

# Math146 - Lecture notes

George McNinch

2025-03-29 22:13:58 EDT (george@valhalla)

# Contents

|          |  |           |
|----------|--|-----------|
| <b>1</b> | <b>Commutative rings</b>   | <b>4</b>  |
| 1.1      | Definitions . . . . .  | 4         |
| 1.2      | Polynomial rings . . . . .   | 4         |
| <b>2</b> | <b>Properties of rings</b>   | <b>6</b>  |
| 2.1      | Ring Homomorphisms . . . . .   | 6         |
| 2.2      | Ideals of a ring . . . . .   | 6         |
| 2.3      | Quotient rings . . . . .   | 6         |
| 2.4      | Principal ideals . . . . .   | 7         |
| 2.5      | Isomorphism Theorem . . . . .  | 7         |
| 2.6      | A Homomorphism from the polynomial ring to the scalars . . . . .       | 8         |
| <b>3</b> | <b>Polynomials over a field and the division algorithm</b>             | <b>9</b>  |
| 3.1      | Some general notions for commutative rings . . . . .                   | 9         |
| 3.2      | An important result on polynomial rings . . . . .                      | 10        |
| 3.3      | The degree of a polynomial . . . . .                                   | 10        |
| 3.4      | The division algorithm . . . . .                                       | 11        |
| <b>4</b> | <b>Ideals of the polynomial ring</b>                                   | <b>13</b> |
| 4.1      | Description of ideals of the polynomial ring . . . . .                 | 13        |
| 4.2      | Principal ideal domains (PIDs) . . . . .                               | 14        |
| 4.3      | PIDs and greatest common divisors . . . . .                            | 14        |
| <b>5</b> | <b>Prime elements and unique factorization</b>                         | <b>16</b> |
| 5.1      | Irreducible elements . . . . .   | 16        |
| 5.2      | Unique factorization in a PID . . . . .                                | 16        |
| <b>6</b> | <b>The Field of fractions of an Integral Domain</b>                    | <b>19</b> |
| <b>7</b> | <b>Irreducible polynomials over a field</b>                            | <b>22</b> |
| 7.1      | Fields as quotient rings . . . . .                                     | 22        |
| 7.2      | The rational roots test . . . . .                                      | 22        |
| 7.3      | The Gauss Lemma . . . . .  | 23        |
| 7.4      | Eisenstein's irreducibility criterion . . . . .                        | 25        |
| 7.5      | Irreducibility of certain cyclotomic polynomials . . . . .             | 26        |
| <b>8</b> | <b>Some recollections of Linear Algebra</b>                            | <b>27</b> |
| 8.1      | Vector Spaces . . . . .  | 27        |
| 8.2      | Linear Transformations, subspaces and quotient vector spaces . . . . . | 27        |
| 8.3      | Bases and dimension . . . . .  | 29        |
| <b>9</b> | <b>Field extensions</b>  | <b>31</b> |
| 9.1      | Algebraic extensions of fields . . . . .                               | 31        |
| 9.2      | The minimal polynomial . . . . .                                       | 31        |
| 9.3      | Generation of extensions and primitive extensions . . . . .            | 33        |
| 9.4      | The degree of a field extension . . . . .                              | 35        |
| 9.5      | Examples of finite extensions . . . . .                                | 38        |

|           |  |           |
|-----------|--|-----------|
| 9.6       | Algebraic extensions . . . . .                                   | 39        |
| 9.7       | Another example . . . . .  | 40        |
| <b>10</b> | <b>Constructible real numbers</b>                                | <b>42</b> |
| 10.1      | Ruler and compass constructions . . . . .                        | 42        |
| 10.2      | Constructions . . . . .  | 43        |
| 10.3      | Lines and Circles over a field . . . . .                         | 44        |
| 10.4      | Characterizing constructible numbers . . . . .                   | 44        |
| 10.5      | Angle trisection . . . . .                                       | 45        |
| <b>11</b> | <b>Splitting fields</b>  | <b>47</b> |
| 11.1      | The notion of a splitting field . . . . .                        | 47        |
| 11.2      | More examples of splitting fields . . . . .                      | 48        |
| 11.3      | Uniqueness of splitting fields . . . . .                         | 48        |
| <b>12</b> | <b>Finite fields</b>   | <b>53</b> |
| 12.1      | The prime subfield of a field . . . . .                          | 53        |
| 12.2      | Some properties of finite fields . . . . .                       | 53        |
| 12.3      | Finite fields as splitting fields over the prime field . . . . . | 54        |
| 12.4      | Existence of a finite field of any prime-power order . . . . .   | 55        |
| 12.5      | Some examples of finite fields . . . . .                         | 57        |
| 12.6      | The multiplicative group of a finite field . . . . .             | 61        |
| <b>13</b> | <b>Perfect fields and separable polynomials</b>                  | <b>63</b> |
| 13.1      | Common roots and root multiplicity . . . . .                     | 63        |
| 13.2      | Multiple roots and the characteristic . . . . .                  | 64        |
| 13.3      | Perfect fields . . . . .   | 65        |
| <b>14</b> | <b>Automorphisms of algebraic objects</b>                        | <b>67</b> |
| 14.1      | Automorphism examples . . . . .                                  | 67        |
| 14.2      | Automorphisms of field extensions . . . . .                      | 68        |
| <b>15</b> | <b>The Fundamental Theorem of Galois Theory</b>                  | <b>71</b> |
| 15.1      | Subfields from subgroups . . . . .                               | 71        |
| 15.2      | Splitting fields and Galois groups . . . . .                     | 71        |
| 15.3      | Fixed fields and some linear algebra . . . . .                   | 72        |
| 15.4      | Normal extensions . . . . .                                      | 74        |
| 15.5      | The Fundamental Theorem . . . . .                                | 75        |

# 1 Commutative rings

See [Stewart, chapter 16] <sup>1</sup> for general results about commutative rings.

## 1.1 Definitions

*Definition 1.1.1.* A ring  $R$  is an additive abelian group together with an operation of multiplication  $R \times R \rightarrow R$  given by  $(a, b) \mapsto a \cdot b$  such that the following axioms hold:

- multiplication is *associative*
- multiplication *distributes* over addition: for every  $a, b, c \in R$  we have <sup>2</sup>

$$a(b + c) = ab + ac$$

and

$$(b + c)a = ba + ca$$

We say that the ring  $R$  is *commutative* if the operation of multiplication is commutative; i.e. if  $ab = ba$  for all  $a, b \in R$ .

And we say that  $R$  has identity if multiplication has an identity, i.e. if there is an element  $1_R \in R$  such that  $a \cdot 1_R = 1_R \cdot a = a$  for every  $a \in R$ . <sup>3</sup>

In the course, we will consider (almost?) exclusively rings which are commutative and have identity.

Here are some examples of commutative rings:

*Example 1.1.2.* (a)  $\mathbf{Z}, \mathbf{Q}, \mathbf{R}, \mathbf{C}$

(b) if  $X$  is a set and if  $R$  is a commutative ring, the set  $X^R$  of all  $R$ -valued functions on  $X$  can be viewed as a commutative ring in a natural way.

## 1.2 Polynomial rings

If  $R$  is a commutative ring, the collection of all polynomials in the variable  $T$  having coefficients in  $R$  is denoted  $R[T]$ .

Notice that the set of *monomials*  $S = \{T^i \mid i \in \mathbb{N}\}$  has the following properties:

(M1) every element of  $R[T]$  is an  $R$ -linear combination of elements of  $S$ . This just amounts to the statement that every polynomial  $f(T) \in R[T]$  has the form

$$f(T) = \sum_{i=0}^N a_i T^i$$

for a suitable  $N \geq 0$  and suitable coefficients  $a_i \in R$ .

---

<sup>1</sup>As noted in the course syllabus, Tisch library has an entry for this item here; click to find online access to the text *Galois Theory*, Ian Stewart. (CRC Press, 4th edition 2022).

<sup>2</sup>We often just denote multiplication by juxtaposition: i.e. we may write  $ab$  instead of  $a \cdot b$  for  $a, b \in R$

<sup>3</sup>Usually we write 1 for  $1_R$ . The idea is that  $1_R$  is the multiplicative identity of  $R$ . For example, the identity matrix  $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$  is the multiplicative identity  $1_R$  of the matrix ring  $R = \text{Mat}_2(\mathbf{R})$ .

(M2) the elements of  $S$  are linearly independent i.e. if

$$\sum_{i=0}^N a_i T^i = 0 \quad \text{for} \quad a_i \in R,$$

then  $a_i = 0$  for every  $i$ .

Polynomials in  $R[T]$  can be added in a natural way. (This is just like adding vectors in a vector space).

And there is a product operation on polynomials, as follows:

if  $f(T) = \sum_{i=0}^N a_i T^i$  and  $g(T) = \sum_{i=0}^M b_i T^i$  then

$$f(T) \cdot g(T) = \sum_{i=0}^{N+M} c_i T^i \quad \text{where} \quad c_i = \sum_{s+t=i} a_s b_t.$$

**Proposition 1.2.1.**  $R[T]$  is a commutative ring with identity.

## 2 Properties of rings

### 2.1 Ring Homomorphisms

*Definition 2.1.1.* If  $R$  and  $S$  are rings, a function  $\phi : R \rightarrow S$  is called a *ring homomorphism* provided that

- (a)  $\phi$  is a homomorphism of *additive groups*,
- (b)  $\phi$  preserves multiplication; i.e. for all  $x, y \in R$  we have  $\phi(xy) = \phi(x)\phi(y)$ , and
- (c)  $\phi(1_R) = 1_S$ .

*Definition 2.1.2.* The *kernel* of the ring homomorphism  $\phi : R \rightarrow S$  is given by

$$\ker \phi = \phi^{-1}(0) = \{x \in R \mid \phi(x) = 0\};$$

thus  $\ker \phi$  is just the kernel of  $\phi$  viewed as a homomorphism of additive groups.

Here are some properties of the kernel:

- (K1)  $\ker \phi$  is an additive subgroup of  $R$
- (K2) for every  $r \in R$  and every  $x \in \ker \phi$  we have  $rx \in \ker \phi$ .

### 2.2 Ideals of a ring

For simplicity suppose that the ring  $R$  (and  $S$ ) are *commutative* rings.

*Definition 2.2.1.* A subset  $I$  of  $R$  is an *ideal* provided that

- (a)  $I$  is an additive subgroup of  $R$ , and
- (b) for every  $r \in R$  and every  $x \in I$  we have  $rx \in I$ .

We sometimes describe condition (b) by saying that “ $I$  is closed under multiplication by every element of  $R$ ”.

The proof of the following is immediate from definitions:

**Proposition 2.2.2.** *If  $\phi : R \rightarrow S$  is a ring homomorphism, then  $\ker \phi$  is an ideal of  $R$ .*

### 2.3 Quotient rings

Let  $R$  be a commutative ring and let  $I$  be an ideal of  $R$ .

Since  $I$  is a subgroup of the (abelian) additive group  $R$ , we may consider the quotient group  $R/I$ . Its elements are (additive) cosets  $a + I$  for  $a \in R$ .

It follows from the definition of cosets that the  $a + I = b + I$  if and only if  $b - a \in I$ .

The additive group can be made into a commutative ring by defining the multiplication as follows:

For  $a + I, b + I \in R/I$  (so that  $a, b \in R$ ), the product is given by

$$(a + I)(b + I) = ab + I.$$

In order to make this definition, one must confirm that this rule is well-defined. Namely, if we have equalities  $a + I = a' + I$  and  $b + I = b' + I$ , we need to know that

$$(a + I)(b + I) = (a' + I)(b' + I).$$

Applying the definition, we see that we must confirm that

$$ab = I = a'b' + I.$$

For this, we need to argue that  $a'b' - ab \in I$ .

Since  $a + I = a' + I$ , we know that  $a' - a = x \in I$  and since  $b + I = b' + I$  we know that  $b' - b = y \in I$ .

Thus  $a' = a + x$  and  $b' = b + y$ . Now we see that

$$a'b' = (a + x)(b + y) = ab + ay + xb + xy$$

Since  $I$  is an ideal, we see that  $ay, xb, xy \in I$  hence  $ay + xb + xy \in I$ . Now conclude that  $a'b' + I = ab + I$  as required.

It is now straightforward to confirm that the ring axioms hold for the set  $R/I$  with these operations.

**Proposition 2.3.1.** *If  $I$  is an ideal of the commutative ring  $R$ , then  $R/I$  is a commutative ring with the addition and multiplication just described.*

## 2.4 Principal ideals

*Definition 2.4.1.* If  $R$  is a commutative ring and  $a \in R$ , the *principal ideal generated by  $a$*  – written  $Ra$  or  $\langle a \rangle$  – is defined by

$$Ra = \langle a \rangle = \{ra \mid r \in R\}.$$

**Proposition 2.4.2.** *For  $a \in R$ ,  $Ra$  is an ideal of  $R$ .*

*Example 2.4.3.* Let  $n \in \mathbf{Z}_{>0}$  and consider the principal ideal  $n\mathbf{Z}$  of the ring  $\mathbf{Z}$  generated by  $n \in \mathbf{Z}$ .

As an additive group,  $n\mathbf{Z}$  is the infinite cyclic group generated by  $n$ .

The quotient ring  $\mathbf{Z}/n\mathbf{Z}$  is the finite commutative ring with  $n$  elements; these elements are precisely the *congruence classes* of integers modulo  $n$ .

## 2.5 Isomorphism Theorem

**Theorem 2.5.1.** *Let  $R, S$  be commutative rings with identity and let  $\phi : R \rightarrow S$  be a ring homomorphism. Assume that  $\phi$  is surjective (i.e. onto). Then  $\phi$  determines an isomorphism  $\bar{\phi} : R/I \rightarrow S$  where  $I = \ker \phi$ , where  $\bar{\phi}$  is determined by the rule*

$$\bar{\phi}(a + I) = \phi(a) \quad \text{for } a \in R.$$

*Proof.* First, you must confirm that  $\bar{\phi}$  is *well-defined*; i.e. that if  $a + I = a' + I$  then  $\bar{\phi}(a + I) = \bar{\phi}(a' + I)$ .

Next, you must confirm that  $\bar{\phi}$  is a ring homomorphism (this is immediate from the definition of ring operations on  $R/I$ ).

Finally, you must confirm that  $\ker \bar{\phi} = \{0\}$ , where here  $0$  refers to the additive identity of the quotient ring  $R/I$ . This additive identity is of course the trivial coset  $I = 0 + I \in R/I$ .  $\square$

## 2.6 A Homomorphism from the polynomial ring to the scalars

Let  $F$  is a field and let  $a \in F$ . consider the mapping

$$\Phi : F[T] \rightarrow F$$

given by  $\Phi(f(T)) = f(a)$ . Namely, applying  $\Phi$  to a polynomial  $f(T)$  results in the value  $f(a)$  of  $f(T)$  at  $a$ .

The definition of multiplication in  $F[T]$  guarantees that  $\Phi$  is a ring homomorphism.



### 3 Polynomials over a field and the division algorithm

#### 3.1 Some general notions for commutative rings

*Definition 3.1.1.* If  $R$  is a commutative ring with 1 and if  $u \in R$  we say that  $u$  is a *unit* - or that  $u$  is *invertible* - provided that there is  $v \in R$  with  $uv = 1$ ; then  $v = u^{-1}$ .

We write  $R^\times$  for the units in  $R$ .

A commutative ring  $R$  is a *field* provided that every non-zero element is invertible. Thus  $R$  is a field if  $R^\times = R \setminus \{0\}$ .

**Proposition 3.1.2.** *If  $R$  is a commutative, then  $R^\times$  is an abelian group (with operation the multiplication in  $R$ ).*

For any commutative ring  $R$  and elements  $a, b \in R$  we say that  $a$  **divides**  $b$  - written  $a \mid b$  - if  $\exists x \in R$  with  $ax = b$ .

**Proposition 3.1.3.** *For  $a, b \in R$  we have  $a \mid b$  if and only if  $b \in \langle a \rangle$ .*

Recall that we introduced the principal ideal  $\langle a \rangle = aR$  for any commutative ring  $R$  and any  $a \in R$ . In fact, given  $a_1, \dots, a_n \in R$  we can consider the ideal

$$\langle a_1, \dots, a_n \rangle = \sum_{i=1}^n a_i R$$

defined as

$$\langle a_1, \dots, a_n \rangle = \left\{ \sum_{i=1}^n r_i a_i \mid r_i \in R \right\}.$$

It is straightforward to check that  $\langle a_1, \dots, a_n \rangle$  is indeed an ideal of  $R$ .

*Definition 3.1.4.* A non-zero element  $a \in R$  is said to be a *0-divisor* provided that there is  $0 \neq b \in R$  with  $ab = 0$ .

*Example 3.1.5.* Let  $n$  be a composite positive integer, so that  $n = ij$  for integers  $i, j > 0$ . Consider the elements  $[i] = i + n\mathbf{Z}, [j] = j + n\mathbf{Z}$  in the quotient ring  $\mathbf{Z}/n\mathbf{Z}$ .

Then  $[i]$  and  $[j]$  are both non-zero since  $0 < i, j < n$  so that  $n \nmid i$  and  $n \nmid j$ . But  $[i] \cdot [j] = [n] = 0$  so that  $[i]$  and  $[j]$  are 0-divisors of the ring  $\mathbf{Z}/n\mathbf{Z}$ .

*Definition 3.1.6.* A commutative ring  $R$  is said to be an *integral domain* provided that it has no zero-divisors.

*Example 3.1.7.* (a) Any field is an integral domain.

(b) The ring  $\mathbf{Z}$  of integers is an integral domain.

(c) Any subring of an integral domain is an integral domain.

For example, the ring  $\mathbf{Z}[i] = \{a + bi \mid a, b \in \mathbf{Z}\}$  of gaussian integers is an integral domain.

(d)  $\mathbf{Z}/n\mathbf{Z}$  is not an integral domain whenever  $n$  is composite.

(e) If  $R$  and  $S$  are commutative rings, the direct product  $R \times S$  is *never* an integral domain.

Indeed, the elements  $(1, 0)$  and  $(0, 1)$  are 0-divisors.

**Lemma 3.1.8. (Cancellation)** *Let  $R$  be an integral domain and let  $a, b, c \in R$  with  $c \neq 0$ . If  $ac = bc$  then  $a = b$ .*

*Proof.* The equation  $ac = bc$  implies that  $ac - bc = 0$  so that  $(a - b)c = 0$  by the distributive property. Since  $R$  has no zero divisors and since  $c \neq 0$  by assumption, conclude that  $a - b = 0$  i.e. that  $a = b$ .  $\square$

**Proposition 3.1.9.** *Let  $R$  be an integral domain and let  $d, d' \in R \setminus \{0\}$ . If  $\langle d \rangle = \langle d' \rangle$  then  $d$  and  $d'$  are associate.*

*Proof.* Since  $d \in \langle d' \rangle$  we may write  $d = xd'$  and since  $d' \in \langle d \rangle$  we may write  $d' = yd$ . Now we see that  $d = xd' = xyd$ . Since  $d \neq 0$  cancellation (Lemma 3.1.8) implies that  $xy = 1$ . Thus  $x, y \in R^\times$  and indeed  $d, d'$  are associate.  $\square$

### 3.2 An important result on polynomial rings

**Proposition 3.2.1.** *Let  $R$  and  $S$  be rings, let  $\phi : R \rightarrow S$  be a ring homomorphism, and let  $\alpha \in S$  be an element. There is a unique ring homomorphism*

$$\Psi : R[T] \rightarrow S$$

*such that  $\Psi(T) = \alpha$  and such that  $\Psi|_R = \phi$ .*

*Proof.* Let  $f, g \in R[T]$ , say

$$f = \sum_{i=0}^n a_i T^i \quad \text{and} \quad g = \sum_{i=0}^m b_i T^i$$

be elements of  $R[T]$ .

To see that  $\Psi$  is an additive homomorphism, note that  $f + g = \sum_{i=0}^{\max(n,m)} (a_i + b_i) T^i$  so that

$$\Psi(f + g) = \sum_{i=0}^{\max(n,m)} (a_i + b_i) \alpha^i = \sum_{i=0}^n a_i \alpha^i + \sum_{i=0}^m b_i \alpha^i = \Psi(f) + \Psi(g)$$

Similarly, to see that  $\Psi$  is multiplicative, note that  $fg = \sum_{i=0}^{n+m} c_i T^i$  where  $c_i = \sum_{s+t=i} a_s b_t$ . Now,

$$\Psi(fg) = \sum_{i=0}^{n+m} \phi(c_i) \alpha^i = \left( \sum_{i=0}^n \phi(a_i) \alpha^i \right) \left( \sum_{i=0}^m \phi(b_i) \alpha^i \right) = \Psi(f) \cdot \Psi(g)$$

$\square$

### 3.3 The degree of a polynomial

Let  $F$  be a field and consider the ring of polynomials  $F[T]$ .

**Definition 3.3.1.** The *degree* of a polynomial  $f = f(T) \in F[T]$  is defined to be  $\deg(f) = -\infty$  if  $f = 0$ , and otherwise  $\deg(f) = n$  where

$$f = \sum_{i=0}^n a_i T^i \quad \text{with each } a_i \in F \text{ and } a_n \neq 0.$$

We have some easy and familiar properties of the degree function:

**Proposition 3.3.2.** *Let  $f, g \in F[T]$ .*

(a)  $\deg(fg) = \deg(f) + \deg(g)$ .

(b)  $\deg(f + g) \leq \max\{\deg(f), \deg(g)\}$  and equality holds if  $\deg(f) \neq \deg(g)$ .

(c)  $f \in F[T]^\times$  if and only if  $\deg(f) = 0$ . In particular,  $F[T]^\times = F^\times$ .

**Corollary 3.3.3.** *For a field  $F$ , the polynomial ring  $F[T]$  is an integral domain.*

*Proof.* Let  $f, g \in F[T]$  and suppose that  $fg = 0$ . We must argue that either  $f = 0$  or  $g = 0$ .  $\square$

**Proposition 3.3.4.** *Let  $f, g \in F[T]$ . If  $g \neq 0$  and  $\deg g < \deg f$  then  $[g] = g + \langle f \rangle$  is a non-zero element of  $F[T]/\langle f \rangle$ .*

### 3.4 The division algorithm

**Theorem 3.4.1.** *Let  $F$  be a field, and let  $f, g \in F[T]$  with  $0 \neq g$ . Then there are polynomials  $q, r \in F[T]$  for which*

$$f = qg + r$$

*and  $\deg r < \deg g$ .*

*Proof.* First note that we may suppose  $f$  to be non-zero. Indeed, if  $f = 0$ , we just take  $q = r = 0$ . Clearly  $f = qg + r$ , and  $\deg(r) = -\infty < \deg(g)$  since  $g$  is non-zero.

We now proceed by induction on  $\deg(f) \geq 0$ .

For the base case in which  $\deg(f) = 0$ , we note that  $f = c$  is a constant polynomial; here  $c \in F^\times$ .

If  $\deg(g) = 0$  as well, then  $g = d \in F^\times$  and then  $c = (c/d)d + 0$  so we may take  $q = c/d$  and  $r = 0$ . Now  $\deg(r) = -\infty < \deg(g)$  as required.

