $P = R$, contradicting the assumption that P is proper, and that $a \neq 0$ as P is not zero.

Suppose toward contradiction that $\langle a \rangle \subsetneq \langle b \rangle$ for some $b \in R$. Then, $a = bc$ for some $c \in R$. If $c \notin \langle a \rangle$, then since $\langle a \rangle$ is prime, we must have $b \in \langle a \rangle$, contradicting strict inclusion. Thus, $c \in \langle a \rangle$, so $c = at$ for some $t \in R$. Therefore, we have $a = abt$, so $bt = 1_R$, and $\langle b \rangle = R$.

(b) Since R is a PID, and P is prime, we know that $P = \langle a \rangle$ is generated by an irreducible element. Thus, if $\langle a \rangle \subseteq \langle b \rangle$, then $a = bc$ for some $c \in R$. Since we have unique factorization (as all PIDs are UFDs), and a is irreducible, this means either b or c is a unit. If b is a unit, then $\langle b \rangle = R$, and if c is a unit, then $\langle b \rangle = \langle a \rangle$. Thus, $\langle a \rangle$ is maximal.

Exercise (Exercise 1.4)**:** Let k be an infinite field, $f \in k[x_1, \dots, x_n]$. Suppose $F(a_1, \dots, a_n) = 0$ for all $a_1, \dots, a_n \in k$. Show that $f = 0$.

Exercise (Exercise 1.5)**:** Let k be any field. Show that there are an infinite number of irreducible monic polynomials in $k[x]$.

Solution: Suppose $F_1, \dots, F_n$ were all the irreducible monic polynomials in $k[x]$. Consider the polynomial $P = F_1F_2 \cdots F_n + 1$. We note that P is monic. We will show that P is irreducible.

Suppose toward contradiction that P were reducible. We know that $k[x]$ is a principal ideal domain, so $P \in \langle F_i \rangle$ for some irreducible monic F_i. However, we know that, for any F_i, $1 \leqslant i \leqslant n$, $P \nmid F_i$, as, applying the division algorithm to P, we get

$$P = (F_i) \prod_{j \neq i} F_j + 1,$$

where $r \neq 0$. Thus, P is not reducible and monic, so there are infinitely many irreducible monic polynomials in $k[x]$.

Exercise (Exercise 1.6)**:** Show that any algebraically closed field is infinite.

Solution: Note that if k is any field, then there are infinitely many irreducible monic polynoimals in $k[x]$. If k is algebraically closed, then $(x-a)$, for $a \in k$, is the only irreducible monic polynomial. Since there are infinitely many irreducible monic polynomials in $k[x]$, there are infinitely many $a \in k$ such that $(x-a)$ is irreducible in $k[x]$. Thus, k is infinite.

Exercise (Exercise 1.7)**:** Let k be any field, and $F \in k[x_1, \dots, x_n]$, with $a_1, \dots, a_n \in k$.

(a) Show that

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

where $\lambda_{(i)} \in k$.

(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 necessarily unique $G_i \in k[x_1, \dots, x_n]$.

Solution:

(a) We let

$$G = F(x_1 + a_1, x_2 + a_2, \dots, x_n + a_n).$$

Then, since $G \in k[x_1, \dots, x_n]$, we have

$$G = \sum \lambda_{(i)} x_1^{i_1} \cdots x_n^{i_n}.$$

Then, we have

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

(b) Note that if $F(a_1, \dots, a_n) = 0$, then $(x_i - a_i) \mid F(a_1, \dots, a_{i-1}, x_i, a_{i+1}, \dots, a_n)$. Thus, we have

$$F(a_1, \dots, a_{i-1}, x_i, a_{i+1}, \dots, a_n) = (x_i - a_i)\underbrace{g(a_1, \dots, a_{i-1}, x_i, a_{i+1}, \dots, a_n)}_{G_i}.$$

This yields

$$F(x_1, \dots, x_n) = \sum_{i=1}^{n}(x_i - a_i)G_i.$$

Affine Space and Algebraic Sets

Definition. If k is a field, then when we write $\mathbb{A}^n(k)$, or $\mathbb{A}^n$, to be the cartesian product of k with itself n times.

We call $\mathbb{A}^n(k)$ the affine n-space over k. Its elements are called points. We call $\mathbb{A}^1(k)$ the affine line and $\mathbb{A}^2(k)$ the affine plane.

Definition. If $F \in k[x_1, \dots, x_n]$, then $P = (a_1, \dots, a_n) \in \mathbb{A}^n(k)$ is called a zero of F if $F(P) = (a_1, \dots, a_n) = 0$.

If F is not constant, then the zeros of F are called the hypersurface defined by F, defined by $V(F)$. A hypersurface in $\mathbb{A}^2(k)$ is called an affine plane curve.

If F is a polynomial of degree 1, then $V(F)$ is called a hyperplane in $\mathbb{A}^n(k)$; if $n = 2$, then an affine hyperplane is a line.

Definition. If S is any set of polynomials in $k[x_1, \dots, x_n]$, then $V(S) = \{P \in \mathbb{A}^n \mid F(P) = 0 \text{ for all } F \in S\}$. In other words, $V(S) = \bigcap_{F \in S} V(F)$. If $S = \{F_1, \dots, F_r\}$, we write $V(F_1, \dots, F_r)$.

A subset $X \subseteq \mathbb{A}^n(k)$ is an affine algebraic set (or algebraic set) if $X = V(S)$ for some S.

Proposition:

(1) If I is the ideal in $k[x_1, \dots, x_n]$ generated by S, then $V(S) = V(I)$; thus, every algebraic set is equal to $V(I)$ for some ideal I.

(2) If $\{I_\alpha\}$ is a collection of ideals, then $V(\bigcup_\alpha I_\alpha) = \bigcap_\alpha V(I_\alpha)$.

(3) If $I \subseteq J$, then $V(I) \supseteq V(J)$.

(4) For any polynomialsF, G, $V(FG) = V(F) \cup V(G)$. Furthermore, $V(I) \cup V(J) = V(\{FG \mid F \in I, G \in J\})$.

(5) We have that $V(0) = \mathbb{A}^n(k)$, $V(1) = \emptyset$, $V(x_1 - a_1, \dots, x_n - a_n) = \{(a_1, \dots, a_n)\}$ for $a_i \in k$. Thus, any finite subset of $\mathbb{A}^n(k)$ is an algebraic set.

Exercise (Exercise 1.8)**:** Show that the algebraic subsets of $\mathbb{A}^1(k)$ are just the finite subsets together with $\mathbb{A}^1(k)$ itself.

Solution: Since $k[x]$ is a principal ideal domain, we know that the zero set $V(S)$ for any $S \subseteq k[x]$ is of the form $V(\langle f \rangle) = V(f)$, where $f \in k[x]$. Since f is a polynomial, f has finitely many roots, so there are finitely many elements in the algebraic subset.

Additionally, since $0 \in k[x]$, we know that k is also an algebraic subset.

Exercise (Exercise 1.14)**:** Let F be a nonconstant polynomial in $k[x_1, \dots, x_n]$, where k is algebraically closed. Show that $\mathbb{A}^n(k) \setminus V(F)$ is infinite if $n \geqslant 1$ and that $V(F)$ is infinite if $n \geqslant 2$. Conclude that the complement of any proper algebraic set is infinite.

Solution: We know that k is infinite as k is algebraically closed.

Let $F \in k[x_1, \dots, x_n] \cong k[x_1, \dots, x_{n-1}][x_n]$.

In the base case with $n = 1$, we know that there are finitely many roots in $\mathbb{A}^1(k)$, so we have the base case. If $n \geqslant 2$, then we write $F = \sum G_i x_n^i$. We know that since F is nonzero, then there is at least one nonzero G_i. We showed in Exercise 1.4 that there is some $a_1, \dots, a_{n-1} \in k$ such that $G_i(a_1, \dots, a_{n-1}) \neq 0$. Thus, $F(a_1, \dots, a_{n-1}, x_n)$ is not the zero polynomial, meaning there are finitely many roots, and thus infinitely many non-roots.

Thus, there are infinitely many $a_1, \dots, a_n \in k$ with $a_1, \dots, a_n \neq 0$.

We write $F = \sum G_i x_n^i$. We know that if all the G_i are constant, then we have a single-variable polynomial in x_n, and any choice of $a_1, \dots, a_{n-1} \in k$ provide other elements of $V(F)$. We assume that there is some G_i that is a nonconstant polynomial in $x_1, \dots, x_{n-1}$.

Since G_i is nonzero, we may use the previous paragraph to state that G_i has infinitely many non-roots, and for each choice of those $a_1, \dots, a_{n-1}$, we have a polynomial in x_n. This polynomial has a root, meaning there are infinitely many roots.

Exercise (Exercise 1.15)**:** Let $V \subseteq \mathbb{A}^n(k)$ and $W \subseteq \mathbb{A}^m(k)$ be algebraic sets. Show that

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

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

Solution: Consider the set of polynomials in $k[x_1, \dots, x_n, x_{n+1}, \dots, x_{n+m}]$ given by $P = F(x_1, \dots, x_n) + G(x_{n+1}, \dots, x_m)$, where F is a polynomial in the ideal whose algebraic set is V and G is an ideal in the algebraic set whose ideal is W. Then, the collection of zeros are those of the form $(a_1, \dots, a_n, b_1, \dots, b_m)$, where $(a_1, \dots, a_n) \in V$ and $(b_1, \dots, b_m) \in W$.

Solution (A Real Solution)**:** We have that V and W are defined by $\{F_1, \dots, F_r\}$ and $\{G_1, \dots, G_s\}$ for some polynomials. We define $V \times W$ to be the algebraic set defined by the polynomials in $\{F_1, \dots, F_r, G_1, \dots, G_s\}$ that are constant with respect to the other variables.

The Ideal of a Set of Points

Definition. If $X \subseteq \mathbb{A}^n(k)$, then the polynomials that vanish on X form an ideal in $k[x_1, \dots, x_n]$, called the ideal of X, or $I(X)$.

$$I(X) := \{F \in k[x_1, \dots, x_n] \mid F(a_1, \dots, a_n) = 0 \text{ for all } (a_1, \dots, a_n) \in X\}.$$

The following hold.

- If $X \subseteq Y$, then $I(X) \supseteq I(Y)$.
- We have $I(\emptyset) = k[x_1, \dots, x_n]$, $I(\mathbb{A}^n(k)) = \langle 0 \rangle$ if k is infinite, and $I(\{(a_1, \dots, a_n)\}) = \langle x_1 - a_1, \dots, x_n - a_n \rangle$ for $a_1, \dots, a_n \in k$.
- We have $I(V(S)) \supseteq S$ for any set S of polynomials, and $V(I(X)) \supseteq X$ for any set X of points.
- We have $V(I(V(S))) = V(S)$ for any set of polynomials S, and $I(V(I(X))) = I(X)$ for any set X of points. If V is an algebraic set, $V = V(I(V))$ and if I is the ideal of an algebraic set, then $I = I(V(I))$.

Definition. If I is any ideal in a ring R, we define the radical of I, written $\operatorname{rad}(I) = \{a^n \mid a \in I \text{ for some } n > 0\}$. We have that $\operatorname{rad}(I)$ is an ideal containing I. An ideal I is called a radical ideal if $I = \operatorname{rad}(I)$.

- We have $I(X)$ is a radical ideal for any $X \subseteq \mathbb{A}^n(k)$.

