

Algebra

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Inhaltsverzeichnis

I	Galois theory	5
§ 1	Algebraic field extensions	5
§ 2	Simple field extensions	11
§ 3	Galois extensions	18
§ 4	Solvability of equations by radicals	23
§ 5	Norm and trace	31
§ 6	Normal series of groups	36
II	Valuation theory	41
§ 7	Discrete valuations	41
§ 8	The Gauß Lemma	45
§ 9	Absolute values	49
§ 10	Completions, p -adic numbers and Hensel's Lemma	55
III	Rings and modules	63
§ 11	Multilinear Algebra	63
§ 12	Hilbert's basis theorem	74
§ 13	Integral ring extensions	77
§ 14	Dedekind domains	83

Kapitel I

Galois theory

§ 1 Algebraic field extensions

Notations 1.1 If k, L are fields and $K \subseteq L$, L/k is called a *field extension*. The *dimension* $[L : k] := \dim_k L$ of L considered as a k -vector space, is called the *degree* of the field extension of L over k . A field extension L/k is called *finite*, if $[L : k] < \infty$. The *polynomial ring* over k is defined as

$$k[X] := \left\{ f = \sum_{i=0}^n a_i X^i \mid n \geq 0, a_i \in k \forall i \in \{0, \dots, n\}, a_n \neq 0 \right\} \cup \{0\}.$$

Reminder 1.2 Let L/k a field extension, $\alpha \in L$, $f \in k[X]$.

- (i) $f(\alpha)$ is well defined.
- (ii) $\phi_\alpha : k[X] \rightarrow L$, $f \mapsto f(\alpha)$ is a homomorphism.
- (iii) $\text{im}(\phi_\alpha) := k[\alpha]$ is the smallest subring of L containing k and α .
- (iv) $\ker(\phi_\alpha) = \{f \in k[X] \mid f(\alpha) = 0\} \triangleleft k[X]$ is a prime ideal.
- (v) $\ker(\phi_\alpha)$ is a principle ideal.
- (vi) If $f_\alpha \neq 0$ and the leading coefficient of f_α is 1, f_α is called the *minimal polynomial* of α , i.e. $f_\alpha(\alpha) = 0$ and f_α is the polynomial of smallest degree with this property. In this case, f_α is irreducible and $\ker(\phi_\alpha) = (f_\alpha)$ is a maximal ideal.
- (vii) Then $L_\alpha := k[X] / \ker(\phi_\alpha) = k[X] / (f_\alpha)$ is a field.
- (viii) We have $k[\alpha] = \text{im}(\phi_\alpha) \cong k[X] / \ker(\phi_\alpha) = L_\alpha$, if $f_\alpha \neq 0$. Moreover $k[\alpha] = k(\alpha)$, where $k(\alpha)$ is the smallest field containing k and α . In particular, $\frac{1}{\alpha} \in k[\alpha]$.
- (ix) The degree of the field extension $k[\alpha]/k$ is $[k[\alpha] : k] = \deg(f_\alpha)$.

proof. (ii) For $f, f_1, f_2 \in k[X]$, $\lambda \in k$ we have

$$(f_1 + f_2)(\alpha) = f_1(\alpha) + f_2(\alpha) \text{ and } (\lambda f)(\alpha) = \lambda f(\alpha)$$

(iii) Clear.

(iv) Let $f, g \in k[X]$ such that $f \cdot g \in \ker(\phi_\alpha)$: Then

$$0 = (f \cdot g)(\alpha) = f(\alpha) \cdot g(\alpha)$$

and since L has no zero divisors, $f(\alpha) = 0$ or $g(\alpha) = 0$ and hence $f \in \ker(\phi_\alpha)$ or $g \in \ker(\phi_\alpha)$

(v) Remember that the polynomial ring is euclidean. Take $f_\alpha \in \ker(\phi_\alpha)$ of minimal degree. We will show, that $\ker(\phi_\alpha)$ is generated by f_α . Let $g \in \ker(\phi_\alpha)$ arbitrary and write

$$g = q \cdot f_\alpha + r \text{ with } q, r \in k[X], \quad \deg(r) < \deg(f_\alpha) \text{ or } r = 0.$$

Since $r = g - q \cdot f_\alpha \in \ker(\phi_\alpha)$ and the choice of f_α , $\deg(r) < \deg(f_\alpha)$, hence $r = 0 \Rightarrow g \in (f_\alpha)$.

(vi) If $f_\alpha = g \cdot h$, either $g(\alpha) = 0$ or $h(\alpha) = 0$. As above, this implies $g \in k$ or $h \in k^\times$, i.e. f or g is irreducible. Now assume, there is an ideal $I \triangleleft k[X]$ satisfying $(f_\alpha) \subsetneq I \subsetneq k[X]$. Let $g \in I \setminus (f_\alpha)$, such that $(g) = I$. Such a g exists by proof of (v). Then $f_\alpha = g \cdot h$, $h \in k[X]$. This implies, that either g or h is a constant polynomial, hence a unit. In the first case, $I = k[X]$ and in the second one $I = (f_\alpha)$, which implies the claim.

(vii) We show the more general argument: If R is a ring, $\mathfrak{m} \triangleleft R$ a maximal ideal, then R/\mathfrak{m} is a field. Let $\bar{a} \in R/\mathfrak{m}$ for some $a \in R$, $\bar{a} \neq 0$. Let $I := (\mathfrak{m}, a)$ the smallest ideal in R containing \mathfrak{m} and a . Since $\bar{a} \neq 0$, hence $a \notin \mathfrak{m}$ we have $\mathfrak{m} \subsetneq I$ and since \mathfrak{m} is a maximal ideal, $I = R$. Hence $1 \in I$, so we can write $1 = x + ab$ for some $x \in \mathfrak{m}$ and $b \in R$. Then we get

$$\bar{1} = \overline{x + ab} = \bar{x} + \bar{a}\bar{b} = \bar{a}\bar{b},$$

hence \bar{a} is invertible in R/\mathfrak{m} .

(viii) Let

$$f_\alpha = \sum_{i=0}^n a_i X^i$$

Note, that $a_n = 1$ and $a_0 \neq 0$, since f_α is irreducible. We get

$$\begin{aligned} \implies 0 &= f_\alpha(\alpha) = \sum_{i=0}^n a_i \alpha^i = a_0 + a_1 \alpha + \cdots + a_n \alpha^n \\ \implies a_0 &= -\alpha \cdot (a_1 + a_2 \alpha + \cdots + a_{n-2} \alpha^{n-2} + \alpha^{n-1}) \\ \implies 1 &= -\alpha \cdot \left(\frac{a_1}{a_0} + \frac{a_2}{a_0} \alpha + \cdots + \frac{a_{n-2}}{a_0} \alpha^{n-2} + \frac{1}{a_0} \alpha^{n-1} \right) \\ \implies \frac{1}{\alpha} &= -\frac{a_1}{a_0} - \frac{a_2}{a_0} \alpha - \cdots - \frac{a_{n-2}}{a_0} \alpha^{n-2} - \frac{1}{a_0} \alpha^{n-1} \end{aligned}$$

Hence $\frac{1}{\alpha} \in k[X]$ and $k[X]$ is a field.

(ix) The family $\{1, \alpha, \dots, \alpha^{n-1}\}$ forms a basis of $k[\alpha]$ as a k -vector space. \square

Example 1.3 Let $k = \mathbb{Q}$, $L = \mathbb{C}$, $\alpha = 1 + i$, $\beta = \sqrt{2}$. Then the minimal polynomials of α and β are

$$f_\alpha = (X - 1)^2 + 1, \quad f_\beta = X^2 - 2.$$

Proposition 1.4 (Kronecker) *Let k be a field, $f \in k[X]$, $\deg(f) \geq 1$.*

Then there exists a finite field extension L/k and $\alpha \in L$, such that $f(\alpha) = 0$.

proof. W.l.o.g. we may assume, that f is irreducible, since $f = g \cdot h = 0 \Rightarrow g = 0$ or $h = 0$. Then by 1.2 $(f) = \{f \cdot g \mid g \in k[X]\}$ is a maximal ideal and $L := k/(f)$ is a field.

Clearly k is a subfield of L , since (f) does not contain any constant polynomial, i.e., if

$$\pi : k[X] \longrightarrow k[X]/(f)$$

denotes the residue map, we have $\ker(\pi) \cap k = \{0\}$, hence $\pi|_k$ is injective. Write

$$f = \sum_{i=0}^n a_i X^i.$$

Then we have

$$f(\pi(X)) = \sum_{i=0}^n a_i \pi(X)^i = \sum_{i=0}^n \pi(a_i) \pi(X)^i = \pi \left(\sum_{i=0}^n a_i X^i \right) = \pi(f) = 0,$$

hence $\alpha := \pi(X)$ is a zero of f in L . Moreover L/k is finite with degree $[L : k] = \deg(f) = n$, since $\{1, \alpha, \dots, \alpha^{n-1}\}$ is basis of L as a k -vector space. For the independence write

$$\sum_{i=0}^{n-1} \lambda_i \alpha^i = 0, \quad \lambda_i \in k.$$

Assume, there is $0 \leq j \leq n-1$ with $\lambda_j \neq 0$. Then the polynomial

$$g = \sum_{i=0}^{n-1} \lambda_i X^i$$

satisfies $g(\alpha) = 0$ with $\deg(g) < \deg(f)$, which is not possible by irreducibility of f . It remains to show, that L is generated by the powers of α . We have $\alpha^n + a_{n-1}\alpha^{n-1} + \dots + a_1\alpha + a_0 = 0$, hence we write

$$\alpha^n = - (a_{n-1}\alpha^{n-1} + \dots + a_1\alpha + a_0) \in (1, \dots, \alpha^{n-1}).$$

By induction on n , we get $\alpha^k \in (1, \dots, \alpha^{n-1})$ for all $k \geq n$. □

Example 1.5 Let $k = \mathbb{Q}$, $f = X^n - a$ for some $a \in \mathbb{Q}$. For now we assume that f is irreducible (we may be able to prove this later). Then

$$L := \mathbb{Q}[X]/(f) = \mathbb{Q}[X]/(X^n - a) \cong \mathbb{Q}[\sqrt[n]{a}] = \mathbb{Q}(\sqrt[n]{a})$$

and the degree of the extension is equal to n .

Definition 1.6 Let L/k a field extension, $\alpha \in L$.

- (i) α is called *algebraic over k* , if there exists $f \in \mathbb{X}[X] \setminus \{0\}$, such that $f(\alpha) = 0$.
- (ii) Otherwise α is called *transcendental*.
- (iii) L/k is called an *algebraic field extension*, if every $\alpha \in L$ is algebraic over k .

Proposition 1.7 Every finite field extension L/k is algebraic.

proof. Let $\alpha \in L$, $n := [L : k]$ the degree of L/k . Then $1, \alpha, \dots, \alpha^n$ are linearly dependant over k , i.e. there exist $\lambda_0, \dots, \lambda_n \in k$, $\lambda_j \neq 0$ for at least one $0 \leq j \leq n$, such that

$$\sum_{i=0}^n \lambda_i \alpha^i = 0.$$

Hence the polynomial

$$f = \sum_{i=0}^n \lambda_i X^i \neq 0$$

satisfies $f(\alpha) = 0$, thus α is algebraic over k . Since α was arbitrary, L/k is algebraic. \square

Proposition 1.8 Let L/k a field extension, $\alpha, \beta \in L$.

- (i) If α, β are algebraic over k , then $\alpha + \beta$, $\alpha - \beta$, $\alpha \cdot \beta$ are also algebraic over k .
- (ii) If $\alpha \neq 0$ is algebraic over k , then $\frac{1}{\alpha}$ is also algebraic over k .
- (iii) $k_L := \{\alpha \in L \mid \alpha \text{ is algebraic over } k\} \subseteq L$ is a subfield of L .

proof. (i) Since $\alpha \in L$ is algebraic over $k \Rightarrow k[\alpha] = k(\alpha)$ is a finite field extension of k . Since β is algebraic over $k \Rightarrow \beta$ is algebraic over $k[\alpha]$, hence $(k[\alpha])[\beta]/k[\alpha]$ is a finite field extension. Further, we have

$$k \subseteq k[\alpha] \subseteq (k[\alpha])[\beta] = k[\alpha, \beta].$$

Thus $k[\alpha, \beta]/k$ is algebraic with Proposition 1.5. This implies the claim, as $\alpha + \beta$, $\alpha - \beta$, $\alpha \cdot \beta \in k[\alpha, \beta]$.

- (ii) If $\alpha \neq 0$, $\frac{1}{\alpha}$ is algebraic over k with part (i).
- (iii) Follows from (i) and (ii). \square

Definition + proposition 1.9 Let k be a field, $f \in k[X]$, $\deg(f) = n$.

- (i) A field extension L/k is called a *splitting field of f* , if L is the smallest field in which f decomposes into linear factors.
- (ii) A splitting field $L(f)$ exists.
- (iii) The field extension $L(f)/k$ is algebraic over k .
- (iv) For the degree we have $[L(f) : k] \leq n!$.

proof.

- (ii) Do this by induction on n .

n=1 Clear.

n>1 Write $f = f_1 \cdots f_r$ with irreducible polynomials $f_i \in k[X]$. Then f splits if and only every f_i splits. Hence we may assume that f is irreducible

Consider $L_1 := k/(f)$. Then f has a zero in L_1 ; say α . Then we have $L_1 = k[\alpha]$. Now we can write $f = (X - \alpha) \cdot g$ for some $g \in k[X]$ with $\deg(g) = n - 1$. By induction hypothesis, there exists a splitting field $L(g)$ for g . Then f splits over $L(g)[\alpha]$.

(iii) Follows by part (iv) and Proposition 1.5

(iv) Do this again by induction.

n=1 Clear.

n>1 In the notation of part (ii) we have $[k[\alpha] : k] = \deg(f) = n$. By the multiplication formula for the degree and induction hypothesis we have

$$[L(f) : k] = [L(g)[\alpha] : k] = [L(g)[\alpha] : L(g)] \cdot [L(g) : k] \leq n \cdot (n - 1)! = n!$$

Definition + proposition 1.10 Let k be a field.

(i) k is called *algebraically closed*, if every $f \in k[X]$ splits over k .

(ii) The following statements are equivalent:

- (1) k is algebraically closed
- (2) Every nonconstant polynomial $f \in k[X]$ has a zero in k .
- (3) There is no proper algebraic field extension of k .
- (4) If $f \in k[X]$ is irreducible, then $\deg(f) = 1$.

proof. '(1) \Rightarrow (2)' Let $f \in k[X]$ be a non-constant polynomial of degree n . Then f splits over k , i.e. we have a presentation

$$f = \prod_{i=1}^n (X - \lambda_i)$$

with $\lambda_i \in k$ for $1 \leq i \leq n$. Every λ_i is a zero. Since $n \geq 1$, we find a zero for any nonconstant polynomial.

'(2) \Rightarrow (3)' Assume L/k is algebraic, $\alpha \in L$. Let f_α be the minimal polynomial of α . By assumption, f_α has a zero in k . Since f_α is irreducible, we must have $f_\alpha = X - \alpha$, hence $\alpha \in k$, since $f \in k[X]$.

'(3) \Rightarrow (4)' Let $f \in k[X]$ irreducible. Then $L := k[X]/(f)$ is an algebraic field extension. By (3), $L = k$, hence $1 = [L : k] = \deg(f)$.

'(4) \Rightarrow (1)' For $f \in k[X]$ write $f = f_1 \cdots f_r$ with irreducible polynomials f_i for $1 \leq i \leq r$.

With (4), $\deg(f_i) = 1$ for any i , hence f splits. □

Lemma 1.11 Let k be a field. Then there exists an algebraic field extension k'/k , such that every $f \in k[X]$ has a zero in k' .

proof. For every irreducible polynomial $f \in k[X]$ introduce a symbol X_f and consider

$$R := k[\{X_f | f \in k[X] \text{ irreducible}\}] \supseteq k.$$

Monomials in R look like

$$g = \lambda \cdot X_{f_1}^{n_1} X_{f_2}^{n_2} \cdots X_{f_k}^{n_k}$$

with $\lambda \in k$, $n_i \in \mathbb{N}$. Let $I \triangleleft R$ be the ideal generated by the $f(X_f)$, $f \in k[X]$ irreducible. The following claims prove the lemma:

Claim (a) $I \neq R$

Claim (b) There exists a maximal ideal $\mathfrak{m} \triangleleft R$ containing I .

Claim (c) $k' = R/\mathfrak{m}$

To finish the proof, it remains to show the claims.

(a) Assume $I = R$. Then $1 \in I$, i.e.

$$1 = \sum_{i=1}^k g_{f_i} f_i(X_{f_i})$$

for suitable $g_{f_i} \in R$. Let L/k be a field extension in which all f_i have a zero α_i . Define a ring homomorphism by

$$\pi : R \longrightarrow L, X_f \mapsto \begin{cases} \alpha_i, & f = f_i \\ 0, & \text{otherwise} \end{cases}$$

Then we obtain

$$1 = \pi(1) = \pi\left(\sum_{i=1}^k g_{f_i} f_i(X_{f_i})\right) = \sum_{i=1}^k \pi(g_{f_i}) f_i(\pi(X_{f_i})) = \sum_{i=1}^k \pi(g_{f_i}) f_i(\alpha_i) = 0,$$

hence our assumption was false and we have $I \neq R$.

(b) Let \mathcal{S} be the set of all proper ideals of R containing I . By claim 2, $I \in \mathcal{S}$. Let now

$$S_1 \subseteq S_2 \subseteq S_3 \subseteq \dots$$

be elements of \mathcal{S} . More generally let N be a totally ordered subset of \mathcal{S} and

$$S := \bigcap_{J \in N} J$$

Then $S \in \mathcal{S}$, hence \mathcal{S} is nonempty. By Zorn's Lemma we know that \mathcal{S} contains a maximal element $\mathfrak{m} \neq R$. Then \mathfrak{m} is maximal ideal of R , since an ideal $J \triangleleft R$ satisfying $\mathfrak{m} \subsetneq J \subsetneq R$ is contained in \mathcal{S} , which is a contradiction considering the choice of \mathfrak{m} .

(c) Clearly k' is a field extension of k . Let $f \in k[X]$ be irreducible and

$\pi : R \longrightarrow k/\mathfrak{m}$ denote the residue map. Then

$$f(X_f) \in I \subseteq \mathfrak{m}$$

i.e. we have

$$\pi(X_f) = 0$$

and thus $f(\pi(X_f)) = 0$. Hence $\pi(X_f)$ is algebraic over k .

Since k' is generated by the $\pi(X_f)$, k'/k is algebraic, which finishes the proof. \square

Theorem 1.12 *Let k be a field. Then there exists an algebraic field extension \bar{k}/k such that \bar{k} is algebraically closed. \bar{k} is called the algebraic closure of k .*

proof. By Lemma 1.9 there is an algebraic field extension k'/k , such that every $f \in k[X]$ has a zero in k' . Then let

$$k_0 := k, \quad k_1 = k'_0, \quad k_2 = k'_1, \quad k_{i+1} = k'_i \quad \text{for } i \geq 1$$

Clearly k_i is algebraic over k for all $i \in \mathbb{N}_0$ and $k_i \subseteq k_{i+1}$. Define

$$\bar{k} := \bigcup_{i \in \mathbb{N}_0} k_i$$

Then \bar{k}/k is an algebraic field extension. For $f \in \bar{k}[X]$ we find $i \in \mathbb{N}_0$ with $f \in k_i[X]$, hence f has a zero in k_i . With proposition 1.8, \bar{k} is algebraically closed. \square

§ 2 Simple field extensions

Definition 2.1 A field extension L/k is called *simple*, if there exists some $\alpha \in L$ such that $L = k[\alpha]$.

Example 2.2 Let $f \in k[X]$ be irreducible, $L := k[X]/(f)$. Then $L = k[\alpha]$ where $\alpha = \pi(X) = \bar{X}$ and $\pi : k[X] \rightarrow L$ denotes the residue map. Conversely, if L/k is simple and algebraic, then $L = k[\alpha]$ for some algebraic $\alpha \in L$. Let $f \in k[X]$ be the minimal polynomial of α over k , then

$$L = k[\alpha] = k(\alpha) = k[X]/(f).$$

Proposition 2.3 *Let L be a field. Then any finite subgroup G of the multiplicative group L^\times is cyclic.*

proof. Let $\alpha \in G$ be an element of maximal order, $n := \text{ord}(\alpha)$. Define

$$G' := \{\beta \in G : \text{ord}(\beta) \mid n\}$$

We first show $G' = G$ and then $G' = \langle \alpha \rangle$. Let $\beta \in G$, $m := \text{ord}(\beta)$. Then

$$\text{ord}(\alpha\beta) = \text{lcm}(m, n) \leq n$$

by the property of n . Thus $m|n$ and $\beta \in G'$ and hence $G \subseteq G'$. Since $G' \subseteq G$ by definition, we have $G' = G$. Let now $\gamma \in G'$. We have $\gamma^n = 1$, hence γ is zero of

$$f = X^n - 1$$

f has at most n zeros, but since $|\langle \alpha \rangle| = n$, we have $\langle \alpha \rangle = G'$ which finishes the proof. \square

Corollary 2.4 *Let k be a finite field. Then every finite field extension L/k is simple.*

proof. We have $|L| = |k|^{[L:k]}$ and thus L is also finite. With proposition 2.2 there exists some $\alpha \in L$ such that $L^\times = L \setminus \{0\} = \langle \alpha \rangle$, hence $L = k[\alpha]$, which proves the claim. \square

Remark 2.5 *Let L/k be a finite field extension, $f \in k[X]$ and $\alpha \in L$ a zero of f . Let \bar{k} be an algebraic closure of k and $\sigma : L \rightarrow \bar{k}$ a homomorphism of field such that $\sigma|_k = id_k$. Then $\sigma(\alpha)$ is a zero of f .*

proof. Write

$$f = \sum_{i=0}^n a_i X^i$$

with coefficients $a_i \in k$, hence we have $\sigma(a_i) = a_i$ for $0 \leq i \leq n$. We obtain

$$f(\sigma(\alpha)) = \sum_{i=0}^n a_i (\sigma(\alpha))^i = \sum_{i=0}^n \sigma(a_i) (\sigma(\alpha))^i = \sigma\left(\sum_{i=0}^n a_i \alpha^i\right) = \sigma(f(\alpha)) = \sigma(0) = 0,$$

which finishes the proof. \square

Theorem 2.6 *Let L/k be a finite field extension of degree $n := [L : k]$ and \bar{k} an algebraic closure of k . If there exist n different field homomorphisms $\sigma_1, \dots, \sigma_n : L \rightarrow \bar{k}$ such that $\sigma_i|_k = id_k$, then L/k is simple.*

proof. Let $L = k[\alpha_1, \dots, \alpha_r]$ for some $r \geq 1$ and $\alpha_i \in L$. Prove the statement by induction on r .

r=1 $L = k[\alpha_1]$, hence L is simple.

r>1 Let now $L' = k[\alpha_1, \dots, \alpha_{r-1}]$. By hypothesis, L'/k is simple, say $L' = k[\beta]$. Then we have

$$L = k[\alpha_1, \dots, \alpha_r] = L'[\alpha_r] = k[\alpha, \beta]$$

with $\alpha := \alpha_r$. For $\lambda \in k$ consider

$$\gamma := \gamma_\lambda = \alpha + \lambda\beta.$$

By remark 2.4 it suffices to show

$$\sigma_i(\gamma) \neq \sigma_j(\gamma) \text{ for } i \neq j.$$

Assume there are $i \neq j$ such that $\sigma_i(\gamma) = \sigma_j(\gamma)$. Then

$$\sigma_i(\alpha) + \lambda\sigma_i(\beta) = \sigma_j(\alpha) + \lambda\sigma_j(\beta),$$

so we get

$$\sigma_i(\alpha) - \sigma_j(\alpha) + \lambda(\sigma_i(\beta) - \sigma_j(\beta)) = 0.$$

Consider the polynomial

$$g := \prod_{1 \leq i \neq j \leq n} (\sigma_i(\alpha) - \sigma_j(\alpha) + X \cdot (\sigma_i(\beta) - \sigma_j(\beta))).$$

By proposition 2.2 we may assume, that k is infinite. Note that g is not the zero polynomial: If $g = 0$, we find $i \neq j$ such that $\sigma_i(\alpha) = \sigma_j(\alpha)$ and $\sigma_i(\beta) = \sigma_j(\beta)$. Since α, β generate L , σ_i and σ_j must be equal on L , which is a contradiction. Therefore we find $\lambda \in k$, such that $g(\lambda) \neq 0$. Hence the minimal polynomial m_{γ_λ} of $\gamma_\lambda = \alpha + \lambda\beta$ has at least n zeroes, i.e.

$$\deg(m_{\gamma_\lambda}) \geq n \Rightarrow [k[\gamma_\lambda] : k] \geq n$$

and hence $k[\gamma_\lambda] = L$. □

Proposition 2.7 *Let $L = k[\alpha]$ be a simple, finite field extension, \bar{k} an algebraic closure of k . Let $f \in k[X]$ the minimal polynomial of α . Then for every zero β of f in \bar{k} there exists a unique homomorphism of fields $\sigma : L \rightarrow \bar{k}$ such that $\sigma(\alpha) = \beta$.*

proof. The uniqueness is clear. It remains to show the existence. Define

$$\phi_\beta : k[X] \rightarrow \bar{k}, \quad g \mapsto g(\beta).$$

We have $f(\beta) = 0$, thus $(f) \subseteq \ker(\phi_\beta)$ and hence ϕ_β factors to a homomorphism

$$\bar{\phi}_\beta : L \cong k[X]/(f) \rightarrow \bar{k}$$

such that $\phi_\beta = \bar{\phi}_\beta \circ \pi$ where $\pi : k[X] \rightarrow k[X]/(f)$ denotes the residue map. Let

$$\tau : L \rightarrow k[X]/(f)$$

be an isomorphism. Then

$$\sigma := \bar{\phi}_\beta \circ \tau : L \rightarrow \bar{k}$$

satisfies

$$\sigma(\alpha) = (\bar{\phi}_\beta \circ \tau)(\alpha) = \bar{\phi}_\beta(\tau(\alpha)) = \bar{\phi}_\beta(\bar{X}) = \bar{\phi}_\beta(\pi(X)) = \phi_\beta(X) = \beta,$$

thus the claim. □

Corollary 2.8 *Let $f \in k[X]$ be a nonconstant polynomial. Then the splitting field of f over k is unique, i.e. any two splitting fields L, L' of f over k are isomorphic.*

proof. Let $L = k[\alpha_1, \dots, \alpha_n]$, $L' = k[\beta_1, \dots, \beta_m]$.

Assume that f is irreducible. W.l.o.g. we have $f(\alpha_1) = f(\beta_1) = 0$. By Proposition 2.6 we find field homomorphisms

$$\sigma_1 : k[\alpha_1] \longrightarrow k[\beta_2] \text{ such that } \sigma_1|_k = \text{id}_k \text{ and } \alpha_1 \mapsto \beta_1$$

$$\tau_1 : k[\beta_1] \longrightarrow k[\alpha_1] \text{ such that } \tau_1|_k = \text{id}_k \text{ and } \beta_1 \mapsto \alpha_1$$

Hence, since $\sigma_1 \circ \tau_1 = \text{id}_{k[\beta_1]}$ and $\tau_1 \circ \sigma_1 = \text{id}_{k[\alpha_1]}$, σ_1 and τ_1 are isomorphisms, i.e. $k[\alpha_1] \cong k[\beta_1]$. By induction on n the corollary follows. \square

Definition + proposition 2.9 Let $L/k, L'/k$ be field extension.

(i) We define

$$\text{Hom}_k(L, L') := \{ \sigma : L \longrightarrow L' \text{ field homomorphism s.t. } \sigma|_k = \text{id}_k \}$$

$$\text{Aut}_k(L) := \{ \sigma : L \longrightarrow L \text{ field automorphism s.t. } \sigma|_k = \text{id}_k \}$$

(ii) If L/k is finite, \bar{k} an algebraic closure of k , then

$$|\text{Hom}_k(L, L')| \leq [L : k].$$

proof. Assume first $L = k[\alpha]$ for some algebraic $\alpha \in L$. Let f be the minimal polynomial of α over k , i.e. $f \in k[X]$, $\deg(f) = [L : k]$. By 2.4 and 2.6, the elements of $\text{Hom}_k(L, \bar{k})$ correspond bijectively to the zeroes of f . Then we get

$$|\text{Hom}_k(L, \bar{k})| = |\{\text{zeroes of } f \text{ in } \bar{k}\}| \leq \deg(f) = [L : k].$$

Now consider the general case. Let $L = k[\alpha_1, \dots, \alpha_n]$ and $L' = k[\alpha_1, \dots, \alpha_{n-1}] \subseteq L = L'[\alpha_n]$.

By induction on n we have $|\text{Hom}_k(L', \bar{k})| \leq [L' : k]$. Let now

$$f = \sum_{i=0}^d a_i X^i \in L'[X]$$

with coefficients $a_i \in L'$ be the minimal polynomial of α_n over L' . Let $\sigma \in \text{Hom}_k(L, \bar{k})$ and $\sigma' = \sigma|_{L'} \in \text{Hom}_k(L', \bar{k})$, $f^{\sigma'} := \sum_{i=0}^d \sigma'(a_i) X^i$. Then

$$f^{\sigma'}(\sigma(\alpha_n)) = \sum_{i=0}^d \sigma'(a_i) (\sigma(\alpha_n))^i = \sum_{i=0}^d \sigma(a_i) (\sigma(\alpha_n))^i = \sigma \left(\sum_{i=0}^d a_i \alpha_n^i \right) = 0.$$

Thus

$$|\{\text{Hom}_{L'}(L, \bar{k})\}| = |\{\sigma \in \text{Hom}_k(L, \bar{k}) \mid \sigma|_{L'} = \text{id}_{L'}\}| \leq \deg(f^{\sigma'}) = \deg(f) = [L' : L]$$

So all in all we have

$$|\text{Hom}_k(L, \bar{k})| \leq |\text{Hom}_k(L', \bar{k})| \cdot [L : L'] \leq [L : L'] \cdot [L' : k] = [L : k],$$

which is exactly the assignment. □

Definition 2.10 Let k be a field, $f = \sum_{i=0}^d a_i X^i \in k[X]$, \bar{k} an algebraic closure of k , L/k an algebraic field extension.