If  $\deg(g) > 0$ , we simply take  $q = 0$  and  $r = f$ : we then have  $f = 0 \cdot g + f$  and  $\deg(f) = 0 < \deg(g)$  as required.

We have now confirmed the Theorem holds when  $\deg(f) = 0$ .

Proceeding with the induction, we now suppose  $n > 0$  and that the Theorem holds whenever  $f$  has degree  $< n$ . We must prove the Theorem holds when  $f$  has degree  $n$ .

Since  $f$  has degree  $n$ , we may write  $f = a_n T^n + f_0$  where  $a_n \in F^\times$  and  $f_0 \in F[T]$  has  $\deg(f_0) < n$ .

Let us write  $g = \deg(g)$ ; we may write  $g = b_m T^m + g_0$  where  $b_m \in F^\times$  and  $g_0 \in F[T]$  has  $\deg(g_0) < m$ .

If  $n < m$  we take  $q = 0$  and  $r = f$  to find that  $f = qg + r$  and  $\deg(r) < \deg(g)$ .

Finally, if  $m \leq n$  we set

$$f_1 = f - (a_n/b_m)T^{n-m}g = a_n T^n + f_0 - \left( \frac{a_n}{b_m} b_m T^n + \frac{a_n}{b_m} T^{n-m} g_0 \right) = f_0 - \frac{a_n}{b_m} T^{n-m} g_0.$$

We have  $\deg(f_0) < n$  by assumption, and  $\deg\left(\frac{a_n}{b_m} T^{n-m} g_0\right) < n$  by the Proposition together with the fact that  $\deg(g_0) < m$ .

Thus  $\deg(f_1) < n$ . Now we apply the induction hypothesis to write

$$f_1 = q_1 g + r_1 \quad \text{with } \deg(r_1) < \deg(g).$$

Finally, we have

$$f = f_1 + (a_n/b_m)T^{n-m}g = q_1 g + r_1 + (a_n/b_m)T^{n-m}g = (q_1 + (a_n/b_m)T^{n-m})g + r_1$$

so we have indeed written  $f = qg + r$  in the required form.  $\square$

**Corollary 3.4.2.** *Let  $F$  be a field and let  $f \in F[T]$ . For  $a \in F$ , there is a polynomial  $q \in F[T]$  for which*

$$f = q(T - a) + f(a).$$

**Corollary 3.4.3.** *For  $f \in F[T]$  an element  $a \in F$  is a root of the polynomial  $f$  if and only if  $T - a \mid f$  in  $F[T]$ . In particular, if  $d = \deg(f)$ ,  $f$  has no more than  $d$  distinct roots in  $F$ .*

*Proof.* The first statement is clear from Corollary 3.4.2. Now consider the distinct roots

$$\alpha_1, \dots, \alpha_e \in F$$

of  $f$ . Then  $T - \alpha_1$  divides  $f$  so that  $f = (T - \alpha_1)f_1$  for some  $f_1 \in F[T]$ . Since  $\alpha_2$  is a root of  $f$  we see that

$$0 = f(\alpha_2) = (\alpha_2 - \alpha_1)f_1(\alpha_2)$$

which shows that  $\alpha_2$  is a root of  $f_1$  since  $\alpha_1 \neq \alpha_2$ . Thus we find that

$$f = (T - \alpha_1)(T - \alpha_2)f_2$$

for some  $f_2 \in F[T]$ . Continuing in this way we find that  $\prod_{i=1}^e (T - \alpha_i)$  divides  $f$ , so that  $e \leq \deg f$  by Proposition 3.3.2.  $\square$

## 4 Ideals of the polynomial ring

### 4.1 Description of ideals of the polynomial ring

**Corollary 4.1.1.** *Let  $F$  be a field and let  $I$  be an ideal of the ring  $F[T]$ . Then  $I$  is a principal ideal; i.e. there is  $g \in I$  for which*

$$I = \langle g \rangle = g \cdot F[T].$$

*Proof.* If  $I = \{0\}$  <sup>4</sup> the results is immediate. Thus we may suppose  $I \neq 0$ .

Consider the set  $\{\deg(g) \mid 0 \neq g \in I\}$ . This is a non-empty set of natural numbers, hence it contains a minimal element by the *well-ordering principle*.

Choose  $g \in I$  such that  $\deg(g)$  is this minimal degree; we claim that  $I = \langle g \rangle$ .

Clearly  $\langle g \rangle \subseteq I$ . To complete the proof, it remains to establish the inclusion  $I \subseteq \langle g \rangle$ . Let  $f \in I$  and use the **Division Algorithm** to write  $f = qg + r$  for  $q, r \in F[T]$  with  $\deg r < \deg g$ .

Observe that  $f - qg \in I$  so that  $r \in I$ . Since  $\deg r < \deg g$  conclude that  $r = 0$ . This shows that  $f = qg \in \langle g \rangle$  as required, completing the proof.  $\square$

Let  $F$  be a field,  $F[T]$  be the ring of polynomials with coefficients in  $F$ , let  $f, g \in F[T]$  be polynomials which are not both 0.

**Definition 4.1.2.** The **greatest common divisor**  $\gcd(f, g)$  of the pair  $f, g$  is a monic polynomial  $d$  such that

(a)  $d \mid f$  and  $d \mid g$ ,

(b) if  $e \in F[T]$  satisfies  $e \mid f$  and  $e \mid g$ , then  $e \mid d$ .

**Remark 4.1.3.** If  $d, d'$  are two gcds of  $f, g$  then  $d \mid d'$  and  $d' \mid d$ . In particular,  $\deg(d) = \deg(d')$  and  $d' = \alpha d$  for some  $\alpha \in F^\times$ . It is then clear that there is no more than one monic polynomial satisfying i. and ii.

**Proposition 4.1.4.** *Let  $f, g \in F[T]$  not both 0 <sup>5</sup>.*

(a)  $\langle f, g \rangle$  is an ideal. According to the previous

corollary, there is a monic polynomial  $d \in F[T]$  with

$$\langle d \rangle = \langle f, g \rangle.$$

Then  $d = \gcd(f, g)$

(b) In particular,  $d = \gcd(f, g)$  may be written in the form  $d = uf + vg$  for  $u, v \in F[T]$ .

*Proof.* For a., write  $I = \langle f, g \rangle = \langle d \rangle$ . Since  $f, g \in I$ , the definition of  $\langle d \rangle$  shows that  $d \mid f$  and  $d \mid g$ .

Now suppose that  $e \in F[T]$  and that  $e \mid f$  and  $e \mid g$ . Then  $f, g \in \langle e \rangle$  which shows that  $\langle f, g \rangle \subseteq \langle e \rangle$ .

But this implies that  $\langle d \rangle \subset \langle e \rangle$  so that  $e \mid d$  as required. Thus we see that  $d$  is indeed equal to  $\gcd(f, g)$ .

Since  $d \in \langle d \rangle = \langle f, g \rangle$ , assertion b. follows from the definition of  $\langle f, g \rangle$ .  $\square$

<sup>4</sup>We will write simply 0 for the ideal  $\{0\}$ .

<sup>5</sup>Note that  $f, g$  are not both 0 if and only if the ideal  $\langle f, g \rangle$  is not 0.

## 4.2 Principal ideal domains (PIDs)

*Definition 4.2.1.* An integral domain  $R$  is said to be a **principal ideal domain** (abbreviated PID) provided that every ideal  $I$  of  $R$  has the form

$$I = \langle a \rangle \quad \text{for some } a \in R;$$

i.e. provided that every ideal of  $R$  is principal.

*Example 4.2.2.* (a) The ring  $\mathbf{Z}$  of integers is a PID.

(b) For any field  $F$ , the ring  $F[T]$  of polynomials is a PID - this follows from the Corollary to the division algorithm, above.

(c) The rings  $\mathbf{Z}[i]$  and  $\mathbf{Z}[\sqrt{2}]$  are PIDs - to see this one can argue that these rings are Euclidean domains and then one proves that any Euclidean domain is a PID.

## 4.3 PIDs and greatest common divisors

Let  $R$  be a PID.

The results about gcd in the polynomial ring proved in Section 4.1 actually hold in the generality of the PID  $R$ . We quickly give the statements:

*Definition 4.3.1.* Let  $a, b \in R$  such that  $\langle a, b \rangle \neq 0$ . A gcd of  $a$  and  $b$  is an element  $d \in R$  such that

- (i)  $d \mid a$  and  $d \mid b$  (in words: “ $d$  is a common divisor of  $a$  and  $b$ ”)
- (ii) if  $e \mid a$  and  $e \mid b$  then  $e \mid d$ . (in words: “any common divisor of  $a$  and  $b$  divides  $d$ ”)

**Lemma 4.3.2.** *If  $R$  is a PID and if  $d$  and  $d'$  are gcds of  $a$  and  $b$  then  $d$  and  $d'$  are associates.*

*Proof.* This follows from Proposition 3.1.9 □

*Proof.* Using the definition of gcd we see that  $d \mid d'$  and  $d' \mid d$ . Thus  $d' = dv$  and  $d = d'u$  for  $u, v \in R$ .

This shows that  $d' = dv = d'uv$ . Using cancellation, find that  $1 = uv$  so that  $u, v \in R^\times$ . □

*Remark 4.3.3.* This definition of course covers the cases when  $R = \mathbf{Z}$  and when  $R = F[T]$ . The main thing to point out is that when  $R = \mathbf{Z}$ , there is a unique **positive** gcd for any pair  $a, b \in \mathbf{Z}$  and when  $R = F[T]$  there is a unique **monic** gcd for any pair  $f, g \in F[T]$ .

For a general PID there need not be a natural choice of gcd, so for  $x, y \in R$  we can only speak of  $\gcd(x, y)$  up to multiplication by a unit of  $R$ .

**Proposition 4.3.4.** *Let  $R$  be a PID and let  $x, y \in R$  with  $\langle x, y \rangle \neq 0$ .*

(a) *Since  $R$  is a PID, we may write find  $d \in R$  with*

$$\langle d \rangle = \langle x, y \rangle.$$

*Then  $d = \gcd(x, y)$ .*

(b) *In particular,  $d = \gcd(x, y)$  may be written in the form  $d = ux + vy$  for  $u, v \in R$ .*

To prove Proposition 4.3.4 proceed as in the proof of Proposition 4.1.4.

**Proposition 4.3.5.** *Let  $R$  be a PID and let  $a, b \in R$  not both 0. Put  $d = \gcd(a, b)$ , so that  $\frac{a}{d}, \frac{b}{d} \in R$ . Then  $\gcd\left(\frac{a}{d}, \frac{b}{d}\right) = 1$ .*

*Proof.* According to Proposition 4.3.4 (b), we may write  $d = ax + by$  for suitable  $x, y \in R$ . Since  $d \mid a$  we know that  $\frac{a}{d} \in R$ ; similarly  $\frac{b}{d} \in R$ . We now see that

$$d = d\frac{a}{d}x + d\frac{b}{d}y = d\left(\frac{a}{d}x + \frac{b}{d}y\right);$$

now applying *cancellation* – i.e. Lemma 3.1.8 – we conclude that

$$1 = \frac{a}{d}x + \frac{b}{d}y.$$

This shows that  $1 \in \left\langle \frac{a}{d}, \frac{b}{d} \right\rangle$ , the ideal generated by  $\frac{a}{d}$  and  $\frac{b}{d}$ . But this implies that  $R \subset \left\langle \frac{a}{d}, \frac{b}{d} \right\rangle$  so that  $\langle 1 \rangle = R = \left\langle \frac{a}{d}, \frac{b}{d} \right\rangle$ . According to Proposition 4.3.4 this proves that  $\gcd\left(\frac{a}{d}, \frac{b}{d}\right) = 1$  as required.  $\square$

## 5 Prime elements and unique factorization

### 5.1 Irreducible elements

Let  $R$  be a principal ideal domain.

*Definition 5.1.1.* A non-zero element  $p \in R$  is said to be *irreducible* provided that  $p \notin R^\times$  and whenever  $p = xy$  for  $x, y \in R$  then either  $x \in R^\times$  or  $y \in R^\times$ .

*Remark 5.1.2.* Assume that  $p, a \in R$  with  $p$  irreducible. Then either  $\gcd(p, a) = 1$  or  $\gcd(p, a) = p$ .

**Proposition 5.1.3.**  $p \in R$  is irreducible if and only if ( $\clubsuit$ ): whenever  $a, b \in R$  and  $p \mid ab$  then either  $p \mid a$  or  $p \mid b$ .

*Proof.* ( $\Rightarrow$ ): Assume that  $p$  is irreducible, suppose that  $a, b \in R$  and that  $p \mid ab$ . We must show that  $p \mid a$  or  $p \mid b$ .

For this, we may as well suppose that  $p \nmid a$ ; we must then prove that  $p \mid b$ . Since  $p \nmid a$ , we see that  $\gcd(a, p) = 1$  by the Remark above. Then  $ua + vp = 1$  for elements  $u, v \in R$ .

Now we see that

$$b = 1 \cdot b = (ua + vp) \cdot b = uab + vpb.$$

Since  $p \mid ab$  we see that  $p \mid uab + vpb$  which proves that  $p \mid b$ , as required.

( $\Leftarrow$ ): Assume that condition ( $\clubsuit$ ) holds for  $p$ . We must show that  $p$  is irreducible. For this, assume  $p = xy$  for  $x, y \in R$ ; we must show that either  $x \in R^\times$  or  $y \in R^\times$ .

Since  $p = xy$ , in particular  $p \mid xy$  and we may apply ( $\clubsuit$ ) to conclude without loss of generality that  $p \mid x$ .

Write  $x = pa$ . We now see that  $p = xy = pay$ ; by cancellation, find that  $1 = ay$  so that  $y \in R^\times$ . We conclude that  $p$  is irreducible, as required.  $\square$

*Remark 5.1.4.* For any integral domain  $R$ , we can speak of *irreducible elements* defined as in Definition 5.1.1. And we can speak of *prime elements*, where an element  $p \in R$  is *prime* if it satisfies condition ( $\clubsuit$ ) of Proposition 5.1.3. In this language, Proposition 5.1.3 shows that in a PID, an element is prime iff it is irreducible.

**Corollary 5.1.5.** Let  $R$  be a PID, let  $p, a_1, \dots, a_n \in R$  with  $p$  prime, and suppose that  $p \mid a_1 a_2 \cdots a_n = \prod_{i=1}^n a_i$ . Then  $p \mid a_i$  for some  $1 \leq i \leq n$ .

*Example 5.1.6.* Let  $F$  a field and let  $f \in F[T]$  be a non-constant polynomial; i.e.  $\deg(f) > 0$ . If  $f$  is reducible there are polynomials  $g, h \in F[T]$  for which  $f = gh$  and  $\deg(g), \deg(h) > 0$ .

*Example 5.1.7.* If  $f \in F[T]$  is reducible (i.e. not irreducible) then the quotient ring  $F[T]/\langle f \rangle$  is not an integral domain.

Indeed, write  $f = gh$  for  $g, h \in F[T]$  non-units. Thus  $\deg f > \deg g, \deg h > 0$  by Proposition 3.3.2. According to Proposition 3.3.4, the classes  $[g], [h] \in F[T]$  are non-zero, but  $[g] \cdot [h] = [f] = 0$ . Thus  $F[T]/\langle f \rangle$  has zero divisors and is not an integral domain.

### 5.2 Unique factorization in a PID

The Fundamental Theorem of Arithmetic says that any integer  $n > 1$  may factored uniquely as a product of primes. This result holds for any PID, as follows:

**Theorem 5.2.1.** Let  $R$  be a PID, let  $0 \neq a \in R$ , and suppose that  $a$  is not a unit.



- (a) There are irreducible elements  $p_1, p_2, \dots, p_n \in R$  such that  $a = p_1 \cdot p_2 \cdots p_n$ .
- (b) if  $q_1, \dots, q_m \in R$  are irreducibles such that  $a = q_1 \cdots q_m$  then  $n = m$  and – after possibly reordering the  $q_i$  – there are units  $u_i \in R^\times$  for which  $q_i = u_i p_i$  for each  $i$ .

*Proof.* We first prove (a). For this, we first prove the following claim:

(\*) : if the conclusion of (a) fails, there is a sequence of elements  $a_1, a_2, \dots \in R \setminus R^\times$  with the property that for each  $i \geq 1$  we have: (i)  $a_{i+1} \mid a_i$  and (ii)  $a_{i+1}$  and  $a_i$  are not associate.

To prove (\*), let  $x_1 = a$ . Now suppose we have found elements  $a_1, a_2, \dots, a_n$  such that for each  $1 \leq i \leq n$  conditions (i) and (ii) hold, and such that the conclusion of (a) fails for  $a_n$ . In particular,  $a_n$  is reducible, so we may write  $a_n = xy$  with  $x, y \in R$  and  $x, y \notin R^\times$ . Without loss of generality, we may suppose that the conclusion of (a) fails for  $x$  and we set  $a_{n+1} = x$ . By construction,  $a_{n+1} \mid a_n$ ; moreover  $a_{n+1}$  and  $a_n$  are not associates. Thus we have proved by induction that (\*) holds.

To prove (a), we will now show that (\*) leads to a contradiction.

Let  $\{a_i\}$  be a sequence of elements as in (\*) and let  $I$  be given by

$$I = \bigcup_{i \geq 1} \langle a_i \rangle.$$

Since

$$\langle a_1 \rangle \subset \langle a_2 \rangle \subset \langle a_3 \rangle \subset \cdots$$

it is straightforward to see that  $I$  is an ideal. Since  $R$  is a PID, we may write  $I = \langle d \rangle$  for some  $d \in R$ . By the definition of  $I$ , we may find an index  $N$  for which  $d \in \langle a_j \rangle$  for each  $j \geq N$ .

Fix  $j \geq N$ . We may write  $d = x \cdot a_j$  for  $x \in R$ .

On the other hand,  $\langle a_j \rangle \subseteq \langle d \rangle$ , we may write  $a_j = y \cdot d$  for  $y \in R$ .

We now see that  $d = x \cdot a_j = xy d$  so that  $x, y \in R^\times$  by cancellation (Lemma 3.1.8). Thus  $d$  and  $a_j$  are *associates* so that  $\langle d \rangle = \langle a_j \rangle$ . In particular, we have proved that

$$\langle d \rangle = \langle a_N \rangle = \langle a_{N+1} \rangle = \langle a_{N+2} \rangle = \cdots$$

contradicting the assumption (ii) that  $a_{j+1}$  and  $a_j$  are not associates. This contradiction proves (a).

We now prove (b). We are given an equality

$$p_1 \cdots p_n = q_1 \cdots q_m$$

with  $p_i, q_j$  irreducible and  $n, m \geq 1$ .

We proceed by induction on the minimum  $\min(n, m)$ , and without loss of generality we suppose that  $n \leq m$  so that  $n = \min(n, m)$ .

In case  $n = 1$ , our assumption is  $p_1 = q_1 \cdots q_m$ . Applying Corollary 5.1.5 we see that  $p_i \mid q_j$  for some  $1 \leq j \leq m$ . Since  $p_i$  and  $q_j$  are irreducible, we see that  $q_j = u \cdot p_1$  for some unit  $u \in R^\times$ . Thus

$$p_1 = u \cdot p_1 \cdot \prod_{i \neq j} q_i.$$

Applying cancellation (Lemma 3.1.8) we see  $u \cdot \prod_{i \neq j} q_i = 1$  so that  $q_i \in R^\times$  for  $i \neq j$ . Thus  $m = 1$  and  $p_1$  and  $q_1$  are associates, as required. This confirms the base-case of the induction.

Now suppose that  $n > 1$  and that the result is known when the element has an expression as a product of  $< n$  irreducibles.

Thus we have

$$p_1 \cdots p_n = q_1 \cdots q_m$$

and  $m \geq n$ . Now  $p_n \mid q_1 \cdots q_m$  and as before we see for some  $1 \leq j \leq m$  that  $q_j = up_n$  for a unit  $u \in R^\times$ . Without loss of generality we may suppose that  $j = m$ . We find

$$p_1 \cdots p_{n-1} \cdot p_n = u \cdot p_n \cdot q_1 \cdots q_{m-1}$$

Applying cancellation (Lemma 3.1.8) we find that

$$p_1 \cdots p_{n-1} = uq_1 \cdots q_{m-1}$$

Replacing  $q_1$  by the irreducible  $uq_1$ , we can view the right-hand side as a product of  $m - 1$  irreducibles. Since  $m - 1 \geq n - 1$  we may apply the induction hypothesis to find that  $m - 1 = n - 1$  and that after re-ordering we have  $p_i$  associate to  $q_i$  for  $1 \leq i \leq m - 1$ . Since  $p_n$  and  $q_m$  are associate as well, this proves (b).  $\square$

## 6 The Field of fractions of an Integral Domain

Recall Example 3.1.7 that any subring of a field is an integral domain. We now want to argue that the *converse* to this statement is true, as well. Namely, an integral domain  $R$  is a subring of a field. In fact, we are essentially going to give a *construction* of such a field from  $R$ .

Let's fix an integral domain  $R$ . To confirm the suggested converse to the above Corollary, we must construct a field  $F$  and an inclusion  $i : R \subset F$ .

Of course, if we have such a mapping  $i$ , then for any  $0 \neq b \in R$ , the element  $i(b)$  is non-zero in  $F$  and hence  $i(b)^{-1} = \frac{1}{i(b)}$  should be an element of  $F$  (even though  $i(b)^{-1}$  is possibly not an element of  $R$ ). For any  $a \in R$  we should be able to multiply  $i(a)$  and  $\frac{1}{i(b)}$  in  $F$  to form the *fraction*  $\frac{i(a)}{i(b)}$ . If we choose to identify  $R$  with the image  $i(R)$ , we might simply write  $\frac{a}{b} = \frac{i(a)}{i(b)}$  for this *fraction*.

So if the field  $F$  *exists*, it must contain all fractions  $\frac{a}{b}$  for  $a, b \in R$  with  $0 \neq b$ .

In fact, we are going to construct a field  $F$  by formally introducing such fractions.

Consider the set  $W = \{(a, b) \mid a, b \in R, b \neq 0\}$  and define a relation  $\sim$  on the set  $W$  by the condition

$$(a, b) \sim (s, t) \iff at = bs.$$

This relation is motivated by the observation that for *fractions* in a field  $F$  we have

$$\frac{a}{b} = \frac{s}{t} \iff at = bs.$$

One needs to check the following:

**Proposition 6.0.1.**  $\sim$  defines an equivalence relation on  $W$ .

*Proof.* We must confirm properties of  $\sim$ :

(*reflexive*) if  $(a, b) \in W$ , then  $ab = ba \implies (a, b) \sim (a, b)$ .

(*symmetric*) if  $(a, b), (s, t) \in W$  then

$$(a, b) \sim (s, t) \implies at = bs \implies sb = ta \implies (s, t) \sim (a, b).$$

(*transitive*) Let  $(a, b), (s, t), (u, v) \in W$  and suppose that  $(a, b) \sim (s, t)$  and  $(s, t) \sim (u, v)$ . The assumptions mean that  $at = bs$  and  $sv = tu$ .

Multiplying the equation  $at = bs$  by  $v$  on each side, we see that

$$atv = bsv \implies atv = btu \implies (av)t = (bu)t;$$

since  $t \neq 0$  and since the cancellation law holds in an integral domain – see Lemma 3.1.8, conclude  $av = bu$ . Hence  $(a, b) \sim (u, v)$  which confirms the transitive law.