Exercise (Exercise 1.16)**:** Let V and W be algebraic sets in $\mathbb{A}^n(k)$. Show that $V = W$ if and only if $I(V) = I(W)$.

Solution: Let $V = W$. Then, if $F \in I(V)$, then $F = 0$ on W, so $F \in I(W)$, and vice versa.

Suppose $I(V) = I(W)$. We know that $V(I(V)) = V$ and $V(I(W)) = W$. Thus, if $(a_1, \dots, a_n) \in V$, we know that for all $F \in I(W)$, that $F(a_1, \dots, a_n) = 0$ as $F \in I(V)$, meaning $(a_1, \dots, a_n) \in V(I(W)) = W$. By symmetry, we have $V = W$.

Exercise (Exercise 1.17)**:**

(a) Let V be an algebraic set in $\mathbb{A}^n(k)$ and $P \in \mathbb{A}^n(k)$ not a point 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 $F(P) = 1$.

(b) Let $P_1, \dots, P_r$ e distinct points in $\mathbb{A}^n(k)$ not in an algebraic set V. Show that there are polynomials $F_1, \dots, F_r \in I(V)$ such that $F_i(P_j) = \delta_{ij}$.

(c) With $P_1, \dots, P_r$ and V as in (b), and $a_{ij} \in k$ for $1 \leqslant i, j \leqslant r$, show that there are $G_i \in I(V)$ such that $G_i(P_j) = a_{ij}$ for all i and j.

Solution:

(a) We know that there is some $F \in I(V)$ such that $F(P) \neq 0$. Letting $a = F(P)$, we have that $\frac{1}{a}F(P) = 1$.

(b) We find $F_i \in I(V \cup \{P_{-i}\})$, where $\{P_{-i}\} = \{P_1, \dots, P_r\} \setminus \{P_i\}$. Applying (a) to F_i, we get that $F_i(P_i) = 1$ and $F_i(P_j) = 0$ for $j \neq i$. By symmetry, this holds for $F_1, \dots, F_r$.

(c) With $P_1, \dots, P_r$ and V as in (b), find $F_1, \dots, F_r$ as in (b). Then, $G_i = \sum_j a_{ij} F_j$ yields our desired outcome.

Exercise (Exercise 1.18)**:** Let I be an ideal in a ring R. If $a^n \in I$ and $b^m \in I$, show that $(a+b)^{n+m} \in I$. Show that $\operatorname{rad}(I)$ is a (radical) ideal. Show that any prime ideal is radical.

Solution:

- Applying binomial theorem, we have
$$\begin{aligned}(a+b)^{n+m} &= \sum_{k=0}^{n+m} \binom{n+m}{k} a^{n+m-k} b^k \\ &\in I,\end{aligned}$$
where $a^0 = b^0 := 1$.
- We have $I \subseteq \operatorname{rad}(I)$, since we can take $n = 1$. If $a, b \in \operatorname{rad}(I)$, we know that there is some n such that $a^n, b^m \in I$, so by the same logic as above, $(a-b)^{n+m} \in I$, meaning $a - b \in \operatorname{rad}(I)$. Now, if $a \in \operatorname{rad}(I)$ and $x \in R$, then

we have that $a^n \in I$ for some n, meaning $x^n a^n \in I$ as I is an ideal, so $(xa)^n \in I$, so $xa \in \text{rad}(I)$, so $\text{rad}(I)$ is an ideal.

- Let I be prime, and let $a \in \text{rad}(I)$. Then, $a^n \in I$ for some $n > 0$, meaning $(a)\left(a^{n-1}\right) \in I$. Then, either $a \in I$, or $a^{n-1} \in I$, so by the implicit inductive hypothesis, we have $a \in I$, so $\text{rad}(I) \subseteq I$, so $\text{rad}(I) = I$.

Exercise (Exercise 1.20)**:** Show that for any ideal I in $k[x_1, \dots, x_n]$, $V(I) = V(\text{rad}(I))$, and $\text{rad}(I) \subseteq I(V(I))$.

Solution:

- Clearly, $V(\text{rad}(I)) \subseteq V(I)$ because $I \subseteq \text{rad}(I)$. We know that if $P \in V(I)$, then there is some polynomial $F \in I$ such that $F(P) = 0$.

Exercise (Exercise 1.21)**:** Show that any $I = \langle x_1 - a_1, \dots, x_n - a_n \rangle \subseteq k[x_1, \dots, x_n]$ is a maximal ideal, and that the natural homomorphism from k to $k[x_1, \dots, x_n]/I$ is an isomorphism.

Solution: Note that $\langle x_1 - a_1, \dots, x_n - a_n \rangle \subseteq k[x_1, \dots, x_n]$ is isomorphic to $\langle x_1, \dots, x_n \rangle \subseteq k[x_1 + a_1, \dots, x_n + a_n]$, $k[x_1, \dots, x_n]/I \cong k$.

The Hilbert Basis Theorem

Earlier, we allowed any algebraic set $V(S)$ to be defined by an arbitrary set $\{F_i\}_{i \in I} \subseteq k[x_1, \dots, x_n]$. However, the Hilbert Basis Theorem will show that a finite number will do.

Theorem: Every algebraic set is the intersection of a finite number of hypersurfaces.

Proof. We know that $V(I)$ is the algebraic set for some $I \subseteq k[x_1, \dots, x_n]$. It is enough to show that I is finitely generated, as if $I = \langle F_1, \dots, F_n \rangle$, then $V(I) = V(F_1) \cap \dots \cap V(F_n)$. □

Now, to prove this, we need to show that any arbitrary ideal $I \subseteq k[x_1, \dots, x_n]$ is finitely generated. This is where the Hilbert Basis Theorem comes into play.

Definition. If R is a commutative ring, with identity, we say R is Noetherian if every ideal of R is finitely generated.

Note that all PIDs are Noetherian.

Now, we may state and prove the Hilbert Basis Theorem.

Theorem (Hilbert Basis Theorem)**:** If R is a Noetherian ring, then $R[x_1, \dots, x_n]$ is a Noetherian ring.

Proof. Since $R[x_1, \dots, x_n]$ is canonically isomorphic to $R[x_1, \dots, x_{n-1}][x_n]$. The theorem will follow by induction if we can prove that $R[x]$ is Noetherian whenever R is Noetherian.

Let $I \subseteq R[x]$ be an ideal. We wish to find a finite set of generators for I.

Let $F = a_d x^d + \cdots a_1 x + a_0 \in R[x]$ with $a_d \neq 0$. We call a_d the leading coefficient of F. Let J be the set of leading coefficients of polynomials in I. Then, $J \subseteq R$ is an ideal, so there are polynomials $F_1, \dots, F_r \in I$ whose leading coefficients generate J.

Select N larger than the degree of each F_i. For each $m \leqslant N$, let J_m be the ideal in R consisting of all leading coefficients of polynomials $F \in I$ with $\deg(F) \leqslant m$. Let $\left\{F_{m_j}\right\}$ be the finite set of polynomials in I with degree $\leqslant m$ such that their leading coefficients generate J_m. Let I' be the ideal generated by F_i and F_{m_j} for each i, m_j. It is enough to show that $I = I'$.

Suppose $I' \subsetneq I$. Let G be an element of I of minimal degree such that $G \notin I'$. If $\deg(G) > N$, then we may find Q_i such that $\sum Q_i F_i$ and G have the same leading term. However, this means $\deg(G - \sum Q_i F_i) < \deg(G)$, so $G - \sum Q_i F_i \in I'$, meaning $G \in I'$. Similarly, if $\deg(G) = m \leqslant N$, then we may lower the degree by subtracting $\sum Q_j F_{m_j}$ for some Q_j. □

Exercise (Exercise 1.22)**:** Let I be an ideal in a ring R, $\pi\colon R \to R/I$ the canonical projection.

(a) Show that for every ideal $J' \subseteq R/I$, that $\pi^{-1}(J') = J$ is an ideal of R containing I. Furthermore, show that for every ideal $J \subseteq R$, that $\pi(J) = J'$ is an ideal of R/I. This establishes a natural 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, show this for J prime and maximal.

(c) Show that J' is finitely generated if J is. Conclude that R/I is Noetherian if R is Noetherian. Thus, we get that $k[x_1, \dots, x_n]/I$ is Noetherian for any ideal $I \subseteq k[x_1, \dots, x_n]$ by the Hilbert Basis Theorem.

Solution:

(a) We know that $I \subseteq \pi^{-1}(J')$, as $I = \pi^{-1}(0 + I) \subseteq \pi^{-1}(J')$. Notice that, if $a, b \in \pi^{-1}(J')$ and $r \in R$, then $a + I, b + I \in J'$ and $r + I \in R/I$. Then, $a - b + I \in J'$, so $a - b \in \pi^{-1}(J')$, and $ra + I \in J'$, so $ra \in \pi^{-1}(J')$, so $\pi^{-1}(J')$ is an ideal of R.

Now, let $a + I, b + I \in \pi(J)$. Then, we know that there exist $c_1, c_2 \in J$ such that $a - c_1, b - c_2 \in I$. Thus, $(a - b) + (c_2 - c_1) \in I$. Since we have $c_2 - c_1 \in J$ as J is an ideal, so $\pi(a - b) = \pi(c_2 - c_1)$, and $(a - b) + I \in \pi(J)$. Now, let $a + I \in \pi(J)$, and let $r + I \in R/I$. Then, there exist $c_1 \in R$, $c_2 \in J$ such that $r - c_1 \in I$ and $a - c_2 \in I$, meaning that $\pi(c_1c_2) = \pi(ra) = ra + I \in \pi(J)$.

(b) Let J be maximal. Then, $R/J \cong (R/I)/(\pi(J))$, is a field, meaning $\pi(J) \subseteq R/I$ is also maximal. This gives both directions.

Similarly, if J is prime, then $R/J \cong (R/I)/(\pi(J))$ is an integral domain, so $\pi(J) \subseteq R/I$ is also an integral domain. This gives both directions.

Let J be a radical ideal. Then, $J = \bigcap\left\{\mathfrak{p} \,\middle|\, J \subseteq \mathfrak{p}, \mathfrak{p} \text{ is prime}\right\}$. We know that for all $\mathfrak{p}$, $\pi(\mathfrak{p}) \subseteq R/I$ is prime. We know that $\pi(J) \subseteq \pi(\mathfrak{p})$ if and only if $J \subseteq \mathfrak{p}$, so $\pi(J) = \bigcap\left\{\pi(\mathfrak{p}) \,\middle|\, J \subseteq \mathfrak{p}, \mathfrak{p} \text{ is prime}\right\}$. In the reverse direction, we se that if $a \in \pi^{-1}(J)$, then $a + I \in J$, so $a^n + I \in J$ for some $n \in \mathbb{N}$, so $a^n \in \pi^{-1}(J)$, so $\pi^{-1}(J)$ is a radical ideal.

(c) Letting $\langle a_1, \dots, a_n\rangle = J$, then we know that $\langle \pi(a_1), \dots, \pi(a_n)\rangle = \pi(J)$. Thus, $\pi(J)$ is finitely generated.

Since R is an ideal, if R is Noetherian, then R/I is Noetherian, so by the Hilbert Basis Theorem, any ring of the form $k[x_1, \dots, x_n]/I$ is Noetherian.