- (i) f is called *separable* over k , if f has $\deg(f)$ different roots in \bar{k} , i.e. there are no multiple roots.
- (ii) $\alpha \in L$ is called *separable* over k , if the minimal polynomial of α over k is separable.
- (iii) L/k is called *separable*, if any $\alpha \in L$ is separable over k .
- (iv) We define the *formal derivative* of f by

$$f' := \sum_{i=1}^d i \cdot a_i X^{i-1}$$

We have well known properties of the derivative:

$$(f + g)' = f' + g', \quad 1' = 0, \quad (f \cdot g)' = f \cdot g' + f' \cdot g.$$

Proposition 2.11 *Let*

$$f = \prod_{i=1}^n (X - \alpha_i) \in k[X], \quad \alpha_i \in \bar{k} \text{ for } 1 \leq i \leq n$$

Then the following statements are equivalent:

- (i) f is separable.
- (ii) $(X - \alpha_i) \nmid f'$ for $1 \leq i \leq n$.
- (iii) $\gcd(f, f') = 1$ in $k[X]$.

proof. '(i) \Leftrightarrow (ii)' We have

$$f' = \sum_{i=1}^n \prod_{j \neq i} (X - \alpha_j),$$

thus we get

$$(X - \alpha_i) \mid f' \Leftrightarrow (X - \alpha_i) \mid \prod_{j \neq i} (X - \alpha_j) \Leftrightarrow \alpha_i = \alpha_j \text{ for some } i \neq j.$$

'(ii) \Rightarrow (iii)' Assume $(X - \alpha_i) \nmid f'$ for all $1 \leq i \leq n$. Then

$$\gcd(f, f') = 1 \text{ in } \bar{k}[X] \implies \gcd(f, f') = 1 \text{ in } k[X].$$

'(iii) \Rightarrow (ii)' Let now $\gcd(f, f') = 1$ in $k[X]$. Then we can write

$$1 = af + bf', \quad a, b \in k[X].$$

Since again $k[X] \subseteq \bar{k}[X]$, we can write $1 = af + bf'$ for $a, b \in \bar{k}[X]$ and hence we obtain $\gcd(f, f') = 1$ in $\bar{k}[X]$. This implies

$$(X - \alpha_i) \nmid f' \text{ for all } 1 \leq i \leq n,$$

which was to be shown. □

Corollary 2.12 (i) An irreducible polynomial $f \in k[X]$ is separable if and only if $f' \neq 0$.
(ii) Any algebraic field extension in characteristic 0 is separable.

Example 2.13 Let $\text{char}(k) = p > 0$. Then

$$X^p - 1 = (X - 1)^p$$

Let $k = \mathbb{F}_p(t)$ and $f = X^p - t \in \mathbb{F}_p(t)[X]$. Then $f' = 0$, hence f is not separable, but f is irreducible in $\mathbb{F}_p(t)[X]$.

Definition + proposition 2.14 Let L/k be a finite field extension, \bar{k} an algebraic closure of k and L .

(i) $[L : k]_s := |\text{Hom}_k(L, \bar{k})|$ is called the *degree of separability* of L/k .

(ii) If $L = k[\alpha]$ for some separable $\alpha \in L$ with minimal polynomial m_α over k , then

$$[L : k]_s = \deg(m_\alpha) = [L : k].$$

(iii) If $L = k[\alpha]$ for some $\alpha \in L$, $\text{char}(k) = p > 0$, then there exists $n \geq 0$, such that

$$[L : k] = p^n \cdot [L : k]_s$$

(iv) If $k \subseteq \mathbb{F} \subseteq L$ is an intermediate field extension, then

$$[L : k]_s = [L : \mathbb{F}]_s \cdot [\mathbb{F} : k]_s$$

proof. (i) This follows from Proposition 2.6:

$$[L : k]_s = |\text{Hom}_k(L, \bar{k})| = |\{\text{different zeroes of } f\}| = n = [L : k].$$

(iii) Write

$$f = \sum_{i=0}^n a_i X^i.$$

If α is separable over k , we are done with part (ii). Otherwise by Corollary 2.11 we have

$$f' = \sum_{i=1}^n i \cdot a_i \cdot X^{i-1} \stackrel{!}{=} 0 \iff i \cdot a_i \equiv 0 \pmod{p} \text{ for all } 0 \leq i \leq n$$

Thus we can write $f = g(X^p)$ for some $g \in k[X]$. Continue this way until we can write $f = g(X^{p^n})$ for some $n \in \mathbb{N}_0$ and separable g . Then

$$[k[\alpha] : k]_s = |\{\text{zeroes of } g \text{ in } \bar{k}\}| = \deg(g)$$

and thus we obtain

$$[k[\alpha] : k] = \deg(f) = \deg(g) \cdot p^n = p^n \cdot [k[\alpha] : k]_s.$$

(iv) Consider first the simple case $L = k(\alpha)$. Let

$$f = \sum_{i=0}^n a_i X^i \in \mathbb{F}[X]$$

be the minimal polynomial of α over \mathbb{F} . Let $\tau \in \text{Hom}_k(\mathbb{F}, \bar{k})$ and let

$$f^\tau = \sum_{i=0}^n \tau(a_i) X^i.$$

Given $\sigma \in \text{Hom}_k(L, \bar{k})$ with $\sigma|_{\mathbb{F}} = \tau$, notice that $\sigma(\alpha)$ is a zero of f^τ . Moreover by Proposition 2.6, every zero β of f^τ determines a unique σ such that $\sigma(\alpha) = \beta$. Thus we have

$$\begin{aligned} |\{\sigma \in \text{Hom}_k(L, \bar{k}) \mid \sigma|_{\mathbb{F}} = \tau\}| &= |\{\beta \in \bar{k} \mid f^\tau(\beta) = 0\}| \\ &= |\{\beta \in \bar{k} \mid f(\beta) = 0\}| \stackrel{2.6}{=} [L : \mathbb{F}]_s. \end{aligned}$$

We conclude

$$\begin{aligned} [L : k]_s &= |\text{Hom}_k(L, \bar{k})| = \left| \bigcup_{\tau \in \text{Hom}_k(\mathbb{F}, \bar{k})} \{\sigma \in \text{Hom}_k(L, \bar{k}) \mid \sigma|_{\mathbb{F}} = \tau\} \right| \\ &= |\{\sigma \in \text{Hom}_k(L, \bar{k}) \mid \sigma|_{\mathbb{F}} = \tau\}| \cdot |\text{Hom}_k(\mathbb{F}, \bar{k})| \\ &= [L : \mathbb{F}]_s \cdot [\mathbb{F} : k]_s \end{aligned}$$

For the general case we can write $L = \mathbb{F}(\alpha_1, \dots, \alpha_n)$. Define $L_i := \mathbb{F}(\alpha_1, \dots, \alpha_i)$, $L_0 := \mathbb{F}$

and $L_n = L$. Then L_i/L_{i-1} is simple and by the special case above we get

$$\begin{aligned}
[L : k]_s &= [L_n : L_{n-1}]_s \cdot [L_{n-1} : k]_s \\
&\vdots \\
&= [L_n : L_{n-1}]_s \cdots [L_2 : L_1]_s \cdot [L_1 : L_0]_s \cdot [L_0 : k]_s \\
&= [L_n : L_{n-1}]_s \cdots [L_2 : L_1]_s \cdot [L_1 : \mathbb{F}]_s \cdot [\mathbb{F} : k]_s \\
&= [L_n : L_{n-1}]_s \cdots [L_2 : \mathbb{F}]_s \cdot [\mathbb{F} : k]_s \\
&\vdots \\
&= [L_n : \mathbb{F}]_s \cdot [\mathbb{F} : k]_s \\
&= [L : \mathbb{F}]_s \cdot [\mathbb{F} : k]_s,
\end{aligned}$$

which implies the claim. □

Proposition 2.15 *A finite field extension L/k is separable if and only if $[L : k] = [L : k]_s$.*

proof. '⇒' Let $L = k[\alpha_1, \dots, \alpha_n]$. Prove this by induction on n .

n=1 This is proposition 12.2(ii)

n>1 Let $L' = k[\alpha_1, \dots, \alpha_{n-1}]$. Then by induction hypothesis $[L' : k]_s = [L' : k]$. Moreover $[L : L']_s = [L : L']$, since L/L' is simple by $L = L'[\alpha_n]$. By proposition 12.2 (iv) we get

$$[L : k]_s = [L : L']_s \cdot [L' : k]_s = [L : L'] \cdot [L' : k] = [L : k].$$

'⇐' Let $\alpha \in L$ and $f = m_\alpha \in k[X]$ its minimal polynomial. If $\text{char}(k) = 0$, f is separable, so α is separable by corollary 2.11. Let now $\text{char}(k) = p > 0$. By proposition 12.2 there exists $n \geq 0$ such that

$$[k[\alpha] : k] = p^n \cdot [k[\alpha] : k]_s$$

We find

$$[L : k] = [L : k[\alpha]] \cdot [k[\alpha] : k] \geq [L : k[\alpha]]_s \cdot p^n [k[\alpha] : k]_s = p^n [L : k]_s = p^n [L : k],$$

Hence we must have $n = 0$, i.e. $[k[\alpha] : k] = [k[\alpha] : k]_s$. Thus α is separable over k . □

§ 3 Galois extensions

Definition 3.1 A field extension L/k is called *normal*, if there is a subset $\mathcal{F} \subseteq k[X]$ such that L is the smallest field which any $f \in \mathcal{F}$ splits over.

Remark 3.2 Let L/k be a normal field extension, \bar{k} an algebraic closure of k . Then

$$\text{Hom}_k(L, \bar{k}) = \text{Aut}_k(L).$$

proof. '⊇' Clear.

'⊆' Let L be the splitting field of \mathcal{F} . Let

$$f = \sum_{i=0}^d a_i X^i \in \mathcal{F}$$

and $\alpha \in L$ such that $f(\alpha) = 0$. Let $\sigma \in \text{Hom}_k(L, \bar{k})$. Then

$$f(\sigma(\alpha)) = \sum_{i=0}^d a_i \sigma(\alpha)^i = \sum_{i=0}^d \sigma(a_i) \sigma(\alpha)^i = \sigma \left(\sum_{i=0}^d a_i \alpha^i \right) = \sigma(f(\alpha)) = 0,$$

hence $\sigma(\alpha)$ is zero of f . Since f splits over L , i.e. all zeroes of f are in L , we have $\sigma(\alpha) \in L$. Moreover L is generated over k by the zeroes of $f \in \mathcal{F}$, thus $\sigma(L) \subseteq L$ and hence we get $\sigma \in \text{Hom}_k(L, L)$.

It remains to show bijectivity. σ is clearly injective. For the surjectivity consider that σ permutes all the zeroes of any $f \in \mathcal{F}$. Finally $\sigma \in \text{Aut}_k(L)$. □

Definition 3.3 An algebraic field extension L/k is called *Galois extension* or *Galois*, if it is normal and separable. In this case, the *Galois group* of L/k is defined as

$$\text{Gal}(L, k) := \text{Aut}_k(L).$$

Proposition 3.4 A finite field extension L/k is Galois if and only if $|\text{Aut}_k(L)| = [L : k]$.

proof. '⇒' We have

$$|\text{Aut}_k(L)| = |\text{Hom}_k(L, \bar{k})| = [L : k]_s = [L : k]$$

'⇐' We have to show that L/k is separable and normal. First we see

$$[L : k] = |\text{Aut}_k(L)| \leq |\text{Hom}_k(L, \bar{k})| = [L : k]_s \leq [L : k]$$

Hence we have equality on each inequality, i.e. $[L : k] = [L : k]_s$ and L/k is separable.

By Theorem 2.5 we know that L/k is simple, say $L = k[\alpha]$ for some $\alpha \in L$.

Let $m_\alpha \in k[X]$ be the minimal polynomial of α over k . Moreover let $\beta \in \bar{k}$ be another zero of m_α . Then there exists $\sigma \in \text{Hom}_k(L, \bar{k})$ such that $\sigma(\alpha) = \beta$. By the (in-)equality above we know $\text{Aut}_k(L) = \text{Hom}_k(L, \bar{k})$, hence $\sigma(\beta) \in L$. Since β was arbitrary, m_α , f splits over L , i.e. L is the splitting field of f over k . Thus L/k is normal and finally Galois. □

Example 3.5 All quadratic field extensions are normal. Moreover, if $\text{char}(k) \neq 2$, then all quadratic field extensions of k are Galois.

Remark 3.6 Let L/k be a Galois extension and $k \subseteq K \subseteq L$ an intermediate field.

(i) Then L/K is Galois and

$$\text{Gal}(L/K) \leq \text{Gal}(L/k)$$

(ii) If K/k is Galois, then $\text{Gal}(L/K) \trianglelefteq \text{Gal}(L/k)$ is a normal subgroup and

$$\text{Gal}(L/k) / \text{Gal}(L/K) \cong \text{Gal}(K/k).$$

proof. (i) Clearly L/K is normal, since L is the splitting field for the same polynomials as in L/k . Let now $\alpha \in L$. Then the minimal polynomial m_α of α over K divides the minimal polynomial m'_α of α over k , since $k \subseteq K$. Since m'_α has no multiple roots, m_α does not either and hence L/K is separable and thus Galois.

(ii) Define

$$\rho : \text{Gal}(L/k) \longrightarrow \text{Gal}(K/k), \sigma \mapsto \sigma|_K.$$

ρ is well defined since $\sigma|_K \in \text{Hom}_K k(K, \bar{k}) = \text{Aut}_k(K) = \text{Gal}(K/k)$ as K/k is Galois:

$$[K : k] = |\text{Aut}_k(K)| \leq |\text{Hom}_k(K, \bar{k})| \leq [K : k].$$

Moreover ρ is surjective. For the kernel we get

$$\ker(\rho) = \{\sigma \in \text{Gal}(L/k) \mid \sigma|_K = \text{id}_K\} = \text{Gal}(L/K)$$

and thus we obtain $\text{Gal}(L/k) / \text{Gal}(L/K) \cong \text{Gal}(K/k)$. □

Theorem 3.7 (Main theorem of Galois theory) Let L/k be a finite Galois extension and $G := \text{Gal}(L/k)$. Then the subgroups $H \leq G$ correspond bijectively to the intermediate fields $k \subseteq K \subseteq L$. Explicitly we have inverse maps

$$K \mapsto \text{Gal}(L/K) \leq G$$

$$H \mapsto L^H := \{\alpha \in L \mid \sigma(\alpha) = \alpha \text{ for all } \sigma \in H\}.$$

proof. Clearly L^H is a field for any $H \leq G$. We now have to show

(i) $\text{Gal}(L/L^H) = H$ for any $H \leq G$.

(ii) $L^{\text{Gal}(L/K)} = K$ for any intermediate field $k \subseteq K \subseteq L$.

These prove the theorem.

(i) We show both inclusion.

' \supseteq ' Clear by definition.

' \subseteq ' It suffices to show $|\text{Gal}(L/L^H)| \leq |H|$. By 3.4(i) we have

$$|\text{Gal}(L/L^H)| = [L : L^H].$$

By theorem 2.5 L/L^H is simple, say $L = L^H[\alpha]$. Define

$$f = \prod_{\sigma \in H} (X - \sigma(\alpha))$$

with $\deg(f) = |H|$. Further, since $\text{id} \in H$, we have $f(\alpha) = 0$. Clearly $f \in L[X]$. We want to show that $f \in L^H[X]$. Therefore for $\tau \in H$ define

$$g^\tau := \sum_{i=0}^n \tau(a_i)X^i \text{ for } g = \sum_{i=0}^n a_iX^i$$

Then for f as defined above we have

$$f^\tau = \prod_{\sigma \in H} (X - \tau(\sigma(\alpha))) = \prod_{\sigma \in H} (X - \sigma(\alpha)) = f$$

hence $f \in L^H[X]$. From $f(\alpha) = 0$ we know that the minimal polynomial m_α of α over L^H divides f , thus

$$|\text{Gal}(L/L^H)| = [L : L^H] = \deg(m_\alpha) \leq \deg(f) = |H|$$

(ii) '⊇' Clear by definition.

'⊆' Let $H := \text{Gal}(L/K)$. Since $K \subseteq L^H$ it suffices to show $[L^H : K] = 1$. Since L^H/K is separable, this is equivalent to $[L^H : K]_s = 1$. Let now $\sigma \in \text{Hom}_K(L^H, \bar{k})$. By 2.6 we can extend σ to

$$\tilde{\sigma} : L \longrightarrow \bar{k}$$

with $\tilde{\sigma}|_{L^H} = \sigma$. Explicitly: Let $L = L^H[\alpha]$ and $f \in L^H[X]$ its minimal polynomial. Choose a zero $\beta \in \bar{k}$ of f^σ . Then by 2.6 there exists $\tilde{\sigma} : L \longrightarrow \bar{k}$ with $\tilde{\sigma}(\alpha) = \beta$ and $\tilde{\sigma}|_{L^H} = \sigma$. We get $\tilde{\sigma} \in \text{Gal}(L/K) = H$ and $\sigma = \tilde{\sigma}|_{L^H} = \text{id}_K$ which finally implies $[L^H : K] = 1$. □

Remark 3.8 *An intermediate field $k \subseteq K \subseteq L$ is Galois over k if and only if $\text{Gal}(L/K) \trianglelefteq \text{Gal}(L/k)$ is a normal subgroup.*

proof. '⇒' If K/k is Galois, then $\text{Gal}(L/K) = \ker(\rho)$ is a normal subgroup by 3.5.

'⇐' Conversely let $\text{Gal}(L/K) =: H \trianglelefteq \text{Gal}(L/k)$ be a normal subgroup. By 3.4 it suffices to show $\text{Hom}_k(K, \bar{k}) = \text{Aut}_k(K)$. Let now $\sigma \in \text{Hom}_k(K, \bar{k})$ and $\alpha \in K$. Extend σ to $\tilde{\sigma} : L \longrightarrow \bar{k}$. Then $\tilde{\sigma} \in \text{Gal}(L/k)$. By the theorem it suffices to show that $\sigma(\alpha) \in L^{\text{Gal}(L/K)} = K$, i.e. $\sigma(K) \subseteq K$. Let $\tau \in \text{Gal}(L/L^H)$. Then, since $\text{Gal}(L/K)$ is normal, we obtain

$$\tau(\sigma(\alpha)) = \tau(\tilde{\sigma}(\alpha)) = (\tilde{\sigma} \circ \tau)(\alpha) = \tilde{\sigma}(\alpha) = \sigma(\alpha),$$

which implies the claim. □

Example 3.9 Let $k = \mathbb{Q}$, $f = X^5 - 4X + 2 \in \mathbb{Q}[X]$. Further let $L = L(f)$ be the splitting field of f over \mathbb{Q} . What is $\text{Gal}(L/\mathbb{Q})$?

We first want to show that f is irreducible. But this immediately follows by Eisenstein's criterion for irreducibility with $p = 2$.

Thus L is an extension of $\mathbb{Q}/(f)$. Therefore $[L : \mathbb{Q}]$ is multiple of $[\mathbb{Q}/(f)] = 5$, hence $|\text{Gal}(L/\mathbb{Q})|$ is divisible by 5. By Lagrange's theorem we know that $\text{Gal}(L/\mathbb{Q})$ contains an element of order 5. Further note that f has exactly 3 zeroes in \mathbb{R} . With

$$\lim_{x \rightarrow -\infty} f(x) = -\infty < 0, \quad f(0) = 2 > 0, \quad f(1) = -1 < 0, \quad \lim_{x \rightarrow \infty} f(x) = \infty > 0$$

we see by the intermediate value theorem that f has at least 3 zeroes. Moreover

$$f' = 5X^4 - 4 = 5 \cdot \left(X^4 - \frac{4}{5}\right) = 5 \cdot \left(X^2 - \frac{2}{\sqrt{5}}\right) \cdot \left(X^2 + \frac{2}{\sqrt{5}}\right)$$

Obviously, since the second factor has not real zeroes, the derivative of f has 2 zeroes, hence f has at most 3 zeroes. Together we obtain that f has exactly 3 zeroes. Since f splits over \mathbb{C} , f has two more conjugate zeroes in \mathbb{C} , say $\beta, \bar{\beta}$. Hence we know that the conjugation in \mathbb{C} must be an element of $\text{Gal}(L/\mathbb{Q})$.

To sum it up, we know: $\text{Gal}(L/\mathbb{Q})$ is isomorphic to a subgroup of S_5 , contains the conjugation, which corresponds to a transposition and moreover an element of order 5, i.e. a 5-cycle. But these two elements generate the whole group S_5 . Hence we have $\text{Gal}(L/\mathbb{Q}) \cong S_5$.

Proposition 3.10 (Cyclotomic fields) Let k be a field, $n \in \mathbb{N}$, $\text{char}(k) \nmid n$ and L the splitting field of the polynomial $f = X^n - 1$.

Then L/k is Galois and $\text{Gal}(L_n/k)$ is isomorphic to a subgroup of $(\mathbb{Z}/n\mathbb{Z})^\times$.

proof. We have $f' = nX^{n-1}$ and $f' = 0 \Leftrightarrow X = 0$ but $f(0) \neq 0$, hence f' and f_n are coprime. Thus f is separable. Since L is the splitting field of f by definition, L/k is normal, thus Galois. The zeroes of f form a group $\mu_n(k)$ under multiplication. By proposition 2.3 $\mu_n(k)$ is cyclic. Let ζ_n be a generator of $\mu_n(k)$. Define a map

$$\chi_n : \text{Gal}(L_n/k) \longrightarrow (\mathbb{Z}/n\mathbb{Z})^\times \quad \sigma \mapsto m \text{ if } \sigma(\zeta_n) = \zeta_n^m$$

where m is relatively coprime to n . We obtain that χ_n is a homomorphism of groups since for $\sigma_1, \sigma_2 \in \text{Gal}(L_n/k)$ we have $\sigma_2\sigma_1(\zeta_n) = \sigma_2(\zeta_n^{k_1}) = (\zeta_n^{k_1})^{k_2} = \zeta_n^{k_1 k_2}$ and hence

$$\chi_n(\sigma_1\sigma_2) = k_1 \cdot k_2 = \chi_n(\sigma_1) \cdot \chi_n(\sigma_2).$$

Moreover χ_n is injective, since

$$\chi_n(\sigma) = 1 \Leftrightarrow \sigma(\zeta_n) = \zeta_n \Leftrightarrow \sigma = \text{id}.$$

This proves the proposition. Recall that $|(\mathbb{Z}/n\mathbb{Z})^\times| = \phi(n)$ Where ϕ is Euler's ϕ -function. \square

§ 4 Solvability of equations by radicals

Definition + remark 4.1 Let k be a field, $f \in k[X]$ separable.

- (i) Let $L(f)$ be the splitting field of f over k . The *Galois group of the equation* $f = 0$ is defined by

$$\text{Gal}(f) := \text{Gal}(L(f)/k).$$

- (ii) There exists an injective homomorphism of groups $\text{Gal}(f) \longrightarrow S_n$ where $n := \deg(f)$.
 (iii) If L/k is a finite, separable field extension, the $\text{Aut}_k(L)$ is isomorphic to a subgroup of S_n , where $n = [L : k]$.

proof. (ii) Clear, since automorphisms permute the zeroes of f , of which we have at most n .

- (iii) We know L/k is simple, say $L = k[\alpha]$ for some $\alpha \in L$. Let m_α be the minimal polynomial of α over k . Then $\deg(f) = n$. Every $\sigma \in \text{Aut}(L/k)$ maps α to a zero of f and the same for every zero of f . Hence the claim follows. \square

Definition 4.2 (i) A simple field extension $L = k[\alpha]$ of a field k is called an *elementary radical extension* if either

- (1) α is a root of unity, i.e. a zero of the polynomial $X^n - 1$ for some $n \in \mathbb{N}$.
- (2) α is a root of $X^n - \gamma$ for some $\gamma \in k, n \in \mathbb{N}$ such that $\text{char}(k) \nmid n$.
- (3) α is a root of $X^p - X - \gamma$ for some $\gamma \in k$ where $p = \text{char}(k)$.

In the following, we will denote (1), (2) and (3) as the three *types* of elementary radical extensions.

- (ii) A finite field extension L/k is called a *radical extension*, if there is a field extension L'/L and a chain of field extension

$$k = L_0 \subseteq L_1 \subseteq \cdots \subseteq L_m = L'$$

such that L_i/L_{i-1} is an elementary radical extension for every $1 \leq i \leq m$.

Example 4.3 Let $k = \mathbb{Q}$, $f = X^3 - 3X + 1$. The zeroes of f (in \mathbb{C}) are

$$\alpha_1 = \zeta + \zeta^{-1} \in \mathbb{R}, \quad \alpha_2 = \zeta^2 + \zeta^{-2} \quad \text{and} \quad \alpha_3 = \zeta^4 + \zeta^{-4}$$

where $\zeta = e^{\frac{2\pi i}{9}}$ is a primitive ninth root of unity. We show this exemplarily for α_1 . We have

$$f(\alpha_1) = (\alpha_1^3 - 3\alpha_1 + 1) = \zeta^3 + 3\zeta + 3\zeta^{-1} + \zeta^{-3} - 3\zeta - 3\zeta^{-1} + 1 = \zeta^3 + \zeta^{-3} + 1 = 0$$

where we use $\zeta^{-3} = \overline{\zeta^3}$ and since $z + \bar{z} = 2 \cdot \Re(z)$ for any $z \in \mathbb{C}$ we have

$$\zeta^3 + \zeta^{-3} = 2 \cdot \Re(\zeta^3) = 2 \cdot \Re\left(e^{\frac{2\pi i}{3}}\right) = 2 \cdot \Re\left(\cos \frac{2\pi}{3} + i \cdot \sin \frac{2\pi}{3}\right) = 2 \cdot \cos \frac{2\pi}{3} = 2 \cdot \left(-\frac{1}{2}\right) = -1.$$

Further we have

$$\alpha_1^2 = \zeta^2 + 2\zeta^{-2} + 2 = \alpha_2 + 2,$$

hence $\alpha_2 \in \mathbb{Q}(\alpha_1)$ and $\alpha_1 + \alpha_2 + \alpha_3 = 0$, hence $\alpha_3 \in \mathbb{Q}(\alpha_1, \alpha_2) = \mathbb{Q}(\alpha_1)$.

This means that $\mathbb{Q}(\alpha_1)$ contains all the zeroes of f , i.e. is a splitting field of f . We conclude

$$\mathbb{Q}(\alpha_1) \cong \mathbb{Q}/(f), \quad [\mathbb{Q}(\alpha_1) : \mathbb{Q}] = 3.$$

From the f we see that $\mathbb{Q}(\alpha_1)/\mathbb{Q}$ is not an elementary radical extension, but a radical extension, since for $\mathbb{Q}(\zeta)$ we have $\mathbb{Q}(\alpha_1) \subseteq \mathbb{Q}(\zeta)$ and $\mathbb{Q}(\zeta)/\mathbb{Q}$ is an elementary radical extension.

Definition 4.4 Let k be a field, $f \in k[X]$ a separable, non-constant polynomial. We say f is *solvable by radicals*, if the splitting field $L(f)$ is a radical extension.

Remark 4.5 Let L/k be an elementary field extension, referring to Definition 4.1 of type

- (1) $L = k[\zeta]$ for some root of unity ζ (primitive for some suitable $n \in \mathbb{N}$, $\text{char}(k) \nmid n$). Then L/k is Galois with abelian Galois group

$$\text{Gal}(L/k) \cong (\mathbb{Z}/n\mathbb{Z})^\times.$$

- (2) $L = k[\alpha]$ where α is a root of $X^n - \gamma$ for some $\gamma \in k$, $n \in \mathbb{N}$, $\text{char}(k) \nmid n$. If k contains the n -th roots of unity, i.e. $\mu_n(\bar{k})$, then L/k is Galois with cyclic Galois group.

- (3) $L = k[\alpha]$, where α is a root of $X^p - X - \gamma$ for some $\gamma \in k^\times$. Then L/k is Galois with Galois group

$$\text{Gal}(L/k) \cong \mathbb{Z}/p\mathbb{Z}.$$

proof. (1) We proved this in proposition 3.9.

- (2) Let $\zeta \in k$ be a primitive n -th root of unity. Then $\zeta^i \cdot \alpha$ is a zero of $X^n - \gamma$, where we assume n to be minimal such that $X^n - \gamma$ is irreducible. Then L contains all roots of $X^n - \gamma$, i.e. L/k is normal and thus Galois with

$$|\text{Gal}(L/k)| = [L : k] = \deg(X^n - \gamma) = n$$

Since the automorphism $\sigma \in \text{Gal}(L/k)$ that maps $\alpha \mapsto \zeta \cdot \alpha$ has order n , $\text{Gal}(L/k)$ is cyclic.

- (3) $f = X^p - X - \gamma$ has p zeroes in $L = k[\alpha]$. Since $f(\alpha) = 0$, we have

$$f(\alpha + 1) = (\alpha + 1)^p - (\alpha + 1) - \gamma = \alpha^p + 1 - \alpha - 1 - \gamma = \alpha^p - \alpha - \gamma = f(\alpha) = 0$$

Hence L is the splitting field of f and L/k is normal. Moreover $f' = -1 \neq 0$, hence L/k is separable and thus Galois with

$$|\text{Gal}(L/k)| = [L : k] = \deg(f) = p$$

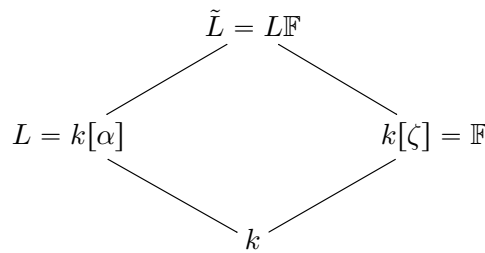
Further $\text{Gal}(L/k) \ni \sigma : \alpha \mapsto \alpha + 1$ has order p , hence $\text{Gal}(L/k)$ is cyclic and thus

$$\text{Gal}(L/k) \cong \mathbb{Z}/p\mathbb{Z},$$

which is the claim. □

Remark 4.6 Let L/k be an elementary radical extension of type (ii), i.e. $L = k[\alpha]$, where α is the root of $f = X^n - \gamma$ for some $\gamma \in k, n \geq 1, \text{char}(k) \nmid n$. $X^n - \gamma$ is irreducible

Let \mathbb{F} be a splitting field of $X^n - 1$ over k and $L\mathbb{F} = k(\alpha, \zeta)$ be the compositum of L and \mathbb{F} , i.e. the smallest subfield of \bar{k} containing L and \mathbb{F} .