□

We are now going to show that the fractions - i.e. the equivalence classes in  $W$  - form a field. We define  $Q = Q(R)$  to be the set of equivalence classes of  $W$  under the equivalence relation  $\sim$ .

We write  $\frac{a}{b} = [(a, b)]$  for the equivalence class of  $(a, b) \in W$ . Thus  $Q$  is the set of (formal) fractions of elements of  $R$ , and

$$\frac{a}{b} = \frac{s}{t} \iff (a, b) \sim (s, t) \iff at = bs$$

It remains to argue that  $Q$  has the structure of a field. To do this, we must define binary operations  $+$  and  $\cdot$  on the set  $Q$  and check that they satisfy the correct axioms.

Define addition of fractions: for  $a, b, s, t \in R$  with  $b, t \neq 0$ ,

$$(\clubsuit) \quad \frac{a}{b} + \frac{s}{t} = \frac{at + bs}{bt}.$$

And define multiplication of fractions:

$$(\diamond) \quad \frac{a}{b} \cdot \frac{s}{t} = \frac{as}{bt}.$$

**Theorem 6.0.2.** *For an integral domain  $R$ , the set  $Q(R)$  of fractions of  $R$  forms a field with the indicated addition and multiplication.*

*Sketch of proof.* What must be checked??

- must first confirm that  $(\clubsuit)$  is *well-defined*! i.e. if  $a', b', s', t' \in R$  with  $\frac{a}{b} = \frac{a'}{b'}$  and  $\frac{s}{t} = \frac{s'}{t'}$ , we must check that  $\frac{a}{b} + \frac{s}{t} = \frac{a'}{b'} + \frac{s'}{t'}$ ; i.e. that

$$\frac{at + bs}{bt} = \frac{a't' + b's'}{b't'}.$$

This is straightforward if a bit tedious.

- One readily checks that  $0 = \frac{0}{1}$  is an identity for the binary operation  $+$  on  $Q$ .
- One readily checks that  $+$  is commutative for  $Q$ .
- One readily checks that  $\frac{-a}{b}$  is an additive inverse for  $\frac{a}{b}$ .
- With some more effort, one confirms that  $+$  is *associative* on  $Q$ ; i.e. for  $\alpha, \beta, \gamma \in Q$

$$(\alpha + \beta) + \gamma = \alpha + (\beta + \gamma).$$

Thus  $(Q, +)$  is an abelian group. Now consider the operation  $\diamond$  of multiplication.

- must again confirm that  $(\diamond)$  is *well-defined*! i.e. if  $a', b', s', t' \in R$  with  $\frac{a}{b} = \frac{a'}{b'}$  and  $\frac{s}{t} = \frac{s'}{t'}$ , we must check that  $\frac{a}{b} \cdot \frac{s}{t} = \frac{a'}{b'} \cdot \frac{s'}{t'}$ ; i.e. that

$$\frac{as}{bt} = \frac{a's'}{b't'}.$$

- One readily checks that  $1 = \frac{1}{1}$  is an identity for the binary operation  $\cdot$  on  $Q$ .
- One readily checks that  $\cdot$  is commutative for  $Q$ .
- With some more effort, one confirms that  $\cdot$  is *associative* on  $Q$ ; i.e. for  $\alpha, \beta, \gamma \in Q$

$$(\alpha \cdot \beta) \cdot \gamma = \alpha \cdot (\beta \cdot \gamma).$$

- Next, one must confirm the *distributive law*: for  $\alpha, \beta, \gamma \in Q$ ,

$$\alpha(\beta + \gamma) = \alpha\beta + \alpha\gamma.$$

*Phew!* □

*Remark 6.0.3.* Despite the details of the preceding proof, all that is happening is confirming properties of operations of fractions that you have used since grade-school...

Now, we want to emphasize a crucial property of the field of fractions of an integral domain.

Let  $Q(R)$  be the field constructed above, and note that there is a natural ring homomorphism  $i : R \rightarrow Q(R)$  given by  $r \mapsto i(r) = \frac{r}{1}$  for  $r \in R$ . This homomorphism is one-to-one: indeed, if  $\frac{r}{1} = 0 = \frac{0}{1}$ , then  $r \cdot 1 = 0 \cdot 1 \implies r = 0$ . Thus, we may identify  $R$  with a subring of  $Q(R)$ .

**Proposition 6.0.4.** *Let  $R$  be an integral domain, let  $\phi : R \rightarrow S$  be any ring homomorphism, and suppose that for all  $0 \neq d \in R$ ,  $\phi(d) \in S^\times$  - i.e.  $\phi(d)$  is a unit in  $S$ . Then there is a unique homomorphism  $\tilde{\phi} : Q(R) \rightarrow S$  with the property that  $\tilde{\phi}|_R = \phi$ .*

*Proof.* Let  $x \in Q(R)$  be any element. Thus  $x = \frac{a}{b} = \frac{a}{1} \cdot \frac{1}{b}$  for  $a, b \in R$  with  $b \neq 0$ .

Let's first argue that uniqueness of  $\tilde{\phi}$ . If  $\tilde{\phi}$  is a ring homomorphism, then

$$1 = \tilde{\phi}(1) = \tilde{\phi}(b \cdot \frac{1}{b}) = \phi(b)\tilde{\phi}(\frac{1}{b}) \implies \tilde{\phi}(\frac{1}{b}) = \phi(b)^{-1}$$

Since  $\tilde{\phi}$  is a ring homomorphism, we must have

$$(\clubsuit) \quad \tilde{\phi}(x) = \tilde{\phi}(\frac{a}{1})\tilde{\phi}(\frac{1}{b}) = \phi(a) \cdot \phi(b)^{-1}$$

which confirms the uniqueness.

It now only remains to check that the rule  $(\clubsuit)$  determines a ring homomorphism, which is straightforward. □

*Example 6.0.5.* The field of rational functions

Let  $F$  be a field, and consider  $R = F[T]$  the ring of polynomials. This is an integral domain, and its field of fractions  $Q(R)$  is usually written  $F(T)$  and is known as the field of rational functions over  $F$ .

Note that

$$F(T) = \left\{ \frac{f}{g} \mid f, g \in F[T], g \neq 0 \right\};$$

thus elements of  $F(T)$  are fractions  $\frac{f}{g}$  whose numerator and denominator are *polynomials*; we usually call such expressions *rational functions*.

## 7 Irreducible polynomials over a field

### 7.1 Fields as quotient rings

**Proposition 7.1.1.** *Let  $R$  be a PID and let  $p \in R$  be an irreducible element. Then the quotient ring  $A = R/\langle p \rangle$  is a field.*

*Proof.* Let  $\alpha \in A$  be non-zero. To prove that  $A$  is a field, we must show that  $\alpha$  has a multiplicative inverse. Thus  $\alpha$  has the form  $h + \langle p \rangle$  and since  $\alpha \neq 0$  we know that  $p \nmid h$ . Since  $p$  is irreducible, Remark 5.1.2 shows that  $\gcd(p, h) = 1$ .

Thus according to Proposition 4.3.4 there are elements  $x, y \in R$  for which

$$1 = xp + yh$$

Let  $\beta = y + \langle p \rangle \in A$ . Then

$$\alpha\beta = yh + \langle p \rangle = 1 + \langle p \rangle$$

since  $yh \equiv 1 \pmod{p}$ . Thus  $\beta$  is the multiplicative inverse of  $\alpha$  in  $A$ .  $\square$

*Example 7.1.2.* •  $\mathbf{Z}/p\mathbf{Z}$  is a field for a prime number  $p$ .

As a special case of Proposition 7.1.1, we have:

**Corollary 7.1.3.** *Let  $F$  be a field and let  $f$  be an irreducible polynomial in  $F[T]$ . Then  $A = F[T]/\langle f \rangle$  is a field.*

For small degree polynomials, one can confirm irreducibility just by considering roots, as follows:

**Proposition 7.1.4.** *Let  $F$  be a field and let  $f \in F[T]$  be a polynomial with  $\deg(f) \leq 3$ . If  $f$  has no root in  $F$  then  $f$  is irreducible.*

*Proof.* Suppose that  $f$  is reducible, say  $f = gh$  with  $\deg(g), \deg(h) > 0$ . Since  $\deg(f) \leq 3$  and since  $\deg(g) + \deg(h) = \deg(f)$  by Proposition 3.3.2, we see that at least one of  $g$  or  $h$  must have degree 1; without loss of generality we suppose  $\deg(g) = 1$ .

Thus  $g = aT + b$  for  $a, b \in F$  with  $a \neq 0$ . Set  $\alpha = \frac{-b}{a} \in F$  and observe that  $f(\alpha) = g(\alpha)h(\alpha) = 0$ ; thus  $f$  has the root  $\alpha \in F$ .  $\square$

*Example 7.1.5.* Let  $p$  be a prime number. Then the polynomial  $T^2 - p \in \mathbf{Q}[T]$  is *irreducible*. In particular,

$$\mathbf{Q}(\sqrt{p}) = \mathbf{Q}[T]/\langle T^2 - p \rangle$$

is a field.

### 7.2 The rational roots test

**Theorem 7.2.1.** *Let  $R$  be a PID with field of fractions  $F$  and let  $f \in R[T]$ , say*

$$f = a_0 + a_1T + \cdots + a_nT^n$$

*with  $a_i \in R$  and  $a_n \neq 0$ .*

*If  $\alpha = \frac{x}{y} \in F$  is a root of  $f$  for  $x, y \in R$  and  $y \neq 0$  and  $\gcd(x, y) = 1$  then  $x \mid a_0$  and  $y \mid a_n$ .*

*Proof.* Since  $\alpha$  is a root of  $f$  we have the equation

$$0 = f(\alpha) = a_0 + a_1 \left(\frac{x}{y}\right) + \cdots + a_n \left(\frac{x}{y}\right)^n = \sum_{i=0}^n a_i \left(\frac{x}{y}\right)^i$$

in the field  $F$ . Multiplying by the non-zero element  $y^n \in R$  we find the equation

$$0 = a_0 y^n + a_1 x y^{n-1} + \cdots + a_n x^n = \sum_{i=0}^n a_i x^i y^{n-i}$$

in  $R$ .

Thus we see that

$$a_0 y^n = -(a_1 x y^{n-1} + \cdots + a_n x^n) = - \sum_{i=1}^n a_i x^i y^{n-i} = -x \sum_{i=1}^n a_i x^{i-1} y^{n-i}$$

which shows that  $x \mid a_0 y^n$ . Since  $\gcd(x, y) = 1$  also  $\gcd(x, y^n) = 1$ . Now conclude that  $x \mid a_0$ .

Similarly, we see that

$$a_n x^n = - \sum_{i=0}^{n-1} a_i x^i y^{n-i} = -y \sum_{i=0}^{n-1} a_i x^i y^{n-i-1}$$

which shows that  $y \mid a_n x^n$ . Since  $\gcd(x^n, y) = 1$  we conclude that  $y \mid a_n$  as required.  $\square$

*Remark 7.2.2.* Let  $f = \sum_{i=0}^n a_i T^i \in R[T]$  as in the statement of Theorem 7.2.1. According to the theorem, to find a root of  $f$  in the field of fractions  $F$  of  $R$ , we must consider all fractions  $\alpha = \frac{x}{y}$  where  $\gcd(x, y) = 1$ , where  $x$  is a divisor of  $a_0$  and where  $y$  is a divisor of  $a_n$ .

Writing  $a_0 = p_1 p_2 \cdots p_n$  and  $a_n = q_1 q_2 \cdots q_m$  for irreducibles  $p_i$  and  $q_j$ , we see that it is possible in principle to make a list of all possible  $\alpha$  and then check for each candidate whether or not  $\alpha$  is a root of  $f$ .

*Example 7.2.3.* Consider the polynomial  $f = T^3 - 3T^2 + 2T - 6 \in \mathbf{Z}[T]$ . For any root  $\alpha = \frac{x}{y} \in \mathbf{Q}$  with  $\gcd(x, y) = 1$  we must have that  $x \mid 6$  and  $y \mid 1$ . Thus according to Theorem 7.2.1, the possible rational roots are  $\alpha = \pm 1, \pm 2, \pm 3, \pm 6$ .

Notice that if  $x \in \mathbf{R}$  is negative, then  $f(x) < 0$ . Thus the possible rational roots are simple  $\alpha = 1, 2, 3, 6$ . We notice that  $f(1) = -6$ ,  $f(2) = -6$  and  $f(3) = 0$ . Using the division algorithm we see that

$$T^3 - 3T^2 + 2T - 6 = (T^2 + 2)(T - 3)$$

It is now clear that 6 is not a root and that  $T^2 + 2$  is irreducible. We  $f$  has exactly one rational root, namely  $\alpha = 3$ .

### 7.3 The Gauss Lemma

Let  $R$  be a PID with field of fractions  $F$ . The polynomial ring  $R[T]$  is the subring of  $F[T]$  consisting of polynomials whose coefficients lie in  $R$ . In particular  $R[T]$  is itself an integral domain.

*Remark 7.3.1.* Note that in the case where  $R$  is *already* a polynomial ring  $F[X]$ , we introduce a *new* variable  $T$  different from  $X$ .

*Definition 7.3.2.* The *content*  $\text{content}(f)$  of the element  $f = \sum_{i=0}^N a_i T^i \in R[T]$  where  $a_i \in R$  is defined to be

$$\text{content}(f) = \gcd(a_0, a_1, \dots, a_N).$$

We say that the polynomial  $f \in R[T]$  is *primitive* if  $\text{content}(f) = 1$ .

**Lemma 7.3.3.** *Let  $f \in R[T]$  be a non-zero polynomial and let  $c = \text{content}(f) \in R$ . Then  $f$  may be written  $f = cf_0$  where  $f_0 \in R[T]$  is primitive.*

*Proof.* Write  $f = \sum_{i=0}^n a_i T^i$  with  $a_i \in R$ . Then by definition we have  $c = \gcd(a_0, \dots, a_n)$ . Note that  $c \mid a_i$  for each  $i$ ; we write  $b_i = \frac{a_i}{c} \in R$ .

We set  $f_0 = \sum_{i=0}^n b_i T^i \in R[T]$  and notice that

$$c \cdot f_0 = \sum_{i=0}^n c \cdot b_i T^i = \sum_{i=0}^n a_i T^i = f$$

as required. Finally,

$$\text{content}(f_0) = \gcd(b_0, \dots, b_n) = \gcd\left(\frac{a_0}{c}, \dots, \frac{a_n}{c}\right) = 1$$

by Proposition 4.3.5. Thus  $f_0$  is indeed primitive.  $\square$

**Lemma 7.3.4.** *Let  $p \in R$  be irreducible and consider the assignment*

$$h \mapsto \bar{h} : R[T] \rightarrow (R/\langle p \rangle)[T]$$

*defined as follows: for  $h = \sum_{i=0}^N c_i T^i \in R[T]$  with  $c_i \in R$ , the polynomial  $\bar{h} \in (R/\langle p \rangle)[T]$  is given by*

$$\bar{h} = \sum_{i=0}^N [c_i] T^i$$

*where  $[c_i] = c_i + pR$  is the class of  $c_i$  modulo  $pR$ .*

(a) *This assignment is a ring homomorphism.*

(b) *For  $h \in R[T]$ ,  $\bar{h} = 0$  if and only if  $p \mid \text{content}(h)$ .*

*Proof.* (a) follows from Proposition 3.2.1. For (b), just observe that  $\bar{h} = 0$  if and only if  $p \mid c_i$  for every  $i$ .  $\square$

**Proposition 7.3.5.** (*“The Gauss Lemma”*) *If  $f, g \in R[T]$  are primitive, then the product  $fg$  is primitive.*

*Proof.* Suppose on the contrary that there are primitive polynomials  $f, g \in R[T]$  for which  $fg$  is not primitive. Writing  $d = \text{content}(fg)$  for the content of the product, we know that  $\langle d \rangle \neq R$  so that  $d$  is divisible by some prime  $p \in R$ .

Consider the ring homomorphism  $h \mapsto \bar{h}$  of Lemma 7.3.4.

Now,  $p \mid \text{content}(fg) \implies 0 = \overline{fg} = \bar{f} \cdot \bar{g}$ . Since  $R/pR$  is a field, the ring  $(R/pR)[T]$  is an integral domain, so we may conclude that either  $\bar{f} = 0$  or  $\bar{g} = 0$ .

But according to Lemma 7.3.4 (b),  $\bar{f} = 0 \implies p \mid \text{content}(f)$  and  $\bar{g} = 0 \implies p \mid \text{content}(g)$ . This contradicts our assumption that  $1 = \text{content}(f) = \text{content}(g)$ . Thus indeed  $\text{content}(fg) = 1$ .  $\square$



**Theorem 7.3.6.** Suppose that  $f \in R[T]$  is a primitive polynomial, and that  $g, h \in K[T]$  are polynomials for which  $f = gh$  in  $K[T]$ . Then there are polynomials  $g_1, h_1 \in R[T]$  with  $\deg g = \deg g_1$  and  $\deg h = \deg h_1$  for which  $f = g_1 h_1$  in  $R[T]$ .

*Proof.* Using Lemma 7.3.3, we may write  $g = \frac{x}{y}g_1$  and  $h = \frac{z}{w}h_1$  where  $g_1, h_1 \in R[T]$  are primitive and  $x, y, z, w \in R$  with  $y, w \neq 0$ . We now see that

$$(\heartsuit) \quad yw \cdot f = xz \cdot g_1 h_1.$$

Since  $f$  is primitive, notice that  $yw = \text{content}(yw f)$ . Moreover, the Gauss Lemma – i.e. Proposition 7.3.5 – shows that  $g_1 h_1$  is primitive; thus, we have  $\text{content}(xz g_1 h_1) = xz$ .

It follows that

$$\langle yw \rangle = \langle xz \rangle$$

i.e. that  $(\clubsuit) \quad u \cdot yw = xz$  for a unit  $u \in R^\times$  – see Proposition 3.1.9.

But then  $(\heartsuit)$  and  $(\clubsuit)$  together show that  $yw \cdot f = u \cdot yw \cdot g_1 h_1$  and now the cancellation law Lemma 3.1.8 in the integral domain  $R[T]$  implies  $f = (u g_1) \cdot h_1$  which proves the Theorem.  $\square$

## 7.4 Eisenstein's irreducibility criterion

**Theorem 7.4.1.** Let  $p \in R$  be irreducible, and let

$$f = \sum_{i=0}^n a_i T^i \in R[T], \quad (\text{where } a_i \in R, \ 0 \leq i \leq n)$$

be a polynomial with  $a_n \neq 0$ . Suppose that  $p \nmid a_n$ , that  $p \mid a_i$  for  $0 \leq i \leq n-1$  and that  $p^2 \nmid a_0$ . Then  $f$  is irreducible when viewed as an element of  $F[T]$ .

*Proof.* Let  $c = \text{content}(f)$ . Then  $c \not\equiv 0 \pmod{p}$  since  $p \nmid a_n$ . Observe now that the polynomial  $\tilde{f} = \frac{1}{c}f \in R[T]$  still satisfies the assumptions of the Theorem. Since  $\tilde{f}$  is irreducible in  $K[T]$  if and only if the same is true for  $f$ , it suffices to prove the Theorem when  $f = \tilde{f}$  is primitive.

Now, according to Theorem 7.3.6 the irreducibility of  $f \in F[T]$  will follow once we show that if  $f = gh$  for  $g, h \in R[T]$  then either  $\deg g = 0$  or  $\deg h = 0$ . So suppose  $f = gh$  for  $g, h \in R[T]$ .

Consider the ring homomorphism  $f \mapsto \bar{f} : R[T] \rightarrow (R/pR)[T]$  as in Lemma 7.3.4. Assumptions on the coefficients  $a_i$  show  $\bar{f} = \bar{g}\bar{h}$  to be a non-zero multiple of  $T^n$ . Using unique factorization in the principal ideal domain  $(R/pR)[T]$  – see Theorem 5.2.1 –, it follows that  $\bar{g}$  is a non-zero multiple of  $T^i$  and  $\bar{h}$  is a non-zero multiple of  $T^j$  where  $i + j = n$  and  $0 \leq i, j \leq n$ . Moreover  $i = \deg g$  and  $j = \deg h$ .

Now the Theorem follows since if  $i, j > 0$  then  $p$  divides the constant term of both  $g$  and  $h$ , and then  $p^2 \mid a_0$  contradicting our assumption.  $\square$

*Example 7.4.2.* (a) Let  $p$  be a prime integer, let  $n \geq 1$  and let  $f = T^n - p$ . Then Theorem 7.4.1 shows that  $f \in \mathbf{Q}[T]$  is irreducible.

(b) Let  $K$  be a field and consider the ring  $K[X]$  of polynomials over  $K$ . The field of fractions of  $K[X]$  is the field  $F = K(X)$  of rational functions.

Let  $n \geq 1$  and consider the polynomial  $f = T^n - X \in F[T] = K(X)[T]$ . Then  $f$  is irreducible in  $K(X)[T]$  by Theorem 7.4.1.

## 7.5 Irreducibility of certain cyclotomic polynomials

For a prime number  $p$  consider the polynomial

$$F(T) = F_p(T) = \frac{T^p - 1}{T - 1} = T^{p-1} + T^{p-2} + \cdots + T + 1 \in \mathbf{Q}[T].$$

Applying the change of variables  $U = T - 1$  we see that

$$\begin{aligned} F(U+1) &= \frac{(U+1)^p - 1}{(U+1) - 1} = \frac{\sum_{i=1}^p \binom{p}{i} U^i}{U} \\ &= \frac{U^p + \binom{p}{p-1} U^{p-1} + \cdots + \binom{p}{2} U^2 + \binom{p}{1} U}{U} \\ &= U^{p-1} + \binom{p}{p-1} U^{p-2} + \cdots + \binom{p}{2} U + p \end{aligned}$$

In particular,  $g(U) = F(U+1) = \sum_{i=0}^{p-1} c_i U^i \in \mathbf{Q}[U]$  has degree  $p-1$  and the coefficients are given by the formulae

$$c_i = \binom{p}{i+1}, \quad 0 \leq i \leq p-1.$$

**Proposition 7.5.1.** *For a prime number  $p > 0$ , the polynomial*

$$F(T) = \frac{T^p - 1}{T - 1} = T^{p-1} + T^{p-2} + \cdots + T + 1 \in \mathbf{Q}[T]$$

*of degree  $p-1$  is irreducible.*

*Proof.* Clearly  $F(T) \in \mathbf{Q}[T]$  is irreducible if and only if  $g(U) \in \mathbf{Q}[U]$  is irreducible. Now,  $g(U) \in \mathbf{Z}[U]$  since binomial coefficients  $\binom{n}{m}$  are always integers. We are going to apply Eisenstein's criteria to show the irreducibility of  $g(U)$ . For this, we first note that  $c_{p-1} = 1$  is not divisible by  $p$  and that  $c_0 = p$  is divisible by  $p$  but not by  $p^2$ .

The irreducibility will now follow from Theorem 7.4.1 once we argue that  $(\clubsuit) : p \mid \binom{p}{i}$  for each  $1 \leq i \leq p-1$ .