Irreducible Components of an Algebraic Set

An algebraic set can be the union of several smaller algebraic sets. If $V \subseteq \mathbb{A}^n$ is such that $V = V_1 \cup V_2$, where V_1, V_2 are algebraic sets and $V_i \neq V$ for each i, then we say V is reducible. Else, we say V is irreducible.

Proposition: An algebraic set V is irreducible if and only if $I(V)$ is prime.

Proof. If $I(V)$ is not prime, then we have $F_1F_2 \in I(V)$ with $F_i \notin I(V)$. Then, $V = (V \cap V(F_1)) \cup (V \cap V(F_2))$, with $V \cap V(F_i) \subsetneq V$, meaning V is irreducible.

If $V = V_1 \cup V_2$ with $V_i \subsetneq V$, then $I(V_i) \supsetneq I(V)$. Let $F_i \in I(V_i)$ with $F_i \notin I(V)$. Then, $F_1F_2 \in I(V)$, so $I(V)$ is not prime. □

Now, we want to show that an algebraic set is a finite union of irreducible algebraic sets. To see this, we need to show an equivalent definition of a Noetherian ring.

Lemma: Let $\mathcal{I}$ be a nonempty collection of ideals in a Noetherian ring R. Then, $\mathcal{I}$ has a maximal member.

Proof. We will choose an ideal from each subset of $\mathcal{I}$. Letting I_0 be the chosen ideal for $\mathcal{I}$ itself, we let $\mathcal{I}_1 = \{I \in \mathcal{I} \mid I \supsetneq I_0\}$, with I_1 as the chosen ideal of $\mathcal{I}_1$. Continuing, we define

$$\mathcal{I}_j = \left\{I \in \mathcal{I} \,\middle|\, I \supsetneq I_{j-1}\right\},$$

and select $I_j \in \mathcal{I}_j$. It suffices to show that some $\mathcal{I}_n$ is empty.

Define $I = \bigcup_{n=0}^{\infty} I_n$ to be an ideal of R, and let $F_1, \dots, F_r$ be generators of I. We must have $F_i \in I_n$ for all i if n is sufficient large. Then, $I_n = I$, meaning $I_{n+1} = I_n$, which is a contradiction. □

Effectively, we have shown that every Noetherian ring satisfies the ascending chain condition on its ideals.

It follows that any collection of algebraic sets $\{V_\alpha\}$ in $\mathbb{A}^n(k)$ has a minimal element, by selecting the maximal member of $\{I(V_\alpha)\}$.

Theorem: Let V be an algebraic set in $\mathbb{A}^n(k)$. Then, there rae unique irreducible algebraic sets $V_1, \dots, V_m$ such that $V = V_1 \cup \dots \cup V_m$, and $V_i \nsubseteq V_j$ for all $i \neq j$.

Proof. Let $\mathcal{I}$ be the set of algebraic sets in $\mathbb{A}^n(k)$ such that V is not the union of a finite number of irreducible algebraic sets. We wish to show that $\mathcal{I}$ is empty.

If not, let V be a minimal member of $\mathcal{I}$. Since $V \in \mathcal{I}$, V is not irreducible, so $V = V_1 \cup V_2$ with $V_i \subsetneq V$, meaning $V_i \notin \mathcal{I}$, so $V_i = V_{i,1} \cup \cdots V_{i,m_i}$, with $V_{i,j}$ irreducible. However, $V = \bigcup_{i,j} V_{i,j}$, which is a finite union.

Thus, any algebraic set V may be written as $V = V_1 \cup \dots \cup V_m$ with V_i irreducible. To obtain the second condition, we may discard any V_i with $V_i \subseteq V_j$ with $i \neq j$.

To show uniqueness, let $V = W_1 \cup \dots \cup W_m$ be another decomposition. Then, $V_i = \bigcup_j (W_j \cap V_i)$, so $V_i \subseteq W_{j(i)}$ for some $j(i)$. Similarly, $W_{j(i)} \subseteq V_k$ for some k. However, this means $V_i \subseteq V_k$, so $i = k$, so $V_i = W_{j(i)}$. Likewise, $W_j = V_{i(j)}$ for some $i(j)$. □

We call V_i the irreducible components of V, and $V = V_1 \cup \dots \cup V_m$ is the decomposition of V into irreducible components.

Exercise (Exercise 1.25)**:**

(a) Show that $V\left(y - x^2\right) \subseteq \mathbb{A}^2(\mathbb{C})$ is irreducible; in fact, $I\left(V\left(y - x^2\right)\right) = \left\langle y - x^2 \right\rangle$.

(b) Decompose $V\left(y^4 - x^2, y^4 - x^2y^2 + xy^2 - x^3\right) \subseteq \mathbb{A}^2(\mathbb{C})$ into irreducible components.

Solution:

(a) Suppose there exists $g \in \mathbb{C}[x, y]$ such that $g | y - x^2$, meaning there exists $f \in \mathbb{C}[x, y]$ such that $fg = y - x^2$. Since $y - x^2$ has degree in y equal to 1, one of either f or g has degree in y equal to zero.

Therefore, without loss of generality, $f \in \mathbb{C}[x]$. Then, $g = yh_1 + h_2$, where $h_1, h_2 \in \mathbb{C}[x]$. Note that $h_1 \neq 0$, then $fg = fyh_1 + fh_2 = yfh_1 + fh_2$; since $fh_1 \neq 0$, we must have $fh_1 = 1$, so f is constant, so g is some constant multiple of $y - x^2$, so $y - x^2$ is irreducible. Thus, $\left\langle y - x^2 \right\rangle$ is maximal, hence prime, so $I\left(V\left(y - x^2\right)\right) = \left\langle y - x^2 \right\rangle$.

(b) Factoring, we see that both polynomials vanish whenever $y^2 + x = 0$. Finding all pairs, we get

$$\begin{aligned} V &= V\left(y^2 - x, y^2 + x\right) \cup V\left(y^2 - x, y - x\right) \cup \cdots \\ &= V\left(y^2 + x\right) \cup V(x - 1, y - 1) \cup V(x - 1, y + 1). \end{aligned}$$

Solution:

(a) Let $g \in I(V)$. Then,

$$g(x, y) = f_0(x) + \left(y - x^2\right) f_1(x, y),$$

wherein we order $y > x$ and do polynomial long division over y. This yields $f_0(x) = 0$ for all x, so that $I(V)$ is prime.

Exercise (Exercise 1.29)**:** Show that $\mathbb{A}^n(k)$ is irreducible if k is infinite.

Solution: We know that any polynomial that vanishes on $\mathbb{A}^n(k)$ is the zero polynomial, and $k[x_1, \dots, x_n]$ is an integral domain, so $\langle 0 \rangle \subseteq k[x_1, \dots, x_n]$ is a prime ideal.

Algebraic Subsets of the Plane

We focus on the affine plane, $\mathbb{A}^2(k)$, and find its algebraic subsets.

It is enough to look at the irreducible algebraic subsets.

Exercise (Exercise 1.30)**:** Let $k = \mathbb{R}$.

(a) Show that $I\left(V\left(x^2 + y^2 + 1\right)\right) = \langle 1 \rangle$.

(b) Show that every algebraic subset of $\mathbb{A}^2(\mathbb{R})$ is equal to $V(F)$ for some $F \in \mathbb{R}[x, y]$.

Solution:

(a) Since $x^2 + y^2 + 1 = 0$ if and only if $x^2 + y^2 = -1$, which means $V\left(x^2 + y^2 + 1\right) = \emptyset$. Thus, $I\left(V\left(x^2 + y^2 + 1\right)\right) = \mathbb{R}[x, y] = \langle 1 \rangle$.

(b)

Exercise (Exercise 1.31)**:**

(a) Find the irreducible components of $V\left(y^2 - xy - x^2y + x^3\right)$ in $\mathbb{A}^2(\mathbb{R})$, and in $\mathbb{A}^2(\mathbb{C})$.

(b) Do the same for $V\left(y^2 - x\left(x^2 - 1\right)\right)$, and for $V\left(x^3 + x - x^2y - y\right)$.

Hilbert's Nullstellensatz

Given an algebraic set V, we have a criterion for determining whether or not V is irreducible. However, we do not have a way to describe V in terms of the set that defines V. This is what the Nullstellensatz, or zero locus theorem, will tell us.

We assume throughout this section that k is algebraically closed.

Theorem (Weak Nullstellensatz)**:** If I is a proper ideal in $k[x_1, \dots, x_n]$, then $V(I) \neq \emptyset$.

Proof. We may assume that I is a maximal ideal, as $J \supseteq I$ is maximal and $V(J) \subseteq V(I)$.

Thus, $L = k[x_1, \dots, x_n]/I$ is a field, and k is a subfield of L.

Suppose we knew that $k = L$. For each i, there is $a_i \in k$ such that $x_i - a_i \in I$. However, $\langle x_1 - a_1, \dots, x_n - a_n \rangle$ is a maximal ideal. Thus, $I = \langle x_1 - a_1, \dots, x_n - a_n \rangle$, and $V(I) = \{(a_1, \dots, a_n)\} \neq \emptyset$. □

Now, we have reduced the problem to showing that if an algebraically closed field k is a subfield of a field L, and there is a ring homomorphism of $k[x_1, \dots, x_n]$ onto L that is the identity on k, then $k = L$.

Theorem (Hilbert's Nullstellensatz)**:** Let I be an ideal in $k[x_1, \dots, x_n]$ with k algebraically closed. Then, $I(V(I)) = \operatorname{rad}(I)$.

Remark: In concrete terms, if $F_1, \dots, F_r, G$ are in $k[x_1, \dots, x_n]$, and G vanishes wherever $F_1, \dots, F_r$ vanish, then there is some equation $G^N = A_1F_1 + \cdots A_rF_r$ for some $N > 0$ and $A_i \in k[x_1, \dots, x_n]$.

Proof. We can see that $\operatorname{rad}(I) \subseteq I(V(I))$. Now, let G be in the ideal $I(V(F_1, \dots, F_r))$, where $F_i \in k[x_1, \dots, x_n]$. Let $J = \langle F_1, \dots, F_r, x_{n+1}G - 1 \rangle \subseteq k[x_1, \dots, x_n, x_{n+1}]$.

Then, $V(J) \subseteq \mathbb{A}^{n+1}(k)$ is empty, since G vanishes wherever all the G_i are zero. Applying the weak Nullstellensatz to J, we have $1 \in J$, so there is an equation $1 = \sum A_i(x_1, \dots, x_{n+1})F_i + B(x_1, \dots, x_{n+1})(x_{n+1}G - 1)$. Now, let $y = 1/x_{n+1}$, and multiply the equation by a high power of y such that $y^N = \sum C_i(x_1, \dots, x_n, y)F_i + D(x_1, \dots, x_n, y)(g - y)$ in $k[x_1, \dots, x_n, y]$. Now, substituting G for y, we obtain our desired result. □

Corollary: If I i a radical ideal in $k[x_1, \dots, x_n]$, then $I(V(I)) = I$. Thus, there is a one-to-one correspondence between radical ideals and algebraic sets.

Corollary: If I is a prime ideal, then $V(I)$ is irreducible. Thus, there is a one-to-one correspondence between prime ideals and irreducible algebraic sets. The maximal ideals correspond to points.