\tilde{L} is a splitting field of $X^n - \gamma$ over \mathbb{F} , hence \tilde{L}/\mathbb{F} is Galois and by 4.4(ii), $\text{Gal}(\tilde{L}/\mathbb{F})$ is cyclic. Moreover \mathbb{F}/k is Galois and $\text{Gal}(\mathbb{F}/k)$ is abelian. Hence \tilde{L}/k is Galois and

$$\text{Gal}(\tilde{L}/k) / \text{Gal}(\tilde{L}/\mathbb{F}) \cong \text{Gal}(\mathbb{F}/k)$$

i.e. we have a short exact sequence

$$1 \longrightarrow \underbrace{\text{Gal}(\tilde{L}/\mathbb{F})}_{\text{cyclic}} \xrightarrow{\text{inj.}} \text{Gal}(\tilde{L}/k) \xrightarrow{\text{surj.}} \underbrace{\text{Gal}(\mathbb{F}/k)}_{\text{abelian}} \longrightarrow 1.$$

Example 4.7 Let $k = \mathbb{Q}, f = X^3 - 2$. Then $L = \mathbb{Q}[\alpha]$ with $\alpha = \sqrt[3]{2}$ and $\mathbb{F} = \mathbb{Q}[\zeta]$ with $\zeta = e^{\frac{2\pi}{3}}$. Then $\tilde{L} = L(f)$ with $[\tilde{L} : \mathbb{Q}] = 6$. We obtain

$$\text{Gal}(\tilde{L}/\mathbb{F}) \cong \mathbb{Z}/3\mathbb{Z}, \text{Gal}(\mathbb{F}/k) \cong \mathbb{Z}/2\mathbb{Z}, \text{Gal}(\tilde{L}/\mathbb{Q}) \cong S_3.$$

Definition 4.8 A group G is called *solvable*, if there exists a chain of subgroups

$$1 = G_0 \triangleleft G_1 \triangleleft \dots \triangleleft G_n = G$$

where $G_{i-1} \triangleleft G_i$ is a normal subgroup and G_i/G_{i-1} is abelian for all $1 \leq i \leq n$.

Example 4.9 (i) Every abelian group is solvable.

(ii) S_4 is solvable by

$$1 \triangleleft V_4 \triangleleft A_4 \triangleleft S_4$$

where $V_4 = \{\text{id}, (12)(34), (13)(24), (14)(23)\}$. For the quotients we have

$$V_4/\{1\} \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}, \quad A_4/V_4 \cong \mathbb{Z}/3\mathbb{Z}, \quad S_4/A_4 \cong \mathbb{Z}/2\mathbb{Z}.$$

(iii) S_5 is not solvable, since A_5 is simple (EAZ 6.6) but the quotient $A_5/\{1\}$ is not abelian.

(iv) If G, H are solvable groups, then the direct product $G \times H$ is solvable.

Proposition 4.10 (i) *Let G be a solvable group. Then*

(1) *Every subgroup $H \leq G$ is solvable.*

(2) *Every homomorphic image of G is solvable.*

(ii) *Let*

$$1 \longrightarrow G' \longrightarrow G \longrightarrow G'' \longrightarrow 1$$

be a short exact sequence. Then G is solvable if and only if G' and G'' are solvable.

proof. (i) (1) Let G be solvable, i.e. we have a chain $1 = G_0 \triangleleft G_1 \triangleleft \dots \triangleleft G_n = G$. Let $G' \leq G$ a subgroup. Then

$$1 \triangleleft G_1 \cap G' \triangleleft \dots \triangleleft G_n \cap G' = G'$$

is a chain of subgroups of G' and we have $G_i \cap G' \triangleleft G_{i+1} \cap G'$ and moreover

$$(G_{i+1} \cap G') / (G_i \cap G') \cong G_i (G_{i+1} \cap G') / G_i \leq G_{i+1} / G_i.$$

Hence we have abelian quotients and G' is solvable.

(2) Let H be a group and $\phi : G \longrightarrow H$ be a surjective homomorphism of groups. Let

$$1 \triangleleft G_1 \triangleleft \dots \triangleleft G_n = G.$$

Let $H_i := \phi(G_i)$. Then H_i is normal in H_{i+1} . It remains to show that the quotients are abelian. Consider

$$\begin{array}{ccccc} G_i & \longrightarrow & G_{i+1} & \xrightarrow{\pi_G} & G_{i+1}/G_i \\ \downarrow \phi & & \downarrow \phi & \searrow \tilde{\phi} & \downarrow \bar{\phi} \\ H_i & \longrightarrow & H_{i+1} & \xrightarrow{\pi_H} & H_{i+1}/H_i \end{array}$$

(We have $G_i \subseteq \ker(\tilde{\phi})$, since $\phi(G_i) = H_i = \ker(\pi_H)$). Hence $\tilde{\phi}$ factors to

$$\bar{\phi} : \underbrace{G_{i+1}/G_i}_{\text{abelian}} \longrightarrow \underbrace{H_{i+1}/H_i}_{\text{abelian!}}$$

and we get $\bar{\phi}(a)\bar{\phi}(b) = \bar{\phi}(ab) = \bar{\phi}(ba) = \bar{\phi}(b)\bar{\phi}(a)$, hence the quotient is abelian and

$H = \phi(G)$ is solvable.

(ii) '⇒' Clear.

'⇐' Let

$$1 \triangleleft G_1 \triangleleft \cdots \triangleleft G_m = G', \quad 1 \triangleleft H_{m+1} \triangleleft \cdots \triangleleft H_{m+k} = G''$$

chains of subgroups with abelian quotients. Define

$$G_i := \pi^{-1}(H_i)_{m+1 \leq i \leq m+k}, \quad \pi : G \longrightarrow G''.$$

Then G_i is normal in G_{i+1} and we have

$$G_{m+0} = \pi^{-1}(\{1\}) = G' = G_m.$$

For $m+1 \leq i \leq m+k$ we have

$$G_{i+1}/G_i = \pi^{-1}(H_{i+1}/H_i) \cong H_{i+1}/H_i$$

and hence the chain

$$1 \triangleleft G_1 \triangleleft \cdots \triangleleft G_m = G' \triangleleft G_{m+1} \triangleleft \cdots \triangleleft G_{m+k} = G$$

reveals the solvability of G . □

Lemma 4.11 *A finite separable field extension L/k is a radical extension if and only if there exists a finite Galois extension L'/k , $L \subseteq L'$ such that $\text{Gal}(L'/k)$ is solvable.*

proof. '⇒' Let

$$k = k_0 = L_0 \subseteq L_1 \subseteq \cdots \subseteq L_n$$

a chain as in definition 4.7 with $L \subseteq L_n$. we prove the statement by induction.

n=1 This is exactly remark 4.5, 4.6

n>1 By induction hypothesis L_{n-1}/k is solvable. Moreover L_n/L_{n-1} is solvable, too. This is equivalent to the fact, that L_{n-1} is contained in a Galois extension \tilde{L}_{n-1}/k such that $\text{Gal}(\tilde{L}/k)$ is solvable and L_n is contained in a Galois extension \tilde{L}/L_{n-1} such that $\text{Gal}(\tilde{L}/L_{n-1})$ is solvable. We have a diagramm

$$\begin{array}{ccccc} \tilde{L}_{n-1} & \subseteq & \tilde{L}L_{n-1} & := & \mathbb{M} \\ \cup & & & & \cup \\ k & \subseteq & L_{n-1} & \subseteq & L_n & \subseteq & \tilde{L} \end{array}$$

We obtain, that \mathbb{M} is Galois over L_{n-1} , since $\tilde{L}, \tilde{L}_{n-1}$ are Galois over L_{n-1} , hence by

$$\iota : \text{Gal}(\mathbb{M}/\tilde{L}_{n-1}) \longrightarrow \text{Gal}(\tilde{L}/L_{n-1}), \quad \sigma \mapsto \sigma|_{\tilde{L}}$$

an injective homomorphism of groups is given, hence

$$\text{Gal}(\mathbb{M}/\tilde{L}_{n-1}) \leq \text{Gal}(\tilde{L}/L_{n-1})$$

is solvable as a subgroup of a solvable group.

Let now $\tilde{\mathbb{M}}/\mathbb{M}$ be a minimal extension, such that $\tilde{\mathbb{M}}/k$ is Galois. Explicitly, $\tilde{\mathbb{M}}$ is defined as the *normal hull* of \mathbb{M} , i.e. the splitting field of the minimal polynomial of a primitive element of \mathbb{M}/k .

Now we want to show that $\text{Gal}(\mathbb{M}/k)$ is solvable. This finishes the proof of the sufficiency of our Lemma. Consider the short exact sequence

$$1 \longrightarrow \text{Gal}(\tilde{\mathbb{M}}/\tilde{L}_{n-1}) \longrightarrow \text{Gal}(\mathbb{M}/k) \longrightarrow \text{Gal}(\tilde{L}_{n-1}/k) \longrightarrow 1.$$

By proposition 4.8 and our induction hypothesis it suffices to show that $\text{Gal}(\tilde{\mathbb{M}}/\tilde{L}_{n-1})$ is solvable. Therefore observe that $\tilde{\mathbb{M}}$ is generated over k by the $\sigma(k)$ for $\sigma \in \text{Hom}_k(\mathbb{M}, \bar{k})$, where \bar{k} denotes an algebraic closure of k . For any $\sigma \in \text{Hom}_k(\mathbb{M}, \bar{k})$, $\sigma(\mathbb{M})/\sigma(L_{n-1}) = \sigma(\mathbb{M})/\tilde{L}_{n-1}$ is Galois. Hence

$$\Phi : \text{Gal}(\tilde{\mathbb{M}}/\tilde{L}_{n-1}) \longrightarrow \prod_{\sigma \in \text{Hom}_k(\mathbb{M}, \bar{k})} \text{Gal}(\sigma(\mathbb{M})/\tilde{L}_{n-1}), \quad \tau \mapsto (\tau|_{\sigma(\mathbb{M})})_{\sigma}$$

is injective. Hence $\text{Gal}(\tilde{\mathbb{M}}/\tilde{L}_{n-1})$ is solvable as a subgroup of a product of solvable groups.

' \Leftarrow ' Let now \tilde{L}/L finite such that $\text{Gal}(\tilde{L}/k)$ is solvable. Let

$$1 \triangleleft G_1 \triangleleft \dots \triangleleft G_n = G$$

be a chain of subgroups as in definition 4.7. By the main theorem we have bijectively correspond intermediate fields

$$\tilde{L} = L_n \supseteq L_{n-1} \supseteq \dots \supseteq L_0 = k$$

where L_{i+1}/L_i is Galois and $\text{Gal}(L_{i+1}/L) \cong \mathbb{Z}/p\mathbb{Z}$ for all $1 \leq i \leq n-1$. We now have to differ between three cases.

case 1 $p_i = \text{char}(k)$. Then L_{i+1}/L_i is an elementary radical extension of type (iii), i.e. L/k is a radical extension.

case 2 $p_i \neq \text{char}(k)$ and L_i contains a primitive p_i -th root of unity. Then L_{i+1}/L_i is an elementary radical extension of type (ii), i.e. L/k is a radical extension.

case 3 $p_i \neq \text{char}(k)$ and L_i does not contain any primitive p_i -th root of unity. Then define

$$d := \prod_{p \in \mathbb{P}, p \mid |G|} p$$

And let \mathbb{F} be the splitting field of $X^d - 1$ over k . Then \mathbb{F}/k is an elementary radical extension of type (i). Let $L' := \tilde{L}\mathbb{F}$ be the composite of \tilde{L} and \mathbb{F} in \bar{k} . Then L'/\mathbb{F} is Galois by remark 4.5. Let $G' = \text{Gal}(L'/\mathbb{F})$. Consider the map

$$\Psi : \text{Gal}(L'/\mathbb{F}) \longrightarrow \text{Gal}(\tilde{L}/k), \sigma \mapsto \sigma|_{\tilde{L}}.$$

Ψ is a well defined injective homomorphism of groups, hence $\text{Gal}(L'/\mathbb{F}) \leq \text{Gal}(\tilde{L}/k)$ is solvable as a subgroup of a solvable group. Let

$$1 \triangleleft G_1 \triangleleft \dots \triangleleft G_n = G'$$

a chain of subgroups as in definition 4.7. Let further be

$$k \subseteq \mathbb{F} = L_0 \subseteq L_1 \subseteq \dots \subseteq L_n = L'$$

be the corresponding chain of intermediate fields, i.e. L_i/L_{i-1} is Galois and $\text{Gal}(L_i/L_{i-1}) \cong \mathbb{Z}/p\mathbb{Z}$ for $1 \leq i \leq n$. Hence, L_i/L_{i-1} is a radical extension of type (ii). Thus L/k is a radical extension, which finishes the proof. \square

Theorem 4.12 *Let $f \in k[X]$ be a separable non-constant polynomial. Then f is solvable by radicals if and only if $\text{Gal}(f) = \text{Gal}(L(f)/k)$ is solvable.*

proof. Let f be solvable by radicals, i.e. $L(f)/k$ be a radical field extension.

$\iff L(f)$ is contained in some Galois extension \tilde{L}/k and $\text{Gal}(\tilde{L}/k)$ is solvable.

\iff In $k \subseteq L(f) \subseteq \tilde{L}$ all extensions are Galois.

$\stackrel{3.5}{\iff} \text{Gal}(L(f)/k) \cong \text{Gal}(\tilde{L}/k) / \text{Gal}(\tilde{L}/L(f))$

$\stackrel{4.8}{\iff} \text{Gal}(L(f)/k)$ is solvable. \square

Theorem 4.13 *Let G be a group, k a field. Then the subset $\text{Hom}(G, k^\times) \subseteq \text{Maps}(G, k)$ is linearly independant in the k -vector space $\text{Maps}(G, k)$.*

proof. Suppose $\text{Hom}(G, k^\times)$ is linearly dependant. Then let $n > 0$ minimal, such that there exist distinct elements $\chi_1, \dots, \chi_n \in \text{Hom}(G, k^\times)$ and $\lambda_1, \dots, \lambda_n \in k^\times$ such that

$$\sum_{i=0}^n \lambda_i \chi_i = 0.$$

The χ_i are called *characters*. Clearly we have $n \geq 2$. Choose $g \in G$ such that $\chi_1(g) \neq \chi_2(g)$. For any $h \in G$ we have

$$0 = \sum_{i=0}^n \lambda_i \chi_i(gh) = \sum_{i=0}^n \underbrace{\lambda_i \chi_i(g)}_{=: \mu_i} \chi_i(h) = \sum_{i=0}^n \mu_i \chi_i(h).$$

Then we get

$$0 = \sum_{i=0}^n \mu_i \chi_i(h) = \sum_{i=0}^n \lambda_i \chi_i(g) \chi_i(h) \Rightarrow \sum_{i=0}^n \underbrace{(\mu_i - \lambda_i \chi_1(g))}_{=: \nu_i} \chi_i(h) = 0.$$

Consider

$$\nu_1 = \mu_1 - \lambda_1 \chi_1(g) = \lambda_1 \chi_1(g) - \lambda_1 \chi_1(g) = 0,$$

$$\nu_2 = \mu_2 - \lambda_2 \chi_1(g) = \lambda_2 \chi_2(g) - \lambda_2 \chi_1(g) = \underbrace{\lambda_2}_{\neq 0} \cdot \underbrace{(\chi_2(g) - \chi_1(g))}_{\neq 0} \neq 0.$$

Hence χ_2, \dots, χ_n are linearly dependent. This is a contradiction to the minimality of n . \square

Proposition 4.14 *Let L/k be a Galois extension such that $G := \text{Gal}(L/k) = \langle \sigma \rangle$ is cyclic of order d for some $\sigma \in G$, where $\text{char}(k) \nmid d$. Let $\zeta_d \in k$ be a primitive d -th root of unity.*

Then there exists $\alpha \in L^\times$ such that $\sigma(\alpha) = \zeta \cdot \alpha$.

proof. Let

$$f : L \longrightarrow L, \quad f(X) = \sum_{i=0}^{d-1} \zeta^{-i} \cdot \sigma^i(X).$$

Applying Theorem 4.10 on $G = L^\times$ and $k = L$ shows $f \neq 0$. Then let $\gamma \in L$ such that $\alpha := f(\gamma) \neq 0$. Then we have

$$\begin{aligned} \sigma(\alpha) &= \sigma(f(\gamma)) = \sigma\left(\sum_{i=0}^{d-1} \zeta^{-i} \cdot \sigma^i(\gamma)\right) = \sum_{i=0}^{d-1} \zeta^{-i} \cdot \sigma^{i+1}(\gamma) = \zeta \cdot \sum_{i=0}^{d-1} \zeta^{-(i+1)} \cdot \sigma^{i+1}(\gamma) \\ &= \zeta \cdot \sum_{i=1}^d \zeta^{-i} \cdot \sigma^i(\gamma) = \zeta \cdot \left(\left(\sum_{i=1}^{d-1} \zeta^{-i} \cdot \sigma^i(\gamma) \right) + \gamma \right) \\ &= \zeta \cdot f(\gamma) = \zeta \cdot \alpha. \end{aligned}$$

Remark: The claim follows from Proposition 5.2 by inserting $\beta = \zeta$. \square

Corollary 4.15 *Let L/k be a Galois extension, such that $G := \text{Gal}(L/k) = \langle \sigma \rangle$ is cyclic of order d for some $\sigma \in G$, where $\text{char}(k) \nmid d$. Assume k contains a primitive d -th root of unity.*

Then L/k is an elementary radical extension of type (ii).

proof. Let $\zeta_d \in k$ be a primitive d -th root of unity and $\alpha \in L^\times$ such that $\sigma(\alpha) = \zeta \cdot \alpha$.

We have

$$\sigma^i(\alpha) = \zeta^i \cdot \alpha \quad \text{for } 1 \leq i \leq d.$$

The minimal polynomial of α over k has at least d zeroes, namely $\alpha, \sigma(\alpha), \dots, \sigma^{d-1}(\alpha)$. Thus $L = k[\alpha]$. Moreover we have

$$\sigma(\alpha^d) = (\sigma(\alpha))^d = (\zeta \cdot \alpha)^d = \alpha^d,$$

hence

$$\alpha^d \in L^{(\sigma)} = L^{\text{Gal}(L/k)} = k$$

where the last equation follows by the main theorem. Define $\gamma := \alpha^d$. Then the minimal polynomial of α over k is $X^d - \gamma \in k[X]$, which proves the claim. \square

Proposition 4.16 *Let L/k be a Galois extension of degree $p = \text{char}(k)$ with cyclic Galois group $\text{Gal}(L/k) \cong \mathbb{Z}/p\mathbb{Z} = \langle \sigma \rangle$. Then there exists $\alpha \in L^\times$ such that $\sigma(\alpha) = \alpha + 1$.*

proof. The proof follows by Proposition 5.4 by setting $\beta = -1$. \square

Corollary 4.17 *Let L/k be a Galois extension of degree $p = \text{char}(k)$ with cyclic Galois group $\text{Gal}(L/k) \cong \mathbb{Z}/p\mathbb{Z} = \langle \sigma \rangle$. Then L/k is an elementary radical extension of type (iii).*

proof. Let $\alpha \in L^\times$ such that $\sigma(\alpha) = \alpha + 1$. We have

$$\sigma^i(\alpha) = \alpha + i \quad \text{for } 1 \leq i \leq p,$$

thus we have $L = k[\alpha]$. Moreover we have

$$\sigma(\alpha^p - \alpha) = \sigma^p(\alpha) - \sigma(\alpha) = (\alpha + 1)^p - (\alpha + 1) = \alpha^p + 1 - \alpha - 1 = \alpha^p - \alpha.$$

Thus again we have $\alpha^p \in k$. Define $\gamma := \alpha^p - \alpha$. Then the minimal polynomial of α over k is $X^p - X - \gamma$, which proves the claim. \square

§ 5 Norm and trace

Definition + remark 5.1 Let L/k be a finite separable field extension, $[L : k] = n$. Let $\text{Hom}_k(L, \bar{k}) = \{\sigma_1, \dots, \sigma_n\}$.

(i) For $\alpha \in L$ we define the *norm* of α over k by

$$N_{L/k}(\alpha) := \prod_{i=1}^n \sigma_i(\alpha).$$

(ii) $N_{L/k} \in k$ for all $\alpha \in L$.

(iii) $N_{L/k} : L^\times \rightarrow k^\times$ is a homomorphism of groups.

proof. (ii) Let $\alpha \in L$. Assume first that L/k is Galois. Then $\text{Hom}_k(L, \bar{k}) = \text{Aut}_k(L) = \text{Gal}(L/k)$.

For $\tau \in \text{Gal}(L/k)$ we have

$$\tau(N_{L/k}) = \tau\left(\prod_{i=1}^n \sigma_i(\alpha)\right) = \prod_{i=1}^n \underbrace{(\tau\sigma_i)}_{\in \text{Gal}(L/k)}(\alpha) = N_{L/k},$$

hence $N_{L/k} \in L^{\text{Gal}(L/k)} = k$. Now consider the general case. Let $\tilde{L} \supseteq L$ be the normal hull of L over k . Recall that \tilde{L} is the composition of the $\sigma_i(L)$, i.e. we have

$$\tilde{L} = \prod_{i=1}^n \sigma_i(L).$$

Then \tilde{L}/k is Galois and for $\tau \in \text{Gal}(\tilde{L}/k)$ we have

$$\tau(N_{L/k}(\alpha)) = \prod_{i=1}^n \underbrace{(\tau\sigma_i)}_{\in \text{Hom}_k(L, \bar{k})}(\alpha) = \prod_{i=1}^n \sigma_i(\alpha) = N_{L/k}(\alpha),$$

hence $N_{L/k}(\alpha) \in \tilde{L}^{\text{Gal}(\tilde{L}/k)} = k$.

(iii) We have $N_{L/k}(\alpha) = 0 \iff \sigma_i(\alpha) = 0$ for some $1 \leq i \leq n \iff \alpha = 0$.

Moreover

$$\begin{aligned} N_{L/k}(\alpha \cdot \beta) &= \prod_{i=1}^n \sigma_i(\alpha\beta) = \prod_{i=1}^n \sigma_1(\alpha)\sigma_i(\beta) = \left(\prod_{i=1}^n \sigma_i(\alpha) \right) \cdot \left(\prod_{i=1}^n \sigma_i(\beta) \right) \\ &= N_{L/k}(\alpha) \cdot N_{L/k}(\beta), \end{aligned}$$

which proves the claim. □

Example 5.2 (i) Let $\alpha \in k$. Then

$$N_{L/k}(\alpha) = \prod_{i=1}^n \sigma_i(\alpha) = \prod_{i=1}^n \alpha = \alpha^n.$$

(ii) Let $k = \mathbb{R}$, $L = \mathbb{C}$. Then $\text{Hom}_{\mathbb{R}}(\mathbb{C}, \bar{\mathbb{R}}) = \text{Gal}(\mathbb{C}/\mathbb{R}) = \{\text{id}, z \mapsto \bar{z}\}$ and thus the norm is $N_{L/k}(z) = z\bar{z} = |z|^2$.

(iii) Let $k = \mathbb{Q}$, $L = \mathbb{Q}[\sqrt{d}]$ for $d \in \mathbb{Z}$ squarefree. We have $[\mathbb{Q}[\sqrt{d}] : \mathbb{Q}] = 2$ and

$$\text{Gal}(\mathbb{Q}[\sqrt{d}]/\mathbb{Q}) = \{\text{id}, \sqrt{d} \mapsto -\sqrt{d}\} = \{a + b\sqrt{d} \mapsto a + b\sqrt{d}, a + b\sqrt{d} \mapsto a - b\sqrt{d}\}.$$

Then we have

$$N_{\mathbb{Q}[\sqrt{d}]/\mathbb{Q}}(a + b\sqrt{d}) = (a + b\sqrt{d})(a - b\sqrt{d}) = a^2 - db^2$$

- $d < 0$: $d = -\tilde{d}$, hence $a^2 + \tilde{d}b^2 \stackrel{!}{=} 1 \Rightarrow$ either $a = \pm 1, b = 0$ or $a = 0, b = \pm 1, \tilde{d} = 1$.
- $d > 0$: Infinitely many solutions for $a^2 - bd^2 = 1$.

Proposition 5.3 (*Hilbert's theorem 90 - multiplicative version*) Let L/k a finite Galois extension with cyclic Galois group $\text{Gal}(L/k) = \langle \sigma \rangle$, $n = [L : k]$. Let $\beta \in L$ with $N_{L/k}(\beta) = 1$.

Then there exists $\alpha \in L^\times$ such that $\beta = \frac{\alpha}{\sigma(\alpha)}$.

proof. Define

$$f = \text{id}_L + \beta\sigma + \beta\sigma(\beta)\sigma^2 + \dots + \beta\sigma(\beta)\sigma^2(\beta) \cdots \sigma^{n-2}(\beta)\sigma^{n-1} = \sum_{j=0}^{n-1} \sigma^j \prod_{i=1}^j \sigma^{i-1}(\beta).$$

Then by Theorem 4.10 $f \neq 0$. Choose $\gamma \in L$ such that $\alpha := f(\gamma) \neq 0$. Then we have

$$\begin{aligned} \beta \cdot \sigma(\alpha) &= \beta \cdot \sigma(f(\gamma)) = \beta \cdot \left(\sigma \left(\gamma + \beta\sigma(\gamma) + \dots + \prod_{i=0}^{n-2} \sigma^i(\beta)\sigma^{n-1}(\gamma) \right) \right) \\ &= \beta \cdot \left(\sigma(\gamma) + \sigma(\beta)\sigma^2(\gamma) + \dots + \prod_{i=0}^{n-2} \sigma^{i+1}(\beta)\sigma^n(\gamma) \right) \\ &= \beta \cdot \left(\sigma(\gamma) + \sigma(\beta)\sigma^2(\gamma) + \dots + \frac{1}{\beta} N_{L/k}(\beta) \cdot \gamma \right) \\ &= \beta \cdot (\sigma(\gamma) + \sigma(\beta)\sigma^2(\gamma) + \dots + \gamma) \\ &= \gamma + \beta\sigma(\gamma) + \beta\sigma(\beta)\sigma^2(\gamma) + \dots + \beta \cdot \prod_{i=1}^{n-2} \sigma^i(\beta)\sigma^{n-1}(\gamma) \\ &= f(\gamma) = \alpha, \end{aligned}$$

which is the claim. □

Definition + remark 5.4 Let L/k be a finite separable field extension, $[L : k] = n$. Let $\text{Hom}_k(L, \bar{k}) = \{\sigma_1, \dots, \sigma_n\}$.

(i) For $\alpha \in L$,

$$\text{tr}_{L/k}(\alpha) := \sum_{i=0}^n \sigma_i(\alpha)$$

is called the *trace* of α over k .

(ii) $\text{tr}_{L/k}(\alpha) \in k$ for all $\alpha \in L$.

(iii) $\text{tr}_{L/k} : L \longrightarrow k$ is k -linear.

proof. (ii) As in proof 5.1, $\text{tr}_{L/k}(\alpha)$ is invariant under $\text{Gal}(\tilde{L}/k)$.

(iii) Clear. □

Example 5.5 (i) Let $\alpha \in k$. Then

$$\text{tr}_{L/k}(\alpha) = \sum_{i=0}^n \sigma_i(\alpha) = \sum_{i=0}^n \alpha = n \cdot \alpha.$$

(ii) Let $k = \mathbb{R}$, $L = \mathbb{C}$. Then $\text{tr}_{\mathbb{C}/\mathbb{R}}(z) = z + \bar{z} = 2 \cdot \Re(z)$.

Proposition 5.6 (*Hilbert's theorem 90 - additive version*) Let L/k be a Galois extension with cyclic Galois group $\text{Gal}(L/k) = \langle \sigma \rangle$ and $[L : k] = \text{char}(k) = p \in \mathbb{P}$. Then for every $\beta \in L$ with $\text{tr}_{L/k}(\beta) = 0$ there exists $\alpha \in L$ such that $\beta = \alpha - \sigma(\alpha)$.

proof. Define

$$g = \beta \cdot \sigma + (\beta + \sigma(\beta)) \cdot \sigma^2 + \dots + \left(\sum_{i=0}^{p-2} \sigma^i(\beta) \right) \cdot \sigma^{p-1} = \sum_{i=0}^{p-2} \left(\sum_{j=0}^i \sigma^j(\beta) \right) \cdot \sigma^{i+1}.$$

Let now $\gamma \in L$ such that $\text{tr}_{L/k}(\gamma) \neq 0$ (existing by 4.11). Then for

$$\alpha := \frac{1}{\text{tr}_{L/k}(\gamma)} \cdot g(\gamma)$$

we have

$$\begin{aligned} \alpha - \sigma(\alpha) &= \frac{1}{\text{tr}_{L/k}(\gamma)} \cdot (g(\gamma) - \sigma(g(\gamma))) \\ &= \frac{1}{\text{tr}_{L/k}(\gamma)} \left(\left(\sum_{i=0}^{p-2} \left(\sum_{j=0}^i \sigma^j(\beta) \right) \sigma^{i+1}(\gamma) \right) - \left(\sum_{i=0}^{p-2} \left(\sum_{j=0}^i \sigma^{j+1}(\beta) \right) \sigma^{i+2}(\gamma) \right) \right) \\ &= \frac{1}{\text{tr}_{L/k}(\gamma)} \left(\left(\sum_{i=0}^{p-2} \left(\sum_{j=0}^i \sigma^j(\beta) \right) \sigma^{i+1}(\gamma) \right) - \left(\sum_{i=1}^{p-1} \left(\sum_{j=1}^i \sigma^j(\beta) \right) \sigma^{i+1}(\gamma) \right) \right) \\ &= \frac{1}{\text{tr}_{L/k}(\gamma)} \cdot \left(\sum_{i=0}^{p-1} \beta \cdot \sigma^i(\gamma) \right) = \beta, \end{aligned}$$

and we obtain the claim. □

Proposition 5.7 *Let L/k be a finite separable extension, $\alpha \in L$. Consider the k -linear map*

$$\phi_\alpha : L \longrightarrow L, \quad x \mapsto \alpha \cdot x.$$

Then

$$(i) \quad N_{L/k}(\alpha) = \det(\phi_\alpha).$$

$$(ii) \quad \text{tr}_{L/k}(\alpha) = \text{tr}(\phi_\alpha).$$

proof. Let

$$f = \sum_{i=0}^d a_i X^i$$

be the minimal polynomial of α over k . Then it holds

$$(f \circ \phi_\alpha)(x) = f(\phi_\alpha(x)) = \sum_{i=0}^d a_i \phi_\alpha^i(x) = \sum_{i=0}^d a_i \alpha^i \cdot x = x \cdot \sum_{i=0}^d a_i \alpha^i = x \cdot f(\alpha) = 0$$

For arbitrary $x \in L$, hence $f(\phi_\alpha) = 0$.

case 1.1 Assume first $L = k[\alpha]$ for some $\alpha \in k$. Then $[L : k] = \deg(f) = d$, so $\{1, \alpha, \dots, \alpha^{d-1}\}$ is a k -basis of L . Then we have a transformation matrix of ϕ_α with respect to the basis $\{1, \alpha, \dots, \alpha^{d-1}\}$

$$D = \begin{pmatrix} 0 & 0 & 0 & 0 & a_0 \\ 1 & 0 & & \vdots & -a_1 \\ 0 & 1 & & \vdots & \vdots \\ \vdots & \vdots & \ddots & 0 & \vdots \\ 0 & \dots & 0 & 1 & -a_{d-1} \end{pmatrix}$$

thus we have $\text{tr}(\phi_\alpha) = -a_{d-1}$ and $\det(\phi_\alpha) = (-1)^d \cdot a_0$. We know that f splits over \bar{k} , say

$$f = \prod_{i=1}^d (X - \lambda_i) = \prod_{i=1}^d (X - \sigma_i(\alpha))$$

Then we easily see

$$\det(\phi_\alpha) = (-1)^d \cdot a_0 = (-1)^d \cdot f(0) = (-1)^d \cdot \prod_{i=1}^d (0 - \sigma_i(\alpha)) = \prod_{i=1}^d \sigma_i(\alpha) = N_{L/k}(\alpha),$$

$$\text{tr}(\phi_\alpha) = -a_{d-1} = \text{tr}_{L/k}(\alpha).$$

case 1.2 For the case $\alpha \in k$, ϕ_α is represented by the diagonal matrix $\begin{pmatrix} \alpha & & 0 \\ & \ddots & \\ 0 & & \alpha \end{pmatrix} \in k^{d \times d}$.