To prove  $(\clubsuit)$  just note that

$$\binom{p}{i} = \frac{p!}{i!(p-i)!}.$$

Since  $0 < i < p$ , neither  $i!$  nor  $(p-i)!$  is divisible by  $p$ . On the other hand

$$p! = p \cdot (p-1) \cdot (p-2) \cdots 2 \cdot 1$$

is divisible by  $p$ .

Since one knows that  $\binom{p}{i} \in \mathbf{Z}$ , unique factorization – see Section 5.2 – implies that  $p \mid \binom{p}{i}$  as required.  $\square$

*Example 7.5.2.* For example,  $f(T) = T^4 + T^3 + T^2 + T + 1 \in \mathbf{Q}[T]$  is an irreducible since  $f(T) = \frac{T^5 - 1}{T - 1}$  and since  $p = 5$  is prime.

## 8 Some recollections of Linear Algebra

Let  $F$  be a field. Much of what you learned in a course on linear algebra remains valid for vector spaces over  $F$  and not just for vector spaces over  $\mathbf{R}$  or  $\mathbf{C}$ .

### 8.1 Vector Spaces

*Definition 8.1.1.* A *vector space* over  $F$  is an additive abelian group  $V$  together with a mapping

$$F \times V \rightarrow V$$

denoted by

$$(\alpha, v) \mapsto \alpha v$$

called *scalar multiplication* that is required to satisfy several axioms:

(VS1) the multiplicative identity  $1 = 1_F \in F$  satisfies  $1 \cdot v = v$  for all  $v \in V$ .

(VS2) scalar multiplication is associative: for all  $\alpha, \beta \in F$  and all  $v \in V$ , we have  $\alpha(\beta v) = (\alpha\beta)v$ .

(VS3) scalar multiplication distributes over addition in  $V$ : for all  $\alpha, \beta \in F$  and for all  $v, w \in V$ , we have

$$\alpha \cdot (v + w) = \alpha \cdot v + \alpha \cdot w$$

and

$$(\alpha + \beta) \cdot v = \alpha v + \beta v.$$

You should compare these requirements with axioms you may have seen in a course in linear algebra. The present list is probably shorter – that is because one needs axioms governing the behavior of addition, which we have handled by requiring  $V$  to be an additive abelian group.

### 8.2 Linear Transformations, subspaces and quotient vector spaces

*Definition 8.2.1.* Let  $V$  be a vector space over  $F$ . A subset  $W \subset V$  is called a **subspace** (or more precisely, an  $F$ -subspace) provided that

- (a)  $W$  is an additive subgroup of  $V$ , and
- (b)  $W$  is closed under scalar multiplication by  $F$  – i.e.

$$\alpha w \in W \quad \text{for all } \alpha \in F \text{ and all } w \in W.$$

*Definition 8.2.2.* If  $V$  and  $W$  are vector spaces over  $F$ , a function  $T : V \rightarrow W$  is a *linear transformation* (or more precisely, an  $F$ -linear transformation) if

- (a)  $T$  is a homomorphism of additive groups  $V \rightarrow W$ , and
- (b)  $T$  commutes with scalar multiplication – i.e.  $T(\alpha v) = \alpha T(v)$  for all  $\alpha \in F$  and all  $v \in V$ .

*Definition 8.2.3.* If  $V, W$  are vector spaces, a linear transformation  $T : V \rightarrow W$  is an *isomorphism* if there is a linear transformation  $S : W \rightarrow V$  such that  $T \circ S = 1_W$  and  $S \circ T = 1_V$ .

If  $T$  is an isomorphism, one says that  $V$  and  $W$  are isomorphic vector spaces.

**Proposition 8.2.4.** *Let  $V, W$  be  $F$ -vector spaces and let  $T : V \rightarrow W$  be a linear transformation. Then  $T$  is an isomorphism if and only if  $T$  is bijective.*

*Proof.* Suppose that  $T$  is bijective. Then we know that  $T$  is an isomorphism of additive groups, and hence there is an inverse isomorphism  $S : W \rightarrow V$ . It only remains to show that  $S$  is a linear transformation (rather than simply a group homomorphism).

So let  $\alpha \in F$  and  $w \in W$ . Since  $T$  is onto, we may write  $w = T(v)$  for some  $v \in V$ . Now,

$$S(\alpha w) = S(\alpha T(v)) = S(T(\alpha v)) = 1_W(\alpha v) = \alpha v = \alpha S(T(v)) = \alpha S(w).$$

On the other hand, if  $T$  is an isomorphism, then the inverse isomorphism  $S$  is an inverse function to  $T$  so in particular  $T$  is one-to-one and onto.  $\square$

**Proposition 8.2.5.** *If  $T : V \rightarrow W$  is a linear transformation, then*

- (a)  $\ker(T)$  is a subspace of  $V$ , and
- (b) the image  $T(V) = \{T(v) \mid v \in V\}$  is a subspace of  $W$ .

*Proof.* Exercise!  $\square$

**Proposition 8.2.6.** *Let  $W$  be a subspace of the  $F$ -vector space  $V$ . The quotient group  $V/W$  has the structure of an  $F$ -vector space, and the natural quotient mapping  $\pi : V \rightarrow V/W$  given by  $\pi(v) = v + W$  is an  $F$ -linear transformation.*

*Proof.* We must define a scalar multiplication for the additive group  $V/W$ . Given  $\alpha \in F$  and an element  $v + W \in V/W$ , define

$$\alpha \cdot (v + W) = (\alpha v) + W.$$

We must confirm that this rule is independent of the choice of coset representative  $v$  for  $v + W$ . Thus, we must suppose that

$$v + W = v' + W$$

and we must show that  $\alpha \cdot (v + W) = \alpha \cdot (v' + W)$  i.e. that  $\alpha v + W = \alpha v' + W$ .

The assumption that  $v + W = v' + W$  means that  $v - v' \in W$ . Since  $W$  is a  $F$ -subspace, we find that  $\alpha(v - v') \in W$  and using the distributive law we conclude that  $\alpha v - \alpha v' \in W$ . This shows that  $\alpha v + W = \alpha v' + W$  as required. This proves that we've given a well-defined operation of scalar multiplication.

It now remains to check that the associative and distributive laws hold for this operation. Since these properties hold for the scalar multiplication in  $V$ , the verification is straightforward; details are left to the reader.  $\square$

**Proposition 8.2.7.** *If  $T : V \rightarrow W$  is a linear transformation, there is an isomorphism  $\tilde{T} : V/\ker(T) \rightarrow T(V)$  given by  $\tilde{T}(v + \ker T) = T(v)$  for  $v \in V$ .*

*Proof.* The first isomorphism theorem for groups tells us that the rule  $\tilde{T}$  is an isomorphism of groups. In view of @prop:inv-iso, it remains to argue that  $\tilde{T}$  is a linear transformation.

Thus, let  $\alpha \in F$  and  $x \in V/\ker T$ . We may write  $x = v + \ker T$  for some  $v \in V$ . Now, by definition we have

$$\alpha x = \alpha(v + \ker T) = \alpha v + \ker T.$$

Thus, since  $T$  is a linear transformation we find the following:

$$\tilde{T}(\alpha x) = \tilde{T}(\alpha v + \ker T) = T(\alpha v) = \alpha T(v) = \alpha \tilde{T}(v + \ker T).$$

This confirms that  $\tilde{T}$  commutes with scalar multiplication and is thus a linear transformation.  $\square$

### 8.3 Bases and dimension

You are probably familiar with the notions of *spanning set* and of *linear independence*. One issue to be aware of is how to handle possibly-infinite sets in this setting.

To quote from Michael Artin's algebra text (Artin 2011):

In algebra it is customary to speak only of linear combinations of finitely many vectors. Therefore, the span of an infinite set  $S$  must be interpreted as the set of those vectors  $V$  which are linear combinations of finitely many elements of  $S$ ...

**Definition 8.3.1.** If  $S \subset V$  is a set of elements, the span of  $S$  is defined to be

$$\text{span}(S) = \left\{ \sum_{i=1}^r a_i x_i \mid r \in \mathbf{Z}_{\geq 0}, a_i \in F, x_i \in V (1 \leq i \leq r) \right\}$$

It is clear that  $\text{span}(S)$  is a *subspace* of  $V$ .

**Definition 8.3.2.** A subset  $S \subset V$  of the vector space  $V$  is said to be *linearly independent* if whenever  $n \in \mathbf{Z}_{\geq 0}$ , whenever  $x_1, \dots, x_n \in V$  are *distinct* elements of  $V$ , and whenever  $\alpha_1, \dots, \alpha_n \in F$  then

$$\sum_{i=1}^n \alpha_i x_i = 0 \implies \alpha_j = 0 \quad \text{for each } 1 \leq j \leq n.$$

**Remark 8.3.3.** We say that the vector space is *finitely generated* if there is a *finite* set  $S \subset V$  for which  $V = \text{span}(S)$ . In fact,  $V$  is then *finite dimensional* (see Definition 8.3.6 below).

**Definition 8.3.4.** Let  $V$  be a vector space over the field  $F$ . A *basis* for  $V$  is a subset  $S \subset V$

- (a)  $S$  spans  $V$ ; i.e.  $V = \text{span}(S)$ , and
- (b)  $S$  is linearly independent.

**Proposition 8.3.5.** *Let  $V$  be an  $F$ -vector space.*

- (a) *There is a basis  $\mathcal{B}$  for  $V$ .*
- (b) *If  $W \subset V$  is a subspace of  $V$ , and if  $\mathcal{C}$  is a basis for  $W$ , there is a basis  $\mathcal{B}$  for  $V$  with  $\mathcal{C} \subseteq \mathcal{B}$ .*
- (c) *If  $V = \text{span}(S)$  then there is a basis of  $V$  contained in  $S$ .*
- (d) *If  $S \subset V$  is a linearly independent subset, there is a basis of  $V$  containing  $S$ .*
- (e) *Any two bases of  $V$  have the same cardinality.*

*Proof.* When  $V$  is finitely generated, results (a)-(e) can be found in (Hoffman and Kunze 1971), §2.2 and 2.3, and in (Friedberg, Insel, and Spence 2002) §1.6.

For the general case of (a)-(d) see (Friedberg, Insel, and Spence 2002) §1.7.

A proof of (e) in case  $\mathcal{B}_1$  and  $\mathcal{B}_2$  are *infinite* bases for  $V$  requires the Schroeder-Bernstein Theorem; we won't need this result in the course.  $\square$

*Definition 8.3.6.* If  $V$  is a vector space with basis  $\mathcal{B}$ , the *dimension* of  $V$

- written  $\dim V$  or  $\dim_F V$  - is equal to the cardinality of the set  $\mathcal{B}$ .

It follows from Proposition 8.3.5 (e) that the dimension of  $V$  doesn't depend on the choice of basis.

**Proposition 8.3.7.** *Let  $V, W$  be  $F$ -vector spaces, let  $\mathcal{B}$  be a basis for  $V$ , and let  $x_b \in W$  for each  $b \in \mathcal{B}$ . Then there is a unique linear transformation  $T : V \rightarrow W$  such that  $T(b) = x_b$  for each  $b \in \mathcal{B}$ .*

*Example 8.3.8.* Let  $F[T]$  be the polynomial ring over the field  $F$ . Then  $F[T]$  is in particular a vector space over  $F$  with countably infinite basis given by  $\{T^i \mid i \geq 0\}$ .

The linear independence of this basis precisely means that if  $f = \sum_{i=0}^N a_i T^i \in F[T]$  for  $a_i \in F$ , then  $f = 0$  if and only if all  $a_i = 0$ .

**Proposition 8.3.9.** *Let  $T : V \rightarrow W$  be a linear transformation of  $F$ -vector spaces with  $\dim V < \infty$ . Then*

$$\dim_F V = \dim_F T(V) + \dim_F \ker(V).$$

## 9 Field extensions

*Definition 9.0.1.* Let  $F$  and  $E$  be fields and suppose that  $F \subset E$  is a *subring*. We say that  $F$  is a *subfield* of  $E$  and that  $E$  is a *field extension* of  $F$ .

Throughout this discussion, let  $F \subseteq E$  be an extension of fields.

### 9.1 Algebraic extensions of fields

*Definition 9.1.1.* An element  $\alpha \in E$  is said to be *algebraic* over  $F$  provided that there is some polynomial  $0 \neq f \in F[T]$  for which  $\alpha$  is a root – i.e. for which  $f(\alpha) = 0$ .

If  $\alpha$  is not algebraic over  $F$ , we say that  $\alpha$  is *transcendental* over  $F$ .

*Example 9.1.2.* • it is a fact that  $\pi, e \in \mathbf{R}$  are transcendental over  $\mathbf{Q}$ .

- Of course,  $\pi, e$  are algebraic over  $\mathbf{R}$ .
- Any element  $\alpha = a + bi \in \mathbf{C}$  (for  $a, b \in \mathbf{R}$ ) is algebraic over  $\mathbf{R}$ . Indeed,  $\alpha$  is a root of the polynomial

$$\begin{aligned} f(T) &= (T - \alpha)(T - \bar{\alpha}) \\ &= T^2 - 2\operatorname{Re}(\alpha)T + |\alpha|^2 \\ &= T^2 - 2aT + (a^2 + b^2) \in \mathbf{R}[T] \end{aligned}$$

where  $\operatorname{Re}(\alpha) = a$  denotes the *real part* of the complex number  $\alpha$ .

### 9.2 The minimal polynomial

**Proposition 9.2.1.** *Let  $\alpha \in E$  and suppose that  $\alpha$  is algebraic over  $F$ . Then there is a unique monic irreducible polynomial  $p \in F[T]$  for which  $\alpha$  is a root.*

*Moreover,*

(a)  *$p$  is the monic polynomial of smallest degree for which  $\alpha$  is a root.*

(b) *if  $f \in F[T]$  is any polynomial with  $f(\alpha) = 0$ , then  $p \mid f$ .*

*Proof.* Let  $I = \{f \in F[T] \mid f(\alpha) = 0\}$ . It is straightforward to check that it is an additive subgroup, and it is closed under multiplication with any polynomial in  $F[T]$ ; thus  $I$  is an ideal of  $F[T]$ .

Since  $\alpha$  is algebraic,  $I \neq \{0\}$ . Thus  $I$  coincides with the principal ideal  $I = \langle p \rangle$  for some monic  $0 \neq p \in F[T]$ , and  $p$  is the unique monic element of smallest degree in  $I$ .

It only remains to argue that  $p$  is irreducible. Suppose that  $f, g \in F[T]$  and that  $p \mid fg$ . We need to argue that  $p \mid f$  or  $p \mid g$ . Well, since  $fg = pq$  for  $q \in F[T]$ , we see that

$$0 = (pq)(\alpha) = (fg)(\alpha) = f(\alpha) \cdot g(\alpha).$$

Since  $f(\alpha), g(\alpha)$  are elements of the field  $E$ , the only way their product can be 0 is for at least one factor to be zero – i.e. either  $f(\alpha) = 0$  or  $g(\alpha) = 0$ . But then either  $f \in I$  or  $g \in I$  and thus  $p \mid f$  or  $p \mid g$ .  $\square$

**Corollary 9.2.2.** *Let  $\alpha \in E$ . If  $p \in F[T]$  is irreducible and monic, and if  $p(\alpha) = 0$ , then  $p$  is the minimal polynomial of  $\alpha$  over  $F$ .*

*Definition 9.2.3.* Let  $\alpha \in E$  be algebraic over  $F$ .

- The irreducible polynomial  $p$  of the proposition is known as the *minimal polynomial* of  $\alpha$  over  $F$ .
- The *degree* of  $\alpha$  over  $F$  is defined to be the degree of the minimal polynomial  $p$ .

*Example 9.2.4.* An element  $\alpha \in F$  has degree 1 over  $F$ , since it is the root of the irreducible degree 1 polynomial  $T - \alpha \in F[T]$ .

*Example 9.2.5.* Consider the complex number  $z = a + bi \in \mathbf{C}$  with  $a, b \in \mathbf{R}$ . Then  $z$  has degree  $\leq 2$  over  $\mathbf{R}$ , and that degree is 2 if and only if  $b \neq 0$ .

Indeed, if  $b = 0$ , then  $z = a \in \mathbf{R}$  is a root of  $T - a \in \mathbf{R}[T]$  so  $z$  has degree 1 over  $\mathbf{R}$ . Otherwise,  $z$  is a root of

$$p = (T - z)(T - \bar{z}) = T^2 - 2aT + (a^2 + b^2) \in \mathbf{R}[T].$$

Since  $p$  has roots  $z, \bar{z}$ , it has no real roots; since it has degree 2,  $p$  is irreducible over  $\mathbf{R}$ . Now the Corollary shows that  $p$  is the minimal polynomial of  $z$ .

*Example 9.2.6.* Let  $F$  be a field and let  $F(X)$  be the field of fractions  $Q(F[X])$  of the polynomial ring  $F[X]$ .

$F(X)$  is often called the field of rational functions over  $F$ ; its elements have the form

$$\frac{f}{g} = \frac{f(X)}{g(X)} \quad \text{for } f, g \in F[X]$$

Then the element  $X \in F(X)$  is *transcendental* over  $F$ .

Indeed, given any non-zero polynomial  $f(T) \in F[T]$ , we wonder: is  $f(X) = 0$ ? and of course, the answer is “no” because  $f(X)$  is just the polynomial  $f(T)$  after the substitution  $T \mapsto X$ .

In particular, the degree of  $X$  over  $F$  is undefined (or we could define it to be  $\infty$ ).

*Example 9.2.7.* Consider the field  $F = \mathbf{Q}(\sqrt{2})$  defined by adjoining to  $\mathbf{Q}$  a root of  $T^2 - 2$ . We identify  $F$  with a subfield of  $\mathbf{R}$ .

Consider the polynomial  $p(T) = T^4 - 2$  and write  $\alpha = 2^{1/4}$  for the positive real root of  $p(T)$ . Since  $p \in \mathbf{Q}[T]$  is irreducible,  $\alpha$  has degree 4 over  $\mathbf{Q}$ .

On the other hand,  $\alpha$  has degree 2 over  $F$ . Indeed, note that in  $F[T]$ ,

$$p(T) = T^4 - 2 = (T^2 - \sqrt{2})(T^2 + \sqrt{2}).$$

Since  $\alpha$  is a root of  $T^2 - \sqrt{2} \in F[T]$ , the degree of  $\alpha$  over  $F$  is  $\leq 2$ . To see that equality holds, we must argue that  $T^2 - \sqrt{2}$  is irreducible over  $F$ .

To establish this irreducibility, we will argue that  $T^2 - \sqrt{2}$  has no root in  $F$ .

A typical element of  $F$  has the form  $x = a + b\sqrt{2}$  for  $a, b \in \mathbf{Q}$ .

Suppose that

$$(\diamond) \quad \sqrt{2} = x^2 = (a + b\sqrt{2})^2 = a^2 + 2b^2 + 2ab\sqrt{2}.$$

But then comparing coefficients we see that  $a^2 + 2b^2 = 0$  and  $2ab = 1$ .



Now

$$a^2 + 2b^2 = 0 \implies a = b = 0 \implies 2ab \neq 1.$$

Thus the assumption ( $\diamond$ ) is impossible and so

$$T^2 - \sqrt{2} \in F[T] = \mathbf{Q}(\sqrt{2})[T]$$

is indeed irreducible.

We repeat for emphasis:

- the minimal polynomial of  $\alpha$  over  $\mathbf{Q}$  is  $T^4 - 2$  and has degree 4,
- the minimal polynomial of  $\alpha$  over  $\mathbf{Q}(\sqrt{2})$  is  $T^2 - \sqrt{2}$  and has degree 2.

### 9.3 Generation of extensions and primitive extensions

*Definition 9.3.1.* Let  $S \subset E$  be a subset. The smallest subfield of  $E$  containing  $F$  and  $S$  is denoted by  $F(S)$ . If  $S = \{u_1, u_2, \dots, u_n\}$  is a finite set, we often write  $F(S) = F(u_1, \dots, u_n)$  for this field.

If  $E = F(u_1, \dots, u_n)$  we say that the elements  $u_i$  *generate* the extension  $E$  of  $F$ .

If  $n = 1$ , the extension  $F(u) = F(u_1)$  of  $F$  is said to be a *primitive extension* (or sometimes: a *simple extension*).

*Remark 9.3.2. Remark:* Note that  $F(S)$  is equal to the intersection

$$F(S) = \bigcap_{K \in \mathcal{E}} K$$

of the collection

$$\mathcal{E} = \{K \subset E \mid K \text{ a subfield of } E \text{ containing } F \text{ and } S\}.$$

Since the intersection of subfields is again a subfield (check!), the notation  $F(S)$  is meaningful.

*Remark 9.3.3.* Note that by definition

$$F(u_1, u_2, \dots, u_n) = F(u_1, u_2, \dots, u_{n-1})(u_n).$$

So to “describe” the extension  $F \subset F(u_1, \dots, u_n)$  we can focus on describing primitive extensions. Given a description of primitive extensions, we can first describe the extension  $F \subset F(u_1)$  of  $F$ , next we can describe the extension  $F(u_1) \subset F(u_1)(u_2)$  of  $F(u_1)$ , and so on.

**Proposition 9.3.4.** *Let  $\alpha \in E$ .*

*a. If  $\alpha$  is algebraic over  $F$  with minimal polynomial  $p \in F[T]$  over  $F$ , then*

$$F(\alpha) \simeq F[T]/\langle p \rangle,$$

*where  $\alpha$  identifies with  $T + \langle p \rangle$ .*

*In particular,  $F(\alpha)$  has as an  $F$ -basis the elements*

$$1, \alpha, \dots, \alpha^{n-1}$$

*where  $n = \deg p = \deg \alpha$ .*

b. If  $\alpha$  is transcendental over  $F$ , then  $F(\alpha) \simeq F(T)$  where  $F(T)$  is the field of fractions of the polynomial ring  $F[T]$ .

*Proof.* Construct the homomorphism

$$\phi : F[T] \rightarrow E \quad \text{such that } \phi|_F \text{ is the identity, and } \phi(T) = \alpha.$$

We are going to argue in both case (a) and (b) that  $\phi$  induces the desired isomorphism.

First consider case (a). Suppose that  $\alpha$  is algebraic with minimal polynomial  $p$ . The previous Proposition now shows that  $\ker \phi = \langle p \rangle$ .

Since  $p$  is irreducible, the quotient  $F[T]/\langle p \rangle$  is a *field*. According to the first isomorphism theorem,  $\phi$  induces an isomorphism between  $F[T]/\langle p \rangle$  and its image  $K$ . Thus  $K \subset E$  is a subfield containing  $F$  and  $\alpha$ , so by definition  $F(\alpha) \subset K$ .

On the other hand,  $\alpha$  identifies with the class  $T + \langle p \rangle$ , and so we've seen that the elements  $1, \alpha, \dots, \alpha^{n-1}$  form an  $F$ -basis for  $K$  viewed as a vector space over  $F$ . Now, any subfield  $K_1$  of  $E$  containing  $F$  and  $\alpha$  must contain all  $F$ -linear combinations of the elements  $\alpha^i$ ; thus  $K \subset K_1$  and this proves that

$$K \subset F(\alpha) = \bigcap_{K_1 \in \mathcal{E}} K_1.$$

We now conclude that  $K = F(\alpha)$  as required.