Corollary: Let F be a nonconstant polynomial in $k[x_1, \dots, x_n]$, and $F = F_1^{n_1} \cdots F_r^{n_r}$ is a decomposition into irreducible factors. Then, $V(F) = V(F_1) \cup \cdots \cup V(F_r)$ is the decomposition of $V(F)$ into irreducible components, and $I(V(F)) = \langle F_1, \dots, F_r \rangle$. There is a one-to-one correspondence between irreducible polynomials $F \in k[x_1, \dots, x_n]$ and irreducible hypersurfaces in $\mathbb{A}^n(k)$.

Corollary: Let I be an ideal in $k[x_1, \dots, x_n]$. Then, $V(I)$ is a finite set if and only if $k[x_1, \dots, x_n]/I$ is a finite-dimensional vector space over k. If so, the number of points in $V(I)$ is at most $\dim_k(k[x_1, \dots, x_n]/I)$.

Proof. Let $P_1, \dots, P_r \in V(I)$. Let $F_1, \dots, F_r \in k[x_1, \dots, x_n]$ such that $F_i(P_j) = \delta_{ij}$. Let $\overline{F_i}$ be the residue of F_i in $k[x_1, \dots, x_n]/I$.

If $\sum \lambda_i \overline{F_i} = 0$, where $\lambda_i \in k$, then $\sum \lambda_i F_i \in I$, so that $\lambda_j = \left(\sum \lambda_i F_i\right)\left(P_j\right) = 0$, meaning the $\overline{F_i}$ are linearly independent over k, and $\dim_k(k[x_1, \dots, x_n]/I)$.

Now, conversely, if $V(I) = \{P_1, \dots, P_r\}$ is finite, let $P_i = (a_{i1}, \dots, a_{in})$, and define F_j by $F_j = \prod_{i=1}^{r}\left(x_i - a_{ij}\right)$ for $j = 1, \dots, n$.

Then, $F_j \in I(V(I))$, so $F_j^N \in I$ for some $N > 0$, and we may take N large enough such that N works for all F_j. Taking residues in I, we have $\overline{F_j}^N = 0$, so that $\overline{x_j}^{rN}$ is a k-linear combination of $\overline{1}, \overline{x_j}, \dots, \overline{x_j}^{rN-1}$. Thus, by induction, $\overline{x_j}^s$ is a k-linear combination of $1, \overline{x_j}, \dots, \overline{x_j}^{rN-1}$ for all s, so the set $\left\{\overline{x_1}^{m_1} \dots \overline{x_n}^{m_n} \;\middle|\; m_i < rN\right\}$ generates $k[x_1, \dots, x_n]/I$ as a k-vector space. $\square$

Exercise (Exercise 1.33)**:**

(a) Decompose $V\left(x^2 + y^2 - 1, x^2 - z^2 - 1\right) \subseteq \mathbb{A}^3(\mathbb{C})$ into irreducible components.

(b) Let $V = \left\{\left(t, t^2, t^3\right) \in \mathbb{A}^3(\mathbb{C}) \;\middle|\; t \in \mathbb{C}\right\}$. Find $I(V)$ and show that V is irreducible.

Solution:

(a) We have that $x^2 = 1 - y^2$, so that $1 - y^2 - z^2 - 1 = 0$, and $y = \pm iz$. Thus, $V\left(x^2 + y^2 - 1, x^2 - z^2 - 1\right) = V\left(x^2 + y^2 - 1, y + iz\right) \cup V\left(x^2 + y^2 - 1, y - iz\right)$. We want to show that these are irreducible sets. Let $I_2 = \left\langle x^2 + y^2 - 1, y + iz\right\rangle$, $I_3 = \left\langle x^2 + y^2 - 1, y - iz\right\rangle$, and $I_1 = \left\langle x^2 + y^2 - 1, x^2 - z^2 - 1\right\rangle$.

By the Third Isomorphism Theorem,

$$\begin{aligned}\mathbb{C}[x, y, z]/I_{2,3} &\cong (\mathbb{C}[x, y, z]/\langle y \pm iz\rangle)/\left(\left\langle x^2 + y^2 - 1, y \pm iz\right\rangle/\langle y \pm iz\rangle\right)\\ &\cong \mathbb{C}[x, y]/\left\langle x^2 + y^2 - 1\right\rangle.\end{aligned}$$

To show that I_2 is prime, we show that $\mathbb{C}[x, y]/\left\langle x^2 + y^2 - 1\right\rangle$ is an integral domain.

Note that $\mathbb{C}[x, y] = \mathbb{C}[x + iy, x - iy] := \mathbb{C}[a, b]$. Then,

$$\begin{aligned}\mathbb{C}[x, y]/\left\langle x^2 + y^2 - 1\right\rangle &\cong \mathbb{C}[a, b]/\langle ab - 1\rangle\\ &\cong (\mathbb{C}[a])[b]/\langle ab - 1\rangle.\end{aligned}$$

Since $ab - 1$ is a degree 1 polynomial in $(\mathbb{C}[a])[b]$, we have $ab - 1$ is irreducible, so that $\langle ab - 1\rangle$ is prime, as $(\mathbb{C}[a])[b]$ is a unique factorization domain.

(b) We have $I(V) = \left\langle x^2 - y, x^3 - z\right\rangle$. To show that this is irreducible, consider the surjective homomorphism $\varphi \colon \mathbb{C}[x, y, z] \to \mathbb{C}[t]$, given by $f(x, y, z) \mapsto f\left(t, t^2, t^3\right)$. This has kernel $I(V)$, so that $\mathbb{C}[x, y, z]/I(V) \cong \mathbb{C}[t]$, and $I(V)$ is prime, so V is irreducible.

Exercise (Exercise 1.36)**:** Let $I = \left\langle y^2 - x^2, y^2 + x^2 \right\rangle \subseteq \mathbb{C}[x, y]$. Find $V(I)$ and $\dim_{\mathbb{C}}(\mathbb{C}[x, y]/I)$.

Solution: We see that I is generated by $\langle (y - x)(y + x), (y - ix)(y + ix) \rangle$. This gives $\{(0, 0)\}$ as $V(I)$.

Note that we have $y^2 + x^2 + I \cong 0$ and $y^2 - x^2 + I \cong 0$, so $x^2 \cong 0$ and $y^2 \cong 0$, meaning the basis for $\dim_{\mathbb{C}}(\mathbb{C}[x, y]/I)$ is $\{1, x, y, xy\}$.

Exercise (Exercise 1.37)**:** Let K be any field, $F \in K[x]$ a polynomial of degree $n > 0$.

Show that the residues $\overline{1}, \overline{x}, \dots, \overline{x}^{n-1}$ form a basis for $K[x]/\langle F \rangle$ over K.

Solution: Without loss of generality, we may assume F is monic, meaning that $x^n = -\left(a_{n-1}x^{n-1} + \cdots + a_1 x + a_0\right)$, meaning that $\overline{x}^n \in \operatorname{span}\left\{\overline{1}, \overline{x}, \dots, \overline{x}^{n-1}\right\}$. Thus, we know that the set $\left\{\overline{1}, \overline{x}, \dots, \overline{x}^{n-1}\right\}$ is spanning for $K[x]/\langle F \rangle$.

To show that this set is linearly independent in $K[x]/\langle F \rangle$, we suppose $gF = s_0\overline{1} + s_1\overline{x} + \cdots + s_{n-1}\overline{x}^{n-1}$. Then $g = 0$ by polynomial long division.

Exercise (Exercise 1.38)**:** Let $R = k[x_1, \dots, x_n]$ with k algebraically closed. Let $V = V(I)$. Show that there is a natural one-to-one correspondence between algebraic subsets of V and radical ideals in $k[x_1, \dots, x_n]/I$, and that irreducible algebraic sets (points) correspond to prime ideals (maximal ideals).

Solution: This follows from the correspondence in Exercise 1.22.

Modules and Finiteness

Definition. Let R be a ring. An R-module is a commutative group M with a scalar multiplication $R \times M \to M$ satisfying

(i) $(a + b)m = am + bm$ for $a, b \in R$, $m \in M$;

(ii) $a(m + n) = am + an$ for $a \in R$, $m, n \in M$;

(iii) $(ab)m = a(bm)$ for $a, b \in R$, $m \in M$;

(iv) $1_R m = m$ for $m \in M$, where 1_R is the multiplicative unit for R.

Example.

(1) A $\mathbb{Z}$-module is an abelian group.

(2) If R is a field, an R-module is an R-vector space.

(3) The multiplication in R makes any ideal of R into an R-module.

(4) If $\varphi\colon R \to S$ is a ring homomorphism, we define $r \cdot s$ by the equation $r \cdot s := \varphi(r)s$, which makes S into an R-module. If R is a subring of S, then S is an R-module.

Definition. A subgroup N of an R-module M is called a submodule if $am \in N$ for all $a \in R$ and $m \in N$.

If S is a set of elements of an R-module M, the submodule generated by S is defined to be

$$\left\{\sum r_i s_i \,\middle|\, r_i \in R, s_i \in S\right\};$$

it is the smallest submodule of M that contains S. If $S = \{s_1, \dots, s_n\}$ is finite, the submodule generated by S is denoted $\sum Rs_i$.

The module M is said to be finitely generated if $M = \sum Rs_i$ for some $s_1, \dots, s_n \in M$.

Definition. Let R be a subring of S.

(a) We say S is module-finite over R if S is finitely generated as an R-module. If S and R are fields, then we denote the dimension of S over R by $[R : S]$.

(b) Let $v_1, \dots, v_n \in S$, and $\varphi\colon R[x_1, \dots, x_n] \to S$ be the ring homomorphism taking x_i to v_i. The image of φ is written $R[v_1, \dots, v_n]$, which is a subring of S containing R and $v_1, \dots, v_n$.

Explicitly, we write

$$R[v_1, \dots, v_n] = \left\{ \sum a_{(i)} v_1^{i_1} \cdots v_n^{i_n} \;\middle|\; a_{(i)} \in R \right\}.$$

The ring S is ring-finite over R if $S = R[v_1, \dots, v_n]$ for some $v_1, \dots, v_n \in S$.

(c) Suppose $R = K$ and $S = L$ are fields. If $v_1, \dots, v_n \in L$ and $K(v_1, \dots, v_n)$ is the quotient field of $K[v_1, \dots, v_n]$. Consider $K(v_1, \dots, v_n) \subseteq L$ as a subfield, which is the smallest subfield of L containing K and $v_1, \dots, v_n$.

We say L is a finitely generated extension of K if $L = K(v_1, \dots, v_n)$ for some $v_1, \dots, v_n \in L$.

Exercise (Exercise 1.41)**:** If S is module-finite over R, then S is ring-finite over R.

Solution: Let S be module-finite. Then, $v \in S$ can be expressed as $v = r_1 s_1 + \cdots + r_n s_n$, so that $v \in R[s_1, \dots, s_n]$. Thus, $S \subseteq R[s_1, \dots, s_n]$. Since $r \in R$ and $s_1, \dots, s_n \in S$, we have that $R[s_1, \dots, s_n] \subseteq S$, and S is ring-finite over R.

Exercise (Exercise 1.43)**:** If L is ring-finite over K, where L and K are fields, then L is a finitely generated field extension of K.

Solution: Let L be ring-finite over K, where L and K are fields. Then, $L = K[v_1, \dots, v_n]$. For each $v_i \in K[v_1, \dots, v_n]$, we have that $v_i^{-1} \in K[v_1, \dots, v_n]$, so $L = K(v_1, \dots, v_n)$.

Exercise (Exercise 1.44)**:** Show that $L = K(x)$ is a finitely generated field extension of K, but L is not ring-finite over K.