We obtain

$$\text{tr}(\phi_\alpha) = d \cdot \alpha = \text{tr}_{L/k}(\alpha) \quad \det(\phi_\alpha) = \alpha^d = \text{tr}_{L/k}(\alpha).$$

case 2 For the general case we have $k \subseteq k(\alpha) \subseteq L$.

Claim (a) The following is true:

$$N_{L/k}(\alpha) = N_{k(\alpha)/k}(N_{L/k(\alpha)}(\alpha)), \quad \text{tr}_{L/k}(\alpha) = \text{tr}_{k(\alpha)/k}(\text{tr}_{L/k(\alpha)}(\alpha))$$

Claim (b) The following identity holds:

$$\det(\phi_\alpha) = (\det(\phi_\alpha|_{k(\alpha)}))^{[L:k(\alpha)]} \quad \text{tr}(\phi_\alpha) = [L:k(\alpha)] \cdot \text{tr}(\phi_\alpha|_{k(\alpha)}).$$

Assuming Claim (a) and (b), we get

$$\begin{aligned} \det(\phi_\alpha) &= (\det(\phi_\alpha|_{k(\alpha)}))^{[L:k(\alpha)]} \stackrel{1.1}{=} (N_{k(\alpha)/k})^{[L:k(\alpha)]} = N_{k(\alpha)/k}(\alpha^{[L:k(\alpha)]}) \\ &\stackrel{1.2}{=} N_{k(\alpha)/k}(N_{L/k(\alpha)}(\alpha)) \\ &\stackrel{(a)}{=} N_{L/k}(\alpha) \end{aligned}$$

And analogously $\text{tr}(\phi_\alpha) = \text{tr}_{L/k}(\alpha)$.

Let's now proof the claims.

- (b) Let x_1, \dots, x_d be a basis of $k(\alpha)/k$ as a k -vector space and y_1, \dots, y_m a basis of L as a $k(\alpha)$ -vector space. Then the $x_i y_j$ for $1 \leq i \leq d$, $1 \leq j \leq m$ form a k -basis for L . Let now $D \in k^{d \times d}$ be the matrix representing $\phi_\alpha|_{k(\alpha)}$. Then we have

$$\alpha x_i y_j = \underbrace{(\alpha x_i)}_{\in k(\alpha)} y_j = (D \cdot x_i) y_j,$$

hence ϕ_α is represented by

$$\tilde{D} = \begin{pmatrix} A & 0 & \dots & 0 \\ 0 & A & & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & A \end{pmatrix}$$

- (a) This is an exercise. □

Definition + remark 5.8 Let L/k be a finite field extension, $r = [L : k]_s = |\text{Hom}_k(L, \bar{k})|$. Let $q = \frac{[L:k]}{[L:k]_s}$.

- (i) For $\alpha \in L$ define

$$N_{L/k}(\alpha) = \det(\phi_\alpha) \quad \text{tr}_{L/k}(\alpha) = \text{tr}(\phi_\alpha).$$

- (ii) Let $\text{Hom}_k(L, \bar{k}) = \{\sigma_1, \dots, \sigma_r\}$. Then

$$N_{L/k}(\alpha) = \left(\prod_{i=1}^r \sigma_i(\alpha) \right)^q, \quad \text{tr}_{L/k}(\alpha) = \left(\sum_{i=1}^r \sigma_i(\alpha) \right) \cdot q.$$

proof. Copy the proof of 5.5. Recall that the minimal polynomial of α over k is given by

$$m_\alpha = \prod_{i=1}^r (X - \sigma_i(\alpha))^q,$$

where q is defined as above. □

§ 6 Normal series of groups

Definition 6.1 Let G be a group.

- (i) A series

$$G = G_0 \triangleright G_1 \triangleright \dots \triangleright G_n$$

of subgroups is called a *normal series* for G , if $G_i \triangleleft G_{i-1}$ is a normal subgroup in G_{i-1} and $G_i \neq G_{i-1}$ for $1 \leq i \leq n$. The groups $H_i := G_{i-1}/G_i$ are called *factors* of the series.

- (ii) A normal series as above is called a *composition series* for G , if all its factors are simple groups and $G_n = \{e\}$.

Example 6.2 (i) For $G = S_4$ we have a composition series

$$G = S_4 \triangleright A_4 \triangleright V_4 \triangleright T_4 \triangleright \{e\}$$

where $T_4 = \{\text{id}, \sigma\} \cong \mathbb{Z}/2\mathbb{Z}$ for some transposition $\sigma \in S_4$. We have quotients

$$S_4/A_4 = \mathbb{Z}/2\mathbb{Z}, \quad A_4/V_4 = \mathbb{Z}/3\mathbb{Z}, \quad V_4/T_4 = \mathbb{Z}/2\mathbb{Z}, \quad T_4/\{e\} = \mathbb{Z}/2\mathbb{Z}$$

- (ii) \mathbb{Z} has no composition series.
 (iii) Every normal series is a composition series.
 (iv) Every finite group has a composition series.

Remark 6.3 If $G = G_0 \triangleright G_1 \triangleright \dots \triangleright G_n = \{e\}$ is a normal composition series for a finite group G , then the following is clear:

$$|G| = \prod_{i=1}^n |G_{i-1}/G_i|$$

Definition + remark 6.4 Let G be a group.

- (i) For subgroups $H_1, H_2 \leq G$ let $[H_1, H_2]$ denote the subgroup of G generated by all *commutators*

$$[h_1, h_2] = h_1 h_2 h_1^{-1} h_2^{-1} \quad \text{with } h_i \in H_i \text{ for } i \in \{1, 2\}.$$

- (ii) $[G, G] = G'$ is called the *derived* or *commutator subgroup* of G .
 (iii) $G' \triangleleft G$ and $G^{\text{ab}} := G/G'$ is abelian.
 (iv) Let A be an abelian group and $\phi : G \rightarrow A$ a homomorphism of groups. Let $\pi : G \rightarrow G^{\text{ab}}$ denote the residue map. Then $G' \subseteq \ker(\phi)$, thus ϕ factors to a unique homomorphism

$$\bar{\phi} : G^{\text{ab}} \rightarrow A, \quad \text{such that } \phi = \bar{\phi} \circ \pi.$$

- (v) The chain

$$G \triangleright G' \triangleright G'' = [G', G'] \triangleright \dots \triangleright G^{(n+1)} = [G^n, G^n]$$

is called the *derived series* of G .

- (vi) G is solvable if and only if its derived series stops at $\{e\}$.

proof. (iii) For $g \in G$, $a, b \in G$ we have

$$g[ab]g^{-1} = gaba^{-1}b^{-1}g^{-1} = ga \underbrace{g^{-1}g}_{=e} b \underbrace{g^{-1}g}_{=e} a^{-1} \underbrace{g^{-1}g}_{=e} b^{-1}g^{-1} = [gag^{-1}, bgb^{-1}] \in G'.$$

Moreover

$$e = [\bar{a}, \bar{b}] = \overline{[a, b]} = \overline{aba^{-1}b^{-1}} \iff \bar{ab} = \bar{a}\bar{b} = \bar{b}\bar{a} = \overline{ba}.$$

(iv) Let A be an abelian group, $\phi : G \rightarrow A$ a homomorphism. For $x, y \in G$ we have

$$\phi([x, y]) = \phi(xy x^{-1} y^{-1}) = \phi(x) \phi(y) \phi(x)^{-1} \phi(y)^{-1} = e \implies G' \subseteq \ker(\phi).$$

(vi) ' \Leftarrow ' If the derived series of G stops at $\{e\}$, G has a normal series with abelian factors and is solvable.

' \Rightarrow ' Let now $G = G_0 \triangleright \dots \triangleright G_n = \{e\}$ be a normal series with abelian factors. We have to show that $G^{(n)} = \{e\}$.

Claim (a) We have $G^{(i)} \subseteq G_i$ for $0 \leq i \leq n$.

Then we see $G^{(n)} \subseteq G_n = \{e\}$ and hence the derived series of G stops at $\{e\}$. It remains to prove the claim.

(a) We have $\pi_i : G_i \rightarrow G_i/G_{i+1}$ is a homomorphism from G to an abelian group.

Then by part (iv), we have $G_i^{(1)} = G'_i \subseteq \ker(\pi_i) = G_{i+1}$.

By induction on n we have $G^{(i)} = (G^{(i-1)})' \subseteq G_i$, hence $(G^{(i)})' \subseteq G_i$?

Thus we get

$$G^{(i+1)} = (G^{(i)})' \subseteq G'_i \subseteq \ker(\pi_i) = G_{i+1},$$

which finishes the proof. \square

Proposition 6.5 *A finite group G is solvable if and only if the factors of its composition series are cyclic of prime order.*

proof. ' \Rightarrow ' Let

$$G = G_1 \triangleright G_2 \triangleright \dots \triangleright G_m = \{1\}$$

be a normal series of G with abelian quotients G_{i-1}/G_i for $1 \leq i \leq m$. Refine it to a composition series

$$G = G_0 = H_{0,0} \triangleright H_{0,1} \triangleright \dots \triangleright H_{0,d_0} = G_1 = H_{1,0} \triangleright \dots \triangleright H_{-1,d_1} = G_2 \triangleright \dots \triangleright G_m = \{1\}.$$

Then we have

$$H_{i,j}/H_{i,j+1} \cong H_{i,j}/G_{i+1} / H_{i,j+1}/G_{i+1} \subseteq G_i/G_{i+1} / H_{i,j+1}/G_{i+1}$$

hence $H_{i,j}/H_{i,j+1}$ is isomorphic to a subgroup of a factor group of an abelian group, thus abelian.

' \Leftarrow ' Since the factor groups of the composition series are isomorphic to $\mathbb{Z}/p\mathbb{Z}$ for some primes p , the quotients are abelian, thus G is solvable. \square

Theorem 6.6 (*Jordan - Hölder*) *Let G be a group and*

$$G = G_0 \triangleright G_1 \triangleright \dots \triangleright G_n = \{e\}$$

$$G = H_0 \triangleright H_1 \triangleright \dots \triangleright H_m = \{e\}$$

be two composition series of G . Then $n = m$ and there is $\sigma \in S_n$ such that

$$H_i / H_{i+1} \cong G_{\sigma(i)} / G_{\sigma(i)+1} \quad \text{for } 0 \leq i \leq n-1$$

proof. We prove the statement by induction on n .

n=1 G is simple and thus $H_1 = \{e\}$.

n>1 Let $\bar{G} := G/G_1$ and $\pi : G \rightarrow \bar{G}$ be the residue map.

Then $\bar{H}_i = \pi(H_i) \trianglelefteq \bar{G}$ is a normal subgroup. Since \bar{G} is simple, hence we have $\bar{H}_i \in \{\{e\}, \bar{G}\}$. If $\bar{H}_1 = \bar{G}$, then \bar{H}_2 is a normal subgroup of $\bar{H}_1 = \bar{H}$, and so on. Hence we find $j \in \{1, \dots, m\}$ such that

$$\bar{H}_i = \bar{G} \text{ for } 0 \leq i \leq j \text{ and } \bar{H}_i = \{e\} \text{ for } j+1 \leq i \leq m.$$

Define $C_i := H_i \cap G_1 < G_1$ for $0 \leq i \leq m$.

Claim (a) If $j \leq m-2$, then we have a composition series for G_1 :

$$G_1 = C_0 \triangleright C_1 \triangleright \dots \triangleright C_j \triangleright C_{j+2} \triangleright \dots \triangleright C_m = \{e\}.$$

If $j = m-1$, we have a composition series for G_1 :

$$G_1 = C_0 \triangleright C_1 \triangleright \dots \triangleright C_{m-1} = \{e\}.$$

Clearly $G_1 \triangleright G_2 \triangleright \dots \triangleright G_n = \{e\}$ is a composition series, too. By induction hypothesis we have $n-1 = m-1$, hence $n = m$. Moreover we have for $i \neq j$

$$\left. \begin{aligned} C_i / C_{i+1} &\cong G_{\sigma(i)} / G_{\sigma(i)+1} \\ C_j / C_{j+2} &\cong G_{\sigma(j)} / G_{\sigma(j)+1} \end{aligned} \right\} (*)$$

For some $\sigma : \{0, 1, \dots, j, j+2, j+3, \dots, n-1\} \rightarrow \{1, \dots, n-1\}$

Claim (b) We have

- (1) $C_{j+1} = C_j$
- (2) $C_i / C_{i+1} \cong H_i / H_{i+1}$ for $i \neq j$.
- (3) $H_j / H_{j+1} \cong \bar{G} = G/G_1$.

By (*) and Claim (a),(b) the theorem is proved.

It remains to show the Claims.

(a) C_{i+1} is a normal subgroup of C_i , $C_{i+1} = H_{i+1} \cap G_1$. Further C_{j+1} is normal in $C_j = C_{j+1}$

by Claim (b)(2) and $C_i/C_{i+1} \cong H_i/H_{i+1}$ for $i \neq j$ is simple by Claim (b)(2). Then $C_j/C_{j+2} = C_j/C_{j+1} = H_j/H_{j+1}$ is simple, too.

(b) (1) We have $H_{j+1} \subseteq G_1$, hence $H_{j+1} \cap G_1 = H_{j+1} = C_{j+1}$. $C_j = H_j \cap G_1$ is normal subgroup of H_j . Thus $H_j \triangleright C_j \triangleright C_{j+1} = H_{j+1}$. Since H_i/H_{i+1} is simple, we must have $C_j = C_{j+1}$.

(2) $\mathbf{i} > \mathbf{j}$ Then $C_i = H_i \cap G_1 = H_i$ since $H_i \subseteq G_1$.

$\mathbf{i} < \mathbf{j}$ We have $\overline{H}_i = \overline{G} = G/G_1$. Then we have $G_1H_i = G$ (*), since:

' \subseteq ' Clear.

' \supseteq ' For $g \in G, \overline{g} \in \overline{G}$ its image there exists $h \in H_i$ such that

$$\overline{h} = \overline{g} \implies \overline{h}^{-1}\overline{g} \in G_1 \iff \overline{h}^{-1}\overline{g} = g_1 \in G_1 \implies g = hg_1 \in H_iG_1.$$

With the isomorphism theorem we obtain

$$C_i/C_{i+1} = C_i/H_{i+1} \cap G_i = C_i/H_{i+1} \cap C_i \cong C_iH_{i+1}/H_{i+1}.$$

Therefore it remains to show that $C_iH_{i+1} = H_i$.

' \subseteq ' Since $C_i, H_{i+1} \subseteq H_i$ we also have $C_iH_{i+1} \subseteq H_i$

' \supseteq ' Let $x \in H_i$. by (*) we have $H_{i+1}G_i = G$. Then there exists $g \in G_1, h \in H_{i+1}$ such that $x = gh$, thus we have $g = xh^{-1} \in H_iH_{i+1} = H_i$, i.e. $g \in G_i \cap H_i = C_1$ and thus $x \in C_iH_{i+1}$.

(3) We have

$$H_i/H_{i+1} = H_i/C_{j+1} = H_j/C_j = H_j/H_j \cap G_1 = G_1H_j/G_1 \stackrel{(*)}{=} G/G_1,$$

which finishes the proof, paragraph and chapter. □

Kapitel II

Valuation theory

§ 7 Discrete valuations

Example 7.1 Let $P \in \mathbb{N}$ prime. For $x \in \mathbb{Z} \setminus \{0\}$ let

$$\nu_p(x) = \max\{k \in \mathbb{N} \mid p^k \mid x\}.$$

Then $p^{\nu_p(x)} \mid x$, $p^{\nu_p(x)+1} \nmid x$. Example: $\nu_2(12) = 2$. Write $x = p^{\nu_p(x)} \cdot x'$ where $p \nmid x'$. For $\frac{x}{y} \in \mathbb{Q}^\times$ define

$$\nu_p\left(\frac{x}{y}\right) = \nu_p(x) - \nu_p(y).$$

This defines a map $\nu_p : \mathbb{Q} \rightarrow \mathbb{Z}$, such that

- (i) $\nu_p(ab) = \nu_p(a) + \nu_p(b)$ (clear)
- (ii) $\nu_p(a+b) \geq \min\{\nu_p(a), \nu_p(b)\}$, since: Write $a = p^{\nu_p(a)} \cdot a'$, $b = p^{\nu_p(b)} \cdot b'$. Let w.l.o.g $\nu_p(b) \leq \nu_p(a)$. Then we have

$$a+b = p^{\nu_p(a)} \cdot a' + p^{\nu_p(b)} \cdot b' = p^{\nu_p(b)} \cdot (b' + a' \cdot p^{\nu_p(a)-\nu_p(b)}).$$

Hence $p^{\nu_p(b)} \mid a+b$ and thus $\nu_p(a+b) \geq \nu_p(b) = \min\{\nu_p(a), \nu_p(b)\}$.

Definition 7.2 Let k be a field. A *discrete valuation* on k is a surjective group homomorphism $\nu_k^\times \rightarrow (\mathbb{Z}, +)$ satisfying

$$\nu(x+y) \geq \min\{\nu(x), \nu(y)\} \quad \text{for all } x, y \in k^\times, x \neq -y.$$

Remark 7.3 Let R be a factorial domain, $k = \text{Quot}(R)$. Let further be $p \in R \setminus \{0\}$ be a prime element. Then $\nu_p : k^\times \rightarrow \mathbb{Z}$ can be defined as in Example 7.1: Write

$$x = e \cdot \prod_{p \in \mathbb{P}} p^{\nu_p(x)}, \quad e \in R^\times$$

where \mathbb{P} denotes set of representatives of prime elements of R . Then ν_p is a discrete valuation on k .

Example 7.4 Let k be a field, $a \in k$, $R = k[X]$ and $p_a = X - a \in k[X]$. For $f \in k[X]$ define $\nu_{p_a}(f) = n$ if f has an n -fold root in a , i.e. $f = (X - a)^n \cdot g$ for some $0 \neq g \in k[X]$. Then ν_{p_a} is a discrete valuation on $k(X) = \text{Quot}(k[X])$ satisfying $\nu_p|_k = 0$.

Remark 7.5 *There is no discrete valuation on \mathbb{C} .*

proof. Assume there exists a discrete valuation on \mathbb{C} , say $\nu : \mathbb{C}^\times \rightarrow \mathbb{Z}$. Since ν is surjective, there exists $z \in \mathbb{C}^\times$ such that $\nu(z) = 1$.

Let now $y \in \mathbb{C}^\times$ such that $y^2 = z$. Then we have

$$1 = \nu(z) = \nu(y^2) = \nu(y \cdot y) = \nu(y) + \nu(y) = 2\nu(y) \iff \nu(y) = \frac{1}{2} \notin \mathbb{Z}$$

which is a contradiction. □

Example 7.6 Let $\nu : \mathbb{Q}^\times \rightarrow \mathbb{Z}$ be a nontrivial discrete valuation. Then there exists $a \in \mathbb{Z}$ such that $\nu(a) \neq 0$ and hence we find $p \in \mathbb{P}$: $\nu(p) \neq 0$.

If $\nu(q) = 0$ for all $q \in \mathbb{P}$, then $\nu = \nu_p$.

Assume we have $\nu(p) \neq 0 \neq \nu(q)$ for some $p \neq q \in \mathbb{P}$ and write $1 = ap + bq$ for suitable $a, b \in \mathbb{Z}$.

Then

$$0 = \nu(1) = \nu(ap + bq) \geq \min\{\nu(ap), \nu(bq)\} = \min\{\underbrace{\nu(a)}_{\geq 0 (*)} + \nu(p), \underbrace{\nu(b)}_{\geq 0 (*)} + \nu(q)\} \geq \min\{\nu(p), \nu(q)\} > 0$$

Hence a contradiction, i.e. we have $\nu(p) \neq 0$ for at most one $p \in \mathbb{P}$, thus $\nu = \nu_p$.

(*) obtain that we have $\nu(1) = \nu(1 \cdot 1) = \nu(1) + \nu(1) \Rightarrow \nu(1) = 0$ and by induction

$$\nu(a) = \nu(1 + (a - 1)) \geq \min\{\nu(1), \nu(a - 1)\} \geq 0$$

Proposition 7.7 *Let k be a field and $\nu : k^\times \rightarrow \mathbb{Z}$ be a discrete valuation on k .*

(i) $\nu(1) = \nu(-1) = 0$.

(ii) $\mathcal{O}_\nu := \{x \in k^\times \mid \nu(x) \geq 0\} \cup \{0\}$ is a ring, called the valuation ring of ν .

(iii) $\mathfrak{m}_\nu := \{x \in k^\times \mid \nu(x) > 0\} \cup \{0\} \triangleleft \mathcal{O}_\nu$ is an ideal in \mathcal{O}_ν , called the valuation ideal of ν .

More precisely, \mathfrak{m}_ν is the only maximal ideal in \mathcal{O}_ν , i.e. \mathcal{O}_ν is a local ring.

(iv) \mathfrak{m}_ν is a principal ideal.

(v) \mathcal{O}_ν is a principal ideal domain. *More precisely, any ideal $I \neq \{0\}$ in \mathcal{O}_ν is of the form $I = (t^d)$ for some $d \in \mathbb{N}$ and $t \in \mathfrak{m}_\nu$ with $\nu(t) = 1$.*

(vi) We have $k = \text{Quot}(\mathcal{O}_\nu)$ and for $x \in k^\times$: $x \in \mathcal{O}_\nu$ or $\frac{1}{x} \in \mathcal{O}_\nu$.

proof. (ii) This is strict calculating, which may be verified by the reader.

(iii) \mathfrak{m}_ν is an ideal, since for $x, y \in \mathfrak{m}_\nu, \alpha \in \mathcal{O}_\nu$ we have

$$\nu(x + y) \geq \min\{\nu(x), \nu(y)\} > 0, \quad \nu(\alpha x) = \underbrace{\nu(\alpha)}_{\geq 0} + \nu(x) \geq \nu(x) > 0.$$

Let now $x \in \mathcal{O}_\nu$ with $\nu(x) = 0$. Then

$$\nu\left(\frac{1}{x}\right) = \nu(1) - \nu(x) = -\nu(x) = 0,$$

hence $x \in \mathcal{O}_\nu^\times$. Thus we have $\mathfrak{m}_\nu = \mathcal{O}_\nu \setminus \mathcal{O}_\nu^\times$ and the claim follows.

(iv) Let $t \in \mathfrak{m}_\nu$ such that $\nu(t) = 1$. Then for $x \in \mathfrak{m}_\nu$ let $\nu(x) = d > 0$. Then we have

$$\nu\left(x \cdot t^{-d}\right) = \nu(x) + \nu\left(\frac{1}{t^d}\right) = d + 0 - d = 0$$

Define $e := x \cdot t^{-d} \in \mathcal{O}_\nu^\times$. Then $x = e \cdot t^d$, hence $\mathfrak{m}_\nu = (t)$.

(v) Let $\{0\} \neq I \neq \mathcal{O}_\nu$ be an ideal in \mathcal{O}_ν . Let $d := \min\{\nu(x) \mid x \in I \setminus \{0\}\} > 0$.

' \supseteq ' Let $x \in I$ such that $\nu(x) = d$. By part (iv) we have $x = e \cdot t^d$ for some $e \in \mathcal{O}_\nu^\times$, hence we have $t^d \in I$; thus $(t^d) \subseteq I$.

' \subseteq ' Let now $y \in I \setminus \{0\}$ and write $y = e \cdot t^{\nu(y)}$ for some $e \in \mathcal{O}_\nu^\times$ and $\nu(y) > d$. Then $y = t^d \cdot e \cdot t^{\nu(y)-d}$, hence $y \in (t^d)$ and thus $I \subseteq (t^d)$.

(vi) If $\nu(x) \geq 0$, then $x \in \mathcal{O}_\nu$. If $\nu(x) < 0$, we have

$$\nu\left(\frac{1}{x}\right) = \nu(1) - \nu(x) = -\nu(x) > 0, \quad \text{hence } \frac{1}{x} \in \mathfrak{m}_\nu \subseteq \mathcal{O}_\nu,$$

which we wanted to show. □

Definition 7.8 An integral domain R is called a *discrete valuation ring*, if there exists a discrete valuation ν of $k = \text{Quot}(R)$ such that $R = \mathcal{O}_\nu$.

Proposition 7.9 Let R be a lokal integral domain. Then the following statements are equivalent.

- (i) R is a discrete valuation ring.
- (ii) R is a principal ideal domain.
- (iii) There exists $t \in R \setminus \{0\}$ such that every $x \in R \setminus \{0\}$ can uniquely be written in the form

$$x = e \cdot t^d \quad \text{for some } e \in R^\times, d \geq 0$$

proof. '(i) \Rightarrow (ii)' This follows by 7.7.

'(ii) \Rightarrow (iii)' We know that principal ideal domains are factorial. Let $t \in R$ be a generator of the maximal ideal \mathfrak{m} of R . Then t is prime, since any maximal ideal is also prime. Let now $p \in R \setminus \{0\}$ a prime element. Then $p \notin R^\times$, hence $p \in \mathfrak{m}$, thus we can write $p = t \cdot x$ for some $x \in R$. Since p is prime, hence irreducible, we have $x \in R^\times \Rightarrow (p) = (t)$. Thus we

have $p = t$ and we have only one prime element in R . The unique prime factorization in factorial domains gives us $x = e \cdot t^d$ for some $e \in R^\times$ and $d \geq 0$.

'(iii) \Rightarrow (i)' For $x = e \cdot t^d \in R \setminus \{0\}$, $e \in R^\times$, $d \geq 0$ define $\nu(x) = d$. We claim that ν is discrete valuation. We have

$$\nu(xy) = \nu(et^d \cdot e't^{d'}) = \nu(ee't^{d+d'}) = \nu(e''t^{d+d'}) = d + d'.$$

Let w.l.o.g. $d \leq d'$. Then

$$\nu(x + y) = \nu(et^d + e't^{d'}) = \nu(t^d(e + e't^{d'-d})) \geq d = \min\{d, d'\}$$

which we extend to

$$\nu : k^\times \longrightarrow \mathbb{Z}, \quad \nu\left(\frac{x}{y}\right) = \nu(x) - \nu(y).$$

This is well defined: For $\frac{x}{y} = \frac{x'}{y'}$ we have $xy' = x'y$ and $\nu(xy') = \nu(x) + \nu(y') = \nu(x') + \nu(y)$, thus

$$\nu\left(\frac{x}{y}\right) = \nu(x) - \nu(y) = \nu(x') - \nu(y') = \nu\left(\frac{x'}{y'}\right).$$

Finally we have $\nu(t) = 1$, hence $\nu : k^\times \longrightarrow \mathbb{Z}$ is surjective. Thus ν is a discrete valuation on k and $R = \mathcal{O}_\nu$. \square

Definition + proposition 7.10 Let R be a local ring with maximal ideal \mathfrak{m} .

- (i) $k := R/\mathfrak{m}$ is called the *residue field* of R .
- (ii) $\mathfrak{m}/\mathfrak{m}^2$ has a structure of a k -vector space.
- (iii) If R is a discrete valuation ring, then $\dim_k(\mathfrak{m}/\mathfrak{m}^2) = 1$.

proof. (ii) For $a \in R$, $x \in \mathfrak{m}$ define $\overline{ax} = \overline{a}\overline{x}$, where $\overline{a}, \overline{x}$ are the images of a, x in k .

This is well defined: Let $a' \in R$ with $\overline{a'} = \overline{a}$ and $x' \in \mathfrak{m}$ with $\overline{x'} = \overline{x}$. We have to show that

$$\overline{a'x'} = \overline{ax} \iff a'x' - ax \in \mathfrak{m}^2$$

We have $\overline{a'} = \overline{a}$, hence $a' = a + y$ for some $y \in \mathfrak{m}$. Analogously we have $\overline{x'} = \overline{x}$, hence $x' = x + z$ for some $z \in \mathfrak{m}^2$. Thus we have

$$a'x' = (a + y)(x + z) = ax + az + xy + yz \equiv ax \pmod{\mathfrak{m}^2},$$

which finishes the proof. \square

§ 8 The Gauß Lemma

Let R be a UFD (unique factorization domain), \mathbb{P} a set of representatives of the primes in R with respect to *associateness*, i.e. $x \sim y \Leftrightarrow y = u \cdot x$ for some $u \in R^\times$. Every $x \in R \setminus \{0\}$ has a unique factorization

$$x = u \cdot \prod_{p \in \mathbb{P}} p^{\nu_p(x)}, \quad \nu_p(x) \geq 0 \text{ for } p \in \mathbb{P}, u \in R^\times$$

where $\nu_p : k^\times \rightarrow \mathbb{Z}$ is a discrete valuation on $k = \text{Quot}(R)$.