Now consider case (b). The condition that  $\alpha$  is transcendental is equivalent to the requirement that  $\ker \phi = \{0\}$ .

Thus for any non-zero polynomial  $f \in F[T]$ ,  $\phi(f) = f(\alpha)$  is a non-zero element of  $F(\alpha)$ . In particular,  $f(\alpha)^{-1} \in E$ .

Now the *defining property* of the field of fractions gives a unique ring homomorphism  $\tilde{\phi} : F(T) \rightarrow E$  for which  $\tilde{\phi}|_{F[T]} = \phi$ .

Since  $F(T)$  is a field,  $\tilde{\phi}$  is one-to-one, and its image is a subfield of  $E$  containing  $\alpha$ . On the other hand, any subfield of  $E$  containing  $\alpha$  must contain the image of  $\tilde{\phi}$  and statement (b) follows at once.  $\square$

*Example 9.3.5.* For any transcendental number  $\gamma \in \mathbf{R}$ , the subfield  $\mathbf{Q}(\gamma)$  of  $\mathbf{R}$  is isomorphic to the field  $\mathbf{Q}(T)$  of rational functions.

In particular, Proposition 9.3.4 shows that there is an isomorphism  $\mathbf{Q}(e) \simeq \mathbf{Q}(\pi)$ .

*Remark 9.3.6.* Here is a question we'll answer in an upcoming lecture. As before, let  $F \subset E$  be a field extension.

If  $\alpha, \beta \in E$  are algebraic over  $F$ , is  $\alpha + \beta$  algebraic over  $F$ ? How about  $\alpha \cdot \beta$ ?

*Example 9.3.7.* Let  $E = \mathbf{Q}[T]/\langle T^3 - 2 \rangle$  and let  $\gamma = T + \langle T^3 - 2 \rangle$ . Of course,  $E \simeq \mathbf{Q}(\sqrt[3]{2})$  and under this isomorphism,  $\gamma$  is mapped to  $\sqrt[3]{2}$ . Put another way,  $\gamma$  is a root of  $T^3 - 2$  in  $F$ .

We recall that since  $T^3 - 2$  has degree 3,  $E$  has dimension 3 as a  $\mathbf{Q}$ -vector space, and  $\{1, \gamma, \gamma^2\}$  is a  $\mathbf{Q}$ -basis for  $E$ .

For an element  $\alpha = a + b\gamma + c\gamma^2$  consider the  $\mathbf{Q}$ -linear mapping

$$\lambda_\alpha : E \rightarrow E$$

given by the left multiplication with  $\alpha$ ; i.e. by the rule  $\lambda_\alpha(\beta) = \alpha \cdot \beta$  for  $\beta \in E$ .

We are going to compute the *matrix* of  $\lambda_\alpha$  in the above basis for  $E$ . For this, note that the choice of basis determines a linear isomorphism  $\phi : E \rightarrow \mathbf{Q}^3$  given by  $\phi(s + t\gamma + u\gamma^2) = \begin{bmatrix} s \\ t \\ u \end{bmatrix}$ .

So we are looking for a  $3 \times 3$  matrix  $M = M_\alpha$  with the property that

$$\phi(\lambda_\alpha(\beta)) = M \cdot \phi(\beta).$$

- $\lambda_\alpha(1) = \alpha$  so that  $\phi(\lambda_\alpha(1)) = \begin{bmatrix} a \\ b \\ c \end{bmatrix}$ . This is the first column of  $M$ .
- $\lambda_\alpha(\gamma) = \alpha\gamma = a\gamma + b\gamma^2 + c\gamma^3 = a\gamma + b\gamma^2 + 2c = 2c + a\gamma + b\gamma^2$  so that  $\phi(\lambda_\alpha(\gamma)) = \begin{bmatrix} 2c \\ a \\ b \end{bmatrix}$ .  
This is the second column of  $M$ .
- $\lambda_\alpha(\gamma^2) = \alpha\gamma^2 = a\gamma^2 + b\gamma^3 + c\gamma^4 = a\gamma^2 + 2b + 2c\gamma = 2b + 2c\gamma + a\gamma^2$  so that  $\phi(\lambda_\alpha(\gamma^2)) = \begin{bmatrix} 2b \\ 2c \\ a \end{bmatrix}$ .  
This is the third column of  $M$ .

Thus

$$M = M_\alpha = M_{a+b\gamma+c\gamma^2} = \begin{bmatrix} a & c & 2b \\ b & a & 2c \\ c & b & a \end{bmatrix}$$

We claim for  $\alpha_1, \alpha_2 \in E$  that  $M_{\alpha_1+\alpha_2} = M_{\alpha_1} + M_{\alpha_2}$  and  $M_{\alpha_1 \cdot \alpha_2} = M_{\alpha_1} \cdot M_{\alpha_2}$ . Since  $M_\alpha$  is the matrix determined by the linear transformation  $\lambda_\alpha$ , our claim will follow if we just observe that  $\lambda_{\alpha_1} + \lambda_{\alpha_2} = \lambda_{\alpha_1+\alpha_2}$  and  $\lambda_{\alpha_1} \circ \lambda_{\alpha_2} = \lambda_{\alpha_1 \cdot \alpha_2}$  (where  $\circ$  denotes the *composition* of linear transformations). But for  $\beta \in E$  notice that  $\lambda_{\alpha_1} \circ \lambda_{\alpha_2}(\beta) = \lambda_{\alpha_1}(\alpha_2\beta) = \alpha_1\alpha_2\beta = \lambda_{\alpha_1\alpha_2}(\beta)$ ; the other verification is similarly straightforward.

This proves that  $\alpha \mapsto M_\alpha$  determines a *ring homomorphism*

$$E \rightarrow \text{Mat}_{3 \times 3}(\mathbf{Q})$$

Consider the element  $1 + \gamma \in E$  and notice that  $M_{1+\gamma} = \begin{bmatrix} 1 & 0 & 2 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix}$ .

Now, we can compute the inverse matrix  $M_{1+\gamma}^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 2 & -2 \\ -1 & 1 & 2 \\ 1 & -1 & 1 \end{bmatrix}$  which we recognize

as the matrix  $M_{(1-\gamma+\gamma^2)/3}$ .

Thus we see that

$$\frac{1}{1+\gamma} = \frac{1}{3}(1-\gamma+\gamma^2)$$

\

## 9.4 The degree of a field extension

*Definition 9.4.1.* We write  $[E : F] = \dim_F E$  and say that  $[E : F]$  is the *degree* of the extension  $F \subset E$ .

If  $E$  is *not* a finite dimensional vector space over  $F$ , then  $[E : F] = \dim_F E = \infty$ .

**Proposition 9.4.2.** *Let  $\alpha \in E$ . Then  $\alpha$  is algebraic over  $F$  if and only if  $[F(\alpha) : F] < \infty$ .*

*Remark 9.4.3.* If  $\alpha$  is transcendental, the cardinality of an  $F$ -basis for  $F(\alpha)$  fails to be countable if  $F$  is uncountable. Indeed, you can show that the elements

$$\left\{ \frac{1}{T-a} \in F(T) \mid a \in F \right\}$$

are linearly independent.

**Proposition 9.4.4.** *Let  $E$  be an extension of the field  $F$  and let  $\alpha \in E$ . The following are equivalent:*

- a.  $\alpha$  is algebraic over  $F$ .*
- b. the primitive extension  $F(\alpha)$  is a finite extension of  $F$ .*
- c.  $\alpha \in E_1$  for some subfield  $E_1 \subset E$  with  $F \subset E_1$  which is a finite extension of  $F$ .*

*Proof.* a.  $\implies$  b: If  $\alpha$  is algebraic, let  $d = \deg \alpha$  be the degree of  $\alpha$  over  $F$ . We have seen that  $1, \alpha, \dots, \alpha^{d-1}$  form an  $F$ -basis for  $F(\alpha)$ , so  $[F(\alpha) : F] = d$  and thus  $F(\alpha)$  is indeed a finite extension of  $F$ .

b.  $\implies$  c: This is immediate; just take  $E_1 = F(\alpha)$ .

c.  $\implies$  a.: Assume  $\dim_F E_1 = d$ . Since  $\alpha \in E_1$  and  $E_1$  is a field, also  $\alpha^i \in E_1$  for all  $i \in \mathbf{Z}_{\geq 0}$ . Since  $E_1$  has dimension  $d$  over  $F$ , it follows from linear algebra that the  $d+1$  elements

$$1, \alpha, \dots, \alpha^{d-1}, \alpha^d$$

are linearly dependent over  $F$ . Let  $c_0, c_1, \dots, c_d \in F$  not all zero be such that

$$\sum_{i=0}^d c_i \alpha^i = 0$$

and consider the *polynomial*

$$f(T) = \sum_{i=0}^d c_i T^i \in F[T].$$

Since not all of the coefficients  $c_i$  are 0,  $f(T) \neq 0$ . Since  $f(\alpha) = 0$ , we have proved that  $\alpha$  is algebraic over  $F$  as required.  $\square$

**Proposition 9.4.5.** *Let  $F \subset E \subset K$  be fields where  $K$  is a finite extension of  $E$  and  $E$  is a finite extension of  $F$ . Then  $K$  is a finite extension of  $F$  and moreover:*

$$[K : F] = [K : E] \cdot [E : F].$$

*Proof.* Let

$$a_1, \dots, a_N \in E \quad \text{be an } F\text{-basis for } E$$

and let

$$b_1, \dots, b_M \in K \quad \text{be an } E\text{-basis for } K$$

Multiplying in the field  $K$ , we consider the elements  $a_s b_t$ , and we assert:

$$\mathcal{B} = \{a_s b_t \mid 1 \leq s \leq N, 1 \leq t \leq M\} \quad \text{is an } F\text{-basis for } K$$

- $\mathcal{B}$  spans  $K$  over  $F$ : indeed, let  $x \in K$ . We must express  $x$  as a linear combination of the vectors  $\mathcal{B}$ .

Since the  $\{b_t\}$  span  $K$  over  $E$ , we may write

$$x = u_1 b_1 + \cdots + u_M b_M \quad \text{for } u_t \in E.$$

Since the  $\{a_s\}$  span  $E$  over  $F$ , for each  $1 \leq t \leq M$  we may write

$$u_t = v_{1,t} a_1 + \cdots + v_{N,t} a_N \quad \text{for } v_{s,t} \in F$$

Now

$$x = \sum_{t=1}^M u_t b_t = \sum_{t=1}^M \left( \sum_{s=1}^N v_{s,t} a_s \right) b_t = \sum_{1 \leq s \leq N, 1 \leq t \leq M} v_{s,t} \cdot a_s b_t$$

- $\mathcal{B}$  is linearly independent over  $F$ .

Suppose that

$$0 = \sum_{1 \leq s \leq N, 1 \leq t \leq M} v_{s,t} \cdot a_s b_t = \sum_{t=1}^M \left( \sum_{s=1}^N v_{s,t} a_s \right) b_t$$

for coefficients  $v_{s,t} \in F$ .

Now use the fact that  $\{b_t\}$  are linearly independent over  $E$  to conclude for each  $1 \leq t \leq M$  that

$$0 = \sum_{s=1}^N v_{s,t} a_s$$

For any  $1 \leq t \leq M$ , use the fact that  $\{a_s\}$  are linearly independent over  $F$  to conclude for each  $1 \leq s \leq N$  that  $v_{s,t} = 0$ .

□

**Corollary 9.4.6.** *Let  $E$  be a finite extension of  $F$ . If  $\alpha \in E$  then the degree of  $\alpha$  over  $F$  is a divisor of  $[E : F]$ :*

$$\deg_F(\alpha) \mid [E : F].$$

*Proof.* Apply Proposition 9.4.5 to the tower of field extensions

$$F \subset F(\alpha) \subset E$$

to deduce that

$$[E : F] = [E : F(\alpha)] \cdot [F(\alpha) : F]$$

and the result follows since  $[F(\alpha) : F] = \deg_F \alpha$ .

□

## 9.5 Examples of finite extensions

*Example 9.5.1.*  $[\mathbf{Q}(\sqrt{2}, \sqrt{3}) : \mathbf{Q}] = 4$ .

The polynomials  $T^2 - 2, T^2 - 3 \in \mathbf{Q}$  are known to be irreducible over  $\mathbf{Q}$  (can you give a quick argument?)

We claim that  $T^2 - 3$  remains irreducible over  $\mathbf{Q}(\sqrt{2})$  –i.e. that  $T^2 - 3 \in \mathbf{Q}(\sqrt{2})[T]$  is irreducible.

If we verify the claim, it follows that

$$[\mathbf{Q}(\sqrt{2}, \sqrt{3}) : \mathbf{Q}(\sqrt{2})] = 2$$

and thus

$$[\mathbf{Q}(\sqrt{2}, \sqrt{3}) : \mathbf{Q}] = [\mathbf{Q}(\sqrt{2}, \sqrt{3}) : \mathbf{Q}(\sqrt{2})] \cdot [\mathbf{Q}(\sqrt{2}) : \mathbf{Q}] = 2 \cdot 2 = 4$$

as required.

Let's now prove the claim. Since  $T^2 - 3$  has degree 2, the irreducibility will follow provided we argue that  $T^2 - 3$  has no root in  $\mathbf{Q}(\sqrt{2})$ .

So: suppose that  $3 = (a + b\sqrt{2})^2$  for  $a, b \in \mathbf{Q}$ . Thus

$$3 + 0 \cdot \sqrt{2} = 3 = a^2 + 2b^2 + 2ab\sqrt{2}$$

and comparing coefficients we find that

$$3 = a^2 + 2b^2 \quad \text{and} \quad 0 = 2ab.$$

Now  $2ab = 0 \implies a = 0$  or  $b = 0$  and the equation  $3 = a^2 + 2b^2$  is then impossible (since neither 3 nor  $3/2$  is a square in  $\mathbf{Q}$ ). This completes the proof that  $T^2 - 3$  is irreducible over  $\mathbf{Q}(\sqrt{2})$ .

*Example 9.5.2.*  $[\mathbf{Q}(\sqrt{2} + \sqrt{3}) : \mathbf{Q}] = 4$ .

To prove the claim, we argue that

$$\mathbf{Q}(\sqrt{2} + \sqrt{3}) = \mathbf{Q}(\sqrt{2}, \sqrt{3});$$

the assertion then follows from the previous example.

Write  $K = \mathbf{Q}(\sqrt{2} + \sqrt{3})$ . To confirm this equality, first note that trivially we have

$$K \subset \mathbf{Q}(\sqrt{2}, \sqrt{3})$$

so it is enough to argue

$$\sqrt{2}, \sqrt{3} \in K.$$

(Why?)

In fact, it is easy to see that  $\sqrt{2} \in K \iff \sqrt{3} \in K$  (since  $\sqrt{2} + \sqrt{3} \in K$  by construction!).

So it only remains to argue e.g. that  $\sqrt{3} \in K$ .

Let's observe that

$$\frac{1}{\sqrt{2} + \sqrt{3}} = \frac{1}{\sqrt{2} + \sqrt{3}} \cdot \frac{\sqrt{3} - \sqrt{2}}{\sqrt{3} - \sqrt{2}} = \frac{\sqrt{3} - \sqrt{2}}{1} \in K$$

and since  $K$  is a field,

$$\frac{1}{\sqrt{2} + \sqrt{3}} + \sqrt{2} + \sqrt{3} = (\sqrt{3} - \sqrt{2}) + (\sqrt{2} + \sqrt{3}) = 2\sqrt{3} \in K$$

so indeed  $\sqrt{3} \in K$ .

The preceding calculation confirms (for example) that  $\sqrt{2}$  may be written in the form

$$\begin{aligned}\sqrt{2} &= a + b\alpha + c\alpha^2 + d\alpha^3 \\ &= a + b(\sqrt{2} + \sqrt{3}) + c(\sqrt{2} + \sqrt{3})^2 + d(\sqrt{2} + \sqrt{3})^3\end{aligned}$$

for some coefficients  $a, b, c, d \in \mathbf{Q}$ , though we'd need to do some work to find  $a, b, c, d$ .

## 9.6 Algebraic extensions

Let  $F \subset E$  be any extension of fields. We are going to argue that

$$E_{\text{alg}} = \{u \in E \mid u \text{ is algebraic over } F\}$$

is a subfield of  $E$ .

For example, this requires us to know that if  $x, y \in E_{\text{alg}}$  then  $x - y \in E_{\text{alg}}$ . It is not completely clear how to find an algebraic equation satisfied by  $x - y$ , so we use a more indirect argument.

Our main tool is the following:

**Lemma 9.6.1.** *Let  $\alpha, \beta \in E$  be algebraic. Then  $[F(\alpha, \beta) : F]$  is a finite extension. In particular,  $\alpha \pm \beta$  and  $\alpha \cdot \beta$  are algebraic over  $F$ ; if  $0 \neq \alpha$ , then also  $\alpha^{-1} = \frac{1}{\alpha}$  is algebraic over  $F$ .*

*Proof.* Indeed,  $\beta$  is algebraic over  $F$  hence algebraic over  $F(\alpha)$  so

$$[F(\alpha, \beta) : F(\alpha)] < \infty$$

since  $F(\alpha, \beta) = F(\alpha)(\beta)$ .

Since  $\alpha$  is algebraic over  $F$ ,  $[F(\alpha) : F] < \infty$  and thus

$$[F(\alpha, \beta) : F] = [F(\alpha, \beta) : F(\alpha)] \cdot [F(\alpha) : F]$$

is finite. The result now follows from Proposition 9.4.4.  $\square$

**Corollary 9.6.2.** *Let  $E$  be an extension field of  $F$ . The set of all elements of  $E$  which are algebraic over  $F$  forms a subfield  $E_{\text{alg}}$  of  $E$ .*

*Proof.* We first observe that  $E_{\text{alg}}$  is an additive subgroup of  $E$ . For this, note that  $0 \in E_{\text{alg}}$  so it just remains to show that if  $x, y \in E_{\text{alg}}$  then  $x - y \in E_{\text{alg}}$ . But this statement follows from the Lemma 9.6.1.

It now remains to argue that  $E_{\text{alg}}$  is closed under multiplication and contains the inverse of its non-zero elements. These statements again follow from Lemma 9.6.1.  $\square$

**Definition 9.6.3.** An extension field  $E$  of  $F$  is *algebraic* over  $F$  if each element of  $E$  is algebraic over  $F$ .

**Proposition 9.6.4.** *Every finite extension of fields is algebraic.*

*Proof.* Let  $F \subset E$  be a finite extension and let  $\alpha \in E$  be an arbitrary element of  $E$ . Since  $[F(\alpha) : F]$  is a divisor of  $[E : F]$ ,  $[F(\alpha) : F]$  is finite and hence  $\alpha$  is algebraic by Proposition 9.4.4. This shows that  $E$  is algebraic over  $F$  as required.  $\square$

**Lemma 9.6.5.** *Let  $F \subset E$  be an algebraic extension, and let  $\alpha_1, \dots, \alpha_n \in E$ . Then*

$$[F(\alpha_1, \dots, \alpha_n) : F] < \infty.$$

*Proof.* Proceed by induction on  $n \geq 1$ .

First consider the case  $n = 1$ . Since  $E$  is algebraic over  $F$ ,  $\alpha = \alpha_1$  is algebraic over  $F$  and  $[F(\alpha) : F]$  is finite by previous results.

Now suppose  $n > 1$  and write  $E_i = F(\alpha_1, \dots, \alpha_i)$  for  $1 \leq i \leq n$ . The induction hypothesis is then:  $[E_i : F] < \infty$  for  $i < n$ . Note that  $E_n = E_{n-1}(\alpha_n)$ , and – since  $\alpha_n$  is algebraic over  $F$  –  $\alpha_n$  is algebraic over  $E_{n-1}$ . Thus

$$[E_n : E_{n-1}] = [E_{n-1}(\alpha_n) : E_{n-1}] < \infty$$

by Proposition 9.4.4 and it follows by induction that

$$[E_n : F] = [E_n : E_{n-1}] \cdot [E_{n-1} : F] < \infty$$

as required.  $\square$

**Proposition 9.6.6.** *Let  $E$  be an algebraic extension of  $F$  and let  $K$  be an algebraic extension of  $E$ . Then  $K$  is an algebraic extension of  $F$ .*

*Proof.* Let  $\alpha \in K$ . We must argue that  $\alpha$  is algebraic over  $F$ . Since  $\alpha$  is algebraic over  $E$ , it is the root of some polynomial

$$f(T) = a_0 + a_1T + a_2T^2 + \dots + a_NT^N \quad a_i \in E.$$

Now, form the extension  $E_1 = F(a_0, a_1, \dots, a_N)$ . Since  $E$  is algebraic over  $F$ , all  $a_i$  are algebraic over  $F$ . It follows from Lemma 9.6.5 that  $[E_1 : F] < \infty$ . Since  $\alpha$  is algebraic over  $E_1$  we know that  $[E_1(\alpha) : E_1] < \infty$  by Proposition 9.4.4. It now follows that

$$[E_1(\alpha) : F] = [E_1(\alpha) : E_1][E_1 : F] < \infty$$

so that  $\alpha$  is algebraic over  $F$  by Proposition 9.6.4.  $\square$

## 9.7 Another example

Consider the field  $K = \mathbf{Q}(T)$  where  $T$  is transcendental over  $\mathbf{Q}$ . It follows from Theorem 7.4.1 that

$$X^n - T - a \in K[X] = \mathbf{Q}(T)[X]$$

is irreducible for  $n = 2, 3$  for any  $a \in \mathbf{Q}$ .

These irreducibility statements mean that

$$[K(\sqrt{T-a}) : K] = 2 \quad \text{and} \quad [K(\sqrt[3]{T-a}) : K] = 3$$

(or writing everything out in full detail, that

$$[\mathbf{Q}(T, \sqrt{T-a}) : \mathbf{Q}(T)] = 2 \quad \text{and} \quad [\mathbf{Q}(T, \sqrt[3]{T-a}) : \mathbf{Q}(T)] = 3.)$$



**Lemma 9.7.1.**  $K(\sqrt{T-a}, \sqrt[3]{T-a}) = \mathbf{Q}(T, \sqrt{T-a}, \sqrt[3]{T-a})$  has degree 6 over  $K = \mathbf{Q}(T)$ .

*Proof.* Let  $L = K(\sqrt{T-a}, \sqrt[3]{T-a})$ . The claim will follow if we show that

$$(\clubsuit) \quad [L : K(\sqrt{T-a})] = 3$$

since then

$$[L : K] = [L : K(\sqrt{T-a})] \cdot [K(\sqrt{T-a}) : K] = 3 \cdot 2 = 6.$$

Now,  $(\clubsuit)$  follows if we argue that  $f(X) = X^3 - T - a \in K(\sqrt{T-a})[X]$  is irreducible; since  $f$  has degree 3, it suffices to argue that  $f$  has no root in  $K(\sqrt{T-a})$ .