Solution: Suppose toward contradiction that $K(x) = L = K\left[\frac{f_1}{g_1}, \dots, \frac{f_n}{g_n}\right]$.

Then, for all $h \in L$, we have that

$$\frac{1}{h} = \sum_i b_{(i)} \frac{f_1^{j_1} \cdots f_n^{j_n}}{g_1^{i_1} \cdots g_n^{i_n}},$$

meaning that

$$\frac{g_1^{i_1} \cdots g_n^{i_n}}{h} \in L[x].$$

However, since there are infinitely many irreducible monic polynomials in $L[x]$, choose h to not be equal to any of these.

Exercise (Exercise 1.45)**:** Let R be a subring of S, S a subring of T.

(a) If $S = \sum Rv_i$ and $T = \sum Sw_j$, then $T = \sum Rv_i w_j$.

(b) If $S = R[v_1, \dots, v_n]$ and $T = S[w_1, \dots, w_m]$, show that $T = R[v_1, \dots, v_n, w_1, \dots, w_m]$.

(c) If R, S, T are fields, and $S = R(v_1, \dots, v_n)$, $T = S(w_1, \dots, w_m)$, show that $T = R(v_1, \dots, v_n, w_1, \dots, w_m)$.

Thus, each of the three finiteness conditions is a transitive relation.

Integral Elements

Definition. Let R be a subring of a ring S. An element $v \in S$ is said to be integral over R if there is a monic polynomial $f = x^n + a_{n-1}x^{n-1} + \cdots + a_1 x + a_0 \in R[x]$ such that $f(v) = 0$.

If R and S are fields, then we say v is algebraic over R if v is integral over R.

Proposition: Let R be a subring of an integral domain S, with $v \in S$. The following are equivalent:

(i) v is integral over R;

(ii) $R[v]$ is module-finite over R;

(iii) there is a subring R' of S containing $R[v]$ that is module-finite over R.

Proof. If $0 = v^n + a_{n-1}v^{n-1} + \cdots + a_1 v + a_0 = 0$, then $v^n \in \sum_{i=0}^{n-1} Rv^i$, so $v^m \in \sum_{i=0}^{n-1} Rv^i$ for all m, so $R[v] = \sum_{i=0}^{n-1} Rv^i$.

Now, to show (ii) implies (iii), all we need to is take $R' = R[v]$.

To show (iii) implies (i), we let $R' = \sum_{i=1}^{n} Rw_i$, so that $vw_i = \sum_{j=1}^{n} a_{ij}w_j$ for some $a_{ij} \in R$. Then,

$$\sum_{j=1}^{n} (\delta_{ij}v - a_{ij})w_j = 0$$

for all i, where δ_{ij} is the Kronecker delta function.

If we consider these equations in the quotient field of S, then $(w_1, \dots, w_n)$ is a nontrivial solution, so

$$\det(\delta_{ij}v - a_{ij}) = 0.$$

Since v only appears on the diagonal of this matrix, we have the form $0 = v^n + a_{n-1}v^{n-1} + \cdots + a_1 v + a_0$, where $a_i \in R$. Thus, v is integral over R. □

Corollary: The set of elements of S that are integral over R is a subring of S containing R.

Proof. If a, b are integral over R, then b is integral over $R[a] \supseteq R$, so $R[a, b]$ is module-finite over R, and $a \pm b, ab \in R[a, b]$, so they are integral over R. □

Exercise (Exercise 1.46)**:** Let R be a subring of S, S a subring of an integral domain T. If S is integral over R, and T is integral over S, show that T is integral over R.

Solution: Let $z \in T$. Then, $z^n + a_{n-1}z^{n-1} + \cdots + a_1 z + a_0 = 0$, where each $a_i \in S$. Note that we have $\{1, z, \dots, z^{n-1}\}$ as a basis for $R[a_0, \dots, a_{n-1}][z]$, so that $R[a_0, \dots, a_{n-1}][z] \subseteq T$ is module-finite over R. This ring contains the subring $R[z]$, so T is integral over R by part (3) of the proposition.

Exercise (Exercise 1.47)**:** Suppose S is an integral domain that is ring-finite over R. Show that S is module-finite over R if and only if S is integral over R.

Solution: Let S be ring-finite over R, so $S = R[a_1, \dots, a_n]$.

If S is integral over R, then for any $z \in S$, there is some polynomial $z^n + r_{n-1}z^{n-1} + \cdots + r_1 z + r_0 = 0$. Therefore, $\{1, z, \dots, z^{n-1}\}$ serves as a basis for $R[z] \subseteq S$ for any $z \in S$. However, this applies for each $a_1, \dots, a_n$, so S is finitely generated as a module over R.

If S is module-finite over R, then for any $v \in S$, $R[v] \subseteq R[a_1, \dots, a_n][v] = R[a_1, \dots, a_n, v] = S$, so $R[v]$ is module-finite over S, so S is integral over R.

Exercise (Exercise 1.48)**:** Let L be a field, k an algebraically closed subfield of L.

(a) Show that any element of L that is algebraic over k is in k.

(b) An algebraically closed field has no module-finite field extensions except itself.

Solution:

(a) If $z \in L$ is algebraic over k, then $z^n + a_{n-1}z^{n-1} + \cdots + a_1 z + a_0 = 0$, where $a_{n-1}, \dots, a_0 \in k$. However, since k is algebraically closed, this means $z \in k$, as z is a root of the polynomial $x^n + a_{n-1}x^{n-1} + \cdots + a_1 x + a_0$.

(b) We know that z is integral over k if and only if $k[z]$ is module-finite over k. However, since every integral/algebraic element over an algebraically closed field is in the field, there cannot be any module-finite extensions over k.

Exercise (Exercise 1.49)**:** Let K be any field, $L = K(x)$.

(a) Show that any element of L that is integral over $K[x]$ is in $K[x]$.

(b) Show that there is no nonzero element $F \in K[x]$ such that for every $z \in L$, $F^n z$ is integral over $K[x]$ for some $n > 0$.

Exercise (Exercise 1.50)**:** Let K be a subfield of L.

(a) Show that the set of elements of L that are algebraic over K is a subfield of L containing K.

(b) Suppose L is module-finite over K and R is a ring such that $K \subseteq R \subseteq L$. Show that R is a field.

Solution:

(a) Let a, b be algebraic over K. Then, $K(a, b)$ is module-finite over K, so $K(a, b)$ is an algebraic extension of K. Therefore, since $a + b, ab, a^{-1} \in K(a, b)$, all such elements algebraic over K, and K is trivially algebraic over K. Thus, the set of elements in L that are algebraic over K forms a subfield of L.

(b) Let $K \subseteq R \subseteq L$. Now, since L is module-finite over K, L is ring-finite over K, so R is ring-finite over K. Now, since $R \subseteq L$, R is module-finite over L, so for any $v \in R$, there is a polynomial such that

$$v^n + b_{n-1}v^{n-1} + \cdots + b_1 v + b_0 = 0.$$

Now, if $b_0 \neq 0$, we have

$$v\left(v^{n-1} + b_{n-1}v^{n-2} + \cdots + b_1\right) = -b_0,$$

meaning that

$$v\left(\frac{-1}{b_0}\left(v^{n-1} + b_{n-1}v^{n-2} + \cdots + b_1\right)\right) = 1,$$

and v has an inverse in R.

Field Extensions

Let K be a subfield of L, and suppose $L = K(v)$ for some $v \in L$. Let $\varphi\colon K[x] \to L$ be the homomorphism mapping $x \mapsto v$. Let $\ker(\varphi) = \langle f \rangle$ for some $f \in k[x]$. Then, $k[x]/\langle f \rangle \cong K[v]$, so $\langle f \rangle$ is prime.

We may consider two cases.

In the first case, if $f = 0$, then $K[v] \cong K[x]$, so $K(v) = L$ is isomorphic to $k(X)$, and thus L is not ring-finite or module-finite over K.

In the second case, if $f \neq 0$, then we may assume f is monic, meaning $\langle f \rangle$ is monic, and f is irreducible, so $\langle f \rangle$ is maximal, and $K[v]$ is a field. Thus, $K[v] = K(v)$, and $f(v) = 0$. Therefore, v is algebraic over K, and $L = K[v]$ is module-finite over K.

To finish the proof of the Nullstellensatz, we must prove that if a field L is a ring-finite extension of an algebraically closed field k, then $L = k$.

Thus, it is enough to show that L is module-finite over k — we already know that any ring-finite extensions are already module-finite. Now, we will show that this is always true, proving the Nullstellensatz.

Proposition: If L is ring-finite over a subfield K, then L is module-finite over K.

Proof. Let $L = K[v_1, \dots, v_n]$. The case for $n = 1$ is taken care of by above, so we assume the result holds for all extensions generated by $n - 1$ elements. Let $K_1 = K(v_1)$; by induction, $L = K_1[v_2, \dots, v_n]$ is module-finite over K_1. Assume towards contradiction that v_1 is not algebraic over K.

Each v_i satisfies an equation $v_i^{n_i} + a_{i,n_i-1}v_i^{n_i-1} + \cdots = 0$, where $a_{ij} \in K_1$. Letting $a \in K[v_1]$ — a multiple of the denominators of a_{ij} — we have equations $(av_i)^{n_i} + aa_{i,n_i-1}(av_i)^{n_i-1} + \cdots = 0$.

Therefore, for any $z \in L$, there is some N such that $a^N z$ is integral over $K[v_1]$. This must hold for all $z \in K(v_1)$; however, since $K(v_1)$ is isomorphic to the field of rational functions in one variable over K, this is impossible. □

Exercise (Exercise 1.51)**:** Let K be a field, $F \in K[x]$ an irreducible monic polynomial of degree $n > 0$.

(a) Show that $L = K[x]/\langle F\rangle$ is a field, and if $\overline{x}$ is the residue of x in L, then $F(\overline{x}) = 0$.

(b) Suppose L' is a field extension of K, $y \in L'$ such that $F(y) = 0$. Show that the homomorphism from $K[x]$ to L' that takes x to y induces an isomorphism of L with $K(y)$.

(c) With L' and y as in (b), suppose $G \in K[x]$ with $G(y) = 0$. Show that F divides G.

(d) Show that $F = (x - \overline{x})f_1$, where $f_1 \in L[x]$.

Solution:

(a) Let $L = K[X]/\langle F\rangle$, $x = X + \langle F\rangle$. Then, $F(x) = F(X + \langle X\rangle) = (X + \langle F\rangle)^n + \cdots + a_1(X + \langle F\rangle) + a_0 = F(X) + \langle F\rangle = 0 + \langle F\rangle$.

(b) Let $\varphi\colon K[X] \to L'$ map $X \mapsto Y$. By the first isomorphism theorem, since $F(y) = 0$ and F is irreducible, $\ker\varphi = \langle F\rangle$, so $K[X]/\langle F\rangle = K(y)$.

(c) Since $G \in \ker(\varphi)$, and F is irreducible, we have $G = FQ$ for some polynomial Q.

(d) This problem statement is too confusing.

Exercise (Exercise 1.52)**:** Let K be a field, $F \in K[x]$.

Show that there is a field L containing K such that $F = \prod_{i=1}^{n}(x - x_i) \in L[x]$.

Solution: Suppose this is the case for a polynomial of degree $\leqslant n$. Now, if F is a polynomial of degree $n+1$ in $K[X]$. We may find $(X - x_i)$ such that $F = (X - x_i)F_1$ with $F_1 \in K[X]$. Splitting F_1, we obtain $F = \prod_{i=1}^{n+1}(X - x_i)$.