Definition + proposition 8.1 Let R be a factorial domain, $k = \text{Quot}(R)$ and

$$f = \sum_{i=0}^n a_i X^i \in k[X] \setminus \{0\}, \quad a_n \neq 0.$$

- (i) For $p \in \mathbb{P}$ let $\nu_p(f) = \min\{\nu_p(a_i) \mid 0 \leq i \leq n\}$.
- (ii) f is called *primitive*, if $\nu_p(f) = 0$ for all $p \in \mathbb{P}$.
- (iii) If f is primitive, then $f \in R[X]$.
- (iv) If $f \in R[X]$ is monic, i.e. $a_n = 1$, then f is primitive.
- (v) There exists $c \in k^\times$ such that $c \cdot f$ is primitive.

proof. (iii) If f is primitive, we have $\min_{1 \leq i \leq n} \{\nu_p(a_i)\} = 0$, i.e. $\nu_p(a_i) \geq 0$ for all $1 \leq i \leq n$.

Thus $a_i \in R$ and $f \in R[X]$.

(iv) If $a_i \in R$ we have $\nu_p(a_i) \geq 0$ for all $1 \leq i \leq n$. Moreover $\nu_p(a_n) = \nu_p(1) = 0$, hence $\nu_p(f) = \min_{1 \leq i \leq n} \{\nu_p(a_i)\} = 0$. thus f is primitive.

(v) For $\nu_p(f) := d$ choose $c := p^{-d} \in k^\times$. Then

$$\nu_p(c \cdot f) = \nu_p(c) + \nu_p(f) = \nu_p(p^{-d}) + d = -d + d = 0,$$

thus $c \cdot f$ is primitive. □

Proposition 8.2 (Gauß-Lemma) For $f, g \in k[X]$ and $p \in \mathbb{P}$ we have

$$\nu_p(f \cdot g) = \nu_p(f) + \nu_p(g).$$

proof. Write

$$f = \sum_{i=0}^n a_i X^i, \quad g = \sum_{j=0}^m b_j X^j, \quad f \cdot g = \sum_{k=0}^{m+n} c_k X^k, \quad c_k = \sum_{i=0}^k a_i b_{k-i}$$

case 1 Assume $m = 0$, i.e. $g = b_0 \in k^\times$. Then $c_k = a_k \cdot b_0$, hence

$$\nu_p(c_k) = \nu_p(a_k) + \nu_p(b_0).$$

Then we obtain

$$\nu_p(f \cdot g) = \min_{0 \leq k \leq n} \nu_p(c_k) = \min_{0 \leq k \leq n} \{\nu_p(a_k) + \nu_p(b_0)\} = \nu_p(b_0) + \min_{0 \leq k \leq n} \{\nu_p(a_k)\} = \nu_p(g) + \nu_p(f)$$

case 2 Assume $\nu_p(f) = 0 = \nu_p(g)$, i.e. f, g are primitive. Clearly $\nu_p(fg) \geq 0$. We have to show: $\nu_p(fg) = 0$. Let $i_0 := \max\{i \mid \nu_p(a_i) = 0\}$ and $j_0 := \max\{j \mid \nu_p(b_j) = 0\}$. Then

$$c_{i_0+j_0} = \sum_{i=0}^{i_0+j_0} a_i b_{i_0+j_0-i} = \underbrace{\sum_{i=0}^{i_0-1} a_i b_{i_0+j_0-i}}_{(A)} + a_{i_0+j_0} + \underbrace{\sum_{i=i_0+1}^{i_0+j_0} a_i b_{i_0+j_0-i}}_{(B)}$$

We have $\nu_p(a_{i_0} b_{j_0}) = \nu_p(a_{i_0}) + \nu_p(b_{j_0}) = 0$. We have $i_0 + j_0 - i > j_0$, hence $\nu_p(b_{i_0+j_0-i}) \geq 1$ for $0 \leq i \leq i_0 - 1$. Then

$$\begin{aligned} \nu_p(A) &= \nu_p \left(\sum_{i=0}^{i_0-1} a_i b_{i_0+j_0-i} \right) \geq \min_{0 \leq i \leq i_0-1} \{\nu_p(a_i b_{i_0+j_0-i})\} \\ &= \min_{0 \leq i \leq i_0-1} \{\nu_p(a_i) + \nu_p(b_{i_0+j_0-i})\} \\ &\geq \min_{0 \leq i \leq i_0-1} \{\nu_p(b_{i_0+j_0-i})\} \\ &\geq 1 \\ \nu_p(B) &= \nu_p \left(\sum_{i=i_0+1}^{i_0+j_0} a_i b_{i_0+j_0-i} \right) \geq 1. \end{aligned}$$

Since we have

$$0 = \nu_p(a_{i_0} b_{j_0}) \geq \min\{\nu_p(c_{i_0+j_0}), \nu_p(A), \nu_p(B)\} = \nu_p(c_{i_0+j_0}) = 0$$

we get $\nu_p(c_{i_0+j_0}) = 0$. Hence we obtain

$$\nu_p(fg) = \min\{\nu_p(c_i) \mid 0 \leq i \leq m+n\} = \nu_p(c_{i_0+j_0}) = 0.$$

case 3 Consider now the general case, i.e. f, g are arbitrary. Multiply f and g by suitable constants a and b , such that $\tilde{f} := af$ and $\tilde{g} := bg$ are primitive. Then by the first two cases we have

$$\begin{aligned} \nu_p(fg) &= \nu_p \left(\frac{1}{a} \frac{1}{b} \tilde{f} \tilde{g} \right) \stackrel{1}{=} \nu_p \left(\frac{1}{a} \frac{1}{b} \right) + \nu_p(\tilde{f} \tilde{g}) \stackrel{2}{=} \nu_p \left(\frac{1}{a} \right) + \nu_p \left(\frac{1}{b} \right) + \underbrace{\nu_p(\tilde{f})}_{=0} + \underbrace{\nu_p(\tilde{g})}_{=0} \\ &= \nu_p \left(\frac{1}{a} \right) + \nu_p(\tilde{f}) + \nu_p \left(\frac{1}{b} \right) + \nu_p(\tilde{g}) = \nu_p \left(\frac{1}{a} \tilde{f} \right) + \nu_p \left(\frac{1}{b} \tilde{g} \right) \\ &= \nu_p(f) + \nu_p(g), \end{aligned}$$

which finishes the proof. □

Theorem 8.3 (*Eisenstein's criterion for irreducibility*) Let R be a factorial domain, $p \in \mathbb{P}$ and

$$f = \sum_{i=0}^n a_i X^i \in R[X] \setminus \{0\}$$

Assume that f is primitive and we have

- (i) $\nu_p(a_0) = 1$,
- (ii) $\nu_p(a_i) \geq 1$ or $a_i = 0$ for $1 \leq i \leq n-1$ and
- (iii) $\nu_p(a_n) = 0$

Then f is irreducible over $R[X]$.

proof. Assume that $f = g \cdot h$ with some $g, h \in R[X]$. Write

$$g = \sum_{i=0}^r b_i X^i, \quad h = \sum_{j=0}^s c_j X^j, \quad \text{with } r + s = n$$

Then we have $a_0 = b_0 c_0$. W.l.o.g. $\nu_p(b_0) = 1$ and $\nu_p(c_0) = 0$. Further $a_n = b_r c_s$, thus we must have $\nu_p(b_r) = \nu_p(c_s) = 0$ for $\nu_p(a_n) = 0$. Let now

$$d := \max\{i \mid \nu_p(b_j) \geq 1 \text{ for } 0 \leq j \leq i\}$$

Obviously $0 \leq d \leq r-1$. Consider

$$a_{d+1} = \underbrace{b_{d+1} c_0}_{=:A} + \underbrace{\sum_{i=0}^d b_i c_{d+1-i}}_{=:B}$$

We have

$$\nu_p(A) = \nu_p(b_{d+1}) + \nu_p(c_0) = 0 + 0 = 0,$$

$$\nu_p(B) \geq \min_{0 \leq i \leq d} \{\nu_p(b_i c_{d+1-i})\} \geq 1$$

and thus $\nu_p(a_{d+1}) = 0$. But this implies $d+1 = n \Leftrightarrow n-1 = d \leq r-1 \Rightarrow n \leq r \Rightarrow n = r$. Then we have $s = 0$, thus $h = c_0$ is constant. Further for $q \in \mathbb{P}$ we have

$$0 = \nu_q(f) = \nu_q(g c_0) = \underbrace{\nu_q(g)}_{\geq 0} + \nu_q(c_0)$$

i.e. $\nu_q(c_0) = 0$, hence $c_0 \in R^\times$ and f is irreducible. □

Theorem 8.4 (*Gauß*) Let R be a factorial domain. Then $R[X]$ is factorial.

proof. Let $f \in R[X] \setminus \{0\} \subseteq k[X]$ where $k = \text{Quot}(R)$. Since $k[X]$ is factorial, we can write

$$f = c \cdot f_1 \cdots f_n, \quad f_i \in k[X] \text{ prime}, \quad c \in k^\times$$

W.l.o.g the. f_i are primitive, otherse multiply them by suitable constants. In particular we have $f_i \in R[X]$. Note that $c \in R$: For $p \in \mathbb{P}$, we have

$$0 = \nu_p(f) = \nu_p(c) + \sum_{i=1}^n \nu_p(f_i) = \nu_p(c).$$

Write $c = \epsilon \cdot p_1 \cdots p_r$ with some $\epsilon \in R^\times$ and $p_i \in \mathbb{P}$. Then by

Claim (a) $f_i \in R[X]$ are prime for $1 \leq i \leq n$.

Claim (b) $p_i \in R[X]$ are prime for $1 \leq i \leq r$.

we have found a factorization of f into prime elements and hence $R[X]$ is factorial. Now prove the claims.

(a) Let $g, h \in R[X]$ such that $gh \in (f_i) = f_i R[X]$.

May assume that $g \in f_i k[X]$, i.e. $g = f_i \tilde{g}$ for some $\tilde{g} \in k[X]$. For $p \in \mathbb{P}$ we obtain

$$0 \leq \nu_p(g) = \underbrace{\nu_p(f_i)}_{=0} + \nu_p(\tilde{g}) = \nu_p(\tilde{g}).$$

Thus we get $\tilde{g} \in R[X]$, which implies $g = f_i \tilde{g} \in f_i R[X] = (f_i)$.

(b) Since $\pi : R \longrightarrow R/(p)$ induces a map $\psi : R[X] \longrightarrow R/(p)[X]$ with $\ker(\psi) = pR[X]$ we have

$$R[X]/pR[X] \cong R/pR[X].$$

Since R/pR is an integral domain, (p) is prime. □

Corollary 8.5 *Let k be a field. Then $k[X_1, \dots, X_n]$ is factorial for any $n \in \mathbb{N}$.*

Corollary 8.6 *Let R be a factorial domain, $k = \text{Quot}(R)$. If $f \in R[X]$ is irreducible over $R[X]$, then f is irreducible over $k[X]$.*

proof. Let $0 \neq f = c \cdot f_1 \cdots f_n$ be decomposition of f in $k[X]$, i.e. $c \in k^\times$ and $f_i \in k[X]$ irreducible for $1 \leq i \leq n$. We may assume that the f_i are primitive, hence contained in $R[X]$, since we can multiply them by suitable constants. We still have to show $c \in R$. Since $f \in k[X]$, i.e. $\nu_p(f) \geq 0$ we have

$$\nu_p(f) = \nu_p(c \cdot f_1 \cdots f_n) = \nu_p(c) + \sum_{i=1}^n \underbrace{\nu_p(f_i)}_{=0} = \nu_p(c) \stackrel{!}{\geq} 0$$

Thus $c \in R$. Then the decomposition from above is in R - but since f is irreducible in R , we have $n = 1$ and $c \in R^\times$. □

§ 9 Absolute values

Definition 9.1 Let k be a field. A map

$$|\cdot| : k \longrightarrow \mathbb{R}_{\geq 0}$$

is called an *absolute value*, if

- (i) *positive definiteness*: $|x| = 0 \iff x = 0$
- (ii) *multiplicativeness*: $|xy| = |x| \cdot |y|$ for all $x, y \in k$.
- (iii) *triangle inequality*: $|x + y| \leq |x| + |y|$ for all $x, y \in k$.

Example 9.2 (i) The 'normal' absolute value $|\cdot|_{\infty}$ on \mathbb{C} and on any of its subfields denotes an absolute value.

(ii) Let $\nu_k^{\times} \rightarrow \mathbb{Z}$ be a discrete valuation, $\rho \in (0, 1)$. Then

$$|\cdot|_{\nu} : k \longrightarrow \mathbb{R}, \quad x \mapsto \begin{cases} \rho^{\nu(x)} & x \neq 0 \\ 0 & x = 0 \end{cases}$$

is an absolute value on k , since

- (1) Trivial, since $|0| = 0$ and $\rho^x \neq 0$ for any $x \in \mathbb{Z}$.
- (2) Clearly $|xy|_{\nu} = \rho^{\nu(xy)} = \rho^{\nu(x)+\nu(y)} = \rho^{\nu(x)}\rho^{\nu(y)} = |x|_{\nu}|y|_{\nu}$.
- (3) Further

$$|x+y|_{\nu} = \rho^{\nu(x+y)} \leq \rho^{\min\{\nu(x), \nu(y)\}} = \max\{\rho^{\nu(x)}, \rho^{\nu(y)}\} = \max\{|x|_{\nu}, |y|_{\nu}\} \leq |x|_{\nu} + |y|_{\nu}$$

(iii) For the p -adic valuation ν_p on \mathbb{Q} we choose $\rho := \frac{1}{p}$. Then $|x|_p = p^{-\nu_p(x)}$ is an absolute value.

Remark + definition 9.3 Let k be a field, $|\cdot|$ an absolute value on k .

- (i) $|1| = |-1| = 1$ and $|x| = |-x|$ for all $x \in k$.
- (ii) The absolute value is called *trivial*, if $|x| = 1$ for all $x \in k$.

proof. We have $|1| = |1 \cdot 1| = |1| \cdot |1|$, hence $|1| = 1$. Moreover $|-1| = |1 \cdot (-1)| = |1| \cdot |-1|$, hence $|-1| = 1$. For $x \in k$ we have $|-x| = |(-1) \cdot x| = |-1| \cdot |x| = |x|$. □

Proposition + definition 9.4 Let k be a field with $\text{char}(k) = 0$, i.e. $k \supseteq \mathbb{Q}$ and $|\cdot|$ an absolute value on k .

- (i) $|\cdot|$ is called *archimedean*, if $|n| > 1$ for all $n \in \mathbb{Z} \setminus \{-1, 0, 1\}$.
- (ii) $|\cdot|$ is called *nonarchimedean*, if $|n| \leq 1$ for all $n \in \mathbb{Z}$.
- (iii) $|\cdot|$ is either archimedean or nonarchimedean.
- (iv) The p -adic absolute value on \mathbb{Q} is nonarchimedean.

proof of (iii). Since $|n| = |-n|$, it suffices to check $n \in \mathbb{N}$. Let $a \in \mathbb{N} \subseteq k$ with $|a| > 1$. Assume there exists $b \in \mathbb{N}_{>1}$ with $|b| \leq 1$. Write

$$a = \sum_{i=0}^N \alpha_i b^i \quad \alpha_i \in \{0, \dots, b-1\}, \quad |N| = \lfloor \log_b(a) \rfloor.$$

Then we have

$$|a| \leq \sum_{i=0}^{\lfloor \log_b(a) \rfloor} |\alpha_i| |b|^i \leq \log_b(a) \cdot \max_{0 \leq i \leq \lfloor \log_b(a) \rfloor} \{|\alpha_i|\} =: \log_b(a) \cdot c,$$

$$|a^n| \leq \log_b(a^n) \cdot c = n \cdot \log_b(a) \cdot c$$

and $|a^n|$ grows linearly in n . Likewise we get for $n \in \mathbb{N}$

$$a^n = \sum_{i=0}^{\lfloor \log_b(a^n) \rfloor} \alpha_i^{(n)} b^i, \quad \alpha_i^{(n)} \in \{0, \dots, b-1\},$$

$$|a^n| = |a|^n \leq (\log_b(a) \cdot c)^n$$

which grows exponentially in n , which is a contradiction. Hence the claim follows. \square

Remark 9.5 *An absolute value $|\cdot|$ on a field k induces a metric*

$$d(x, y) := |x - y|, \quad x, y \in k$$

Therefore, k as a topology and aspects as 'convergence' and 'cauchy sequences' are meaningful.

Definition + remark 9.6 (i) Two absolute values $|\cdot|_1, |\cdot|_2$ on k are called *equivalent*, if there exists $s \in \mathbb{R}$, such that $|x|_1 = |x|_2^s$ for all $x \in k$. In this case, we write $|\cdot|_1 \sim |\cdot|_2$.
(ii) Two absolute values $|\cdot|_1, |\cdot|_2$ are equivalent if and only if they induce the same topology on k .

proof. Is left for the reader as an exercise.

Example 9.7 The p -adic absolute values on \mathbb{Q} are not equivalent for $p \neq q \in \mathbb{P}$. Consider

$$|p^n|_p = p^{-n} \xrightarrow{n \rightarrow \infty} 0, \quad |p^n|_q = 1 \quad \text{for all } n \in \mathbb{N}$$

Moreover we have $|\cdot|_p \not\sim |\cdot|_\infty$, since by the transitivity of equivalence of absolute values, we have

$$|\cdot|_p \sim |\cdot|_\infty \sim |\cdot|_q$$

which is not true.

Theorem 9.8 (Ostrowski) Any nontrivial absolute value $|\cdot|$ on \mathbb{Q} is equivalent either to the standard absolute value $|\cdot|_\infty$ on \mathbb{Q} or to a p -adic absolute value $|\cdot|_p$ for some $p \in \mathbb{P}$.

proof. **case 1** Assume $|\cdot|$ is nonarchimedean. We want to show, that in this case $|\cdot| \sim |\cdot|_p$ for some $p \in \mathbb{P}$. Since $|\cdot|$ is non-trivial, there exists $x \in \mathbb{N}$ such that

$$|x| = \left| \prod_{p \in \mathbb{P}} p^{\nu_p(x)} \right| = \prod_{p \in \mathbb{P}} |p|^{\nu_p(x)} \neq 1$$

for at least one $x \in \mathbb{Q}$, hence, we have $|p| \neq 1$ for at least one $p \in \mathbb{P}$, i.e. $|p| < 1$. Assume there is another prime $q \neq p$ with $|q| < 1$. Then we find $N \in \mathbb{N}$, such that

$$|p|^N \leq \frac{1}{2}, \quad |q|^N \leq \frac{1}{2}.$$

Moreover, since p^N, q^N are coprime, we can write

$$1 = a \cdot p^N + b \cdot q^N \quad \text{for suitable } a, b \in \mathbb{Z}.$$

So the contradiction follows by

$$1 = |1| = |ap^N + bq^N| \leq \underbrace{|a|}_{\leq 1} \underbrace{|p^N|}_{< \frac{1}{2}} + \underbrace{|b|}_{\leq 1} \underbrace{|q^N|}_{< \frac{1}{2}} < 1,$$

hence we have $|q| = 1$ for any $q \neq p \in \mathbb{P}$. Let now $s := -\log_p |p|$. For $x \in \mathbb{Q}^\times$ we obtain

$$|x| = \left| \prod_{\tilde{p} \in \mathbb{P}} \tilde{p}^{\nu_{\tilde{p}}(x)} \right| = \prod_{\tilde{p} \in \mathbb{P}} |\tilde{p}|^{\nu_{\tilde{p}}(x)} = |p|^{\nu_p(x)} = p^{-s \cdot \nu_p(x)} = \left(p^{-\nu_p(x)} \right)^s = |x|_p^s$$

thus we have $|\cdot| \sim |\cdot|_p$.

case 2 Let now $|\cdot|$ be archimedean. We now have to show $|\cdot| \sim |\cdot|_\infty$. For $n \in \mathbb{N}_{\geq 2}$ we have

$$1 < |n| = \left| \sum_{i=1}^n 1 \right| \leq \sum_{i=1}^n |1| = n.$$

For any $a \in \mathbb{N}_{\geq 2}$ we find $s := s(a) \in \mathbb{R}_{<0}$ such that

$$|a| = |a|_\infty^s = a^s$$

namely

$$s = \log_a(|a|) = \frac{\log(|a|)}{\log(a)}.$$

Claim (a) We have

$$\frac{\log(|a|)}{\log(a)} = \frac{\log(|2|)}{\log(2)}.$$

Since now s is independent of a , we have $|\cdot| \sim |\cdot|_\infty$. Prove now the claim:

(a) For $n \in \mathbb{N}$ write

$$2^n = \sum_{i=0}^N \alpha_i a^i \quad \text{with } \alpha_i \in \{0, \dots, a-1\} \text{ and } N \leq \log_a 2^n = n \cdot \frac{\log(2)}{\log(a)}.$$

Then we have

$$|2|^n = |2^n| \leq \sum_{i=0}^N \underbrace{|\alpha_i|}_{\leq \alpha_i < a} \overbrace{|a|^i} \leq |a|^N \leq (N+1) \cdot a \cdot |a|^N,$$

hence we get

$$\begin{aligned} n \cdot \log(|2|) &\leq \log(N+1) + \log(a) + N \log(|a|) \\ &\leq \log\left(n \cdot \frac{\log(2)}{\log(a)} + 1\right) + \log(a) + n \cdot \frac{\log(2)}{\log(a)} \cdot \log(|a|). \end{aligned}$$

Multiplying the equation by $\frac{1}{n} \cdot \frac{1}{\log(2)}$ gives us

$$\frac{\log(|2|)}{\log(2)} \leq \frac{1}{n} \cdot \log\left(n \cdot \frac{\log(2)}{\log(a)} + 1\right) + \frac{\log(|a|)}{\log(a)}$$

and thus

$$\frac{\log(|2|)}{\log(2)} \leq \frac{\log(|a|)}{\log(a)}.$$

Swapping the roles of a and 2 in the equation above gives us the other inequality.

Hence we have equality, which proves the claim. \square

Proposition 9.9 *Let $|\cdot|$ be a nonarchimedean absolute value on a field k .*

(i) $|x + y| \leq \max\{|x|, |y|\}$ for all $x, y \in k$.

(ii) If $|x| \neq |y|$, then equality holds in (i).

proof. (i) If $x = 0$, we have $|y + x| = |y| \leq \max\{0, |y|\} = \max\{|x|, |y|\}$. Thus assume $x \neq 0$.

We have $|x + y| = |x| \left|1 + \frac{y}{x}\right|$. It suffices to show $|x + 1| \leq \max\{1, |x|\}$. Then we get

$$|x + y| = |y| \cdot \left|1 + \frac{x}{y}\right| \leq |y| \cdot \max\left\{\left|\frac{x}{y}\right|, |1|\right\} \leq \max\{|x|, |y|\}$$

For $n \in \mathbb{N}$ we have

$$(x + 1)^n = \sum_{k=0}^n \binom{n}{k} x^k.$$

Then we have

$$|x + 1|^n = |(x + 1)^n| = \left| \sum_{k=0}^n \binom{n}{k} x^k \right| \leq \sum_{k=0}^n \underbrace{\left| \binom{n}{k} \right|}_{\leq 1} \underbrace{|x|^k}_{\leq 1} \leq n + 1,$$

hence

$$|x + 1| \leq \sqrt[n]{n + 1} \quad \text{for all } n \in \mathbb{N}.$$

Thus $|1 + x| \leq 1$. Since we clearly have $|x + 1| \leq |x|$, we all in all have

$$|x + 1| \leq \max\{|x|, 1\}.$$

(ii) Let $z = x + y$ and assume $|x| < |y|$. We have to show $|z| = |y|$. Assume $|z| < |y|$. Then

$$|y| = |z - x| \stackrel{(i)}{\leq} \max\{|z|, |-x|\} < |y| \quad \nexists$$

and the proof is done. □

Proposition 9.10 *Let $|\cdot|$ be an a nonarchimedean absolute value on a field k . Then*

(i) *We have a local ring*

$$\overline{\mathcal{B}}_1(0) := \{x \in k \mid |x| \leq 1\} =: \mathcal{O}_k$$

with maximal ideal

$$\mathcal{B}_1(0) := \{x \in k \mid |x| < 1\} =: \mathfrak{m}_k$$

(ii) *Every point in ball is its center.*

(iii) *Balls are either disjoint or one of them is contained in the other one.*

(iv) *All triangles are isosceles.*

proof. (i) By 9.8(i), $\mathcal{B}_1(0)$ is closed under Addition. The remaining is calculating.

(ii) Let $z \in \overline{\mathcal{B}}_r(x)$. To show: $\overline{\mathcal{B}}_r(z) = \overline{\mathcal{B}}_r(x)$.

' \subseteq ' Let $y \in \overline{\mathcal{B}}_r(z)$, i.e. we have $|y - z| \leq r$. Then

$$|y - x| = |y - z + z - x| \leq \max\{|y - z|, |z - x|\} \leq r \quad \Rightarrow \quad y \in \overline{\mathcal{B}}_r(x).$$

Thus we have $\overline{\mathcal{B}}_r(z) \subseteq \overline{\mathcal{B}}_r(x)$.

' \supseteq ' Follows by symmetry.

(iii) Let $\mathcal{B} := \overline{\mathcal{B}}_r(x)$, $\mathcal{B}' := \overline{\mathcal{B}}_{r'}(x')$ and $y \in \mathcal{B} \cap \mathcal{B}'$. W.l.o.g. $r \leq r'$.

Then for $z \in \mathcal{B}$ we have

$$|z - x'| = |z - x + x - y + y - x'| \leq \max\{|z - x|, |x - y|, |y - x'|\} = \max\{r, r, r'\} = r'$$

which implies $z \in \mathbb{B}'$. Hence we have $\mathcal{B} \subseteq \mathcal{B}'$.

(iv) Follows from 9.8(ii). □

Corollary 9.11 *Let k be a field, $|\cdot|$ a nonarchimedean absolute value on k .*

- (i) *All balls are closed and open, considering the topology on k induced by the metric $d(x, y) = |x - y|$.*
- (ii) *k is totally disconnected, i.e. no subset of k containing more than one element is connected.*

proof. (i) Let $\mathcal{B} := \overline{\mathcal{B}}_r(x)$ be a closed ball for some $x \in k$, $r \in \mathbb{R}_{\geq 0}$. Then \mathcal{B} topologically clearly is closed. Let now $y \in \mathcal{B}$. Then $\mathcal{B}_r(y) \subseteq \mathcal{B}$ by 9.9(ii), i.e. \mathcal{B} is open.

Let now $\mathcal{B} := \mathcal{B}_r(x)$ be an open ball and $y \in k$ a boundary point. Thus for all $s > 0$ we find $z \in \mathcal{B}_s(x) \cap \mathcal{B}_r(x)$. Choose $s \leq r$. Then

$$d(x, y) \leq \max\{d(y, z), d(x, z)\} < \max\{s, r\} = r.$$

Thus $y \in \mathcal{B}_r(x)$, hence $\mathcal{B}_r(x)$ contains its boundary and is closed.

(ii) Let $X \subseteq k$ be a subset with $x \neq y \in X$. Then for $r := |x - y| > 0$ we get

$$X = \left(\overline{\mathcal{B}}_{\frac{r}{2}}(x) \cap X\right) \cup \left(X \setminus \overline{\mathcal{B}}_{\frac{r}{2}}(x)\right)$$

which is a decomposition of X into two nonempty, disjoint open subset, i.e. the claim follows.

Example 9.12 (*Geometry on $(\mathbb{Q}, |\cdot|_p)$*) The unit disc in $(\mathbb{Q}, |\cdot|_p)$ is

$$\left\{\frac{a}{b} \in \mathbb{Q} \mid p \nmid b\right\} =: \mathbb{Z}_{(p)}$$

The maximal ideal is

$$\left\{\frac{a}{b} \in \mathbb{Q} \mid p \nmid b, p \mid a\right\} = p \cdot \mathbb{Z}_{(p)} = \overline{\mathcal{B}}_{\frac{1}{p}}(0)$$

We have

$$\{x \in \mathbb{Q} \mid |x|_p < 1\} = \left\{x \in \mathbb{Q} \mid |x|_\infty < \frac{1}{p}\right\}$$

Moreover

$$\mathbb{Z}_{(p)} / p\mathbb{Z}_{(p)} \cong \mathbb{Z} / p\mathbb{Z} = \mathbb{F}_p = \{\overline{0}, \overline{1}, \dots, \overline{p-1}\}$$

$\overline{\mathcal{B}}_1(0)$ is the disjoint union of the $\overline{\mathcal{B}}_{\frac{1}{p}}(i)$ for $0 \leq i \leq p-1$, where $\overline{\mathcal{B}}_{\frac{1}{p}}(i) = i + p\mathbb{Z}_{(p)}$.

§ 10 Completions, p -adic numbers and Hensel's Lemma

Remark 10.1 Let $|\cdot|$ be an absolute value on a field k . Let

$$\mathcal{C} := \{(a_n)_{n \in \mathbb{N}} \mid (a_n) \text{ is Cauchy sequence in } (k, |\cdot|)\}$$

be the ring (!) of Cauchy sequences in k and

$$\mathcal{N} := \left\{ (a_n)_{n \in \mathbb{N}} \mid \lim_{n \rightarrow \infty} a_n = 0 \right\} \trianglelefteq \mathcal{C}$$

the ideal (!) of Cauchy sequences converging to 0. Then

- (i) \mathcal{N} is a maximal ideal.
- (ii) $k' := \mathcal{C}/\mathcal{N}$ is a field extension of k .
- (iii) $|\overline{(a_n)_{n \in \mathbb{N}}}| := \lim_{n \rightarrow \infty} |a_n| \in \mathbb{R}_{\geq 0}$ is an absolute value on k' extending $|\cdot|$.
- (iv) k' is complete with respect to $|\cdot|$.

Remark 10.2 If $|\cdot|$ is nonarchimedean, for every Cauchy sequence $(a_n)_{n \in \mathbb{N}} \notin \mathcal{N}$ we have $|a_m| = |a_n|$ for all $m, n \gg 0$.

proof. Since $(a_n) \notin \mathcal{N}$, 0 is not an accumulation point of (a_n) . $\implies |a_n| \geq \epsilon$ for some $\epsilon > 0$ and all $n \geq n_0(\epsilon) =: n_0$. Thus for $n, m \geq n_0$ we have $|a_n - a_m| < \epsilon$. This implies by 9.8 (ii)

$$|a_n - a_m| \leq \max\{|a_n|, |a_m|\} \implies |a_n| = |a_m|,$$

which was the claim. □

Definition 10.3 Let $k = \mathbb{Q}$, $|\cdot| = |\cdot|_p$ for some $p \in \mathbb{P}$. Then the field k' on 10.1 is called the field of p -adic numbers and denoted by \mathbb{Q}_p . The valuation ring is called the ring of p -adic integers and is denoted by \mathbb{Z}_p .

