

Theorem 1. Let A be an integral domain, and let L be a field containing A . The elements of L integral over A form a ring.

Remark. The immediate consequence of this theorem is that the ring of integers is indeed a ring.

Definition 2. Symmetric polynomials and elementary symmetric polynomials.

Theorem 3. Let A be a ring. Every symmetric polynomial $P(X_1, \dots, X_r)$ in $A[X_1, \dots, X_n]$ can be represented with a linear combination of elementary symmetric polynomials with coefficients in A .

Proof is constructive and inductive by reducing the polynomial over the lexicographically highest monomial. Not a hard proof, but the indecies are annoying.

The above proof implies:

Let $f(X) = X^n + a_1X^{n-1} + \dots + a_n \in A[X]$, and let $\alpha_1, \dots, \alpha_n$ be the roots of $f(X)$ in some ring containing A , so that $f(X) = \prod (X - \alpha_i)$ in the larger ring. Then

$$a_1 = -S_1(\alpha_1, \dots, \alpha_n), \quad a_2 = S_2(\alpha_1, \dots, \alpha_n), \quad a_n = \pm S_n(\alpha_1, \dots, \alpha_n).$$

(I'm not quite sure why this is the case. Maybe use the multi-binomial theorem.)

Thus the elementary symmetric polynomials in the roots of f lie in A . And so the theorem implies that every symmetric polynomial in the roots of $f(X)$ lies in A .

Proposition 4. Let A be an integral domain and Ω be an algebraically closed field containing A . If $\alpha_1, \dots, \alpha_n$ are the roots in Ω of a monic polynomial in $A[X]$, then every polynomial $g(\alpha_1, \dots, \alpha_n)$ in $A[\alpha_1, \dots, \alpha_n]$ is a root of a monic polynomial in $A[X]$.

Proof. Clearly,

$$h(X) := \prod_{\sigma \in \text{Sym}_n} (X - g(\alpha_{\sigma(1)}, \dots, \alpha_{\sigma(n)}))$$

is a monic polynomial whose coefficients are symmetric polynomials in the α_i , and therefore lie in A . But $g(\alpha_1, \dots, \alpha_n)$ is one of the roots. \square

With this we can prove that the above theorem. I don't quite understand few steps ...

Dedekind's Proof

Proposition 5. Let L be a field containing A . An element α of L is integral over A if and only if there exists a nonzero finitely generated A -submodule of L such that $\alpha M \subset M$ (in fact, we can take $M = A[\alpha]$, the A -subalgebra generated by α).

Proof. • Let $\alpha \in L$ be integral over A . The A -submodule $A[\alpha]$ in L is generated by $1, \alpha, \dots, \alpha^{n-1}$, thus finitely generated and clearly nonzero. $\alpha A[\alpha] \subset A[\alpha]$ also holds.

• Let M be a nonzero, finitely generated A -submodule in L such that $\alpha M \subset M$. Since M is finitely generated, there is a set of generators $v_1, \dots, v_n \in M$. From $\alpha M \subset M$ we have that

$$\alpha v_i = \sum_{j=1}^n a_{i,j} v_j$$

for some $a_{i,j} \in A$. We rewrite this system of equations

$$(\alpha - a_{i,i})v_i - \sum_{j=1, j \neq i}^n a_{i,j}v_j = 0$$

We have the matrix

$$\begin{pmatrix} (\alpha - a_{1,1}) & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & (\alpha - a_{2,2}) & \cdots & a_{2,n} \\ \vdots & & & \vdots \\ a_{n,1} & a_{n,2} & \cdots & (\alpha - a_{n,n}) \end{pmatrix}$$

Applying Cramer's Rule we get $v_i = \frac{\det(C_i)}{\det C}$, but C_i is always 0, and at least one v_i is nonzero, so we have that $\det(C) = 0$.

But calculating the determinant of C gives us

$$\alpha^n + c_1\alpha^{n-1} + \cdots + c_n = 0$$

as desired. □

Now take α and β integral over A and denote $\alpha M \subset M$ and $\beta N \subset N$.

1. MN is an A -submodule of L .

Dedekind's proof is much easier to understand, lol.

Integral Elements

Proposition 6. Let K be the field of fractions of A , and let L be a field containing K . If $\alpha \in L$ is algebraic over K , then there exists a nonzero $d \in A$ such that $d\alpha$ is integral over A .

Corollary 1. Let A be an integral domain with field of fractions K , and let B be the integral closure of A in a field L containing K . If L is algebraic over K , then it is the field of fractions B .

Part I

Exercise

Example 6.1. Let d be a square-free integer. Consider $A = \mathbb{Z}[\sqrt{d}]$. Show that every element of R can be written as a product of irreducible elements.

Proof. Define $N : R \rightarrow \mathbb{N}$ as $N(a + b\sqrt{d}) = a^2 + db^2$ where $a, b \in \mathbb{Z}$. Let $a_1 + b_1\sqrt{d}$ and $a_2 + b_2\sqrt{d}$ be two elements in $\mathbb{Z}[\sqrt{d}]$ with $a_1, b_1, a_2, b_2 \in \mathbb{Z}$, then

$$\begin{aligned} N((a_1 + b_1\sqrt{d})(a_2 + b_2\sqrt{d})) &= N((a_1a_2 + b_1b_2d) + (a_1b_2 + a_2b_1)\sqrt{d}) \\ &= (a_1a_2 + b_1b_2d)^2 + d(a_1b_2 + a_2b_1)^2 \\ &= a_1^2a_2^2 + 2a_1a_2b_1b_2d + b_1^2b_2^2d^2 + a_1^2b_2^2d + 2a_1a_2b_1b_2d + a_2^2b_1^2d \\ &= a_1^2a_2^2 + b_1^2b_2^2d^2 + a_1^2b_2^2d + a_2^2b_1^2d + 4a_1a_2b_1b_2d \end{aligned}$$

and on the other hand

$$\begin{aligned} N(a_1 + b_1\sqrt{d})N(a_2 + b_2\sqrt{d}) &= (a_1^2 + db_1^2)(a_2^2 + db_2^2) \\ &= a_1^2a_2^2 + a_1^2b_2^2d + a_2^2b_1^2d + b_1^2b_2^2d^2 \end{aligned}$$

□