Exercise (Exercise 1.53)**:** Suppose K is a field of characteristic zero, F an irreducible monic polynomial in $K[x]$ of degree $n > 0$, and let L be the splitting field of F. Show that the x_i are distinct.

Solution: See Algebra II Notes regarding splitting fields over characteristic 0 fields.

Exercise (Exercise 1.54)**:** Let R be an integral domain with quotient field K, L a finite algebraic extension of K.

(a) For any $v \in L$, show that there is a nonzero $a \in R$ such that av is integral over R.

(b) Show that there is a basis $v_1, \dots, v_n$ for L over K such that each v_i is integral over R.

Affine Varieties

From now on, k is a fixed algebraically closed field, with affine algebraic sets in $\mathbb{A}^n = \mathbb{A}^n(k)$. Irreducible affine algebraic sets are called *affine varieties*.

All rings and fields contain k as a subring, with all homomorphisms of rings $\varphi\colon R \to S$ fixing k. We call affine varieties "varieties" this section since we are not dealing with other types of varieties yet.

Coordinate Rings

Let $V \subseteq \mathbb{A}^n$ be a nonempty variety. Then, $I(V)$ is prime in $k[x_1, \dots, x_n]$, meaning $k[x_1, \dots, x_n]/I(V)$ is an integral domain.

Definition. Let $\Gamma(V) \coloneqq k[x_1, \dots, x_n]/I(V)$. Then, we call $\Gamma(V)$ the *coordinate ring* of V.

If V is any nonempty set, $\mathcal{F}(V, k)$ consists of all functions from V to k with pointwise operations. We identify k with the subring of $\mathcal{F}(V, k)$ consisting of constants.

Definition. If $V \subseteq \mathbb{A}^n$ is a variety, a function $f \in \mathcal{F}(V, k)$ is called a *polynomial function* if there exists a polynomial $F \in k[x_1, \dots, x_n]$ such that $f(a_1, \dots, a_n) = F(a_1, \dots, a_n)$ for all $(a_1, \dots, a_n) \in V$.

The polynomial functions form a subring of $\mathcal{F}(V, k)$ containing k. Two polynomials determine the same function if $(F - G)(a_1, \dots, a_n) = 0$ for all $(a_1, \dots, a_n) \in V$.

We may identify $\Gamma(V)$ with the subring of $\mathcal{F}(V, k)$ consisting of all the polynomial functions on $\mathcal{F}(V, k)$.

Exercise (Exercise 2.1)**:** Show that the map that 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 $I(V)$.

Solution: The map $\varphi \colon k[x_1, \dots, x_n] \to \mathcal{F}(V, k)$ sends to zero functions all the polynomials that are identically zero on V, which is equal to $I(V)$.

Exercise (Exercise 2.2)**:** Let $V \subseteq \mathbb{A}^n$ be a variety. A subvariety of V is a variety $W \subseteq \mathbb{A}^n$ that is contained in V. Show that there is a natural one-to-one correspondence between algebraic subsets (resp. subvarieties, points) and radical ideals (resp. prime ideals, maximal ideals) in $\Gamma(V)$.

Solution: We know that: algebraic subsets of V correspond to radical ideals in $I(V)$; subvarieties of V correspond to prime ideals in $I(V)$; points in V correspond to maximal ideals in $I(V)$. Since radical ideals, prime ideals, and maximal ideals are preserved under quotients, we see that they correspond to the same objects in $\Gamma(V)$.

Exercise (Exercise 2.3)**:** Let W be a subvariety of V, and let $I_V(W)$ be the ideal of $\Gamma(V)$ corresponding to W.

(a) Show that every polynomial function on V restricts to a polynomial function on W.

(b) Show that the map $\varphi \colon \Gamma(V) \to \Gamma(W)$ defined in part (a) is a surjective homomorphism with kernel $I_V(W)$, so $\Gamma(W)$ is isomorphic to $\Gamma(V)/I_V(W)$.

Solution:

(a) If $f \colon V \to k$ is a polynomial map, then by defining $f|_W \colon W \to k$.

(b) Let $\varphi \colon \Gamma(V) \to \Gamma(W)$ be the map defined by $\varphi([f]) = [f|_W]$; the kernel of this map consists of all polynomials $F \in k[x_1, \dots, x_n]$ such that $F|_W = 0$, which is precisely $I_V(W)$.

Exercise (Exercise 2.4)**:** Let $V \subseteq \mathbb{A}^n$ be a nonempty variety. Show that the following are equivalent:

(i) V is a point;

(ii) $\Gamma(V) = k$;

(iii) $\dim_k(\Gamma(V)) < \infty$.

Solution: If V is a point, then $V = (a_1, \dots, a_n)$ is the zero of $P = s_1(x_1 - a_1) + \cdots + s_n(x_n - a_n)$, so $I(V) = \langle P \rangle$. Since $k[x_1, \dots, x_n] \cong k[x_1 - a_1, \dots, x_n - a_n]$ (by a translation), we have

$$\begin{aligned}\Gamma(V) &= k[x_1, \dots, x_n]/\langle x_1 - a_1, \dots, x_n - a_n \rangle \\ &= k[x_1 - a_1, \dots, x_n - a_n]/\langle x_1 - a_1, \dots, x_n - a_n \rangle \\ &= k.\end{aligned}$$

Since k is a dimension 1 k-vector space, this implies (iii).

If $\dim_k(\Gamma(V)) < \infty$, then $\Gamma(V)$ is a finite-dimensional k-algebra, meaning it is an Artinian ring, hence has Krull dimension zero. Thus, $\left\langle \overline{0} \right\rangle \subseteq \Gamma(V)$ is prime and is not contained in any other prime ideals, meaning $I(V)$ is maximal, hence V is a point.

Polynomial Maps

Definition. Let $V \subseteq \mathbb{A}^n$, $W \subseteq \mathbb{A}^m$ be varieties. A map $\varphi \colon V \to W$ is called a polynomial map if there are polynomials $T_1, \dots, T_m \in k[x_1, \dots, x_m]$ such that $\varphi(a_1, \dots, a_n) = (T(a_1, \dots, a_n), \dots, T_m(a_1, \dots, a_n))$ for all $(a_1, \dots, a_n) \in V$.

Any map $\varphi \colon V \to W$ induces a homomorphism $\widetilde{\varphi} \colon \mathcal{F}(W, k) \to \mathcal{F}(V, k)$ by $\widetilde{\varphi}(f) = f \circ \varphi$.

If φ is a polynomial map, then $\widetilde{\varphi}(\Gamma(W)) \subseteq \Gamma(V)$, so $\widetilde{\varphi}$ restricts to a homomorphism, also written $\widetilde{\varphi}$, from $\Gamma(W)$ to $\Gamma(V)$. If $f \in \Gamma(W)$ is the $I(W)$ residue of F, then $\widetilde{\varphi}(f) = f \circ \varphi$ is the $I(V)$ residue of the polynomial $F(T_1, \dots, T_m)$.

If $V = \mathbb{A}^n$, $W = \mathbb{A}^m$, and $T_1, \dots, T_m \in k[x_1, \dots, x_n]$ determine a polynomial map $T\colon \mathbb{A}^n \to \mathbb{A}^m$, then the T_i are uniquely determined by T, so we usually write $T = (T_1, \dots, T_m)$.

Proposition: Let $V \subseteq \mathbb{A}^n$ and $W \subseteq \mathbb{A}^m$ be affine varieties. There is a natural one to one correspondence between polynomial maps $\varphi\colon V \to W$ and homomorphisms $\widetilde{\varphi}\colon \Gamma(W) \to \Gamma(V)$. Any such φ is the restriction of a polynomial map from $\mathbb{A}^n$ to $\mathbb{A}^m$.

Proof. Let $\alpha\colon \Gamma(W) \to \Gamma(V)$ be a homomorphism. Set $T_i \in k[x_1, \dots, x_n]$ such that $\alpha(\overline{x_i}) = \overline{T_i}$, where the residue of x_i is taken in $I(W)$ and the residue of T_i is taken in $I(V)$. Then, $T = (T_1, \dots, T_m)$ is a polynomial map from $\mathbb{A}^n$ to $\mathbb{A}^m$ that induces $\widetilde{T}\colon k[x_1, \dots, x_m] \to k[x_1, \dots, x_n]$. Note that $\widetilde{T}(I(W)) \subseteq I(V)$ by construction, so $T(V) \subseteq W$, and T restricts to a polynomial map $\varphi\colon V \to W$. Now, on $\Gamma(W)$, we have

$$\begin{aligned}\widetilde{\varphi}(f)(\overline{x_1}, \dots, \overline{x_n}) &= f \circ \varphi(x_1, \dots, x_n)\\ &= (T_1, \dots, T_m)(x_1, \dots, x_n),\end{aligned}$$

so $\widetilde{\varphi} = \alpha$. □

Definition. A polynomial map $\varphi\colon V \to W$ is an isomorphism if there is a polynomial map $\psi\colon W \to V$ such that $\psi = \varphi^{-1}$.

Two affine varieties are isomorphic if and only if their coordinate rings are isomorphic.

Exercise (Exercise 2.6)**:** Let $\varphi\colon V \to W$ and $\psi\colon W \to Z$ be polynomial maps. Show that $\widetilde{\psi \circ \varphi} = \widetilde{\varphi} \circ \widetilde{\psi}$. Show that the composition of polynomial maps is a polynomial map.

Solution: Let $f \in \mathcal{F}(V, k)$ be a polynomial function. Then,

$$\begin{aligned}\widetilde{\psi \circ \varphi}(f) &= f \circ (\psi \circ \varphi)\\ &= (f \circ \psi) \circ \varphi\\ &= \widetilde{\varphi} \circ \widetilde{\psi}(f).\end{aligned}$$

A polynomial map $\varphi\colon V \to W$ is defined by polynomials $T_1, \dots, T_m$; similarly, a polynomial map $\psi\colon W \to Z$ is defined by polynomials $S_1, \dots, S_r$; since the composition of two polynomials is another polynomial, the composition of their respective maps is also a polynomial map.

Exercise (Exercise 2.7)**:** Let $\varphi\colon V \to W$ be a polynomial map, and X an algebraic subset of W. Then, $\varphi^{-1}(X)$ is an algebraic subset of V. If $\varphi^{-1}(X)$ is irreducible and X is contained in the image of φ, show that X is irreducible.

Solution: Let $\varphi\colon V \to W$ be a polynomial map, and let X be an algebraic subset of W, with corresponding radical ideal I in $\Gamma(W)$. There is a homomorphism of coordinate rings, $\widetilde{\varphi}\colon \Gamma(W) \to \Gamma(V)$, and since the homomorphic image of a radical ideal is a radical ideal, the corresponding radical ideal $\widetilde{\varphi}(I) \subseteq \Gamma(V)$ corresponds to $\varphi^{-1}(X)$.

Now, if $\varphi^{-1}(X)$ is irreducible, then there is a corresponding prime ideal $\mathfrak{p} \subseteq \Gamma(V)$. Taking inverse images, $\widetilde{\varphi}^{-1} \circ \widetilde{\varphi}(\mathfrak{p})$ corresponds to $\varphi \circ \varphi^{-1}(X)$. If $X \subseteq \varphi \circ \varphi^{-1}(X) \subseteq X$, then $\mathfrak{p} \subseteq \widetilde{\varphi}^{-1} \circ \widetilde{\varphi}(\mathfrak{p}) \subseteq \mathfrak{p}$, meaning that X has corresponding prime ideal $\widetilde{\varphi}^{-1}(\mathfrak{p})$, and X is irreducible.