- Remark 10.4**
- (i) $\mathbb{Z} \subset \mathbb{Z}_{(p)} \subset \mathbb{Z}_p$.
 - (ii) The maximal ideal in \mathbb{Z}_p is $p\mathbb{Z}_p$.
 - (iii) $\mathbb{Z}_p/p\mathbb{Z}_p \cong \mathbb{Z}/p\mathbb{Z} = \mathbb{F}_p$.
 - (iv) \mathbb{Z}_p is a discrete valuation ring.

proof. (i) The first inclusion is clear. For the second one consider $x = \frac{r}{s} \in \mathbb{Z}_{(p)}$. Then by definition of localization we have $p \nmid s$ and hence

$$|x| = \left| \frac{r}{s} \right| = \frac{|r|}{|s|} = |r| \leq 1$$

and thus $x \in \mathbb{Z}_p$. Now prove that \mathbb{Z} is dense in \mathbb{Z}_p : Let $x \in \mathbb{Z}_p$ with p -adic expansion

$$x = \sum_{i=0}^{\infty} a_i p^i, \quad a_i \in \{0, 1, \dots, p-1\}.$$

Define a sequence $(x_n)_{n \in \mathbb{N}}$ by

$$x_n := \sum_{i=0}^n a_i p^i \in \mathbb{Z}.$$

Then we have

$$|x - x_n| = \left| \sum_{i=n+1}^{\infty} a_i p^i \right| = \max_{i \geq n+1} \{ |p^i| \} = |p^{n+1}| = p^{-(n+1)} \xrightarrow{n \rightarrow \infty} 0$$

and hence \mathbb{Z} is dense in \mathbb{Z}_p .

(ii) Recall that the maximal ideal is given by

$$\mathfrak{m} = \{x \in \mathbb{Z}_p \mid |x| < 1\} \stackrel{!}{=} p\mathbb{Z}_p$$

' \subseteq ' Let $x \in \mathfrak{m}$, i.e. $|x| < 1$. Thus we have $|x| < |\frac{1}{p}|$. This implies

$$|p^{-1}x| \leq 1 \iff p^{-1}x \in \mathbb{Z}_p.$$

and thus $p^{-1}x = y$ for some $y \in \mathbb{Z}_p$. Then we have $x = py \in p\mathbb{Z}_p$.

' \supseteq ' Let $x \in p\mathbb{Z}_p$, i.e. we can write $x = py$ for some $y \in \mathbb{Z}_p$. Then $|x| = |py| = |p||y| < 1$ and hence $x \in \mathfrak{m}$.

(iii) Consider the surjective homomorphism

$$\psi_p : \mathbb{Z}_p \longrightarrow \mathbb{Z}/p\mathbb{Z}, \quad x = \sum_{i=0}^n a_i p^i \mapsto a_0.$$

We have

$$\ker(\psi_p) = \{x \in \mathbb{Z}_p \mid a_0 \equiv 0 \pmod{p}\} = p\mathbb{Z}_p,$$

thus we get $\mathbb{Z}_p/p\mathbb{Z}_p \cong \mathbb{Z}/p\mathbb{Z}$ by homomorphism theorem.

(iv) The absolute value $|\cdot| = |\cdot|_p$ on \mathbb{Q}_p induces a discrete valuation ν on \mathbb{Q}_p^\times . With respect to this valuation we have

$$\mathcal{O}_\nu = \{x \in \mathbb{Q}_p \mid \nu(x) \geq 0\} \cup \{0\} = \{x \in \mathbb{Q}_p \mid |x| \leq 1\} = \mathbb{Z}_p,$$

which finishes the proof. □

Proposition 10.5 (i) Any $x \in \mathbb{Z}_p$ can uniquely be written in the form

$$x = \sum_{i=0}^{\infty} a_i p^i, \quad a_i \in \{0, 1, \dots, p-1\}.$$

(ii) Any $x \in \mathbb{Q}_p$ can uniquely be written in the form

$$x = \sum_{i=-m}^{\infty} a_i p^i, \quad m \in \mathbb{Z}, \quad a_i \in \{0, 1, \dots, p-1\}, \quad a_m \neq 0.$$

proof. (i) We first obtain, that any series

$$\sum_{i=0}^{\infty} a_i p^i, \quad a_i \in \{0, \dots, p-1\}$$

converges, since for $n > m$ we have

$$\left| \sum_{i=0}^n a_i p^i - \sum_{i=0}^m a_i p^i \right| = \left| \sum_{i=n+1}^m a_i p^i \right| = |p^{m+1}| \underbrace{\left| \sum_{i=n+1}^m a_i p^{i-(m+1)} \right|}_{\leq 1} \leq |p^{m+1}|.$$

uniqueness Let

$$x = \sum_{i=0}^{\infty} a_i p^i = \sum_{i=0}^{\infty} b_i p^i, \quad a_i, b_i \in \{0, 1, \dots, p-1\}$$

representations of $x \in \mathbb{Q}_p$. Assume them to be different and define $i_0 := \min\{i \in \mathbb{N}_0 \mid a_i \neq b_i\}$. Then

$$0 = \left| \sum_{i=0}^{\infty} a_i p^i - \sum_{i=0}^{\infty} b_i p^i \right| = \left| \underbrace{p^{i_0} (a_{i_0} - b_{i_0})}_{=:A} + p^{i_0+1} \cdot \underbrace{\left(\sum_{i=i_0+1}^{\infty} a_i p^{i-(i_0+1)} - \sum_{i=i_0+1}^{\infty} b_i p^{i-(i_0+1)} \right)}_{=:B} \right|.$$

We obtain $\nu_p(A) = p^{-i_0}$ and

$$B \in \mathbb{Z}_p, \quad \nu_p(p^{i_0+1} \cdot B) = \nu_p(p^{i_0+1}) \underbrace{\nu_p(B)}_{\leq 1} \leq \nu_p(p^{i_0+1}) = p^{-(i_0+1)},$$

so all in all

$$0 = |A + p^{i_0+1} \cdot B| \stackrel{9.8(ii)}{=} \max\{p^{-i_0}, p^{-(i_0+1)}\} = p^{-i_0} \not\leq 0.$$

existence Look at $\bar{x} \in \mathbb{Z}_p / p\mathbb{Z}_p = \mathbb{F}_p$.

Let a_0 be the representative of x in $\{0, 1, \dots, p-1\}$. Then we have

$$|x - a_0| < 1 \Leftrightarrow |x - a_0| \leq \frac{1}{p}.$$

In the next step, let a_1 be the representative of $\frac{1}{p}(x - a_0)$ in $\{0, 1, \dots, p-1\}$. Then

$$\left| \frac{1}{p}(x - a_0) - a_1 \right| = \left| \frac{1}{p} \right| |x - a_0 - a_1 p| \leq \frac{1}{p}$$

and thus $|x - a_0 - a_1 p| \leq \frac{1}{p^2}$. Inductively we let a_n be the representative of

$$\frac{1}{p^n}(x - a_0 - a_1 p - \dots - a_{n-1} p^{n-1}) = \frac{1}{p^n} \left(x - \sum_{i=0}^{n-1} a_i p^i \right)$$

in $\{0, 1, \dots, p-1\}$. Then we have

$$\left| x - \sum_{i=0}^{n-1} a_i p^i \right| \leq \frac{1}{p^{n+1}}.$$

and finally

$$\lim_{n \rightarrow \infty} \left| x - \sum_{i=0}^{n-1} a_i p^i \right| \leq \lim_{n \rightarrow \infty} \frac{1}{p^{n+1}} = 0 \implies x = \sum_{i=0}^{\infty} a_i p^i.$$

(ii) If $|x| = p^m$ for some $m \in \mathbb{Z}$, we have

$$|x \cdot p^m| = |d| \cdot |p^m| = p^m \cdot p^{-m} = 1, \quad \text{i.e. } x \cdot p^m \in \mathbb{Z}_p^\times$$

By part (i) we conclude

$$x \cdot p^m = \sum_{i=0}^{\infty} a_i p^i, \quad a_0 \neq 0.$$

Thus we have

$$x = \frac{1}{p^m} \cdot x \cdot p^m = \frac{1}{p^m} \cdot \sum_{i=0}^{\infty} a_i p^i = \sum_{i=-m}^{\infty} a_{i+m} p^i,$$

which was the assertion. □

Remark 10.6 *What is -1 in \mathbb{Q}_p ? We have $a_0 = p-1$, since $\overline{p-1} - \overline{(-a)} = \bar{p} = 0$. a_1 is the representative of $\frac{1}{p}(-1 - (p-1)) = -1$, i.e. $a_1 = p-1$. a_2 is the representative of $\frac{1}{p^2}(-1 - (p-1) - (p-1)p) = -1$, i.e. $a_2 = p-1$. Inductively we have $a_n = p-1$ for all $n \in \mathbb{N}_0$, so we get*

$$-1 = \sum_{i=0}^{\infty} a_i p^i = \sum_{i=0}^{\infty} (p-1) p^i.$$

Moreover we obtain

$$\sum_{i=0}^{\infty} (p-1) p^i = (p-1) \sum_{i=0}^{\infty} p^i = (p-1) \cdot \frac{1}{1-p} = \frac{p-1}{1-p} = -1.$$

Remark 10.7 *Let*

$$x = \sum_{i=0}^{\infty} a_i p^i, \quad y = \sum_{i=0}^{\infty} b_i p^i$$

p-adic integers. Then

$$x + y = \sum_{i=0}^{\infty} c_i p^i$$

with coefficients

$$c_0 = \begin{cases} a_0 + b_0 & \text{if } a_0 + b_0 < p \\ a_0 + b_0 - p & \text{if } a_0 + b_0 \geq p \end{cases}$$

$$c_1 = \begin{cases} a_1 + b_1 & \text{if } a_0 + b_0 < p \text{ and } a_1 + b_1 < p \\ a_1 + b_1 - p & \text{if } a_0 + b_0 < p \text{ and } a_1 + b_1 \geq p \\ a_1 + b_1 + 1 & \text{if } a_0 + b_0 \geq p \text{ and } a_1 + b_1 + 1 < p \\ a_1 + b_1 + 1 - p & \text{if } a_0 + b_0 \geq p \text{ and } a_1 + b_1 + 1 \geq p \end{cases}$$

Inductively let

$$\epsilon_0 := 0, \quad \epsilon_i := \begin{cases} 0 & \text{if } a_i + b_i + \epsilon_{i-1} < p \\ 1 & \text{if } a_i + b_i + \epsilon_{i-1} \geq p \end{cases} \quad \text{for } i \geq 1$$

Then we have

$$c_i = \begin{cases} a_i + b_i + \epsilon_i & \text{if } a_i + b_i + \epsilon_i < p \\ a_i + b_i + \epsilon_i - p & \text{if } a_i + b_i + \epsilon_i \geq p \end{cases}$$

Remark 10.8 (i) $\sqrt{p} \notin \mathbb{Q}_p$, since $|\sqrt{p}| = \sqrt{|p|} = \sqrt{\frac{1}{p}} \in \left(\frac{1}{p}, 1\right)$, which is not possible.

(ii) Let $a \in \mathbb{Z}_p^\times$ with image $\bar{a} \in \mathbb{F}_p^\times \setminus \mathbb{F}_p^{\times 2}$, where

$$\mathbb{F}_p^{\times 2} = \{x \in \mathbb{F}_p \mid \text{there exists } y \in \mathbb{F}_p : y^2 = x\}$$

denotes the set of squares. Then $\sqrt{a} \notin \mathbb{Q}_p$. Assume a is a square, i.e. $b^2 = a$. Then

$$|b| = \sqrt{|a|} = 1 \quad \Rightarrow \quad b \in \mathbb{Z}_p^\times$$

But then $\bar{b} \in \mathbb{F}_p$ satisfies $\bar{b}^2 \equiv a$, which is a contradiction, since $a \notin \mathbb{F}_p^{\times 2}$.

(iii) Let now $\overline{\mathbb{Q}}_p$ be the algebraic closure of \mathbb{Q}_p with valuation ring $\overline{\mathbb{Z}}_p$ and maximal ideal $\overline{\mathfrak{m}}_p$. Then $\overline{\mathbb{Z}}_p / \overline{\mathfrak{m}}$ is algebraically closed. Moreover \mathbb{Q}_p is complete with respect to $|\cdot|_p$. The completion \mathbb{C}_p of $\overline{\mathbb{Q}}_p$ is complete and algebraically closed, but:

- (1) $|\cdot|_p$ is not a discrete valuation.
- (2) $\overline{\mathbb{Z}}_p$ is not a discrete valuation ring.
- (3) $\overline{\mathfrak{m}}_p$ is not a principal ideal.

Theorem 10.9 (*Hensel's Lemma*) *Let*

$$f = \sum_{i=0}^n a_i X^i \in \mathbb{Z}_p[X], \quad \bar{f} = \sum_{i=0}^n \bar{a}_i X^i \in \mathbb{F}[X]$$

where \bar{f} is the reduction of f in $\mathbb{F}[X]$. Suppose that $\bar{f} = f_1 \cdot f_2$ with $f_1, f_2 \in \mathbb{F}_p[X]$ relatively prime. Then there exist $g, h \in \mathbb{Z}_p[X]$, such that

$$f = g \cdot h, \quad \bar{g} = f_1, \bar{h} = f_2, \quad \deg(f_1) = \deg(g)$$

proof. Let $d := \deg(f)$, $m := \deg(f_1)$. Then $\deg(f_2) \leq d - m$. Choose $g_0, h_0 \in \mathbb{Z}_p[X]$ such that $\bar{g}_0 = f_1, \bar{h}_0 = f_2, \deg(g_0) = m, \deg(h_0) = d - m$. *Strategy:* Find $g_1 = g_0 + p c_1, h_1 = h_0 + p d_1$ with some $c_1, d_1 \in \mathbb{Z}_p[X]$, such that

$$f - g_1 h_1 \in p^2 \mathbb{Z}_p[X].$$

Therefore we have a

Claim (a) For $n \geq 1$ there exists $c_n, d_n \in \mathbb{Z}_p[X]$ with $\deg(c_n) \leq m, \deg(d_n) \leq d - m$ and

$$f - g_n h_n \in p^{n+1} \mathbb{Z}_p[X], \quad \text{where } g_n = g_{n-1} + p^n c_n, \quad h_n = h_{n-1} + p^n d_n.$$

Assuming (a), write

$$g_n = \sum_{i=0}^m g_{n,i} X^i, \quad h_n = \sum_{i=0}^{d-m} h_{n,i} X^i.$$

By construction, the $(g_{n,i})$ converge to some $\alpha_i \in \mathbb{Z}_p$ and the $(h_{n,i})$ converge to some $\beta_i \in \mathbb{Z}_p$.

Let

$$g := \sum_{i=0}^m \alpha_i X^i, \quad h := \sum_{i=0}^{d-m} \beta_i X^i.$$

Observe, that $\deg(g) = m, \deg(h) = d - m$. Obviously we have

$$f = g \cdot h.$$

It remains to show the claim.

(a) c_n, d_n have to satisfy

$$\begin{aligned} f - g_n h_n &= f - (g_{n-1} + p^n c_n) \cdot (h_{n-1} + p^n d_n) \\ &= f - g_{n-1} h_{n-1} - p^n \cdot (g_{n-1} d_n + h_{n-1} c_n + p^n c_n d_n) \\ &\stackrel{!}{\in} p^{n+1} \mathbb{Z}_p[X] \end{aligned}$$

where $f - g_{n-1}h_{n-1} \in p^n\mathbb{Z}_p[X]$ by hypothesis. We get

$$\tilde{f}_n := \frac{1}{p^n}(f - g_{n-1}h_{n-1}) \equiv c_n h_{n-1} + d_n g_{n-1} \pmod{p} (*)$$

Since f_1, f_2 are relatively prime and $g_j \equiv g_k \pmod{p}$ for any j, k , we find integers $a, b \in \mathbb{Z}$, such that

$$af_1, bf_2 = 1 \implies ag_{n-1} + bh_{n-1} \equiv 1 \pmod{p}.$$

Multiplying the equation by \tilde{f}_n gives us

$$\tilde{f}_n \equiv \underbrace{a\tilde{f}_n}_{=: \tilde{d}_n} g_{n-1} + \underbrace{b\tilde{f}_n}_{=: \tilde{c}_n} h_{n-1} \pmod{p} (**).$$

Further $\mathbb{Z}_p[X]$ is euclidean, thus we can choose $q_n, r_n \in \mathbb{Z}_p[X]$, $\deg(r_n) < m$ such that

$$b\tilde{f}_n = q_n g_{n-1} + r_n.$$

By (**) we have

$$g_{n-1} (a\tilde{f}_n + q_n h_{n-1}) + r_n \equiv \tilde{f}_n \pmod{p}.$$

Let now $c_n = r_n, d_n = a\tilde{f}_n + q_n h_{n-1}$. All the terms are divisible by p . Then

$$d_n \equiv a\tilde{f}_n + q_n h_{n-1} \pmod{p}.$$

Thus (*) holds and we have

$$\deg(d_n) = \deg(\overline{d_n}) \leq \deg \left(\underbrace{\overline{\tilde{f}_n}}_{\leq d} - \underbrace{\overline{\tilde{c}_n}}_{< m} \underbrace{\overline{h_{n-1}}}_{< d-m} \right) - \underbrace{\deg(\overline{g_{n-1}})}_{=m} \leq d - m$$

since $\overline{d_n} \overline{g_{n-1}} = \overline{\tilde{f}_n} - \overline{\tilde{c}_n} \overline{h_{n-1}}$. Thus, the claim is proved. □

Corollary 10.10 *Let $p \in \mathbb{P}$ odd. Then $a \in \mathbb{Z}_p^\times$ is a square if and only if $\bar{a} \in \mathbb{F}_p^\times$ is a square.*

Proposition 10.11 *$a \in \mathbb{Q}$ is a square if and only if $a > 0$ and a is a square in \mathbb{Q}_p for all $p \in \mathbb{P}$.*

Remark: This is a special case of the 'Hasse-Minkowski-Theorem'.

Kapitel III

Rings and modules

§ 11 Multilinear Algebra

In this section, R will always be a commutative, unitary ring.

Reminder 11.1 (i) An R -module is an abelian group $(M, +)$ together with a scalar multiplication

$$\cdot : R \times M \longrightarrow M$$

with the usual properties of a vector space, i.e. for any $m, n \in M, r, s \in R$ we have

$$(1) \quad r \cdot (s \cdot m) = (rs) \cdot m$$

$$(2) \quad (r + s) \cdot m = r \cdot m + s \cdot m$$

$$(3) \quad r \cdot (m + n) = r \cdot m + r \cdot n$$

$$(4) \quad 1_R \cdot m = m$$

(ii) A map $\phi : M \longrightarrow M'$ of R -modules M, M' is called R -linear or R -module homomorphism, if

$$\phi(r \cdot m + s \cdot n) = r \cdot \phi(m) + s \cdot \phi(n) \quad \text{for all } r, s \in R, m, n \in M.$$

(iii) A subset $S \subseteq M$ of an R -module is called an R -submodule of M , if S is an R -module.

(iv) R itself is an R -module, the submodules are the ideals of R .

(v) If $\phi : M \longrightarrow M'$ is R -linear, then

$$\ker(\phi) = \{m \in M \mid \phi(m) = 0\},$$

$$\text{im}(\phi) = \{m' \in M' \mid \phi(m) = m' \text{ for some } m \in M\}$$

are R -submodules.

(vi) If $M \subseteq M'$ is a submodule, then the factor group M/M' is an R -module via

$$a \cdot \bar{m} = \overline{a \cdot m}.$$

(vii) For an R -linear map $\phi : M \longrightarrow M''$, we have

$$\text{im}(\phi) \cong M / \ker(\phi).$$

(viii) An R -module M is called *free*, if there exists a subset $X \subseteq M$, such that every $m \in M$ has a unique representation

$$m = \sum_{x \in X} a_x \cdot x, \quad a_x \in R, \quad a_x \neq 0 \text{ only for finitely many } x \in X.$$

In this case, X is called the rank of M .

(ix) Not every R -module is free: Indeed let $0 \subsetneq I \subsetneq R$ be a proper ideal. Then R/I is not free: Let $X \subseteq R$, such that $\overline{X} \subseteq R/I$ generates the R -module R/I . Let $x \in X$ and $a \in I \setminus \{0\}$. Then we have

$$x \cdot \overline{x} = \overline{a \cdot x} = \overline{0} = \overline{0 \cdot x} = 0 \cdot \overline{x},$$

hence we have found two different representations of 0. Thus R/I is not free.

(x) For any $n \in \mathbb{N}$, $n\mathbb{Z}$ is a free module

(xi) If $I \leq R$ is not a principal ideal, then I is not a free R -module., since for $x, y \in I$ with $y \notin (x)$ we have $xy - yx = 0$. Again we have a nontrivial representation of 0 and I is not free.

Definition + proposition 11.2 Let R be a ring, M, M' R -modules.

(i) The set of R -module homomorphisms

$$\text{Hom}_R(M, M') = \{ \phi : M \longrightarrow M' \mid \phi \text{ is } R\text{-linear} \}$$

is again an R -module.

(ii) $M^* = \text{Hom}_R(M, R)$ is called the *dual module* of M .

Let now

$$0 \longrightarrow M' \xrightarrow{\alpha} M \xrightarrow{\beta} M'' \longrightarrow 0$$

be a short exact sequence of R -modules M, M', M'' , i.e. α is injective and β is surjective.

(iii) Then we have a short exact sequence

$$\begin{array}{ccccccc} 0 & \longrightarrow & \text{Hom}_R(N, M') & \xrightarrow{\alpha^*} & \text{Hom}_R(N, M) & \xrightarrow{\beta^*} & \text{Hom}_R(N, M'') \\ & & \phi & \mapsto & \alpha \circ \phi, & \psi & \mapsto & \beta \circ \psi \end{array}$$

(iv) We have a short exact sequence

$$\begin{array}{ccccccc} 0 & \longrightarrow & \text{Hom}_R(M'', N) & \xrightarrow{\beta^*} & \text{Hom}_R(M, N) & \xrightarrow{\alpha^*} & \text{Hom}_R(M', N) \\ & & \phi & \mapsto & \phi \circ \beta, & \psi & \mapsto & \psi \circ \alpha \end{array}$$

- (v) N is called a *projective* module, if β_* is surjective for all short exact sequences as in (iii).
- (vi) N is called an *injective* module, if α^* is surjective for all short exact sequences as in (iv).

proof. (i) This is clear: For all $\phi, \phi_1, \phi_2 \in \text{Hom}_R(M, M')$ and $a \in R$ we have

$$(\phi_1 + \phi_2)(x) = \phi_1(x) + \phi_2(x), \quad (a \cdot \phi)(x) = a \cdot \phi(x)$$

(iii) α_* is R -linear: For any $\phi_1, \phi_2 \in \text{Hom}_R(N, M')$ and $x \in N$ we have

$$\alpha_*(\phi_1 + \phi_2)(x) = (\alpha \circ (\phi_1 + \phi_2))(x) = \alpha(\phi_1(x) + \phi_2(x)) = \alpha(\phi_1(x)) + \alpha(\phi_2(x))$$

and thus

$$\alpha_*(\phi_1 + \phi_2)(x) = \alpha_*(\phi_1)(x) + \alpha_*(\phi_2)(x) = (\alpha_*(\phi_1) + \alpha_*(\phi_2))(x).$$

Moreover, α_* is injective: Since α is injective we have $\alpha_*(\phi)(x) = \alpha(\phi(x)) = 0$ if and only if $\phi(x) = 0$ for all $x \in N$, thus $\phi = 0$. Now we still have to show $\ker(\beta_*) = \text{im}(\alpha_*)$.

' \supseteq ' For $\phi \in \text{Hom}_R(N, M')$ we have $\beta_*(\alpha \circ \phi) = \beta \circ \alpha \circ \phi = 0 \circ \phi = 0$, i.e. $\alpha \circ \phi = \alpha_*(\phi) \in \ker(\beta_*)$.

' \subseteq ' Let $\phi : N \rightarrow M$, $\phi \in \ker(\beta_*)$, i.e. $\beta \circ \phi = 0$. We have to show, that there exists $\phi' \in \text{Hom}_R(N, M')$ such that $\phi = \alpha_*(\phi') = \alpha \circ \phi'$. Let $x \in N$. Then $\phi(x) \in \ker(\beta) = \text{im}(\alpha)$. Then there exists $z \in M'$ such that $\phi(x) = \alpha(z)$ and z is unique, since α is injective. Define $\phi'(x) := z$. Then we have $\alpha \circ \phi' = \phi$. It remains to show that ϕ' is R -linear. We have $\phi'(x_1 + x_2) = z$ and with $\alpha(z) = \phi(x_1 + x_2) = \phi(x_1) + \phi(x_2)$ we again have $\alpha(z) = \phi(z_1) + \phi(z_2)$ for some suitable, but unique $z_1, z_2 \in M'$. Since we have

$$\alpha(z) = \phi(x_1 + x_2) = \phi(x_1) + \phi(x_2) = \alpha(z_1) + \alpha(z_2) = \alpha(z_1 + z_2)$$

and α is injective, we have $z = z_1 + z_2$, thus

$$\phi'(x_1 + x_2) = z = z_1 + z_2 = \phi'(x_1) + \phi'(x_2).$$

Moreover for $a \in R$ we have $\phi'(ax) = w$ with $\alpha(w) = \phi(ax) = a \cdot \phi(x) = a \cdot \alpha(z)$. Thus

$$\alpha(\phi'(ax)) = \alpha(w) = \phi(ax) = a \cdot \phi(x) = a \cdot \alpha(z) = a \cdot \alpha(\phi'(x)) \xrightarrow{\alpha \text{ inj.}} \phi'(ax) = a \cdot \phi'(x),$$

which proves the claim. □

Remark 11.3 (i) An R -module N is projective if and only if for every surjective R -linear map $\beta : M \rightarrow M''$ and every R -linear map $\phi : N \rightarrow M''$ there is an R -linear map

$\tilde{\phi} : N \longrightarrow M$, such that the diagram below commutes, i.e. $\phi = \beta \circ \tilde{\phi}$.

$$\begin{array}{ccc}
 & & M \\
 & \nearrow \tilde{\phi} & \downarrow \beta \\
 N & \xrightarrow{\phi} & M''
 \end{array}$$

(ii) Free modules are projective.

Definition 11.4 Let M, M_1, M_2 be R -modules. A map

$$\Phi : M_1 \times M_2 \longrightarrow M$$

is called *bilinear*, if the maps

$$\Phi_{x_0} : M_2 \longrightarrow M, \quad y \mapsto \Phi(x_0, y), \quad \Phi_{y_0} : M_1 \longrightarrow M, \quad x \mapsto \Phi(x, y_0)$$

are linear for all $x_0 \in M_1$ and $y_0 \in M_2$.

Definition 11.5 Let M_1, M_2 be R -modules. A *tensor product* of M_1 and M_2 is an R -module T together with a bilinear map

$$\tau : M_1 \times M_2 \longrightarrow T,$$

such that for every bilinear map $\Phi : M_1 \times M_2 \longrightarrow M$ for any R -module M there is a unique linear map $\phi : T \longrightarrow M$, such that the following diagram becomes commutative.

$$\begin{array}{ccc}
 M_1 \times M_2 & \xrightarrow{\tau} & T \\
 & \searrow \Phi & \swarrow \phi \\
 & & M
 \end{array}$$

Remark 11.6 Let (T, τ) and (T', τ') be tensor products of R -modules M_1 and M_2 . Then there exists a unique isomorphism $h : T \longrightarrow T'$, such that

$$\tau' = h \circ \tau.$$

proof. Consider

$$\begin{array}{ccc}
 M_1 \times M_2 & \xrightarrow{\tau} & T \\
 & \searrow \tau' & \nearrow g \\
 & & T' \\
 & & \nwarrow h \\
 & & T
 \end{array}$$

Existence and uniqueness of the linear maps g and h come from Definition 11.5. It remains to show, that $h \circ g = \text{id}_{T'}$ and $g \circ h = \text{id}_T$.

In order to do this, consider the following diagramm.

$$\begin{array}{ccc}
 M_1 \times M_2 & \xrightarrow{\tau} & T \\
 & \searrow \tau' & \swarrow g \circ h \stackrel{!}{=} \text{id}_T \\
 & & T
 \end{array}$$

We have $(g \circ h)\tau = g \circ (h \circ \tau) = g \circ \tau' = \tau$. By the uniqueness we get $\text{id}_T = g \circ h$. Analogously we get $\text{id}_{T'} = h \circ g$ which finishes the proof. \square

Corollary 11.7 *The tensor product (T, τ) of R -modules M_1, M_2 is unique up to isomorphism. The standard notation is*

$$T = M_1 \otimes_R M_2, \quad \tau(x, y) = x \otimes y$$

Example 11.8 Let M_1, M_2 be free R -modules with bases $\{e_i\}_{i \in I}, \{f_j\}_{j \in J}$. Let T be the free R -module with basis $\{g_{ij}\}_{(i,j) \in I \times J}$ and

$$\tau : M_1 \times M_2 \longrightarrow T, \quad (e_i, f_j) \mapsto g_{ij} \quad \text{for all } (i, j) \in I \times J,$$

i.e. for elements in M_1, M_2 we have

$$\tau \left(\sum_{i \in I} a_i e_i, \sum_{j \in J} b_j f_j \right) = \sum_{(i,j) \in I \times J} a_i b_j g_{ij}$$

Then (T, τ) is the tensor product of M_1, M_2 , since: Let $\Phi : M_1 \times M_2 \longrightarrow M$ be bilinear. Define

$$\phi : T \longrightarrow M, \quad g_{ij} \mapsto \Phi(e_i, f_j).$$

Obviously ϕ is linear and satisfies $\Phi = \phi \circ \tau$. Now consider a special case and let $|I| = n, |J| = m$. Identify M_1 via (e_1, \dots, e_n) with R^n and M_2 via (f_1, \dots, f_m) with R^m . Then T is identified with $R^{n \times m}$ via

$$g_{ij} = E_{ij} = \begin{pmatrix} 0 & \dots & 0 & \dots & 0 \\ \vdots & & 1 & & \vdots \\ 0 & \dots & 0 & \dots & 0 \end{pmatrix}$$

where the only nonzero entry is in the i -th row and j -th column. Then $\tau : R^n \times R^m \longrightarrow R^{n \times m}$ is given by

$$\begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix} \otimes \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix} = \begin{pmatrix} a_1 b_1 & \dots & a_1 b_m \\ \vdots & & \vdots \\ a_n b_1 & \dots & a_n b_m \end{pmatrix} = \begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix} \cdot \begin{pmatrix} b_1 & \dots & b_m \end{pmatrix},$$

where the last multiplication is the usual multiplication of matrices.