But were  $\alpha \in K(\sqrt{T-a})$  a root of  $f$ , we know that  $\alpha$  has degree 3 over  $K$ . But this is impossible since

$$\alpha \in K(\sqrt{T-a}) \implies \deg_K \alpha \mid [K(\sqrt{T-a}) : K] = 2.$$

This completes the proof that  $f$  is irreducible over  $K(\sqrt{T-a})$  and thus the Lemma is verified.  $\square$

## 10 Constructible real numbers

As an example of the utility of field theory, we are going to describe a field-theory-based answer to a “geometric-constructions/geometric” question about numbers. Loosely put, we are going to answer the question: “can one trisect an angle using ruler and compass?”

### 10.1 Ruler and compass constructions

As a starting point, we are given two points at *unit distance* in the Euclidean plane.

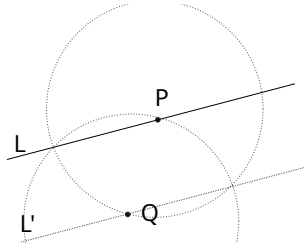
Given any two distinct known points  $P$  and  $Q$ , one can construct:

- the *line* through  $P$  and  $Q$  (this uses a *straightedge*)
- the circle with center  $P$  which passes through  $Q$  (this uses a *compass*)

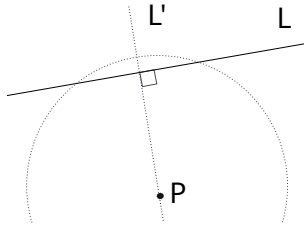
One views the points of intersection of lines and circles that have been constructed as *constructible* (i.e. known) points.

Here are some useful constructions that we are going to use without further argumentation:

**Lemma 10.1.1.** ( $\clubsuit$ ) *Given a point  $P$  on a line  $L$ , and a second point  $Q$  not on  $L$ , we can construct a line  $L'$  parallel to  $L$  passing through  $Q$ .*

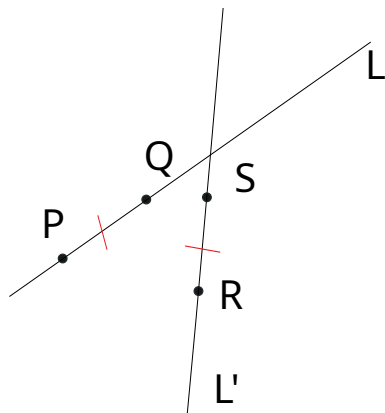


**Lemma 10.1.2.** ( $\heartsuit$ ) *Given a line  $L$  and a point  $P$  not lying on  $L$ , one can construct a line  $L'$  containing  $P$  and perpendicular to  $L$ .*



**Lemma 10.1.3.** ( $\spadesuit$ ) *Given two points  $P \neq Q$  on a line  $L$ , a second line  $L'$ , and a point  $R$  on  $L'$ , we can construct a point  $S$  on  $L'$  such that*

$$|\overline{PQ}| = |\overline{RS}|.$$



## 10.2 Constructions

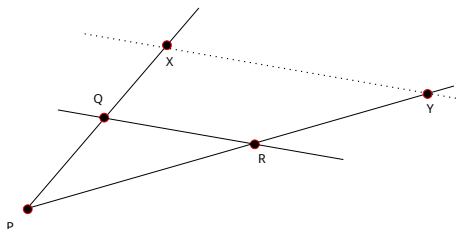
*Definition 10.2.1.* A real number  $r$  is *constructible* if one can construct a line segment of length  $|r|$  using straightedge and compass.

**Proposition 10.2.2.** *The set of constructible real numbers forms a subfield  $C \subset \mathbf{R}$ .*

*Sketch of proof.* First, use Lemma 10.1.3 to show that  $C$  forms an additive subgroup of  $\mathbf{R}$ .

To argue that  $C$  is closed under multiplication, proceed as follows:

- Given positive constructible numbers  $y, z, w$  construct a diagram with points  $P, Q, R, Y$  as follows with  $|PQ| = z$ ,  $|PR| = w$  and  $|PY| = y$ .



- Now use ( $\clubsuit$ ) to construct the line through  $Y$  parallel to the line through  $Q$  and  $R$ .
- Writing  $X$  for the (constructible) point of intersection of the indicated lines, write  $x = |PX|$  and notice that  $x/y = z/w$ .
- Now let  $a, b > 0$  be constructible and let  $y = a$ ,  $z = b$  and  $w = 1$ ; the above argument shows that  $x = yz = ab$  is constructible.

Similar arguments give the constructibility of  $a/b$  where  $a, b > 0$  are constructible.  $\square$

Let's observe that according to the Proposition, every rational number is constructible.

We may and will suppose that the points  $(1, 0)$  and  $(0, 1)$  in the plane are constructible. In particular, the coordinates  $r, s$  of any constructible point  $P = (r, s)$  are constructible real numbers.

### 10.3 Lines and Circles over a field

Of course, any line may be described as the set of solutions to an equation

$$aX + bY + c = 0$$

for  $a, b, c \in \mathbf{R}$ , and any circle may be described as the solutions to an equation

$$X^2 + Y^2 + aX + bY + c = 0$$

for  $a, b, c \in \mathbf{R}$ .

If  $F$  is a subfield of  $\mathbf{R}$ , a *line over  $F$*  means a line with equation  $aX + bY + c = 0$  where  $a, b, c \in F$ .

Similarly, a *circle over  $F$*  means a circle with equation

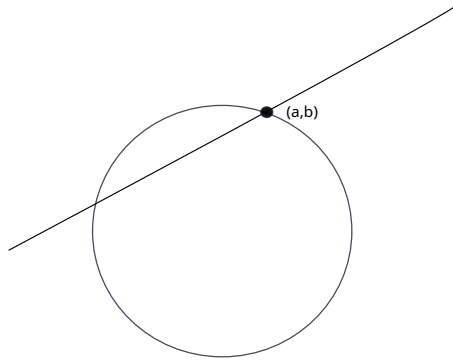
$$X^2 + Y^2 + aX + bY + c = 0 \quad \text{where } a, b, c \in F.$$

**Lemma 10.3.1.** • If the points  $P \neq Q$  both have coordinates in  $F$ , the line through  $P$  and  $Q$  is a line over  $F$ .

- If  $C$  is circle for which both the radius and the coordinates of its center are all in  $F$ , then  $C$  is a circle over  $F$ .

Constructing points via ruler and compass amounts to finding the intersections of lines and circles. We record the following fact about such intersections:

**Proposition 10.3.2.** Let  $F \subset \mathbf{R}$  be a subfield. The coordinates of the points of intersection of lines over  $F$  and circles over  $F$  belong to the field  $F(\sqrt{u})$  for some  $u \in F$ .



If in this diagram the line and the circle are “over  $F$ ”, the conclusion is that  $a, b \in F(\sqrt{u})$  for a suitable  $u \in F$ .

### 10.4 Characterizing constructible numbers

Using Proposition 10.3.2, we can give an important characterization of constructible real numbers:

**Theorem 10.4.1.**  $u \in \mathbf{R}$  is constructible  $\iff$  there are  $u_1, \dots, u_n \in \mathbf{R}$  such that:

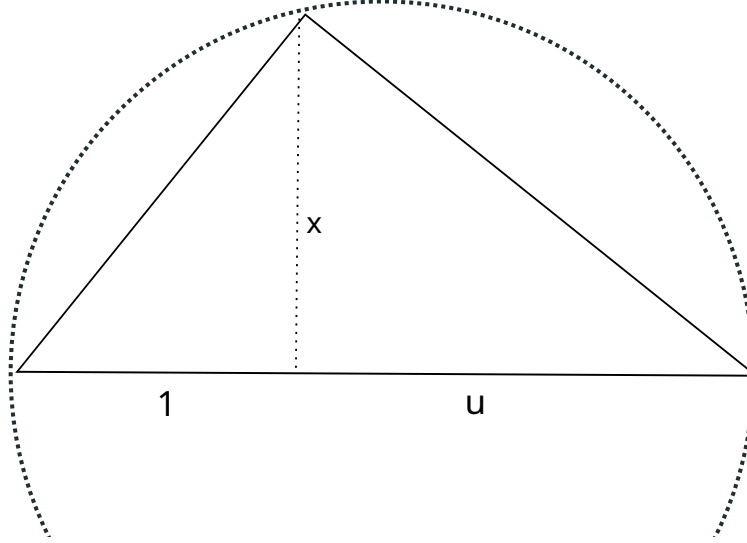
- $u_1^2 \in \mathbf{Q}$ ,

b.  $u_i^2 \in \mathbf{Q}(u_1, \dots, u_{i-1})$  for  $2 \leq i \leq n$ , and

c.  $u \in \mathbf{Q}(u_1, \dots, u_n)$ .

*Proof.*  $\Rightarrow$ : This follows from the Proposition.

$\Leftarrow$ : Use the following: if  $F$  is any subfield of the field of constructible numbers, then  $\sqrt{u}$  is constructible for each positive  $u \in F$ . For this, construct a circle of diameter  $1 + u$ , and a line perpendicular to the diameter, intersecting the diameter 1 unit from the west pole:



Then  $x = \sqrt{u}$ . □

**Corollary 10.4.2.** *If  $u$  is a constructible real number, then  $u$  is algebraic over  $\mathbf{Q}$  and  $\deg(u)$  is a power of 2.*

## 10.5 Angle trisection

**Lemma 10.5.1.** a. *For any angle  $\theta$ , we have the following identities:*

$$4 \cos^3(\theta) - 3 \cos(\theta) - \cos(3\theta) = 0.$$

b. *Let  $\alpha = \cos\left(\frac{\pi}{9}\right)$ .  $\alpha$  is a root of the irreducible polynomial*

$$f(T) = 8T^3 - 6T - 1 \in \mathbf{Q}[T].$$

*In particular, the degree of  $\alpha$  over  $\mathbf{Q}$  is 3.*

c.  $\alpha$  is not a constructible number.

*Proof.* Recall the trigonometric identities:

$$\sin(\alpha + \beta) = \sin(\alpha) \cos(\beta) + \cos(\alpha) \sin(\beta) \tag{10.1}$$

and

$$\cos(\alpha + \beta) = \cos(\alpha) \cos(\beta) - \sin(\alpha) \sin(\beta). \tag{10.2}$$

Taking  $\alpha = \beta$  we get

$$\sin(2\alpha) = 2\sin(\alpha)\cos(\alpha)$$

and

$$\cos(2\alpha) = \cos^2(\alpha) - \sin^2(\alpha).$$

For a real number  $\theta$ , we find that “double angle formula”

$$\begin{aligned}\cos(2\theta) &= \cos^2(\theta) - \sin^2(\theta) \\ &= \cos^2(\theta) - (1 - \cos^2(\theta)) \\ &= 2\cos^2(\theta) - 1\end{aligned}$$

This shows that

$$2\cos^2(\theta) - \cos(2\theta) - 1 = 0 \tag{10.3}$$

To prove (a), let  $\alpha = 2\theta$  and  $\beta = \theta$  in (10.2); we get

$$\begin{aligned}\cos(3\theta) &= \cos(2\theta + \theta) \\ &= \cos(2\theta)\cos(\theta) - \sin(2\theta)\sin(\theta) \\ &= (2\cos^2(\theta) - 1)\cos(\theta) - (2\sin(\theta)\cos(\theta))\sin(\theta) \\ &= 2\cos^3(\theta) - \cos(\theta) - 2\cos(\theta)\sin^2(\theta) \\ &= 2\cos^3(\theta) - \cos(\theta) - 2\cos(\theta)(1 - \cos^2(\theta)) \\ &= 4\cos^3(\theta) - 3\cos(\theta).\end{aligned}$$

This shows that  $4\cos^3(\theta) - 3\cos(\theta) - \cos(3\theta) = 0$  as required.

We now prove (b). If  $\theta = \frac{\pi}{9}$ , then of course  $\cos(3\theta) = \frac{1}{2}$ , so (a) shows  $\theta$  to be a root of the equation  $4T^3 - 3T - \frac{1}{2} \in \mathbf{Q}[T]$ . Multiplying this polynomial by 2 gives  $8T^3 - 6T - 1$  and we can use the *rational roots test* Theorem 7.2.1 to confirm the that this polynomial has no root in  $\mathbf{Q}$  and is thus irreducible in  $\mathbf{Q}[T]$ .

Now (c) follows from Corollary 10.4.2, since  $3 \nmid 2^m$  for any  $m \geq 1$ .  $\square$

**Theorem 10.5.2.** *It is impossible to find a general construction for trisecting an angle.*

*Proof.* Since  $\cos\left(\frac{\pi}{3}\right) = \frac{1}{2}$  and  $\sin\left(\frac{\pi}{3}\right) = \frac{\sqrt{3}}{2}$ , one can construct points  $Q = \frac{1}{2}(1, \sqrt{3})$ ,  $P = (0, 0)$ ,  $R = (1, 0)$  and then  $\angle QPR$  is  $\frac{\pi}{3}$ .

We claim that one can't construct further points  $S, T$  such that the  $\angle QPS$ ,  $\angle SPT$  and  $\angle TPR$  are all equal.

Indeed, if it were so, the coordinates of  $T$  would be  $(\cos\left(\frac{\pi}{9}\right), \sin\left(\frac{\pi}{9}\right))$ , and then  $\cos\left(\frac{\pi}{9}\right)$  would be a constructible number, contrary to Lemma 10.5.1.  $\square$

## 11 Splitting fields

### 11.1 The notion of a splitting field

Let  $F$  be a field and consider a polynomial

$$f = a_0 + a_1T + \cdots + a_nT^n \in F[T]$$

of degree  $n \geq 1$ .

*Definition 11.1.1.* If  $E$  is an extension field of  $F$ , we say that  $f$  *splits over*  $E$  provided that there are elements  $r_1, \dots, r_n \in E$  such that

$$f = (T - r_1)(T - r_2) \cdots (T - r_n) = \prod_{i=1}^n (T - r_i) \in E[T].$$

*Definition 11.1.2.* If  $f$  splits over the field extension  $E$  of  $F$ , and if  $r_1, \dots, r_n \in E$  are the roots of  $f$ , we say that  $E$  is a *splitting field* for  $f$  over  $F$  if moreover  $E = F(r_1, \dots, r_n)$ .

Thus a splitting field  $E$  is somehow a minimal field extension over which  $f$  splits.

*Example 11.1.3.*  $E = \mathbf{Q}(i)$  is a splitting field over  $\mathbf{Q}$  for the polynomial  $f = T^2 - 2T + 2$  since

$$f = (T - 1 - i)(T - 1 + i) \in \mathbf{Q}(i)[T]$$

and since  $\mathbf{Q}(i) = \mathbf{Q}(1 + i, 1 - i)$ .

**Theorem 11.1.4.** *Let  $f \in F[T]$  has degree  $n \geq 1$ . Then there exists a splitting field  $E$  for  $f$  over  $F$  with  $[E : F] \leq n!$ .*

*Proof.* Proceed by induction on  $n \geq 1$ . The result holds when  $n = 1$ , since then  $f$  splits over  $E = F$ .

Now suppose that the result is known for all fields  $F$  and all polynomials of degree  $\leq n - 1$ .

Now, choose an irreducible factor  $p$  of  $f$  in  $F[T]$ , say of degree  $d \leq n$ . Choose a root of  $p$  in some field extension of  $F$ , and consider the field  $K = F(\alpha)$ . We know that  $[K : F] = [F(\alpha) : F] = d = \deg p$ .

Since  $\alpha$  is a root of  $p$ , it is also a root of  $f$ ; thus by the *remainder theorem* – see Corollary 3.4.2 –, we may write

$$f = (T - \alpha) \cdot g \quad \text{for } g \in K[T] \text{ with } \deg g = n - 1.$$

Now use the *induction hypothesis* to construct a splitting field  $E$  for  $g$  over  $K$  with  $[E : K] \leq (n - 1)!$ .

Thus  $E = K(r_2, \dots, r_n)$  and

$$g = \prod_{i=2}^n (T - r_i) \in E[T].$$

We now have

$$f = (T - \alpha) \cdot g = (T - \alpha) \cdot \prod_{i=2}^n (T - r_i) \in E[T];$$

thus,  $f$  splits over  $E$ . Moreover,  $E = K(r_2, \dots, r_n) = F(\alpha, r_2, \dots, r_n)$  which confirms that  $E$  is a splitting field of  $f$  over  $F$ .

Finally, note that

$$[E : F] = [E : K][K : F] \leq (n - 1)! \cdot d \leq n!$$

since  $d \leq n$ .  $\square$

$\square$

## 11.2 More examples of splitting fields

### 11.2.1 Fourth root of 2

The field  $E = \mathbf{Q}(i, \sqrt[4]{2})$  is a splitting field for  $f = T^4 - 2$  over  $\mathbf{Q}$ , and  $[E : \mathbf{Q}] = 8$ .

First, if we write  $\alpha = \sqrt[4]{2}$  for the *real* fourth root of 2, the roots of  $f$  are precisely  $\pm\alpha, \pm i\alpha$ . Indeed,

$$(T - \alpha)(T + \alpha)(T - i\alpha)(T + i\alpha) = (T^2 - \sqrt{2})(T^2 + \sqrt{2}) = f.$$

Now,  $E = \mathbf{Q}(i, \sqrt[4]{2}) = \mathbf{Q}(\pm\alpha, \pm i\alpha)$ .

Finally, to see that  $[E : \mathbf{Q}] = 8$ , first note that  $[\mathbf{Q}(\alpha) : \mathbf{Q}] = 4$  since  $T^4 - 2$  is irreducible over  $\mathbf{Q}$ .

Now  $\alpha \in \mathbf{R} \implies \mathbf{Q}(\alpha) \subset \mathbf{R}$ , so  $\mathbf{Q}(\alpha)$  does not contain a root of  $T^2 + 1$ . Thus  $T^2 + 1$  is irreducible over  $\mathbf{Q}(\alpha)$ .

This shows that

$$[E : \mathbf{Q}] = [E : \mathbf{Q}(\alpha)] \cdot [\mathbf{Q}(\alpha) : \mathbf{Q}] = 2 \cdot 4 = 8.$$

### 11.2.2 Transcendental extension

$E = \mathbf{C}(X, \sqrt[4]{X+1})$  is a splitting field over  $\mathbf{C}(X)$  for  $T^4 - (X+1)$ , and  $[E : \mathbf{C}(T)] = 4$ .

### 11.2.3 Finite field example

Let  $F = \mathbf{F}_7$  be the field with 7 elements.

Let's describe the splitting field for  $f = T^3 - 3 \in F[T]$  over  $F$ .

First, note that the cubes mod 7 are as follows:

```
return [ (n,n**3 % 7) for n in range(7) ]
```

```
[(0, 0), (1, 1), (2, 1), (3, 6), (4, 1), (5, 6), (6, 6)]
```

In particular,  $f = T^3 - 3$  has no root in  $F = \mathbf{F}_7$ . So if  $\alpha$  denotes a root of  $f$  in some extension field, then  $F(\alpha)$  is a degree 3 extension of  $F$ .

Now let's notice that the multiplicative order of (the class of) 2 in  $\mathbf{F}_7^\times$  is 3: indeed  $2^3 = 8 \equiv 1 \pmod{7}$  but  $2, 2^2 \not\equiv 1 \pmod{7}$ . So we can observe that also  $2\alpha$  and  $4\alpha$  are also roots of  $T^3 - 3$ . Thus

$$f = (T - \alpha)(T - 2\alpha)(T - 4\alpha) \in F(\alpha)[T] = \mathbf{F}_7(\alpha)[T].$$

This shows that  $F(\alpha) = \mathbf{F}_7(\alpha)$  is a splitting field over  $F$  of  $f = T^3 - 3$ .

Observe that  $|F(\alpha)| = 7^3 = 343$ ; elements of  $F(\alpha)$  all have the form

$$a + b\alpha + c\alpha^2 \quad a, b, c \in \mathbf{F}_7.$$

## 11.3 Uniqueness of splitting fields

We are going to argue that a splitting field for a polynomial  $f$  over  $F$  is *essentially unique*.

Let us first make an observation: if  $\theta : F \rightarrow F_1$  is an isomorphism of fields, then  $\theta$  may be extended to an isomorphism

$$\theta : F[T] \rightarrow F_1[T]$$



with the property that  $\theta(T) = T$ . Note that polynomials satisfy

$$p \in F[T] \text{ is irreducible} \iff \theta(p) \in F_1[T] \text{ is irreducible.}$$

**Lemma 11.3.1.** *Let  $\theta : F \rightarrow F_1$  be an isomorphism of fields, let  $E = F(u)$  where  $u$  is algebraic over  $F$  with minimal polynomial  $p \in F[T]$ , and let  $p_1 = \theta(p)$ . If  $v$  is a root of  $p_1$  in an extension field of  $F_1$ , there is a unique way of extending  $\theta$  to an isomorphism  $\phi : F(u) \rightarrow F_1(v)$  subject to the conditions (i)  $\phi(u) = v$ , and (ii)  $\phi|_F = \theta$ , i.e. the restriction of  $\phi$  to  $F$  is given by  $\theta$ .*

This diagram might be useful for visualizing the situation:

$$\begin{array}{ccc} F(u) & \xrightarrow{\phi} & F_1(v) \\ \uparrow & \circ & \uparrow \\ F & \xrightarrow{\theta} & F_1 \end{array}$$

*Proof.* We first observe that  $\phi$  is uniquely determined by the indicated conditions. Indeed,  $F(u)$  is spanned as  $F$ -vector space by elements of the form  $u^i$ , and since  $\phi$  is a ring homomorphism it must satisfy  $\phi(u^i) = v^i$ .

We now prove the existence of  $\phi$ . We first note that –according to Proposition 9.3.4 – there are isomorphisms  $\gamma : F[T]/\langle p \rangle \xrightarrow{\sim} F(u)$  and  $\psi : F_1[T]/\langle p_1 \rangle \xrightarrow{\sim} F_1(v)$  with

$$\gamma(T + \langle p \rangle) = u \quad \text{and} \quad \psi(T + \langle p_1 \rangle) = v$$

such that  $\gamma|_F = \text{id}$  and  $\psi|_{F_1} = \text{id}$ .

Now, consider the ring homomorphism  $F[T] \xrightarrow{\theta} F_1[T] \xrightarrow{\pi_1} F_1[T]/\langle p_1 \rangle$  where  $\pi_1$  is the quotient mapping. This mapping  $\pi_1 \circ \theta$  is onto and has kernel  $\langle p \rangle$ ; according to the First Isomorphism Theorem – see Theorem 2.5.1 – it induces an isomorphism

$$\Phi : F[T]/\langle p \rangle \xrightarrow{\sim} F_1[T]/\langle p_1 \rangle$$

such that  $\Phi|_F = \theta$  and such that  $\Phi(T + \langle p \rangle) = T + \langle p_1 \rangle$ .

Now  $\psi \circ \Phi \circ \gamma^{-1} : F(u) \xrightarrow{\sim} F_1(v)$  has the required properties.  $\square$

*Remark 11.3.2.* Using the notations of the preceding proof, the isomorphism  $F(u) \rightarrow F_1(v)$  is given by

$$F(u) \xrightarrow{\gamma^{-1}} F[T]/\langle p \rangle \xrightarrow{\Phi} F_1[T]/\langle p_1 \rangle \xrightarrow{\psi} F_1(v).$$

*Example 11.3.3.* Consider the field  $F = \mathbf{Q}(i)$ . Write  $\sigma : \mathbf{Q}(i) \rightarrow \mathbf{Q}(i)$  for *complex conjugation*; thus  $\sigma(a + bi) = \overline{a + bi} = a - bi$  for  $a, b \in \mathbf{Q}$ . The mapping  $\sigma$  is an *automorphism* of the field  $F = \mathbf{Q}(i)$ .