Exercise (Exercise 2.8)**:**

(a) Show that $\left\{\left(t, t^2, t^3\right) \in \mathbb{A}^3(k) \;\middle|\; t \in k\right\}$ is an affine variety.

(b) Show that $V\left(xz - y^2, yz - x^3, x^2 - x^2y\right) \subseteq \mathbb{A}^2(\mathbb{C})$ is a variety.

Solution:

(a) The set $S = \left\{\left(t, t^2, t^3\right) \in \mathbb{A}^3(k) \;\middle|\; t \in k\right\}$ has $I(S) = \left\langle x^2 - y, x^3 - z\right\rangle \subseteq k[x, y, z]$. From Exercise 1.33 (b), we have that

$$k[x,y,z]/I(S) \cong k[t],$$

given by the surjective ring homomorphism $f(x,y,z) \mapsto f\left(t,t^2,t^3\right)$. Since $k[t]$ is an integral domain, this means $I(S)$ is prime, so S is a variety.

(b) Using the hint, we know that $V = V\left(\left\langle y^3 - x^4, z^3 - x^5, z^4 - y^5\right\rangle\right)$, with algebraic set of $\left\{\left(t^3,t^4,t^5\right) \;\middle|\; t \in k\right\}$. This means we have a map $\varphi\colon \mathbb{A}^1(\mathbb{C}) \to V$ by taking $t \mapsto \left(t^3,t^4,t^5\right)$. This map is bijective, so the induced homomorphism $\varphi\colon \Gamma(V) \to \Gamma\left(\mathbb{A}^1(\mathbb{C})\right)$ is an isomorphism. Since $\Gamma\left(\mathbb{A}^1(\mathbb{C})\right) = \mathbb{C}[x]$ is an integral domain, so too is $\Gamma(V)$, so $I(V)$ is prime, and V is a variety.

Exercise (Exercise 2.9)**:** Let $\varphi\colon V \to W$ be a polynomial map of affine varieties, with $V' \subseteq V$ and $W' \subseteq W$ subvarieties. Suppose $\varphi(V') \subseteq W'$.

(a) Show that $\widetilde{\varphi}(I_W(W')) \subseteq I_V(V')$.

(b) Show that the restriction of φ gives a polynomial map from V' to W'.

Solution:

(a) Let $\overline{x_i}$ be the image of x_i in $\Gamma(V)$, and let $\overline{y_i}$ be the image of y_i in $\Gamma(W)$, where

$$\begin{aligned}\Gamma(V) &= k[x_1,\dots,x_m]/I(V)\\ \Gamma(W) &= k[y_1,\dots,y_n]/I(W).\end{aligned}$$

Let $f(\overline{y}_1,\dots,\overline{y}_n) \in I_W(W')$, meaning $f(a_1,\dots,a_n) = 0$ for all $(a_1,\dots,a_n) \in W'$. Let $(b_1,\dots,b_m) \in V'$. Then,

$$\begin{aligned}\widetilde{\varphi}(f)(b_1,\dots,b_m) &= f(\varphi(b_1,\dots,b_m))\\ &= 0,\end{aligned}$$

where we use the fact that $\varphi(V') \subseteq W'$. Thus, $\varphi(b_1,\dots,b_n) \in W'$, and $\widetilde{\varphi}(I_W(W')) \subseteq I_V(V')$.

(b) Using Exercise 2.3 and the duality relation, we notice that $\widetilde{\varphi}\colon \Gamma(W') \to \Gamma(V')$ is a homomorphism, so we use the proposition to determine that $\varphi|_{V'}$ is a polynomial map.

Exercise (Exercise 2.10)**:** Show that the projection map $P\colon \mathbb{A}^n \to \mathbb{A}^r$, where $n \geqslant r$, defined by $P(a_1,\dots,a_n) = (a_1,\dots,a_r)$ is a polynomial map.

Solution: Define $T_1,\dots,T_r$ to be identity.

Exercise (Exercise 2.12)**:**

(a) Let $\varphi\colon \mathbb{A}^1 \to V = V\left(y^2 - x^3\right) \subseteq \mathbb{A}^2$ be defined by $\varphi(t) = \left(t^2,t^3\right)$. Show that, although φ is an injective polynomial map, φ is not an isomorphism.

(b) Let $\varphi\colon \mathbb{A}^1 \to V = V\left(\left\langle y^2 - x^2(x+1)\right\rangle\right)$ be defined by $\varphi\left(t^2-1, t\left(t^2-1\right)\right)$. Show that φ is one-to-one and onto except that $\varphi(\pm 1) = (0,0)$.

Solution:

(a)

Coordinate Changes

If $T = (T_1,\dots,T_m)$ is a polynomial map from $\mathbb{A}^n$ to $\mathbb{A}^m$, and F is a polynomial in $k[x_1,\dots,x_m]$, we let $F^T = \widetilde{T}(F) = F(T_1,\dots,T_m)$.

For ideals I and algebraic sets V in $\mathbb{A}^m$, I^T is the ideal in $k[x_1,\dots,x_m]$ generated by $\left\{F^T \;\middle|\; F \in I\right\}$, and V^T denotes $T^{-1}(V) = V\left(I^T\right)$, where $I = I(V)$. If V is the hypersurface of F, then V^T is the hypersurface of F^T if F^T is not constant.

A *change of coordinates* on $\mathbb{A}^n$ is a polynomial map $T\colon \mathbb{A}^n \to \mathbb{A}^n$ such that each T_i is a polynomial of degree 1 and T is bijective. If $T_i = \sum a_{ij}x_j + a_{i0}$, then $T = T'' \circ T'$, where T' is a linear map and T'' is a translation. Since translations are invertible, it follows that T is bijective if and only if T' is invertible.

If T and U are affine changes of coordinates on $\mathbb{A}^n$, then so are $T \circ U$ and T^{-1}; in other words, T is an automorphism of the variety $\mathbb{A}^n$.

Exercise (Exercise 2.14)**:** A set $V \subseteq \mathbb{A}^n(k)$ is called a linear subvariety of $\mathbb{A}^n(k)$ if $V = V(\langle F_1, \dots, F_r\rangle)$, where the F_i are polynomials of degree 1.

(a) Show that if T is an affine change of coordinates on $\mathbb{A}^n$, then V^T is also a linear subvariety of $\mathbb{A}^n(k)$.

(b) If $V \neq \emptyset$ is a linear subvariety, show that there is an affine change of coordinates T of $\mathbb{A}^n$ such that $V^T = V(x_{m+1}, \dots, x_n)$

(c) Show that the m that appears in part (b) is independent of the choice of T. It is called the dimension of V.

Solution:

(a) If T is an affine change of coordinates, then each T_i is of the form $T_i = \sum a_{ij}x_j + a_{i0}$. Considering $F_i^T = F_i(T_1, \dots, T_i)$, we must have each F_i as a function of exactly one T_i. Since each T_i is also a polynomial of degree 1, $V^T = T^{-1}(V)$ is a variety generated by a family of polynomials of degree 1, so V^T is a linear subvariety.

(b) Let $V = V(F_1)$ for some degree 1 polynomial $F = \sum a_i x_i + a_0$. Define $T = (T_1, \dots, T_m)$. We may take T_m by defining

$$\begin{aligned} T_m(x_n) &= -\frac{a_0}{a_n} - \frac{a_1}{a_n}x_1 - \frac{a_2}{a_n}\cdots + \frac{1}{a_n}x_m \\ T_m(x_i) &= x_i. && i \leqslant n-1 \end{aligned}$$

Then, $F_1 \circ T = x_m$, so $V^T = V(x_m)$.

For the inductive step, we take $V = V(F_1, \dots, F_r, F_{r+1})$, and suppose T is defined for $V(F_1, \dots, F_r)$. Then, we may define

$$\begin{aligned} V^T &= T^{-1}(V(F_1, \dots, F_r)) \cap T^{-1}(F_{r+1}) \\ &= V(x_{m+1}, \dots, x_n) \cap T^{-1}(F_{r+1}), \end{aligned}$$

and we may set T to be such that $T^{-1}(V(F_{r+1})) = V(x_m)$, satisfying the inductive step.

(c) Suppose there were a change of coordinates $T = (T_1, \dots, T_n)$ such that $V(x_{m+1}, \dots, n)^T = V(x_{s+1}, \dots, x_n)$, where $s < m$. Then, by definition,

$$T^{-1}(V(x_{m+1}, \dots, x_n)) = V(x_{s+1}, \dots, x_n),$$

meaning that, since affine transformations are bijective,

$$T(V(x_{s+1}, \dots, x_n)) = V(x_{m+1}, \dots, x_n).$$

This means that any polynomial in $x_{s+1}, \dots, x_n$ yields a polynomial exclusively in $x_{m+1}, \dots, x_n$; this means that at least one of the affine transformations in $T_1, \dots, T_n$ yields 0 by the pigeonhole principle, so the transformations in $T_1, \dots, T_n$ are not independent.

Exercise (Exercise 2.15)**:** Let $P = (a_1, \dots, a_n)$ and $Q = (b_1, \dots, b_n)$ be distinct points in $\mathbb{A}^n$. The line through P, Q is defined by $\{a_1 + t(b_1 - a_1), \dots, a_n + t(b_n - a_n) \mid t \in k\}$.

(a) Show that if L is defined through P and Q, and T is an affine change of coordinates, then T(L) is the line through T(P) and T(Q).

(b) Show that a line is a linear subvariety of dimension 1, and that any linear subvariety of dimension 1 is the line through any two of its points.

(c) Show that, in $\mathbb{A}^2$, a line is the same thing as a hyperplane.

(d) Let $P, P' \in \mathbb{A}^2$, L_1, L_2 be two distinct lines through P, and L_1', L_2' distinct lines through P'. Show that there is an affine change of coordinates of $\mathbb{A}^2$ such that $T(P) = P'$ and $T(L_i) = L_i'$.

Local Rings

Let V be a nonempty variety in $\mathbb{A}^n$, and let $\Gamma(V)$ be its coordinate ring. We may define the quotient field on $\Gamma(V)$, giving the *field of rational functions* on V, written $k(V)$.

If f is a rational function on V, and $P \in V$, we say f is defined at P if for some $a, b \in \Gamma(V)$, $f = \frac{a}{b}$, and $b(P) \neq 0$. If $\Gamma(V)$ is a unique factorization domain, there is an essentially unique representation $f = a/b$ with a, b having no common factors.

Example. If $V = V(xw - yz) \subseteq \mathbb{A}^4(k)$, then $\Gamma(V) = k[x, y, z, w]/\langle xw - yz\rangle$. Letting $\overline{x}, \overline{y}, \overline{z}, \overline{w}$ represent the residues, we have $\frac{\overline{x}}{\overline{y}} = \frac{\overline{z}}{\overline{w}} = f \in k(V)$ is defined at $p(x, y, z, w)$ whenever y or w are not equal to 0.

Letting $P \in V$, we define $\mathcal{O}_P(V)$ to be the set of rational functions on V that are defined at P. It turns out that $\mathcal{O}_P(V)$ defines a subring of $k(V)$ containing $\Gamma(V)$, which we call the *local ring* of V at P.