Theorem 11.9 For any two R -modules M_1, M_2 there exists a tensor product $(T, \tau) = (M_1 \otimes_R M_2, \otimes)$.

proof. Let F be the free R -module with basis $M_1 \times M_2$ and Q be the submodule generated by all the elements

$$(x + x', y) - (x, y) - (x', y), \quad (x, y + y') - (x, y) - (x, y'), \quad (ax, y) - a(x, y), \quad (x, ay) - a(x, y)$$

for $a \in R, x, x' \in M_1, y, y' \in M_2$. Define

$$T := F/Q, \quad \tau : M_1 \times M_2 \longrightarrow T, \quad (x, y) \mapsto \overline{(x, y)}.$$

Then by the construction of Q , τ is bilinear. Let now be M a further R -module and $\Phi : M_1 \times M_2 \longrightarrow M$ a bilinear map. Define

$$\tilde{\phi} : F \longrightarrow M, \quad (x, y) \mapsto \Phi(x, y).$$

Clearly $\tilde{\phi}$ is linear. Moreover we have $Q \subseteq \ker(\tilde{\phi})$, since Φ is bilinear. By the isomorphism theorem, $\tilde{\phi}$ factors to a linear map $\phi : T \longrightarrow M$ satisfying $\phi(\overline{(x, y)}) = \Phi(x, y)$. The uniqueness of ϕ follows by the fact that T is generated by the $\overline{(x, y)}$ for $x \in M_1, y \in M_2$. \square

Example 11.10 We want to find out what is

$$\mathbb{Z}/2\mathbb{Z} \otimes_{\mathbb{Z}} \mathbb{Z}/3\mathbb{Z}.$$

Let $\Phi : \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z} \longrightarrow A$ bilinear for some \mathbb{Z} -module A . Then we see

$$\Phi(\bar{1}, \bar{1}) = \Phi(\bar{3}, \bar{1}) = \Phi(3 \cdot (\bar{1}, \bar{1})) = 3 \cdot \Phi(\bar{1}, \bar{1}) = \Phi(\bar{1}, \bar{3}) = \Phi(\bar{1}, \bar{0}) = 0 \cdot \Phi(\bar{1}, \bar{1}) = 0$$

Hence $\Phi = 0$, since $(\bar{1}, \bar{1})$ generates $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z}$. Thus $\mathbb{Z}/2\mathbb{Z} \otimes_{\mathbb{Z}} \mathbb{Z}/3\mathbb{Z} = 0$.

Proposition 11.11 For R -modules M, M_1, M_2, M_3 we have the following properties.

- (i) $M \otimes_R R \cong M$.
- (ii) $M_1 \otimes_R M_2 \cong M_2 \otimes_R M_1$.
- (iii) $(M_1 \otimes_R M_2) \otimes_R M_3 \cong M_1 \otimes_R (M_2 \otimes_R M_3)$.

proof. (i) Let $\tau : M \times R \longrightarrow M, (x, a) \mapsto a \cdot x$. Then τ is bilinear. We now can verify the universal property of the tensor product. Let N be an arbitrary R -module and $\Phi : M \times R \longrightarrow N$ be bilinear a bilinear map. Define

$$\phi : M \longrightarrow N, \quad x \mapsto \Phi(x, 1)$$

Then ϕ is R -linear: For $x, y \in M, \alpha \in R$ we have

$$\phi(\alpha \cdot x) = \Phi(\alpha \cdot x, 1) = \alpha \cdot \Phi(x, 1) = \alpha \cdot \phi(x),$$

$$\phi(x + y) = \Phi(x + y, 1) = \Phi(x, 1) + \Phi(y, 1) = \phi(x) + \phi(y)$$

and thus

$$\phi(\tau(x, a)) = \phi(a \cdot x) = a \cdot \Phi(x, 1) = \Phi(x, a)$$

(ii) The isomorphism

$$M_1 \times M_2 \xrightarrow{\cong} M_2 \times M_1, \quad (x, y) \mapsto (y, x)$$

induces an isomorphism $M_1 \otimes_R M_2 \cong M_2 \otimes_R M_1$.

(iii) For fixed $z \in M_3$ define

$$\Phi_z : M_1 \times M_2 \longrightarrow M_1 \otimes_R (M_2 \otimes_R M_3), \quad (x, y) \mapsto x \otimes (y \otimes z) = \tau_{1(23)}(\tau_{23}(x, y)).$$

Then Φ_z is bilinear and induces a linear map

$$\phi_z : M_1 \otimes_R M_2 \longrightarrow M_1 \otimes_R (M_2 \otimes_R M_3).$$

Define

$$\Psi : (M_1 \otimes_R M_2) \times M_3 \longrightarrow M_1 \otimes_R (M_2 \otimes_R M_3), \quad (x \otimes y, z) \mapsto \phi_z(x \otimes y).$$

Ψ is bilinear and induces a linear map

$$\psi : (M_1 \otimes_R M_2) \otimes_R M_3 \longrightarrow M_1 \otimes_R (M_2 \otimes_R M_3)$$

Doing this again the other way round we find a linear map

$$\tilde{\psi} : M_1 \otimes_R (M_2 \otimes_R M_3) \longrightarrow (M_1 \otimes_R M_2) \otimes_R M_3$$

By the uniqueness we obtain as in Remark 11.6 that $\psi \circ \tilde{\psi} = \tilde{\psi} \circ \psi = \text{id}$, hence the claim follows. □

Definition + remark 11.12 Let M, M_1, \dots, M_n be R -modules.

(i) A map

$$\Phi : M_1 \times \dots \times M_n = \prod_{i=1}^n M_i \longrightarrow M$$

is called *multilinear*, if for any $1 \leq i \leq n$ and all choices of $x_j \in M_j$ for $j \neq i$ the map

$$\Phi_i : M_i \longrightarrow M, \quad x \mapsto \Phi(x_1, \dots, x_{i-1}, x, x_{i+1}, \dots, x_n)$$

is linear.

(ii) The map

$$\tau_{M_1, \dots, M_n} : \prod_{i=1}^n M_i \longrightarrow \bigotimes_{i=1}^n M_i, \quad (x_1, \dots, x_n) \mapsto x_1 \otimes \dots \otimes x_n$$

is multilinear.

(iii) For every multilinear map

$$\Phi : \prod_{i=1}^n M_i \longrightarrow M$$

there exists a unique linear map

$$\phi : \bigotimes_{i=1}^n M_i \longrightarrow M$$

such that $\Phi = \phi \circ \tau_{M_1, \dots, M_n}$.

Definition 11.13 Let M, N be R -modules, $\Phi : M^n = \prod_{i=1}^n M \longrightarrow N$ a multilinear map.

(i) Φ is called *symmetric*, if for any $\sigma \in S_n$ we have

$$\Phi(x_1, \dots, x_n) = \Phi(x_{\sigma(1)}, \dots, x_{\sigma(n)}).$$

(ii) Φ is called *alternating*, if

$$x_i = x_j \text{ for some } i \neq j \implies \Phi(x_1, \dots, x_n) = 0.$$

If $\text{char}(R) \neq 2$, this is equivalent to

$$\Phi(x_1, \dots, x_i, \dots, x_j, \dots, x_n) = -\Phi(x_1, \dots, x_j, \dots, x_i, \dots, x_n).$$

Proposition 11.14 Let M be an R -module, $n \geq 1$.

(i) There exists an R -module $S^n(M)$, called the n -th symmetric power of M and a symmetric multilinear map

$$\sigma_M^n : M^n \longrightarrow S^n(M)$$

such that for all symmetric, multilinear maps $\Phi : M^n \longrightarrow N$ for any R -module N there exists a unique linear map $\phi : S^n(M) \longrightarrow N$ satisfying $\Phi = \phi \circ \sigma_M^n$.

(ii) There exists an R -module $\Lambda^n(M)$, called the n -th exterior power of M and an alternating multilinear map

$$\lambda_M^n : M^n \longrightarrow \Lambda^n(M)$$

such that for all alternating, multilinear maps $\Phi : \Lambda^n(M) \longrightarrow N$ for any R -module N there exists a unique linear map $\phi : \Lambda^n(M) \longrightarrow N$ satisfying $\Phi = \phi \circ \lambda_M^n$.

proof. (i) Let $T^n(M) = M \otimes_R \dots \otimes_R M$.

Let now $J_n(M)$ be the submodule of $T^n(M)$ generated by all elements

$$(x_1 \otimes \dots \otimes x_n) - (x_{\sigma(1)} \otimes \dots \otimes x_{\sigma(n)}), \quad x_i \in M, \sigma \in S_n$$

Define

$$S^n(M) := T^n(M) / J_n(M), \quad \sigma_M^n := \text{proj} \circ \tau_{M, \dots, M}$$

Then σ_M^n is multilinear and symmetric by construction. Given a multilinear and symmetric map $\Phi : M^n \rightarrow N$, define ϕ as follows: Let $\tilde{\phi} : T^n(M) \rightarrow N$ be the linear map induced by Φ and observe that $J_n(M) \subseteq \ker(\tilde{\phi})$. Hence $\tilde{\phi}$ factors to a linear map

$$\phi : S^n(M) = T^n(M) / J_n(M) \rightarrow N$$

satisfying $\phi \circ \sigma_M^n = \Phi$.

(ii) Similarly let $I_n(M)$ be the submodule of $T^n(M)$ generated by all the elements

$$x_1 \otimes \dots \otimes x_n, \quad x_i \in M \text{ with } x_i = x_j \text{ for some } i \neq j$$

Analogously we define

$$\Lambda^n(M) := T^n(M) / I_n(M), \quad \lambda_M^n := \text{proj} \circ \tau_{M, \dots, M}$$

and obtain the required properties. □

Proposition 11.15 *Let M be a free R -module of rank r and $\{e_1, \dots, e_r\}$ a basis of M . Then $\Lambda^n(M)$ is a free R -module with basis*

$$\text{proj}(e_{i_1} \otimes \dots \otimes e_{i_n}) =: e_{i_1} \wedge \dots \wedge e_{i_n}, \quad 1 \leq i_1 < \dots < i_n \leq r$$

In particular, $\Lambda^n(M) = 0$ for $n > r$ and $\text{rank}(\Lambda^r(M)) = 1$.

proof. By definition we have $e_{i_1} \wedge \dots \wedge e_{i_n} = 0$ if $i_k = i_j$ for some $k \neq j$, hence we have $\Lambda^n(M) = 0$ for $n > r$, as at least one of the e_k must appear twice.

generating: Clearly the $e_{i_1} \wedge \dots \wedge e_{i_n}, i_k \in \{1, \dots, r\}$ generate $\Lambda^n(M)$. We have to show that we can leave out some of them. Obviously $e_{i_{\sigma(1)}} \wedge \dots \wedge e_{i_{\sigma(n)}}$ is a multiple by ± 1 of $e_{i_1} \wedge \dots \wedge e_{i_n}$.

Thus the $e_{i_1} \wedge \dots \wedge e_{i_n}$ with $1 \leq i_1 < i_2 < \dots < i_n \leq r$ generate $\Lambda^n(M)$.

linear independence: Assume

$$\sum_{1 \leq i_1 < \dots < i_n \leq r} a_{i_1, \dots, i_n} e_{i_1} \wedge \dots \wedge e_{i_n} = 0. \quad (*)$$

For fixed $j := (j_1, \dots, j_n), 1 \leq j_1 < \dots < j_n \leq r$ choose $\sigma_j \in S_r$, such that $\sigma_j(k) = j_k$ for

$1 \leq k \leq n$. Then we obtain

$$e_{i_1} \wedge \dots \wedge e_{i_n} \wedge e_{\sigma_j(n+1)} \wedge \dots \wedge e_{\sigma_j(r)} = \begin{cases} \pm e_1 \wedge \dots \wedge e_r, & \text{if } i_k = j_k \text{ for all } k \\ 0 & \text{otherwise} \end{cases}$$

By (*) we get

$$0 = \left(\sum_{1 \leq i_1 < \dots < i_n \leq r} a_{i_1, \dots, i_n} e_{i_1} \wedge \dots \wedge e_{i_n} \right) \wedge e_{\sigma_j(n+1)} \wedge \dots \wedge e_{\sigma_j(r)} = a_j e_{j_1} \wedge \dots \wedge e_{j_r}$$

and thus $a_j = 0$. □

Example 11.16 Let $M = R^n$. Then $\Lambda^k(M)$ is the free R -module with basis

$$e_{i_1} \wedge \dots \wedge e_{i_k}, \quad 1 \leq i_1 < \dots < i_k \leq n$$

and we have $e_1 \wedge e_2 = -e_2 \wedge e_1$. What is $\Lambda^n(R^n) = \Lambda^n(M)$? And what is λ_n^M ? First we obtain $\Lambda^n(R^n) = (e_1 \wedge \dots \wedge e_n)R \cong R$. Then

$$M^n = (R^n)^n = R^{n \times n}, \quad (a_1, \dots, a_n) = A \in R^{n \times n}, \quad a_i = \begin{pmatrix} a_{1i} \\ \vdots \\ a_{ni} \end{pmatrix} = \sum_{j=1}^n a_{ji} e_j \in R^n = M.$$

For λ_n^M we get

$$\begin{aligned} \lambda_n^M &= \lambda_n^{R^n} = \lambda_n(A) = \lambda_n \left(\sum_{j=1}^n a_{j1} e_j, \dots, \sum_{j=1}^n a_{jn} e_j \right) \\ &= \sum_{j=1}^n a_{j1} e_j \wedge \dots \wedge \sum_{j=1}^n a_{jn} e_j \\ &= \sum_{j=1}^n a_{j1} \left(e_1 \wedge \sum_{j=1}^n a_{j2} e_j \wedge \dots \wedge \sum_{j=1}^n a_{jn} e_j \right) \\ &= \sum_{j=1}^n a_{j1} \cdots \sum_{j=1}^n a_{jn} (e_1 \wedge \dots \wedge e_n) \\ &= \sum_{\sigma \in S_n} a_{\sigma(1)1} \cdots a_{\sigma(n)n} \cdot e_1 \wedge \dots \wedge e_n \cdot \text{sgn}(\sigma) \\ &= \det(A) \cdot e_1 \wedge \dots \wedge e_n, \end{aligned}$$

which is well-known to us.

Definition 11.17 Let M be a R -module. Then we define

$$T(M) := \bigoplus_{n=0}^{\infty} T^n(M), \quad T^0(M) := R, \quad T^1(M) := M$$

$$S(M) := \bigoplus_{n=0}^{\infty} S^n(M). \quad S^0(M) := R, \quad S(M) := M$$

$$\Lambda(M) := \bigoplus_{n=0}^{\infty} \Lambda^n(M), \quad \Lambda^0(M) := R, \quad \Lambda(M) := M$$

On $T(M)$ define a multiplication

$$\begin{aligned} \cdot : T^n(M) \times T^m(M) &\longrightarrow T^{n+m}(M), \\ (x_1 \otimes \dots \otimes x_n) \cdot (y_1 \otimes \dots \otimes y_m) &\mapsto x_1 \otimes \dots \otimes x_n \otimes y_1 \otimes \dots \otimes y_m \end{aligned}$$

Similarly do it for $S(M)$ and $\Lambda(M)$. Then we have R -algebra-structures and feel free to define

- (i) the *tensor algebra* $T(M)$,
- (ii) the *symmetric algebra* $S(M)$
- (iii) the *exterior algebra* $\Lambda(M)$.

Definition 11.18 Let R be an arbitrary ring.

- (i) An R -algebra is a ring R' together with a ring homomorphism $\alpha : R \longrightarrow R'$. In particular R' is an R -module. If α is injective, R'/R is called a *ring extension*.
- (ii) A homomorphism of R -algebras R', R'' is an R -linear map $\phi : R' \longrightarrow R''$, which is a ring homomorphism.

Example 11.19 (i) $R[X_1, \dots, X_N]$ is an R -algebra for every $n \in \mathbb{N}$.

- (ii) If R' is an R -algebra and $I \trianglelefteq R'$ an ideal, then R'/I is an R -algebra.

Remark 11.20 Let R' be an R -algebra, F a free R -module. Then $F' := F \otimes_R R'$ is a free R' -module.

proof. Let $\{e_i\}_{i \in I}$ be basis of F . Let us show, that $\{e_i \otimes 1\}_{i \in I}$ is basis of F' as an R' -module, where F' is an R' module by

$$b \cdot (x \otimes a) := x \otimes b \cdot a, \quad a, b \in R, \quad x \in F$$

Check the universal property of the free R' -module with basis $\{e_i \otimes 1\}_{i \in I}$ for $F \otimes_R R'$. Let M' be an R' -module and $f : \{e_i \otimes 1\}_{i \in I} \longrightarrow M'$ be a map. We have to show: There exists an R' -linear map $\phi : F' \longrightarrow M'$ with $\phi(e_i \otimes 1) = f(e_i \otimes 1)$. Note that the $\{e_i \otimes 1\}$ generate F' as an R' -module, since $e_i \otimes a = a \cdot (e_i \otimes 1)$ for $a \in R'$. Let $\tilde{\phi} : F \longrightarrow M'$ be the unique R -linear map satisfying $\tilde{\phi}(e_i) = f(e_i \otimes 1)$. Then define

$$\phi : F \otimes_R R' \longrightarrow M', \quad x \otimes a \mapsto a \cdot \tilde{\phi}(x).$$

Then ϕ is R' -linear and we have

$$\phi(e_i \otimes 1) = 1 \cdot \tilde{\phi}(e_i) = \tilde{\phi}(e_i) = f(e_i \otimes 1),$$

which gives us the desired structure of an R' -module. □

Proposition 11.21 *Let R be a ring, R', R'' two R -algebras.*

(i) $R' \otimes_R R''$ is an R -algebra with multiplication

$$(a_1 \otimes b_1) \cdot (a_2 \otimes b_2) := (a_1 a_2) \otimes (b_1 b_2)$$

(ii) There are R -algebra homomorphisms

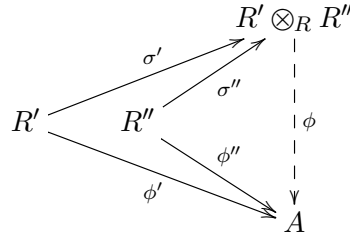
$$\sigma' : R' \longrightarrow R' \otimes_R R'', \quad a \mapsto a \otimes 1$$

$$\sigma'' : R'' \longrightarrow R' \otimes_R R'', \quad b \mapsto 1 \otimes b$$

(iii) For any R -algebra A and R -algebra homomorphisms $\phi' : R' \longrightarrow A, \phi'' : R'' \longrightarrow A$, there is a unique R -algebra homomorphism

$$\phi : R' \otimes_R R'' \longrightarrow A$$

satisfying $\phi' = \phi \circ \sigma'$ and $\phi'' = \phi \circ \sigma''$, i.e. making the following diagram commutative



proof. Defining

$$\tilde{\phi} : R' \times R'' \longrightarrow A, \quad (x, y) \mapsto \phi'(x) \cdot \phi''(y)$$

gives us ϕ , which satisfies the required properties. □

§ 12 Hilbert's basis theorem

Definition 12.1 Let R be a ring, M and R -module.

(i) M is called *noetherian*, if any ascending chain of submodules $M_0 \subset M_1 \subset \dots$ becomes stationary.

- (ii) R is called *noetherian*, if R is noetherian as an R -module, i.e. if every ascending chain of ideals becomes stationary.

Example 12.2 (i) Let k be a field. A k -vector space is noetherian if and only if $\dim(V) < \infty$.

(ii) \mathbb{Z} is noetherian.

(iii) Principle ideal domains are noetherian.

Proposition 12.3 *Let*

$$0 \longrightarrow M' \xrightarrow{\alpha} M \xrightarrow{\beta} M'' \longrightarrow 0$$

be a short exact sequence. Then M is noetherian if and only if M' and M'' are noetherian.

proof. '⇒' Let M be noetherian. Let first $M'_0 \subset M'_1 \subset \dots$ be an ascending chain of submodules in M' . Then $\alpha(M'_0) \subset \alpha(M'_1) \subset \dots$ is an ascending chain in M . Since M is noetherian, there exists some $n \in \mathbb{N}$, such that $\alpha(M'_i) = \alpha(M'_n)$ for all $i \geq n$. Since α is injective, we have $M'_i = M'_n$ for $i \geq n$, hence M' is noetherian. Let now $M''_0 \subset M''_1 \subset \dots$ be an ascending chain of submodules in M'' . Then $\beta^{-1}(M''_0) \subset \beta^{-1}(M''_1) \subset \dots$ is an ascending chain in M , hence becomes stationary. Since β is surjective, $\beta(\beta^{-1}(M''_i)) = M''_i$ and thus $M''_0 \subset M''_1 \subseteq \dots$ becomes stationary.

'⇐' Let $M_0 \subset M_1 \subset \dots$ be an ascending chain in M . Let $M'_i := \alpha^{-1}(M_i) \cong M_i \cap M'$ and $M''_i := \beta(M_i)$. By assumption, there exists $n \in \mathbb{N}$, such that $M'_i = M'_n$ and $M''_i = M''_n$ for all $i \geq n$. Then for $i \geq n$ we have

$$\begin{array}{ccccccc} 0 & \longrightarrow & M'_n & \xrightarrow{\alpha} & M_n & \xrightarrow{\beta} & M''_n & \longrightarrow & 0 & \text{exact} \\ & & \parallel & & \downarrow \gamma & & \parallel & & & \\ 0 & \longrightarrow & M'_i & \xrightarrow{\alpha} & M_i & \xrightarrow{\beta} & M''_i & \longrightarrow & 0 & \text{exact} \end{array}$$

Where γ is injective as an embedding. It remains to show that γ is surjective. Let $z \in M_i$. Since β is surjective, there exists $x \in M_n$, such that $\beta(x) = \beta(z)$. Then $\beta(\gamma(x) - z) = 0 \Rightarrow \gamma(x) - z = \alpha(y)$ for some $y \in M'_i = M'_n$. Let $\tilde{x} := x - \alpha(y)$. Then

$$\gamma(\tilde{x}) = \gamma(x) - \gamma(\alpha(y)) = \gamma(x) - \gamma(x) + z = z$$

hence γ is surjective, thus bijective and we have $M_i = M_n$ for $i \geq n$. □

Corollary 12.4 *Let R be a noetherian ring.*

(i) *Any free R -module F of finite rank n is noetherian.*

(ii) *Any finitely generated R -module M is noetherian.*

proof. (i) Prove this by induction on n .

$n = 1$ Clear.

$n > 1$ Let e_1, \dots, e_n be a basis of F and let F' be the submodule generated by e_1, \dots, e_{n-1} . Then F' is free of rank $n - 1$, thus noetherian by induction hypothesis. Moreover F/F' is free with generator e_n . Thus we have a short exact sequence

$$0 \longrightarrow F' \longrightarrow F \longrightarrow F/F' \longrightarrow 0$$

with $F', F/F'$ noetherian, hence by 12.2, F is noetherian.

- (ii) If M is generated by x_1, \dots, x_n , there is a surjective, R -linear map $\phi : F \longrightarrow M$, sending the e_i to x_i , where F is the free R -module with basis e_1, \dots, e_n . Again by 12.2, M is noetherian which finishes the proof. \square

Proposition 12.5 *For an R -module M the following statements are equivalent:*

- (i) M is noetherian.
- (ii) Any nonempty family of submodules of M has a maximal element with respect to ' \subseteq '.
- (iii) Every submodule of M is finitely generated.

proof. '(i) \Rightarrow (ii)' Let $\mathcal{M} \neq \emptyset$ be a set of submodules of M . Let $M_0 \in \mathcal{M}$. If M_0 is not maximal, there is $M_1 \in \mathcal{M}$ with $M_0 \subsetneq M_1$. If M_1 is not maximal, there is $M_2 \in \mathcal{M}$ with $M_1 \subsetneq M_2$. Since M is noetherian, we come to a maximal submodule M_n after finitely many steps.

'(ii) \Rightarrow (iii)' Let $N \subseteq M$ be a submodule. Let \mathcal{M} be the set of finitely generated submodules of N . Since $(0) \in \mathcal{M}$, we have $\mathcal{M} \neq \emptyset$ and thus there exists a maximal element $N_0 \in \mathcal{M}$. If $N_0 \neq N$, let $x \in N \setminus N_0$ and $N' := N_0 + (x)$ be the submodule generated by N_0 and x . Then clearly $N' \in \mathcal{M}$, which is a contradiction to the maximality of N_0 . Hence $N_0 = N$ and N is finitely generated.

'(iii) \Rightarrow (i)' Let $M_0 \subseteq M_1 \subseteq \dots$ be an ascending chain of submodules in M . Let $N := \bigcup_{n \in \mathbb{N}_0} M_n$. By assumption, N is finitely generated, say by x_1, \dots, x_n . Then there exists $i_0 \in \mathbb{N}$, such that $x_k \in M_{i_0}$ for all $1 \leq k \leq n$. Thus we have $M_i = M_{i_0}$ for $i \geq i_0$, i.e. the chain becomes stationary and M is noetherian. \square

Corollary 12.6 *R is noetherian if and only if every ideal $I \trianglelefteq R$ can be generated by finitely many elements. In particular, every principal ideal domain is noetherian.*

proof. Follows from Proposition 12.4. \square

Theorem 12.7 (Hilbert's basis theorem) *If R is noetherian, $R[X]$ is also noetherian.*

proof. Let $J \trianglelefteq R[X]$ be an ideal. Assume that J is not finitely generated. Let f_1 be an element of $J \setminus \{0\}$ of minimal degree. Then $(f_1) \neq J$. Inductively let $J_i := (f_1, \dots, f_i)$ and pick $f_{i+1} \in J \setminus J_i$ of minimal degree. Let a_i be the leading coefficient of f_i , i.e. we have

$$f_i = a_i X^{\deg(f_i)} + \sum_{j=1}^{\deg(f_i)-1} b_j X^j$$

The ideal $I \triangleleft R$ generated by the a_i for $i \in \mathbb{N}$, is finitely generated by assumption. Then we find $n \in \mathbb{N}$ such that $a_{n+1} \in (a_1, \dots, a_n)$, i.e. we have

$$a_{n+1} = \sum_{i=1}^n \lambda_i a_i$$

for suitable $\lambda_i \in R$. Let $d_i := \deg(f_i)$. Note, that $d_{i+1} \geq d_i$ for all $1 \leq i \leq n$. Let now

$$\rho := \sum_{i=1}^n \lambda_i f_i X^{d_{n+1}-d_i}.$$

Then the leading coefficient of ρ is

$$a_{d_{n+1}} = \sum_{i=1}^n \lambda_i a_i$$

Hence $\deg(\rho - f_{n+1}) < d_{n+1}$, $\rho - f_{n+1} \notin J_n$, since $\rho \in J_n$, so f_{n+1} would be in J_n . This contradicts the choice of f_{n+1} . Hence our assumption was false and J is finitely generated and by Corollary 12.5 $R[X]$ is noetherian.

Corollary 12.8 *Let R be noetherian. Then*

- (i) $R[X_1, \dots, X_n]$ is noetherian for any $n \in \mathbb{N}$.
- (ii) Any finitely generated R -algebra is noetherian.

§ 13 Integral ring extensions

Definition 13.1 Let R be ring, S an R -algebra.

- (i) If $R \subseteq S$, S/R is called a *ring extension*.
- (ii) If $R \subseteq S$, $b \in S$ is called *integral over R* , if there exists a monic polynomial $f \in R[X] \setminus \{0\}$ such that $f(b) = 0$.
- (iii) S/R is called an *integral ring extension*, if every $b \in S$ is integral over R .

Example 13.2 (i) If $R = k$ is a field, then *integral* is equivalent to *algebraic*.

- (ii) $\sqrt{2}$ is integral over \mathbb{Z} , since $f = X^2 - 2$ is monic with $f(\sqrt{2}) = 0$.
- (iii) $\frac{1}{2}$ is not integral over \mathbb{Z} .

Assume $\frac{1}{2}$ is integral over \mathbb{Z} . Then there exists some monic $f \in R[X]$, such that $f(\frac{1}{2}) = 0$, i.e. we have

$$\left(\frac{1}{2}\right)^n + g\left(\frac{1}{2}\right) = 0 \quad (*)$$

for some $g \in \mathbb{Z}[X]$. Then $2^{n-1} \cdot g\left(\frac{1}{2}\right) \in \mathbb{Z}$. Multiplying (*) by 2^{n-1} gives us

$$2^{n-1} \cdot \left(\left(\frac{1}{2}\right)^n + g\left(\frac{1}{2}\right) \right) = 0$$

and hence

$$\frac{1}{2} = -2^{n-1} \cdot g\left(\frac{1}{2}\right) \in \mathbb{Z}.$$

Thus $\frac{1}{2}$ is not integral over \mathbb{Z} . More generally, we easily see that any $q \in \mathbb{Q} \setminus \mathbb{Z}$ is not integral over \mathbb{Z} .

Lemma 13.3 *Let S/R be a ring extension, $b \in S$. If $R[b]$ is contained in a subring $S' \subseteq S$ which is finitely generated as an R -module, then b is integral over R .*

proof. Let s_1, \dots, s_n be generators of S' . Since $b \cdot s_i \in S$ (we have $b \in R[b] \subseteq S$), we find $a_{ik} \in R$, such that

$$b \cdot s_i = \sum_{k=1}^n a_{ik} s_k \iff 0 = \sum_{k=1}^n (a_{ik} - \delta_{ik}) s_k. \quad (*)$$

Claim (a) Let A be the coefficient matrix of $(*)$. Then $\det(A) = 0$

Since the determinant is a monic polynomial in b of degree n with coefficients in R , b is integral over R . It remains to show the claim.