We claim that the polynomials  $f_1 = T^2 - (1 + i)$  and  $f_2 = T^2 - (1 - i)$  in  $F[T]$  are irreducible. Note that  $f_2 = \sigma(f_1)$  so it is sufficient to argue that  $f_1$  is irreducible.

According to Proposition 7.1.4 it is enough to argue that the degree 2 polynomial  $f_1$  has no roots in  $F = \mathbf{Q}(i)$ .

If  $\alpha \in \mathbf{Q}(i)$  is a root of  $f_1$  then  $\alpha^2 = 1 + i$  so that

$$\alpha^2 \cdot \sigma(\alpha^2) = (1 + i) \cdot \sigma(1 + i) = (1 + i)(1 - i) = 2$$

But then  $(\alpha\sigma(\alpha))^2 = 2$ , and it is easy to see that  $\alpha \cdot \sigma(\alpha) = \alpha\bar{\alpha} \in \mathbf{Q}$ . Since  $\sqrt{2} \notin \mathbf{Q}$  this contradiction proves that there is no root  $\alpha \in F$  of  $f_1$ . Thus indeed  $f_1$  and  $f_2$  are irreducible.

In particular  $F(\sqrt{1+i}) = \mathbf{Q}(i, \sqrt{1+i})$  and  $F(\sqrt{1-i}) = \mathbf{Q}(i, \sqrt{1-i})$  are degree 2 extensions of the field  $F = \mathbf{Q}(i)$ .

Now Lemma 11.3.1 shows that there is an isomorphism  $\phi : \mathbf{Q}(i, \sqrt{1+i}) \rightarrow \mathbf{Q}(i, \sqrt{1-i})$  such that  $\phi(\sqrt{1+i}) = \sqrt{1-i}$  and such that  $\phi|_{\mathbf{Q}(i)} = \sigma$ ; in particular,  $\phi(i) = -i$ .

**Proposition 11.3.4.** *Let  $E$  be a splitting field over  $F$  for  $f \in F[T]$ , let  $\theta : F \rightarrow F_1$  be a field isomorphism, and let  $g = \theta(f) \in F_1[T]$ . Let  $E_1$  be a splitting field for  $g$  over  $F_1$ . Then there is an isomorphism  $\phi : E \rightarrow E_1$  such that  $\phi|_F = \theta$ .*

*Proof.* We use induction on  $n = \deg f$ . If  $n = 1$ , then  $E = F$ ,  $E_1 = F_1$  and we can simply take  $\phi = \theta$ .

Now suppose that  $n > 1$  and that the result holds for all field  $F$  and all polynomials of degree  $< n$ .

Let  $p \in F[T]$  be an irreducible factor of  $f$ , so that  $q = \theta(p)$  is an irreducible factor of  $g$ .

Since  $f$  splits over  $E$ , also  $p$  splits over  $E$ . Choose a root  $u \in E$  of  $p$ . Thus  $F \subset F(u) \subset E$ .

Choose also a root  $v \in E_1$  of  $q$ , so that  $F_1 \subset F_1(v) \subset E_1$ .

According to the preceding Lemma, there is an isomorphism  $\hat{\theta} : F(u) \rightarrow F_1(v)$  such that  $\hat{\theta}|_F = \theta$  and such that  $\hat{\theta}(u) = v$ .

Write

$$f = (T - u)s \in F(u)[T] \quad \text{for } s \in F(u)[T]$$

and

$$g = (T - v)s_1 \in F_1(v)[T] \quad \text{for } s_1 \in F_1(v)[T]$$

Now,  $E$  is a splitting field for  $s$  over  $F(u)$  and  $E_1$  is a splitting field for  $s_1$  over  $F_1(v)$ . And since  $\theta(f) = g$  and  $\hat{\theta}(u) = v$  it is easy to see that  $\hat{\theta}(s) = s_1$ .

Thus the induction hypothesis gives an isomorphism  $\phi : E \rightarrow E_1$  such that  $\phi|_{F(u)} = \hat{\theta}$ . This isomorphism  $\phi$  has the required properties.  $\square$

We find the following theorem as an immediate consequence:

**Theorem 11.3.5.** *Let  $f \in F[T]$  be a polynomial with  $\deg f > 0$ . If  $E$  and  $E_1$  are splitting fields for  $f$  over  $F$ , there is an isomorphism  $\phi : E \rightarrow E_1$  such that  $\phi(a) = a$  for each  $a \in F$  – i.e. such that  $\phi|_F$  is the identity mapping.*

*Proof.* In the Proposition, just take  $\theta$  to be the identity map!  $\square$

*Remark 11.3.6.* Observe that the proof of Proposition 11.3.4 requires us to prove the statement involving  $\theta$ , even though in Theorem 11.3.5 we are interested in only in the case  $\theta = \text{id}$ .

### 11.3.1 Example: automorphisms of a splitting field

The ideas behind the results Proposition 11.3.4 and Theorem 11.3.5 will be really important as we start talking about Galois theory. So, it seems useful to first do a non-trivial example.

Let's give an example of automorphisms of a splitting field.

Let's fix a prime number  $p$ , consider the polynomial  $f = T^3 - p \in \mathbf{Q}[T]$ , and let  $E$  be a splitting field for this polynomial over  $\mathbf{Q}$ .

The Theorem 11.3.5 tells us that any splitting field of  $f$  over  $\mathbf{Q}$  is isomorphic to  $E$ . Let's try to understand what this statement could mean about automorphisms of  $E$ .

First, let's make some observations. Notice that if  $\beta$  and  $\beta'$  are roots of  $f$ , then  $\left(\frac{\beta}{\beta'}\right)^3 = 1$  i.e.  $\frac{\beta}{\beta'}$  is a root of  $T^3 - 1$ . Moreover,  $\frac{\beta}{\beta'} = 1$  if and only if  $\beta = \beta'$ .

Let's exclude the "trivial" cube root of unity; observe that

$$\frac{T^3 - 1}{T - 1} = T^2 + T + 1 \in \mathbf{Q}[T]$$

has roots  $\omega, \omega^2 \in \mathbf{C}$  where

$$\omega = \exp\left(\frac{2\pi i}{3}\right) = \cos\left(\frac{2\pi i}{3}\right) + i \sin\left(\frac{2\pi i}{3}\right) \in \mathbf{C};$$

Notice that  $\omega \neq 1$  and  $\omega^3 = 1$  so viewed as an element of the group  $\mathbf{C}^\times$ ,  $\omega$  has order 3.

Neither  $\omega$  nor  $\omega^2$  is rational, so  $T^2 + T + 1$  is *irreducible* over  $\mathbf{Q}$ .

We can now construct a splitting field  $E$  of  $f$  over  $\mathbf{Q}$  *abstractly*. Take  $E = \mathbf{Q}(\alpha, \omega)$  where  $\alpha$  is a root of  $T^3 - p$  and  $\omega$  is a root of  $T^2 + T + 1$ .

First notice that

$$E = \mathbf{Q}(\alpha, \omega) = \mathbf{Q}(\alpha, \omega\alpha, \omega^2\alpha)$$

so that  $E$  is a splitting field. Now notice that  $\deg_{\mathbf{Q}} \alpha = 3$  and  $\deg_{\mathbf{Q}} \omega = 2$  so  $T^2 + T + 1$  remains irreducible over  $\mathbf{Q}(\alpha)$ . Thus we may conclude that

$$[E : \mathbf{Q}] = [\mathbf{Q}(\alpha, \omega) : \mathbf{Q}(\alpha)] \cdot [\mathbf{Q}(\alpha) : \mathbf{Q}] = 6.$$

Now observe that this argument actually shows that if we fix *any* root  $\beta$  of  $f$  in  $E$ , and *any* root  $\zeta$  of  $T^2 + T + 1$  in  $E$  then

$$f = (T - \beta)(T - \zeta\beta)(T - \zeta^2\beta).$$

E.g. if we choose  $\zeta = \omega^2$  and  $\beta = \omega\alpha$ , then

$$f = (T - \beta)(T - \zeta\beta)(T - \zeta^2\beta) = (T - \omega\alpha)(T - \omega^2(\omega\alpha))(T - \omega^4(\omega\alpha))$$

since

$$\{\omega\alpha, \omega^2(\omega\alpha), \omega^4(\omega\alpha)\} = \{\omega\alpha, \omega^3\alpha, \omega^5\alpha\} = \{\omega\alpha, \alpha, \omega^2\alpha\}.$$

The thing to take home from all this is that there are some choices to be made in describing the roots of  $f$ . In this case, you could pin things down more precisely e.g. by taking for  $\alpha$  the "real" cube root of  $P$  and for  $\omega$  the complex root of  $T^2 + T + 1$  which is in "quadrant 2". But a more systematic way of keeping track of choices is through study of automorphisms of the splitting field  $E$ .

Notice that  $\alpha$  and  $\beta = \omega\alpha$  are roots of the irreducible polynomial  $T^3 - p \in \mathbf{Q}[T]$ . Thus, there is an isomorphism of fields

$$\theta : \mathbf{Q}(\alpha) \rightarrow \mathbf{Q}(\beta)$$

such that  $\theta$  is the identity on  $\mathbf{Q}$  and  $\theta(\alpha) = \beta = \omega\alpha$ .

Notice that  $\theta(T^2 + T + 1) = T^2 + T + 1$  is irreducible over  $\mathbf{Q}(\alpha)$  and over  $\mathbf{Q}(\beta)$ .

Now, Lemma 11.3.1 tells us that there is an isomorphism

$$\Theta : \mathbf{Q}(\alpha, \omega) \rightarrow \mathbf{Q}(\beta, \zeta)$$

such that  $\Theta|_{\mathbf{Q}(\alpha)} = \theta$  - i.e. for which  $\Theta(\alpha) = \beta$  - and for which  $\Theta(\omega) = \zeta$ .

This  $\Theta$  is an isomorphism between splitting fields of  $f$ . Since we took  $\beta = \omega\alpha$  and  $\zeta = \omega^2$ , we have

$$E = \mathbf{Q}(\alpha, \omega) = \mathbf{Q}(\beta, \zeta)$$

so in fact  $\Theta : E \rightarrow E$  is an *automorphism* of  $E$ .

Note that  $\Theta$  is not the identity mapping on the roots of  $f$ :

$$(\Theta(\alpha), \Theta(\omega\alpha), \Theta(\omega^2\alpha)) = (\omega\alpha, \zeta\omega\alpha, \zeta^2\omega\alpha) = (\omega\alpha, \alpha, \omega^2\alpha).$$

Also note that upon restriction to  $\mathbf{Q}(\omega)$ ,  $\Theta|_{\mathbf{Q}(\omega)}$  is *complex conjugation*, since

$$\Theta(\omega) = \omega^2 = \overline{\omega}.$$

## 12 Finite fields

### 12.1 The prime subfield of a field

First let's recall for any field  $F$  that there is always a ring homomorphism  $\mathbf{Z} \rightarrow F$  for which  $n \mapsto n \cdot 1_F$ .

**Proposition 12.1.1.** *Let  $F$  be a field.*

- a. *If the homomorphism  $\mathbf{Z} \rightarrow F$  is one-to-one, then  $F$  contains a copy of the field  $\mathbf{Q}$  of rational numbers.*
- b. *If the homomorphism  $\mathbf{Z} \rightarrow F$  is not one-to-one, then  $F$  contains a copy of the field  $\mathbf{Z}/p\mathbf{Z}$  for some prime number  $p$ .*

*Remark 12.1.2.* In case a., we say that  $F$  has *characteristic 0*. Note in that case that the *additive order* of any non-zero element of  $F$  is  $\infty$ .

In case b., we say that  $F$  has *characteristic  $p$* . In that case, the additive order of any non-zero element of  $F$  is  $p$ .

*Definition 12.1.3.* The *prime subfield* of  $F$  is the smallest subfield containing the image of the homomorphism  $\mathbf{Z} \rightarrow F$ ; thus when  $F$  has characteristic 0, the prime subfield identifies with  $\mathbf{Q}$ , and when  $F$  has characteristic  $p > 0$ , the prime subfield identifies with  $\mathbf{Z}/p\mathbf{Z}$ .

*Proof of the Proposition.* If the homomorphism  $\phi : \mathbf{Z} \rightarrow F$  is injective, it maps non-zero elements of  $\mathbf{Z}$  to *invertible* elements of  $F$ . Thus by the *defining property* of the field of fractions  $\mathbf{Q} = Q(\mathbf{Z})$ , the homomorphism  $\phi$  extends to a homomorphism  $\tilde{\phi} : \mathbf{Q} \rightarrow F$ ; see Proposition 6.0.4. Thus  $F$  indeed contains a copy of  $\mathbf{Q}$ .

Suppose on the other hand that the homomorphism  $\phi$  is not one-to-one; thus  $\ker \phi = n\mathbf{Z}$  for some  $n \neq 0$ . The *First Isomorphism Theorem* Theorem 2.5.1 now implies that the image of  $\phi$  is a subring of  $F$  isomorphic to the finite ring  $\mathbf{Z}/n\mathbf{Z}$ . Since  $F$  is a field, this subring must be an integral domain – see Example 3.1.7 (c); thus by Example 3.1.7 (d) we see that  $n = p$  must be a prime number.  $\square$

### 12.2 Some properties of finite fields

We've met some finite fields already, namely  $\mathbf{Z}/p\mathbf{Z}$  for a prime number  $p$ .

We've can construct finite extensions of  $\mathbf{Z}/p\mathbf{Z}$  to get fields  $F$  for which  $|F|$  is not prime. Let's first make an observation about  $|F|$ , as follows:

**Proposition 12.2.1.** *Let  $F$  be a finite field. Then  $F$  has characteristic  $p > 0$  for some prime number  $p$ . The number of elements of  $F$  is  $p^m$  for some whole number  $m \geq 1$ .*

*Proof.* Since  $\mathbf{Q}$  is not finite, the previous proposition shows that  $F$  must have characteristic  $p > 0$  for a prime number  $p$ .

Write  $F_0 \subset F$  where  $F_0$  is the prime subfield; thus  $F_0 \simeq \mathbf{Z}/p\mathbf{Z}$ .

Now,  $F$  may be viewed as an  $F_0$ -vector space. A basic theorem in linear algebra says that  $F$  must have a *basis*  $\mathcal{B}$  as an  $F_0$ -vector space; see Proposition 8.3.5. Since  $F$  is finite, this basis must be finite; say  $|\mathcal{B}| = m$ .

Write  $\mathcal{B} = \{b_1, b_2, \dots, b_m\}$ . Then an element  $x$  of  $F$  may be written uniquely in the form

$$x = t_1 b_1 + t_2 b_2 + \dots + t_m b_m$$

for  $t_i \in F_0$ ; see e.g. Section 8.3. Since  $F_0 \simeq \mathbf{Z}/p\mathbf{Z}$ , there are  $p$  choices for each  $t_i$ ; this shows that the number of elements of  $F$  is

$$|F| = p \cdot p \cdot \dots \cdot p = p^m$$

as required.  $\square$

### 12.3 Finite fields as splitting fields over the prime field

**Proposition 12.3.1.** *Let  $F$  be a finite field with  $p^m$  elements for some prime number  $p$ . Then  $F$  is the splitting field over the prime subfield  $F_0 \simeq \mathbf{Z}/p\mathbf{Z}$  of the polynomial*

$$T^{p^m} - T \in F_0[T].$$

*Proof.* Since  $F$  has  $p^m$  elements, the multiplicative group  $F^\times$  has  $p^m - 1$  elements. This means that every element  $x \in F^\times$  satisfies the condition

$$x^{p^m-1} = 1.$$

It is then immediate that every element  $x \in F$  satisfies

$$x^{p^m} = x.$$

Put another way, every element of  $F$  is a root of the polynomial

$$f = T^{p^m} - T \in F_0[T].$$

Since  $f$  can have no more than  $p^m$  roots in an extension field, it follows that  $F$  contains all roots of  $f$ . Since  $F$  is generated by these roots,  $F$  is a splitting field for  $f$  over  $F_0$ .  $\square$

*Remark 12.3.2.* The proof shows that the identity

$$f = T^{p^m} - T = \prod_{\alpha \in F} (T - \alpha)$$

holds in  $F[T]$ .

**Corollary 12.3.3.** *Two finite fields  $F$  and  $E$  are isomorphic if and only if  $|F| = |E|$ .*

*Proof.* If  $F$  and  $E$  are isomorphic, there is a one-to-one onto function  $\phi : F \rightarrow E$  and thus  $|F| = |E|$ .

On the other hand, if  $|F| = |E|$ , we know that  $|F| = p^m$  and  $|E| = q^n$  for some primes  $p, q$  and some  $m, n \geq 1$ . By unique factorization of integers – see Theorem 5.2.1 –,  $p = q$  and  $m = n$ . Now the Proposition shows that  $E, F$  are splitting fields of  $T^{p^m} - T$  over  $\mathbf{Z}/p\mathbf{Z}$ .

Now the existence of an isomorphism  $F \simeq E$  is a consequence of the uniqueness of splitting fields.  $\square$

## 12.4 Existence of a finite field of any prime-power order

Let  $p$  be a prime number. One might see the following Lemma in a class in elementary number theory:

**Lemma 12.4.1.** *For  $x, y \in \mathbf{Z}$ , we have:*

- a.  $x^p \equiv x \pmod{p}$
- b.  $(x + y)^p \equiv x^p + y^p \equiv x + y \pmod{p}$ .

We are going to prove a slightly more general version of this result that is valid for elements of *any* field of characteristic  $p > 0$ , as follows:

**Lemma 12.4.2.** *Let  $F$  be a field of char.  $p > 0$ , let  $x, y \in F$ , and let  $n \in \mathbf{Z}_{>0}$ . Then:*

- a.  $(x + y)^{p^n} = x^{p^n} + y^{p^n}$ .
- b.  $\{x \in F \mid x^{p^n} = x\}$  is a subfield of  $F$ .

*Proof.* For  $0 < i < p$ , the binomial coefficients  $\binom{p}{i} = \frac{p!}{i! \cdot (p-i)!}$  satisfy the congruence

$$\binom{p}{i} \equiv 0 \pmod{p}.$$

Indeed,  $p$  divides the numerator  $p!$  but  $p$  does not divide the denominator  $i! \cdot (p-i)!$  and the result follows since the quotient is integral.

Since  $\binom{p}{0} = \binom{p}{p} = 1$ , it follows that

$$(x + y)^p = \sum_{i=0}^p \binom{p}{i} x^i y^{p-i} = x^p + y^p \quad (12.1)$$

for elements  $x, y \in F$ . To prove a., proceed by induction on  $n \geq 1$ . The case  $n = 1$  is just (12.1). Assuming the result is valid for  $n - 1$ , we see that

$$(x + y)^{p^n} = \left( (x + y)^{p^{n-1}} \right)^p = \left( x^{p^{n-1}} + y^{p^{n-1}} \right)^p = x^{p^n} + y^{p^n};$$

we used the induction hypothesis for the second equality, and we used (12.1) applied to  $x^{p^{n-1}}$  and  $y^{p^{n-1}}$  for the final equality. This proves a.

For b., write

$$F_1 = \{x \in F \mid x^{p^n} = x\}.$$

To see that  $F_1$  is an additive subgroup of  $F$ , first note that  $0 \in F_1$ . Now, the result from a. shows that if  $x, y \in F_1$  then  $x + y \in F_1$ .

Next we argue that  $F_1$  is closed under multiplication. This follows since if  $x, y \in F_1$  then

$$(xy)^{p^n} = x^{p^n} y^{p^n} = xy.$$

Finally, if  $x \in F_1$  is non-zero, then

$$1 = 1^{p^n} = (x \cdot x^{-1})^{p^n} = x^{p^n} x^{-p^n} = x x^{-p^n}$$

which shows that  $(x^{-1})^{p^n} = x^{-p^n} = x^{-1}$  hence  $x^{-1} \in F_1$ . □

**Lemma 12.4.3.** *Let  $F$  be a field of characteristic  $p > 0$  and let  $\mathcal{F} : F \rightarrow F$  be the mapping  $\mathcal{F}(x) = x^p$ . Then  $\mathcal{F}$  is a ring homomorphism.*

*Proof.* Part a. of Lemma 12.4.2 shows that  $\mathcal{F}$  is a homomorphism of additive group. If  $x, y \in F$  then  $\mathcal{F}(xy) = (xy)^p = x^p y^p = \mathcal{F}(x)\mathcal{F}(y)$  which completes the proof.  $\square$

**Lemma 12.4.4.** *Let  $m, n$  be positive integers for which  $n = qm$ .*

*a.  $T^m - 1 \mid T^n - 1$  in the polynomial ring  $\mathbf{Z}[T]$ .*

*b. For any commutative ring  $R$  (with identity) and any  $y \in R$  we have  $y^m - 1 \mid y^n - 1$ .*

*Proof.* For a., first note that for a polynomial variable  $u$ , we have the identity

$$\frac{u^q - 1}{u - 1} = u^{q-1} + u^{q-2} + \cdots + u + 1 \quad (12.2)$$

in the field of fractions of  $\mathbf{Z}[u]$ . Substituting  $u = T^m$  in (12.2) gives

$$\begin{aligned} f(T) &= \frac{T^n - 1}{T^m - 1} = \frac{(T^m)^q - 1}{T^m - 1} \\ &= (T^m)^{q-1} + (T^m)^{q-2} + \cdots + T^m + 1 \\ &= T^{m(q-1)} + T^{m(q-2)} + \cdots + T^m + 1 \in \mathbf{Z}[T] \end{aligned}$$

Now b. follows from a. Indeed, if  $T^n - 1 = g(T) \cdot (T^m - 1)$  for  $g(T) \in \mathbf{Z}[T]$ , then for  $y \in R$  we see that  $y^n - 1 = g(y) \cdot (y^m - 1)$  since evaluation at  $y$  determines a ring homomorphism  $\mathbf{Z}[T] \rightarrow R$ .  $\square$

**Proposition 12.4.5.** *Let  $F$  be a field with  $p^n$  elements. Each subfield of  $F$  has  $p^m$  elements for some divisor  $m$  of  $n$ . Conversely, for each divisor  $m \mid n$ , there exists a unique subfield of  $F$  having  $p^m$  elements.*

*Proof.* Let  $F_0$  be the prime subfield of  $F$ . Any subfield  $E$  of  $F$  must contain  $F_0$  and must have  $p^m$  elements, where  $m = [E : F_0]$ . Since

$$n = [F : F_0] = [F : E][E : F_0] = [F : E] \cdot m$$

we conclude that  $m$  must be a divisor of  $n$ .

Conversely, let  $m$  be a divisor of  $n$ . Then  $p^m - 1$  is a divisor of  $p^n - 1$  by Lemma 12.4.4. Applying Lemma 12.4.4 a second time, we see that the polynomial  $g(T) = T^{(p^m-1)} - 1$  is a divisor of  $h(T) = T^{(p^n-1)} - 1$  in the polynomial ring  $F_0[T]$ .