The set of points $P \in V$ where a rational function is not defined is called the pole set of f.

Proposition:

(1) The pole set of a rational function is an algebraic subset of V.

(2)
$$\Gamma(V) = \bigcap_{P \in V} \mathcal{O}_P(V).$$

Proof. Suppose $V \subseteq \mathbb{A}^n$. Let $\overline{G}$ be the residue of $G \in k[x_1, \dots, x_n]$ in $\Gamma(V)$. Let $f \in k(V)$, and let

$$J_f = \left\{G \;\middle|\; \overline{G}f \in \Gamma(V)\right\}.$$

Note that J_f is an ideal containing $I(V)$, and points of $V(J_f)$ are those points where f is not defined.

Now, if $f \in \bigcap_{P \in V} \mathcal{O}_P(V)$, $V(J_f) = \emptyset$, so $1 \in J_f$ by the Nullstellensatz, meaning $f \in \Gamma(V)$. □

Let $f \in \mathcal{O}_P(V)$. We can define the value of f at P, written $f(P)$, to be $a(P)/b(P)$. The ideal

$$\mathfrak{m}_P(V) = \{f \in \mathcal{O}_P(V) \mid f(P) = 0\}$$

is called the *maximal ideal* of V at P. It is the kernel of the evaluation homomorphism $f \mapsto f(P)$ onto k, so $\mathcal{O}_P(V)/\mathfrak{m}_P(V)$ is isomorphic to k.

In particular, note that all elements of $\mathcal{O}_P(V)$ that are not in $\mathfrak{m}_P(V)$ are units.

Lemma: The following conditions on a ring R are equivalent.

(1) The set of non-units in R forms an ideal.

(2) R has a unique maximal ideal that contains every proper ideal of R.

Proof. Let $\mathfrak{m} = \{\text{non-units of } R\}$. Every proper ideal of R is contained in $\mathfrak{m}$. □

A ring that satisfies these conditions is known as a local ring. The units are those elements not belonging to the maximal ideal.

Proposition: $\mathcal{O}_P(V)$ is a Noetherian local integral domain.

Proof. We only need to show that every ideal I of $\mathcal{O}_P(V)$ is finitely generated. Since $\Gamma(V)$ is Noetherian, we may choose generators $f_1, \dots, f_r$ for the ideal $I \cap \Gamma(V)$ of $\Gamma(V)$. We claim that $f_1, \dots, f_r$ generate I in $\mathcal{O}_P(V)$. If $f \in I \subseteq \mathcal{O}_P(V)$, there is a $b \in \Gamma(V)$ with $b(P) \neq 0$ and $bf \in \Gamma(V)$. Then, $bf \in \Gamma(V) \cap I$, so $bf = \sum a_i f_i$ for some $a_i \in \Gamma(V)$, meaning $f = \sum (a_i/b) f_i$ as desired. □

Exercise (Exercise 2.17)**:** Let $V = V\left(y^2 - x^2(x+1)\right)$, and $\overline{x}, \overline{y}$ residues in $\Gamma(V)$. Let $z = \frac{\overline{y}}{\overline{x}}$. Find the pole sets of z and z^2.

Solution: We start by verifying the pole sets for z^2. Taking z^2, we have

$$\begin{aligned} z^2 &= \frac{\overline{y}^2}{\overline{x}^2} \\ &= \frac{\overline{x}^2(\overline{x}+1)}{\overline{x}^2} \\ &= \overline{x} + 1, \end{aligned}$$

meaning z^2 has no poles.

Now, since $z = \frac{\overline{y}}{\overline{x}}$, the only possible poles are points (a, b) where $a = 0$. However, if $P \in V$ and $a = 0$, we must have $b^2 = 0$, so $b = 0$. Therefore, the only possible pole is where $P = (0, 0)$. However, we must verify that this is indeed a pole.

Suppose z is defined at $(0, 0)$, so we may write $z = \frac{f(\overline{x},\overline{y})}{g(\overline{x},\overline{y})}$, for some $f, g \in \Gamma(V)$ with $g(0, 0) \neq 0$. Since $\overline{y}^2 = \overline{x}^2(\overline{x}+1)$, we may write $g(\overline{x}, \overline{y}) = g_0(\overline{x}) + \overline{y}g_1(\overline{x})$ (any other factors of $\overline{y}$ can be rewritten in terms of $\overline{x}$), and similarly writing $f(\overline{x}, \overline{y}) = f_0(\overline{x}) + \overline{y}f_1(\overline{x})$. Therefore,

$$\frac{\overline{y}}{\overline{x}} = \frac{f_0(\overline{x}) + \overline{y}f_1(\overline{x})}{g_0(\overline{x}) + \overline{y}g_1(\overline{x})},$$

so

$$\overline{y}(g_0(\overline{x}) + \overline{y}g_1(\overline{x})) = \overline{x}(f_0(\overline{x}) + \overline{y}f_1(\overline{x})).$$

Writing $\overline{y}^2 = \overline{x}^2(\overline{x}+1)$, we get

$$g_0(\overline{x})\overline{y}g_1(\overline{x})\left(\overline{x}^2(\overline{x}+1)\right) = f_0(\overline{x})\overline{x} + \overline{xy}f_1(\overline{x}),$$

so that $g_0(\overline{x}) = \overline{x}f_1(\overline{x})$, and $g_0 = 0$. Therefore, $g(0, 0) = g_0(0) + 0 \cdot g_1(0) = 0$, which is a contradiction.

Exercise (Exercise 2.18)**:** Let $\mathcal{O}_P(V)$ be the local ring of a variety V at point P. Show that there is a natural one-to-one correspondence between the prime ideals in $\mathcal{O}_P(V)$ and the subvarieties of V that pass through P.

Solution: Let I be prime in $\mathcal{O}_P(V)$. Then, $I \cap \Gamma(V) \subsetneq \Gamma(V)$ is prime, so $I \cap \Gamma(V)$ corresponds to a unique subvariety of V. Specifically, since $I \subsetneq \mathcal{O}_P(V)$ is an ideal, it is contained in $\mathfrak{m}_P$, so f is zero at P, meaning the subvariety corresponding to $I \cap \Gamma(V)$ passes through P.

Exercise (Exercise 2.21)**:** Let $\varphi \colon V \to W$ be a polynomial map of affine varieties, $\widetilde{\phi} \colon \Gamma(W) \to \Gamma(V)$ the induced map of coordinate rings.

Suppose $P \in V$, $\varphi(P) = Q$. Show that $\widetilde{\varphi}$ extends uniquely to a ring homomorphism $\overline{\varphi} \colon \mathcal{O}_Q(W) \to \mathcal{O}_P(V)$. Show that $\overline{\varphi}\left(\mathfrak{m}_Q(W)\right) \subseteq \mathfrak{m}_P(V)$.

Solution: Let $f = a/b \in \mathcal{O}_Q(W)$ be in reduced form. Define

$$\begin{aligned} \overline{\varphi}(f) &= (a \circ \varphi)/(b \circ \varphi) \\ &= \widetilde{\varphi}(a)/\widetilde{\varphi}(b). \end{aligned}$$

Since $\widetilde{\varphi}$ is unique, and f is written in its unique reduced form, this gives a unique map $\overline{\varphi} \colon \mathcal{O}_Q(W) \to \mathcal{O}_P(V)$.

Exercise (Exercise 2.22)**:** Let $T \colon \mathbb{A}^n \to \mathbb{A}^n$ be an affine change of coordinates, with $T(P) = Q$. Show that $\widetilde{T} \colon \mathcal{O}_Q(\mathbb{A}^n) \to \mathcal{O}_P(\mathbb{A}^n)$ is an isomorphism. Show that $\widetilde{T}$ induces an isomorphism from $\mathcal{O}_Q(V)$ to $\mathcal{O}_P\left(V^T\right)$ if $P \in V^T$ for any subvariety $V \subseteq \mathbb{A}^n$.

Discrete Valuation Rings

Proposition: Let R be an integral domain that is not a field. The following are equivalent:

(1) R is a local, Noetherian, and the maximal ideal is principal;

(2) there is an irreducible element $t \in R$ such that every nonzero $z \in R$ may be written uniquely in the form $z = ut^n$ for some unit $u \in R$ and n a nonnegative integer.

Proof. Assume (1). Let $\mathfrak{m}$ be the maximal ideal, and t a generator for $\mathfrak{m}$. Suppose $ut^n = vt^m$ with u, v units and $n \geqslant m$. Then, $ut^{n-m} = v$ is a unit, so $n = m$ and $u = v$. Thus, any expression of z is unique.

To show that z has an expression, we may assume $z = z_1 t$ for some $z_1 \in R$. If z_1 is a unit, we are done. Then, we assume $z_1 = z_2 t$, so that we have a sequence $(z_k)_k$, where $z_k = z_{k+1}t$. Since R is Noetherian, the chain of ideals $\langle z_1 \rangle \subseteq \langle z_2 \rangle \subseteq \cdots$ has a maximal member, so $\langle z_n \rangle = \langle z_{n+1} \rangle$ for some n. Thus, $z_{n+1} = vz_n$ for some $v \in R$, and $z_n = vtz_n$, and $vt = 1_R$, but t is not a unit.

Assume (2). We note that $\mathfrak{m} = \langle t \rangle$ is the set of non-units, and that the only ideals in R are the principal ideals, $\langle t^n \rangle$ for some nonnegative integer, meaning R is a principal ideal domain. □

Any ring that satisfies these conditions is called a *discrete valuation ring*, which we call a DVR. The element t is known as a uniformizing parameter for R, and any other uniformizing parameter is of the form ut for some unit $u \in R$.

If K is the field of fractions for R, then for fixed t, a nonzero element $z \in K$ has an expression $z = ut^n$ for a unit u and $n \in \mathbb{Z}$. The exponent n is called the *order* of z, which we write $\operatorname{ord}(z)$. We define $\operatorname{ord}(0) = \infty$.

Forms

Let R be an integral domain. If $F \in R[x_1, \dots, x_{n+1}]$ is a form, then we define $F_* \in F[x_1, \dots, x_n]$ by taking $F_* = F(x_1, \dots, x_n, 1)$.

Conversely, for any polynomial $f \in R[x_1, \dots, x_n]$ of degree d, we write $f = f_0 + f_1 + \cdots + f_d$, and define $f^* \in R[x_1, \dots, x_{n+1}]$ to be

$$f^* = x_{n+1}^d f(x_1/x_{n+1}, \dots, x_n/x_{n+1}).$$

Then, f^* is a form of degree d.

Direct Products

If $R_1, \dots, R_n$ are rings, the cartesian product $R_1 \times \cdots \times R_n$ is made into a ring by taking pointwise addition and pointwise multiplication.

This ring is known as the direct product of $R_1, \dots, R_n$, written $\prod_{i=1}^n R_i$. The natural projection maps $\pi_i \colon \prod_{j=1}^n R_j \to R_i$, given by $(a_1, \dots, a_n) \mapsto a_i$ are ring homomorphism.

The direct product is characterized by the following universal property: given any ring R and family of ring homomorphisms $\varphi_i \colon R \to R_i$, there is a unique ring homomorphism $\varphi \colon R \to \prod_{i=1}^n R_i$ such that $\pi_i \circ \varphi = \varphi_i$.

In particular, if a field k is a subring of each R_i, we may regard k as a subring of the product.

Operations with Ideals

Ideals with a Finite Number of Zeros