(a) Let $A^\#$ be the adjoint matrix

$$A_{ji}^\# = \det(A_{ij} \cdot (-1)^{i+j})$$

where A_{ij} is obtained from A by deleting the i -th row and j -th column. Recall

$$A^\# A = \det(A) \cdot E_n.$$

By $(*)$ we have

$$A \cdot \begin{pmatrix} s_1 \\ \vdots \\ s_n \end{pmatrix} = 0,$$

hence we have

$$A^\# \cdot A \cdot \begin{pmatrix} s_1 \\ \vdots \\ s_n \end{pmatrix} = 0 \implies \det(A) \cdot s_i = 0 \quad \text{for all } 1 \leq i \leq n.$$

Since S' is a subring of S , we have $1 \in S'$, hence there exist $\lambda_1, \dots, \lambda_n \in R$ with

$$1 = \sum_{i=1}^n \lambda_i s_i.$$

Finally

$$\det(A) = \det(A) \cdot 1 = \det(A) \cdot \sum_{i=1}^n \lambda_i s_i = \sum_{i=1}^n \det(A) \cdot \lambda_i \cdot s_i = 0$$

Proposition 13.4 *Let S/R be a ring extension. Define*

$$\overline{R} := \{b \in S \mid b \text{ is integral over } R\} \supseteq R$$

Then \overline{R} is a subring of S , called the integral closure of R in S .

proof. Let $b_1, b_2 \in \overline{R}$. We have to show, that $b_1 \pm b_2 \in \overline{R}$, $b_1 b_2 \in \overline{R}$. Let $R[b_1]$ be the smallest subring of S containing R and b_1 . Then R is finitely generated as an R -module by $1, b_1, b_1^2, \dots, b_1^{n-1}$, where n denotes the degree of the 'minimal polynomial' of f . Thus $R[b_1, b_2] = (R[b_1])[b_2]$ is also finitely generated as an $R[b_1]$ -module. This implies, that $R[b_1, b_2]$ is also finitely generated as an R -module and by Lemma 13.2, $R[b_1, b_2]/R$ is an integral ring extension. In particular, $b_1 \pm b_2$ and $b_1 b_2$ are integral over R . \square

Definition 13.5 Let S/R be a ring extension, \overline{R} the integral closure of R in S .

- (i) R is called *integrally closed* in S , if $\overline{R} = R$.
- (ii) Let R be an integral domain. The integral closure of R in $\text{Quot}(R)$ is called the *normalization* of R . R is called *normal*, if it agrees with its normalization.

Proposition 13.6 *Any factorial domain is normal.*

proof. Let R be a domain and $x = \frac{a}{b} \in \text{Quot}(R)$, $a, b \in R, b \neq 0$ relatively prime. Suppose, x is integral over R , i.e. there exist $\alpha_0, \dots, \alpha_{n-1} \in R$, such that

$$x^n + \alpha_{n-1}x^{n-1} + \dots + \alpha_1x + \alpha_0 = 0$$

Multiplying by b^n gives us

$$a^n + \alpha_{n-1}a^{n-1}b + \dots + \alpha_1ab^{n-1} + \alpha_0b^n = 0$$

and hence

$$a^n = b \cdot \underbrace{(-\alpha_{n-1}a^{n-1} - \dots - \alpha_1ab^{n-2} - \alpha_0b^{n-1})}_{\in R} \iff b \mid a^n$$

Since a and b are coprime, we have $b \in R^\times$. Thus $x = \frac{a}{b} = ab^{-1} \in R$ and R is normal. \square

Definition 13.7 Let R be a ring.

- (i) For a prime ideal $\mathfrak{p} \triangleleft R$ we define

$$ht(\mathfrak{p}) := \sup\{n \in \mathbb{N}_0 \mid \text{there exist prime ideals } \mathfrak{p}_0, \mathfrak{p}_1, \dots, \mathfrak{p}_n, \text{ with } \mathfrak{p}_n = \mathfrak{p} \text{ and } \mathfrak{p}_0 \subsetneq \dots \subsetneq \mathfrak{p}_n\}$$

to be the *height* of \mathfrak{p} .

- (ii) The *Krull-dimension* of R is

$$\dim(R) := \dim_{\text{Krull}}(R) = \sup\{ht(\mathfrak{p}) \mid \mathfrak{p} \triangleleft R \text{ prime}\}$$

Example 13.8 (i) Since $(0) \subsetneq (X_1) \subsetneq (X_1, X_2) \subsetneq \dots \subsetneq (X_1, \dots, X_n)$, we have $\dim(k[X_1, \dots, X_n]) \geq n$.

(ii) $\dim(k) = 0$ for any field k , since (0) is the only prime ideal.

(iii) $\dim(\mathbb{Z}) = 1$, since $(0) \subsetneq (p)$ is a maximal chain of prime ideals for $p \in \mathbb{P}$.

(iv) $\dim(R) = 1$ for any principle ideal domain which is not a field:

Assume p, q are prime element with $(p) \subseteq (q)$. Then $p = q \cdot a$ for some $a \in R$. Since p is irreducible, we have $a \in R^\times$ and hence $(p) = (q)$.

(v) $\dim(k[X]) = 1$ for any field k :

Theorem 13.9 (Going up theorem) Let S/R be an integral ring extension and

$$\mathfrak{p}_0 \subsetneq \mathfrak{p}_1 \subsetneq \dots \subsetneq \mathfrak{p}_n$$

a chain of prime ideals in R . Then there exists a chain of prime ideals

$$\mathfrak{P}_0 \subsetneq \mathfrak{P}_1 \subsetneq \dots \subsetneq \mathfrak{P}_n$$

in S , such that $\mathfrak{p}_i = \mathfrak{P}_i \cap R$.

proof. Do this by induction on n .

n=0 Let $\mathfrak{p} \triangleleft R$ be a prime ideal. We have to find a prime ideal $\mathfrak{P} \triangleleft S$ with $\mathfrak{P} \cap R = \mathfrak{p}$. Let

$$\mathcal{P} := \{I \triangleleft S \text{ ideal} \mid I \cap R = \mathfrak{p}\}$$

Claim (a) $\mathfrak{p}S \in \mathcal{P}$.

Then \mathcal{P} is nonempty. Zorn's lemma provides us then a maximal element $\mathfrak{m} \in \mathcal{P}$.

Claim (b) $\mathfrak{m} \triangleleft S$ is a prime ideal.

This proves the claim. It remains to show the Claims.

(b) Suppose $b_1, b_2 \in S$ with $b_1 b_2 \in \mathfrak{m}$. Assume $b_1, b_2 \in S \setminus \mathfrak{m}$.

Then $\mathfrak{m} + (b_i) \notin \mathcal{P}$, hence $(\mathfrak{m} + (b_i)) \supsetneq \mathfrak{p}$ for $i \in \{1, 2\}$. \implies Thus there exists $p_i \in \mathfrak{m}, s_i \in S$ such that $r_i := p_i + b_i s_i \in R \setminus \mathfrak{p}$. Then we have

$$r_1 r_2 = (p_1 + b_1 s_1)(p_2 + b_2 s_2) = \underbrace{p_1 p_2 + p_1 b_2 s_2 + b_1 s_1 p_2}_{\in \mathfrak{m}} + \underbrace{b_1 b_2}_{\in \mathfrak{m} \text{ by ass.}} s_1 s_2 \in \mathfrak{m}$$

Clearly $r_1 r_2 \in R$, hence $r_1 r_2 \in \mathfrak{m} \cap R = \mathfrak{p}$, which is a contradiction, since \mathfrak{p} is prime.

(a) We have to show $\mathfrak{p}S \cap R = \mathfrak{p}$. We prove both inclusions.

' \supseteq ' This is clear by definition.

' \subseteq ' Let now

$$b = \sum_{i=0}^n p_i t_i, \quad p_i \in \mathfrak{p}, t_i \in S$$

Since the t_i are integral over R , $R[t_1, \dots, t_n] =: S'$ is finitely generated. Let

s_1, \dots, s_m be generators of S' as an R -module. Since $b \in \mathfrak{p}S'$, we have

$$bs_i = \sum_{k=0}^m a_{ki}s_k$$

for suitable $a_{ik} \in \mathfrak{p}$. Then as in lemma 13.3 we have $\det(a_{ik} - \delta_{ik}b) = 0$ and thus b is a zero of monic polynomial with coefficients in \mathfrak{p} , i.e. b satisfies an equation

$$b^n + a_{n-1}b^{n-1} + \dots + a_1b + a_0 = 0 \quad \text{with } a_i \in \mathfrak{p},$$

Write

$$b^n = - \sum_{i=0}^{n-1} a_i b^i \in \mathfrak{p},$$

since $b^i \in \mathfrak{p}$. Since \mathfrak{p} is prime, we must have $b \in \mathfrak{p}$ and hence the required inclusion.

n>1 By induction hypothesis we have a chain

$$\mathfrak{P}_0 \subsetneq \mathfrak{P}_1 \subsetneq \dots \subsetneq \mathfrak{P}_{n-1}$$

satisfying $\mathfrak{P}_i \cap R = \mathfrak{p}_i$. Moreover we find $\mathfrak{P}_n \triangleleft S$ such that $\mathfrak{P}_n \cap R = \mathfrak{p}_n$. It remains to show $\mathfrak{P}_{n-1} \subsetneq \mathfrak{P}_n$. For $x \in \mathfrak{P}_{n-1}$ we have $x \in R \cap \mathfrak{p}_{n-1}$, i.e. $x \in \mathfrak{p}_{n-1} \subset \mathfrak{p}_n$. Thus $x \in \mathfrak{p}_n \cap R = \mathfrak{P}_n$. Assume now $\mathfrak{P}_{n-1} = \mathfrak{P}_n$. Let $x \in \mathfrak{p}_n$. Then

$$x \in \mathfrak{p}_n \in \mathfrak{p}_n \cap R = \mathfrak{P}_n = \mathfrak{P}_{n-1} = \mathfrak{p}_{n-1} \cap R, \implies x \in \mathfrak{p}_{n-1}$$

and thus $\mathfrak{p}_n \subseteq \mathfrak{p}_{n-1}$, hence $\mathfrak{p}_n = \mathfrak{p}_{n-1}$, a contradiction. □

Theorem 13.10 *Let S/R be an integral ring extension. Then $\dim(R) = \dim(S)$.*

proof. '≤' Follows from Proposition 13.7

'≥' Let $\mathfrak{P}_0 \subsetneq \mathfrak{P}_1 \subsetneq \dots \subsetneq \mathfrak{P}_n$ be chain of prime ideals in S and define $\mathfrak{p}_i := \mathfrak{P}_i \cap R$.

Then \mathfrak{p}_i is prime and we have $\mathfrak{p}_i \subseteq \mathfrak{p}_{i+1}$. It remains to show, that $\mathfrak{p}_i \neq \mathfrak{p}_{i+1}$.

Define $S' := S/\mathfrak{P}_i$ and $R' := R/\mathfrak{p}_i$. Then S'/R' is integral (!).

We have to show that $\overline{\mathfrak{P}}_{i+1} \cap R = \overline{\mathfrak{p}}_{i+1} :=$ image of \mathfrak{p}_{i+1} in S' is not (0).

Let $b \in \mathfrak{P}_{i+1} \setminus \{0\}$. Since b is integral over R' , there exist $a_0, \dots, a_{n-1} \in R$, such that

$$b^n + a_{n-1}b^{n-1} + \dots + a_1b + a_0 = 0$$

Let further n be minimal with this property. Write

$$a_0 = -b \cdot \underbrace{(a_1 + a_2b + \dots + a_{n-1}b^{n-2} + b^{n-1})}_{=:c} \in \overline{\mathfrak{P}}_{i+1} \cap R = \overline{\mathfrak{p}}_{i+1}$$

But $c \neq 0$ by the choice of n and $b \neq 0$. Since $R' = R/\mathfrak{p}$ is an integral domain, we have $\bar{0} \neq a_0 \in \bar{\mathfrak{p}}_{i+1}$ and thus $\bar{\mathfrak{p}}_{i+1} \neq (0)$, which proves the claim. \square

Theorem 13.11 (Noether normalization) *Let k be a field. Then every finitely generated k -algebra is an integral extension of a polynomial ring over $k[X]$.*

proof. Let a_1, \dots, a_n be generators of A as a k -algebra. Prove the theorem by induction.

n=1 If a_1 is transcendental over k , then $A \cong k[X]$. Otherwise $A \cong k[X]/(f)$, where f denotes the minimal polynomial of a_1 over k . Thus A is integral over k .

n>1 If a_1, \dots, a_n are algebraically independent, $A \cong k[X_1, \dots, X_n]$. Otherwise there exists some polynomial

$$F \in k[X_1, \dots, X_n] \setminus \{0\} \text{ such that } F(a_1, \dots, a_n) = 0.$$

case 1 Assume we have

$$F = X_n^m + \sum_{i=1}^{m-1} g_i X_n^i$$

with $g_i \in k[X_1, \dots, X_n]$. Then $F(a_1, \dots, a_n) = 0$, hence a_n is integral over $A' := k[a_1, \dots, a_{n-1}]$. By induction hypothesis, A' is integral over some polynomial ring, so is A .

case 2 For the general case write

$$F = \sum_{i=0}^m F_i,$$

where F_i is homogenous of degree i , i.e. the sum of the exponents of any monomial in f_i is equal to i . Then replace a_i by $b_i := a_i - \lambda a_n$ (*) with suitable $\lambda_i \in k$, $1 \leq i \leq n-1$. Then $A \cong k[b_1, \dots, b_{n-1}, a_n]$. For any monomial $a_1^{d_1} \cdots a_n^{d_n}$ we find

$$a_1^{d_1} \cdots a_n^{d_n} = (b_1 + \lambda_1 a_n)^{d_1} \cdots (b_{n-1} + \lambda_{n-1} a_n)^{d_{n-1}} \cdot a_n^{d_n} = \left(\prod_{i=1}^{n-1} \lambda_i^{d_i} \right) \cdot a_n^{\sum_{i=1}^n d_i} + \mathcal{O}(a_n)$$

where $\mathcal{O}(a_n)$ denotes terms of lower degree in a_n . Then for $d := \sum_{i=1}^n d_i$ we obtain

$$F_d(a_1, \dots, a_n) = a_n^d \cdot F_d(\lambda_1, \dots, \lambda_{n-1}, 1) + \mathcal{O}(a_n)$$

and thus

$$F(a_1, \dots, a_n) = a_n^m F_m(\lambda_1, \dots, \lambda_{n-1}, 1) + \mathcal{O}(a_n)$$

Choose now $\lambda_1, \dots, \lambda_{n-1} \in k$, such that $F_m(\lambda_1, \dots, \lambda_{n-1}, 1) \neq 0$. If k is infinite, this is always possible. In the finite case, go back to (*) and use $b_i := a_i + a_n^{\mu_i}$ instead and repeat the procedure. Then by the first case and induction hypothesis the claim follows. \square

§ 14 Dedekind domains

Definition 14.1 A noetherian integral domain R of dimension 1 is called a *Dedekind domain*, if every nonzero ideal $I \triangleleft R$ has a unique representation as a product of prime ideals

$$I = \mathfrak{p}_1 \cdots \mathfrak{p}_r$$

Definition + remark 14.2 Let R be a noetherian integral domain, $k := \text{Quot}(R)$ and $(0) \neq I \subseteq k$ an R -module.

- (i) I is called a *fractional ideal*, if there exists $a \in R \setminus \{0\}$, such that $a \cdot I \subseteq R$.
- (ii) I is a fractional ideal if and only if I is finitely generated as an R -module.
- (iii) For a fractional ideal I let

$$I^{-1} := \{x \in k \mid x \cdot I \subseteq R\}$$

Then I^{-1} is a fractional ideal.

- (iv) I is called *invertible*, if $I \cdot I^{-1} = R$, where $I \cdot I^{-1}$ denotes the R -module generated by all products $x \cdot y$ with $x \in I, y \in I^{-1}$.

proof. (ii) '⇒' If $a \cdot I \subseteq R$, then $a \cdot I$ is an ideal in R . since R is noetherian, $a \cdot I$ is finitely generated, say by x_1, \dots, x_n . Then I is generated by $\frac{x_1}{a}, \dots, \frac{x_n}{a}$.

'⇐' Let y_1, \dots, y_m be generators of I . Write $y_i = \frac{r_i}{a_i}$ with $r_i, a_i \in R \setminus \{0\}$. Define

$$a := \prod_{i=1}^n a_i$$

Then for any generator we have $a \cdot y_i = r \cdot a_1 \cdots a_{i-1} \cdot a_{i+1} \cdots a_m \in R$, hence $a \cdot I \subseteq R$.

Example 14.3 Every principle ideal $I \neq (0)$ is invertible:

Let $I = (a) \triangleleft R$. Then $I^{-1} = \frac{1}{a}R$, since we have

$$I \cdot I^{-1} = (a) \cdot \frac{1}{a}R = aR \cdot \frac{1}{a}R = R$$

Proposition 14.4 Let R be a Dedekind domain. Then every nonzero ideal $I \triangleleft R$ is invertible.

proof. Let $(0) \neq I \triangleleft R$ be a proper ideal. Then by assumption we can write

$$I = \mathfrak{p}_1 \cdots \mathfrak{p}_r$$

with prime ideal $\mathfrak{p}_i \triangleleft R$.

If each \mathfrak{p}_i is invertible, then we have

$$I \cdot \mathfrak{p}_r^{-1} \cdots \mathfrak{p}_1^{-1} = R,$$

hence I is invertible. Thus we may assume that $I = \mathfrak{p}$ is prime. Let $a \in \mathfrak{p} \setminus \{0\}$ and write

$$(a) = \mathfrak{p}_1 \cdots \mathfrak{p}_m$$

with prime ideals $\mathfrak{p}_i \triangleleft R$. Then $(a) \subseteq \mathfrak{p}$, i.e. $\mathfrak{p}_i \subseteq \mathfrak{p}$ for some $1 \leq i \leq m$, say $i = 1$. Since the ideals were proper and $\dim(R) = 1$, we have $\mathfrak{p}_1 = \mathfrak{p}$ and $\mathfrak{p}^{-1} = \mathfrak{p}_1^{-1} = \frac{1}{a} \cdot \mathfrak{p}_2 \cdots \mathfrak{p}_m$, since $\mathfrak{p}_1 \mathfrak{p}_1^{-1} = \frac{1}{a}(a) = (1) = R$. \square

Corollary 14.5 *The fractional ideals in a Dedekind domain R form a group.*

proof. Let $(0) \neq I \subseteq k = \text{Quot}(R)$ be a fractional ideal. Choose $a \in R$ such that $a \cdot I \subseteq R$. By Proposition 14.3, $a \cdot I$ is invertible, i.e. there exists a fractional ideal I' , such that

$$(a \cdot I) \cdot I' = R \implies I \cdot (a \cdot I') = R$$

where R is neutral element of the group. \square

Proposition 14.6 *Every Dedekind domain R is normal.*

proof. Let $x \in k := \text{Quot}(R)$ be integral over R , i.e. we can write

$$x^n + a_{n-1}x^{n-1} + \dots + a_1x + a_0 = 0, \quad a_i \in R$$

By the proof of Proposition 13.3, $R[x]$ is a finitely generated R -module, hence $R[x]$ is a fractional ideal by Remark 14.2. Further by Corollary 14.4 $R[x]$ is invertible, i.e. we can find $I \triangleleft k$, such that $I \cdot R[x] = R$.

On the other hand $R[x]$ is a ring, i.e. $R[x] \cdot R[x] = R[x]$. Multiplying the equation by I gives us $x \in R$. In particular we have

$$R = I \cdot R[x] = I \cdot (R[x] \cdot R[x]) = (I \cdot R[x]) \cdot R[x] = R \cdot R[x] = R[x],$$

which implies the claim. \square

Proposition 14.7 *Let R be noetherian integral domain of dimension 1. Then R is a Dedekind domain if and only if R is normal.*

proof. ' \implies ' This is Proposition 14.5

' \impliedby ' We claim

claim (a) For every prime ideal $(0) \neq \mathfrak{p} \triangleleft R$ the localization $R_{\mathfrak{p}}$ is a discrete valuation ring.

claim (b) Every nonzero ideal in R is invertible.

Then let $(0) \neq I \neq R$ be an ideal in R . Then $I \subseteq \mathfrak{m}_0$ for a maximal ideal $\mathfrak{m}_0 \triangleleft R$. By claim (b), \mathfrak{m}_0 is invertible. Define $I_1 := \mathfrak{m}_0^{-1} \cdot I$. Then $I_1 \subseteq \mathfrak{m}_0^{-1} \cdot \mathfrak{m}_0 = R$ is an ideal. If $I_1 = R$, then

$I = \mathfrak{m}_0$. Otherwise let \mathfrak{m}_1 be a maximal ideal containing I_1 and define $I_2 := \mathfrak{m}_1^{-1} \cdot I_1 \triangleleft R$. If $I_1 = I$, then $\mathfrak{m}_0^{-1} \cdot I = I \xrightarrow{\text{invert.}} \mathfrak{m}_0^{-1} = R$, which is a contradiction.

By this way we obtain a chain of ideals

$$I \subsetneq I_1 \subsetneq I_2 \subsetneq \dots \subsetneq I_n$$

Since R is noetherian, there exists $n \in \mathbb{N}$; such that $I_n = R$. Then

$$R = I_n = \mathfrak{m}_{n-1}^{-1} \cdot I_{n-1} = \mathfrak{m}_{n-1}^{-1} \cdot \mathfrak{m}_{n-1}^{-1} \cdot I_{n-2} = \mathfrak{m}_{n-1}^{-1} \cdot \dots \cdot \mathfrak{m}_0^{-1} \cdot I$$

Thus

$$I = \mathfrak{m}_0 \cdot \mathfrak{m}_1 \cdot \dots \cdot \mathfrak{m}_{n-2} \cdot \mathfrak{m}_{n-1}$$

with maximal, thus prime ideals \mathfrak{m}_i . Hence R is a Dedekind domain.

It remains to show the claims.

(b) Let $(0) \neq I \triangleleft R$ be an ideal. We have to show $I \cdot I^{-1} = R$ for $I^{-1} = \{x \in k \mid x \cdot I \subseteq R\}$.

' \subseteq ' Clear.

' \supseteq ' Assume $I \cdot I^{-1} \neq R$. Then there exists a maximal ideal $\mathfrak{m} \triangleleft R$ such that $I \cdot I^{-1} \subseteq \mathfrak{m}$.

By claim (a), $R_{\mathfrak{m}}$ is a principal ideal domain, thus $I \cdot R_{\mathfrak{m}}$ is generated by one element, say $\frac{a}{s}$ for some $a \in I, s \in R \setminus \mathfrak{m}$. Let now b_1, \dots, b_n be generators of I as an ideal in R .

Then

$$\frac{b_i}{1} = \frac{a}{s} \cdot \frac{r_i}{s_i}, \quad r_i \in R, s_i \in R \setminus \mathfrak{m}, \quad \text{for } 1 \leq i \leq n$$

Define $t := s \cdot s_1 \cdot \dots \cdot s_n \in R \setminus \mathfrak{m}$.

We have $\frac{t}{a} \in I^{-1}$, since

$$\frac{t}{a} \cdot b_i = \frac{t}{a} \cdot \frac{a}{s} \cdot \frac{r_i}{s_i} = r_i \cdot s_1 \cdot \dots \cdot s_{i-1} \cdot s_{i+1} \cdot \dots \cdot s_n \in R$$

for $1 \leq i \leq n$. But then

$$t = \frac{t}{a} \cdot a \in I^{-1} \cdot I \subseteq \mathfrak{m} \quad \not\subseteq$$

(a) We will only give a proof sketch. The strategy is as follows:

(i) It suffices to show, that $\mathfrak{m} := \mathfrak{p}R_{\mathfrak{p}}$ is a principal ideal.

(ii) Show that $\mathfrak{m}^n \neq \mathfrak{m}$.

(iii) Show that \mathfrak{m} is invertible.

Then pick $t \in \mathfrak{m}^2 \setminus \mathfrak{m}$ and obtain $t \cdot \mathfrak{m}^{-1} = R_{\mathfrak{m}}$. This is true, since otherwise, as \mathfrak{m} is the only maximal ideal in $R_{\mathfrak{p}}$, we would have $t \cdot \mathfrak{m}^{-1} \subseteq \mathfrak{m}$ and thus $t \in \mathfrak{m}^2$, which implies $\mathfrak{m} = \mathfrak{m}^2$.

Then we have

$$(t) = t \cdot R = t \cdot (\mathfrak{m} \cdot \mathfrak{m}^{-1}) = R_{\mathfrak{p}} \cdot \mathfrak{m} = \mathfrak{m},$$

which will give us the claim. □

Theorem 14.8 *Let R be a Dedekind domain, L/k a finite separable field extension of $k := \text{Quot}(R)$ and S the integral closure of R in L . Then S is a Dedekind domain.*

proof. We will show all the required properties of a Dedekind domain.

integral domain. This is clear.

dimension 1. We know that S/R is integral and Proposition 13.7 gives us $\dim(S) = 1$.

normal. If $x \in L$ is integral over S , x is integral over R , thus $x \in S$.

noetherian. This is the only hard work in the proof. Let $N := [L : k]$. Since L/k is separable, there exists $\alpha \in L$ such that $L = k(\alpha)$. Moreover we have $|\text{Hom}_k(L, \bar{k})| = n$, say $\text{Hom}_k(L, \bar{k}) = \{\text{id} = \sigma_1, \dots, \sigma_n\}$.

claim (a) α can be chosen in S .

Then let

$$D := \begin{pmatrix} 1 & \alpha & \dots & \alpha^{n-1} \\ 1 & \sigma_2(\alpha) & \dots & \sigma_2(\alpha^{n-1}) \\ \vdots & \vdots & & \vdots \\ 1 & \sigma_n(\alpha) & \dots & \sigma_n(\alpha^{n-1}) \end{pmatrix} = (\sigma_i(\alpha^j))_{(i,j) \in \{1, \dots, n\} \times \{0, \dots, n-1\}}$$

and $d := (\det(D))^2$. $d := d_{L/k}(\alpha)$ is called the *discriminant of L/k with respect to α* .

claim (b) We have

(i) $d \neq 0$

(ii) S is contained in the R -module generated by $\frac{1}{d}, \frac{\alpha}{d}, \dots, \frac{\alpha^{n-1}}{d}$.

Then S is submodule of a finitely generated R -module, and since R is noetherian, S is noetherian as an R -module, thus also as an S -module. This proves *noetherian*. Now prove the claims.

(a) Let $\tilde{\alpha} \in L$ be a primitive element, i.e. $L = k(\tilde{\alpha})$. Let

$$f = X^n - \sum_{i=0}^{n-1} c_i X^i$$

be the minimal polynomial of $\tilde{\alpha}$ over k . Write $c_i = \frac{a_i}{b_i}$ for suitable $a_i, b_i \in R, b_i \neq 0$. Now define

$$b := \prod_{i=0}^{n-1} b_i, \quad \alpha := b \cdot \tilde{\alpha}.$$

Since we have

$$\alpha^n = b^n \tilde{\alpha}^n = b^n \cdot \sum_{i=0}^{n-1} c_i \tilde{\alpha}^i = \sum_{i=0}^{n-1} c_i \cdot \frac{\alpha^i}{b^i} b^n$$

we obtain

$$\alpha^n = b^n \cdot \tilde{\alpha}^n = \sum_{i=0}^{n-1} c_i' \alpha^i, \quad c_i' = c_i \cdot b^{n-i} \in R.$$

Thus α is integral over R , i.e. $\alpha \in S$. We easily see $k(\alpha) = k(\tilde{\alpha})$, hence the claim is proved.

(b) (i) We have

$$d = (\det(D))^2 = \prod_{1 \leq i < j \leq n} (\sigma_i(\alpha) - \sigma_j(\alpha))^2 \neq 0,$$

since otherwise we would have $\sigma_i(\alpha) = \sigma_j(\alpha)$, i.e.e $\sigma_i = \sigma_j$, which is not possible.

(ii) Let $\beta \in S$. Write

$$\beta = \sum_{i=0}^{n-1} c_{i+1} \alpha^i, \quad c_i \in k.$$

We have to show: $c_i \in \frac{1}{d}R$ for all $1 \leq i \leq n$. Therefore we need

claim (c) There is a matrix $A \in R^{n \times n}$ and $b \in R^n$, such that

$$A \cdot \begin{pmatrix} c_1 \\ \vdots \\ c_n \end{pmatrix} = b \quad \text{and} \quad \det(A) = d.$$

Then by Cramer's rule and Claim (c) we have

$$c_i = \frac{\det(A_i)}{\det(A)} = \frac{\det(A_i)}{d} \in \frac{1}{d} \in R$$

where A_i is obtained by replacing the i -th column of A by b . This proves claim (b).

(c) Recall that

$$tr_{L/k} : L \longrightarrow k, \quad \beta \mapsto \sum_{i=1}^n \sigma_i(\beta)$$

is a k -linear map. For β as above we find for $1 \leq i \leq n$

$$(*) \quad tr_{L/k}(\underbrace{\alpha^{i-1} \beta}_{\in S}) = \sum_{j=1}^n tr_{L/k}(\alpha^{i-1} \alpha^{j-1} c_j) = \sum_{j=1}^n tr_{L/k}(\alpha^{i-1} \alpha^{j-1}) c_j \in k \cap S = R$$

where the last equality holds since R is normal and by Proposition 14.5. Let now

$$A = (a_{ij})_{(i,j) \in \{1, \dots, n\} \times \{1, \dots, n\}}, \quad a_{ij} = tr_{L/k}(\alpha^{i-1}, \alpha^{j-1})$$

and

$$b = \begin{pmatrix} b_1 \\ \vdots \\ b_n \end{pmatrix}, \quad b_i = Tr_{L/k}(\alpha^{i-1} \beta).$$

Then by (*) we have

$$A \cdot \begin{pmatrix} c_1 \\ \dots \\ c_n \end{pmatrix} = b,$$

i.e. the first part of the claim. Moreover we have $D^T D = (\tilde{a}_{ij})$, where

$$\tilde{a}_{ij} = \sum_{k=1}^n \sigma_k(\alpha^{i-1})\sigma_k(\alpha^{j-1}) = \sum_{k=1}^n \sigma_k(\alpha^{i-1}\alpha^{j-1}) = \text{tr}_{L/k}(\alpha^{i-1}, \alpha^{j-1}) = a_{ij}.$$

Hence $D^T D = A$ and by $\det(D) = \det(D^T)$ we have

$$\det(D)^2 = \det(D \cdot D) = \det(D \cdot D^T) = \det(A) = d.$$

We have now shown that S is an integral domain, of dimension 1, noetherian and normal. By Proposition 14.6 the theorem is proved. \square