Since  $F$  is the splitting field of  $T \cdot h(T)$  over  $F_0$ , it must contain all  $p^m$  distinct roots of  $T \cdot g(T)$ .

Now, part b. of Lemma 12.4.2 implies that the roots of  $T \cdot g(T) = T^{p^m} - T$  form a subfield  $E$  of  $F$ . Any other subfield having order  $p^m$  must be a splitting field of  $T \cdot g(T)$  and so it must coincide with  $E$ . This completes the proof.  $\square$

**Lemma 12.4.6.** *Let  $F$  be a field of char.  $p > 0$ . If  $n \in \mathbf{Z}_{>0}$  and  $n \not\equiv 0 \pmod{p}$  then  $T^n - 1$  has no repeated roots in any extension field of  $F$ . Put another way, if  $E$  denotes a splitting field of  $T^n - 1$  over  $F$ , then*

$$T^n - 1 = \prod_{i=1}^n (T - \alpha_i)$$

for  $n$  distinct elements  $\alpha_i \in E$ .



*Proof.* Let  $c$  be a root of  $T^n - 1$  in a splitting field  $E$ . The remainder theorem – Corollary 3.4.2 – shows that  $T^n - 1 = (T - c)g(T)$  for some polynomial

$$g(T) = \sum_{i=0}^{n-1} a_i T^i$$

with  $a_0, a_1, \dots, a_{n-1} \in F(c)$ . Now, we have

$$\begin{aligned} T^n - 1 &= (T - c)g(T) = (T - c) \left( \sum_{i=0}^{n-1} a_i T^i \right) = \left( \sum_{i=0}^{n-1} a_i T^{i+1} \right) - \left( \sum_{i=0}^{n-1} c a_i T^i \right) \\ &= \left( \sum_{i=1}^n a_{i-1} T^i \right) - \left( \sum_{i=0}^{n-1} c a_i T^i \right) \\ &= a_{n-1} T^n + \left( \sum_{i=1}^{n-1} a_{i-1} T^i - \sum_{i=1}^{n-1} c a_i T^i \right) - c a_0 \end{aligned}$$

Comparing coefficients, we find that  $a_{n-1} = 1$  and that  $a_{i-1} = c a_i$  for  $1 \leq i \leq n-1$ . Thus we find that  $a_i = c^{n-1-i}$  for  $1 \leq i \leq n-1$  and that  $a_0 = c^{n-1}$  since then  $c a_0 = c^n = 1$ . Thus

$$g(T) = T^{n-1} + c T^{n-2} + c^2 T^{n-3} + \dots + c^{n-2} T + c^{n-1}$$

To prove the Lemma, we must show that  $g = g(T)$  is not divisible by  $T - c$ . By the remainder theorem, it is sufficient to prove that  $g(c) \neq 0$ . But we have:

$$g(c) = c^{n-1} + c c^{n-2} + c^2 c^{n-3} + \dots + c^{n-2} c + c^{n-1} = n \cdot c^{n-1}$$

and the result follows since  $n 1_F \neq 0$  and  $c \neq 0$ . □

**Theorem 12.4.7.** *For every prime  $p$  and every positive integer  $n$ , there is a field  $\mathbf{F}_q$  with  $q = p^n$  elements, and any field of order  $q$  is isomorphic to  $\mathbf{F}_q$ .*

*Proof.* The uniqueness has already been proved; it remains to argue the *existence* of  $\mathbf{F}_q$  for  $q = p^n$ .

Let  $F$  be the splitting field of the polynomial  $T^{p^n} - T$  over  $\mathbf{Z}/p\mathbf{Z}$ . The previous Lemma shows that  $T^{p^n} - T$  has  $p^n$  distinct roots. By an earlier Lemma, these roots form a *subfield* of  $F$ , so we conclude that  $F$  consists exactly in these roots. Thus  $|F| = p^n$  as required. □

*Remark 12.4.8.* For a prime power  $q$ , some texts write  $\text{GF}(q)$  for the field we have denoted  $\mathbf{F}_q$ . The symbol GF stands for “Galois Field”.

## 12.5 Some examples of finite fields

We have seen in Theorem 12.4.7 that for each prime power  $q = p^n$ , there is a field of that order. The computer algebra system **sagemath** knows how to do some computations with finite fields. We are next going to demonstrate this facility with some calculations.

### 12.5.1 Extensions of $\mathbf{F}_{19}$

For example, we can ask to represent the field of  $19^2 = 361$  elements.

```
H.<a>=FiniteField(19^2)
a.minpoly()
```

```
x^2 + 18*x + 2
```

The output here tells us that

$$H = \mathbf{F}_{19}[T]/\langle T^2 + 18T + 2 \rangle.$$

We can construct larger finite fields and ask about subfields:

```
G.<z>=FiniteField(19^6)
z.minpoly()
```

```
x^6 + 17*x^3 + 17*x^2 + 6*x + 2
```

```
G.subfields()
```

```
[(Finite Field of size 19,
  Ring morphism:
    From: Finite Field of size 19
    To:   Finite Field in z of size 19^6
    Defn: 1 |--> 1),
 (Finite Field in z2 of size 19^2,
  Ring morphism:
    From: Finite Field in z2 of size 19^2
    To:   Finite Field in z of size 19^6
    Defn: z2 |--> 18*z^5 + 9*z^4 + 5*z^3 + 2*z^2 + 12*z + 7),
 (Finite Field in z3 of size 19^3,
  Ring morphism:
    From: Finite Field in z3 of size 19^3
    To:   Finite Field in z of size 19^6
    Defn: z3 |--> 13*z^5 + 10*z^4 + 2*z^3 + 15*z^2 + 7*z + 18),
 (Finite Field in z of size 19^6,
  Identity endomorphism of Finite Field in z of size 19^6)]
```

The output here tells us that the field  $G$  of order  $19^6 = 47045881$  – roughly forty seven million elements – has exactly 4 subfields:  $G = \mathbf{F}_{19}(z)$ , a subfield  $\mathbf{F}_{19}(z^3)$  of order  $19^3$ , a subfield  $\mathbf{F}_{19}(z^2)$  of order  $19^2$  and a subfield of order 19.

Here **sage** has found an element  $z$  for which

$$G = \mathbf{F}_{19}(z) \simeq \mathbf{F}_{19}[T]/\langle T^6 + 17 \cdot T^3 + 17 \cdot T^2 + 6 \cdot T + 2 \rangle,$$

The subfield

$$\mathbf{F}_{19}(z^3) = \mathbf{F}_{19}(13 \cdot z^5 + 10 \cdot z^4 + 2 \cdot z^3 + 15 \cdot z^2 + 7 \cdot z + 18)$$

has order  $19^3 = 6859$ .

The subfield

$$\mathbf{F}_{19}(z^2) = \mathbf{F}_{19}(18 \cdot z^5 + 9 \cdot z^4 + 5 \cdot z^3 + 2 \cdot z^2 + 12 \cdot z + 7)$$

has order  $19^2 = 361$ .

Let's pause and ask **sagemath** to compute the non-squares in  $\mathbf{F}_{19}$ :

```
F.<a>=FiniteField(19)
squares = [ x^2 for x in F]
nonSquares = [x for x in F if not(x in squares)]
len(nonSquares)
```

9

This output tells us that there are 9 elements  $a \in \mathbf{F}_{19}$  for which  $T^2 - a$  is **irreducible**. Those elements are:

```
nonSquares
```

[2, 3, 8, 10, 12, 13, 14, 15, 18]

According to Corollary 12.3.3, up to isomorphism there is a unique field of order  $19^2$ . It follows that

$$\mathbf{F}_{19}(\sqrt{2})$$

must contain a square root of each of these **nonSquares**. We can ask **sagemath** to describe these roots in terms of  $a = \sqrt{2}$  as follows:

We first describe solutions to  $T^2 - 2$ :

```
F= FiniteField(19)
R.<T>=PolynomialRing(F)
E.<a> = F.extension(T^2 - 2)
[x for x in E if x^2==2]
```

[a, 18\*a]

And here are solutions to  $T^2 - 13$ :

```
[x for x in E if x^2==13]
```

[4\*a, 15\*a]

Similarly we can find solutions to  $T^2 - 8$ :

```
[x for x in E if x^2==8]
```

[2\*a, 17\*a]

This makes clear for example that

$$\mathbf{F}_{19}(\sqrt{13}) = \mathbf{F}_{19}(4\sqrt{2}) = \mathbf{F}_{19}(\sqrt{2}).$$

In fact, we can get a full list of irreducible polynomials:

```
irred = [T^2 + a*T + b for a in F for b in F if (T^2+a*T+b).is_irreducible()]
len(irred)
```

171

The output tells us that there are 171 monic irreducible quadratic polynomials in  $\mathbf{F}_{19}[T]$ . Let's look at a few:

```
irred[0:11]
```

```
[T^2 + 1,
 T^2 + 4,
 T^2 + 5,
 T^2 + 6,
 T^2 + 7,
 T^2 + 9,
 T^2 + 11,
 T^2 + 16,
 T^2 + 17,
 T^2 + T + 2,
 T^2 + T + 3]
```

We can use the `sage` command `polroots` to find roots of a polynomial:

```
def polroots(p):
    return [x for x in E if p(x)==0]
[irred[10],
 polroots(irred[10])]
```

```
[T^2 + T + 3, [a + 9, 18*a + 9]]
```

The output shows that the two roots of  $T^2 + T + 3$  in  $\mathbf{F}_{19}(\sqrt{2})$  are

$$9 + \sqrt{2} \quad \text{and} \quad 9 + 18\sqrt{2} = 9 - \sqrt{2}.$$

(Of course, we have obtained those roots using the quadratic formula!)

This makes clear that  $\mathbf{F}_{19}(\sqrt{2})$  is a splitting field for  $T^2 + T + 3$ .

In fact, we know that  $\mathbf{F}_{19}(\sqrt{2})$  is a splitting field for all 171 polynomials  $p$  in the list `irred`.

### 12.5.2 Fields of order 4 and 8

There are 4 monic polynomials of degree 2 over the field  $\mathbf{F}_2$  of two elements. Of these, only one is irreducible, namely

$$T^2 + T + 1.$$

Thus

$$\mathbf{F}_4 \simeq \mathbf{F}_2(\alpha)$$

where  $\deg \alpha = 2$  and  $\alpha^2 = \alpha + 1$ . Notice that

$$T^2 + T + 1 = (T + \alpha)(T + \alpha + 1).$$

There are 8 monic polynomials of degree 3 over  $\mathbf{F}_2$ . Of these, only two are irreducible:

```
H = FiniteField(2)
R.<T>=PolynomialRing(H)
[T^3 + a*T^2 + b*T + c
 for a in H
 for b in H
 for c in H
 if (T^3+a*T^2+b*T + c).is_irreducible()]
```

```
[T^3 + T + 1, T^3 + T^2 + 1]
```

Thus  $\mathbf{F}_8 = \mathbf{F}_2(\beta)$  where  $\deg \beta = 3$  and  $\beta^3 = \beta + 1$ . And indeed we may confirm that  $\mathbf{F}_2(\beta)$  is a splitting field for *both* the irreducible polynomials of degree 3:

```
HH.<b>=FiniteField(8)
RR.<T>=PolynomialRing(HH)
[RR(T^3+T+1).factor(),
 RR(T^3+T^2+1).factor()]
```

```
[(T + b) * (T + b^2) * (T + b^2 + b),
 (T + b + 1) * (T + b^2 + 1) * (T + b^2 + b + 1)]
```

## 12.6 The multiplicative group of a finite field

Let  $F = \mathbf{F}_q$  be a finite field, where  $q = p^n$ . Then of course the multiplicative group  $F^\times = F \setminus \{0\}$  is a finite abelian group having  $q - 1$  elements.

In this section we are going to argue that the group  $F^\times$  is *cyclic*, so that

$$F^\times \simeq \mathbf{Z}/(q - 1)\mathbf{Z}.$$

We begin with a Lemma from group theory:

**Lemma 12.6.1.** *Let  $G$  be a finite abelian group (written multiplicatively). If  $a \in G$  is an element of maximal order in  $G$ , then the order of every element of  $G$  is a divisor of the order  $o(a)$  of  $a$ .*

*Proof.* Let  $x \in G$  be any element different from 1. If  $o(x) \nmid o(a)$  then in the prime factorizations of  $o(x)$  and  $o(a)$  we can find a prime  $p$  that occurs to a higher power in  $o(x)$  than in  $o(a)$ .

Write  $o(a) = p^\alpha n$  and  $o(x) = p^\beta m$  where  $\alpha < \beta$  and  $p \nmid n, p \nmid m$ .

Now  $o(a^{p^\alpha}) = n$  and  $o(x^m) = p^\beta$ , so the orders of  $a^{p^\alpha}$  and  $x^m$  are relatively prime. It follows that the order of the product  $a^{p^\alpha} \cdot x^m$  is equal to the product of the orders of the elements, i.e. to  $np^\beta$ . But this exceeds  $o(a)$  contrary to the hypothesis.  $\square$

**Theorem 12.6.2.** *Let  $F$  be any field. Any finite subgroup of the multiplicative group  $F^\times$  is cyclic.*

*Proof.* Let  $H$  be a finite subgroup of  $F^\times$  and let  $a \in H$  be an element with maximal order. Write  $N = o(a)$ . Now Lemma 12.6.1 shows that  $o(x) \mid N$  for all  $x \in H$ . Thus, every element of  $H$  is a root of the polynomial  $T^N - 1$ . Now, this polynomial has no more than  $N$  roots – see Corollary 3.4.3. It follows that  $|H| \leq N$ . Since the cyclic group  $\langle a \rangle$  has order  $N$ , conclude that  $H = \langle a \rangle$ .  $\square$

**Corollary 12.6.3.**  $\mathbf{F}_q^\times$  is a cyclic group of order  $q - 1$  for any prime power  $q = p^n$ .

**Corollary 12.6.4.** *For any prime power  $q = p^n$ , there is  $\alpha \in \mathbf{F}_q$  for which  $\mathbf{F}_q = \mathbf{F}_p(\alpha)$ . In words: each finite field is a primitive extension of its prime subfield.*

*Proof.* Let  $\beta$  be a generator for the cyclic group  $\mathbf{F}_q^\times$ . Then

$$\langle \beta \rangle \subseteq \mathbf{F}_p(\beta) \subseteq \mathbf{F}_q \implies q - 1 \leq |\mathbf{F}_p(\beta)| \leq q.$$

Since  $|\mathbf{F}_p(\beta)|$  must be a power of  $p$  – see Proposition 12.2.1 – it follows that  $\mathbf{F}_p(\beta) = \mathbf{F}_q$ .  $\square$

## 13 Perfect fields and separable polynomials

Let  $F$  be a field.

### 13.1 Common roots and root multiplicity

If  $f \in F[T]$  is a non-zero polynomial, recall that according to Theorem 5.2.1 we may write

$$f = u \prod_{i=1}^r p_i^{e_i}$$

where  $u \in F^\times$ , where the  $p_i \in F[T]$  are pairwise non-associate *irreducible* polynomials, and where  $e_i \geq 0$ . observe that a splitting field for  $f$  over  $F$  is the same as a splitting field for

$$g = \prod_{i=1}^r p_i.$$

**Lemma 13.1.1.** *Suppose that  $f, g \in F[T]$ .*

- a. *If  $\gcd(f, g) = 1$  then  $f$  and  $g$  have no common root in any extension of  $F$ .*
- b. *If  $f, g$  are irreducible and not associate, they have no common root in any extension of  $F$ .*

*Proof.* Assertion b. is of course an immediate consequence of assertion a.

As to a., note that  $\gcd(f, g) = 1 \implies$  that  $1 = uf + vg$  for polynomials  $u, v \in F[T]$  Proposition 4.3.4.

Let  $E$  be an extension field of  $F$  and suppose that  $\alpha \in E$  is a root of both  $f$  and  $g$ . Then  $0 = u(\alpha)f(\alpha) + v(\alpha)g(\alpha) = 1$  which is impossible. Thus there can be no such common root  $\alpha$ .  $\square$

Let  $f \in F[T]$  be monic and let  $E$  be a splitting field for  $f$  over  $F$ . Write

$$f = (T - \alpha_1)^{e_1} \cdots (T - \alpha_r)^{e_r}.$$

for **distinct** elements  $\alpha_i \in E$  and exponents  $e_i \in \mathbf{Z}_{\geq 1}$ . Since the linear polynomials  $T - \alpha_i$  are irreducible and pairwise relatively prime in  $E[T]$ , it follows from Theorem 5.2.1 that this representation is unique (up to re-ordering, of course).

*Definition 13.1.2.* We say that the root  $\alpha_i$  of  $f$  has *multiplicity*  $e_i$ . If  $e_i = 1$ , we say that  $\alpha_i$  is a *simple root* of  $f$ . If  $e_i > 1$ , we say that  $\alpha_i$  is a *\*multiple root* of  $f$ .

**Proposition 13.1.3.** *The polynomial  $f \in F[T]$  has no multiple roots if and only if  $\gcd(f, f') = 1$  where  $f'$  is the formal derivative of  $f$ .*

*Proof.* We are actually going to prove the (equivalent) assertion:  $f$  has a multiple root if and only if  $\gcd(f, f') \neq 1$ .

$\implies$ : We show that if  $f$  has a multiple root, then  $\gcd(f, f') \neq 1$ . Suppose that  $f$  has a multiple root  $\alpha$  in some extension field  $E$ .

In  $E[T]$  we may write

$$f = (T - \alpha)^2 \cdot g \quad \text{for some } g \in E[T].$$

One must check that the product rule holds for formal differentiation; using that rule, one then notes that

$$f' = (T - \alpha)^2 g' + 2(T - \alpha)g.$$

It is evident that  $\alpha$  is a root of both  $f$  and  $f'$  and thus Lemma 13.1.1 implies that  $\gcd(f, f') \neq 1$ .

$\Leftarrow$ : We suppose that  $\gcd(f, f') \neq 1$  and we must prove that  $f$  has a multiple root.

Our assumption implies that there is a polynomial  $g \in F[T]$  of positive degree which divides both  $f$  and  $f'$ . Let  $\alpha$  be a root of  $g$  in some extension field of  $F$ . Thus  $\alpha$  is a root of both  $f$  and  $f'$ . We now claim that  $\alpha$  is a multiple root of  $f$ .

Since  $\alpha$  is a root of  $f$ , we may write

$$f = (T - \alpha) \cdot h \quad \text{for some } h \in F[T].$$

In order to show that  $\alpha$  is a multiple root of  $f$ , we must argue that  $\alpha$  is a root of  $h$ .

Well, we find using the product rule that

$$f' = h + (T - \alpha) \cdot h'.$$

Since  $\alpha$  is a root of  $f'$  we find that

$$0 = f'(\alpha) = h(\alpha) + (\alpha - \alpha)h'(\alpha) = h(\alpha).$$

We have now argued that  $h(\alpha) = 0$ ; as already observed, this proves that  $\alpha$  is a multiple root of  $f$ .  $\square$

## 13.2 Multiple roots and the characteristic

**Lemma 13.2.1.** *Suppose that the field  $F$  has characteristic 0, and let  $g \in F[T]$  be a polynomial with  $\deg g \geq 1$ . Then the formal derivative  $g' \in F[T]$  is non-zero.*

*Proof.* Let  $d = \deg g \geq 1$  and write

$$g = \sum_{i=0}^d a_i T^i \in F[T]$$

with  $a_d \neq 0$ . Then

$$g' = \sum_{i=0}^d i \cdot a_i T^{i-1}$$

so that the coefficient of  $T^{d-1}$  in  $g'$  is equal to  $d \cdot a_d$ . Since  $F$  has characteristic 0,  $d1_F \neq 0$ . Since  $a_d \neq 0$  by assumption, we conclude that the coefficient of  $T^{d-1}$  in  $g'$  is non-zero, hence  $g'$  itself is indeed non-zero.  $\square$

**Proposition 13.2.2.** *Let  $f \in F[T]$  be an irreducible polynomial.*

*a. If  $F$  has characteristic 0, then  $f$  has no multiple roots.*

*b. If  $F$  has characteristic  $p > 0$  then  $f$  has no multiple roots unless  $f$  has the form*

$$f(T) = g(T^p)$$

*for some polynomial  $g \in F[T]$ .*



*Proof.* Suppose that  $f$  has a multiple root. It follows from Proposition 13.1.3 that  $\gcd(f, f') \neq 1$ . But  $\deg(f') < \deg(f)$ . Thus if  $f' \neq 0$ , the irreducibility of  $f$  guarantees that  $f$  and  $f'$  have no common factor. Hence, the assumption that  $f$  has a multiple root implies that ( $\clubsuit$ )  $f' = 0$ .

Now a. follows since if  $F$  has characteristic 0, Lemma 13.2.1 shows that the polynomial  $f'$  is non-zero, contradicting ( $\clubsuit$ ).

Now suppose that the characteristic of  $F$  is  $p > 0$  and write

$$f = \sum_{i=0}^N a_i T^i \quad \text{for } a_i \in F.$$

Suppose that  $f' = 0$ . Then

$$f' = \sum_{i=1}^n a_i \cdot i \cdot T^{i-1}.$$

So  $f' = 0 \implies a_i \cdot i = 0$  for all  $i$ . This equation shows that  $a_i = 0$  whenever  $i \not\equiv 0 \pmod{p}$ .

Thus the polynomial  $f$  has the form

$$f = \sum_{j=0}^M a_{jp} T^{jp} = g(T^p)$$

where

$$g = \sum_{j=0}^M a_{jp} T^j.$$

□

### 13.3 Perfect fields

*Definition 13.3.1.* A polynomial  $f \in F[T]$  is said to be *separable* if each irreducible factor of  $f$  has only simple roots.

*Definition 13.3.2.* A field  $F$  is said to be *perfect* if each irreducible polynomial is separable.

*Remark 13.3.3.* a. Proposition 13.2.2 implies that any field of characteristic 0 is perfect.

b. Let  $F = \mathbb{F}_p(X)$  be the field of rational functions over  $\mathbb{F}_p$  in the variable  $X$ . Then  $F$  is not perfect.

Indeed, the polynomial  $T^p - X \in F[T]$  is irreducible by Eisenstein's criterion Theorem 7.4.1. But this polynomial has only one root  $\alpha$  (with multiplicity  $p$ ) in a splitting field since  $T^p - X = (T - \alpha)^p$  by (12.1).

On the other hand, some fields of characteristic  $p$  are perfect. Here is a useful characterization:

**Proposition 13.3.4.** *Let  $F$  be a field of characteristic  $p > 0$ . Then  $F$  is perfect if and only if*

$$F = F^p = \{x^p \mid x \in F\}.$$

*Proof.*  $\Leftarrow$ : Suppose that  $F = F^p$  and let  $f \in F[T]$  be an irreducible polynomial. We must argue that  $f$  is separable.

If  $f$  has a multiple root, we argued above that  $f = g(T^p)$  for some polynomial

$$g = \sum_{i=0}^r a_i T^i.$$

For each  $i$ , choose  $b_i \in F$  with  $b_i^p = a_i$ . Then

$$f = g(T^p) = \sum_{i=0}^r a_i T^{pi} = \sum_{i=0}^r b_i^p T^{pi} = \left( \sum_{i=0}^r b_i T^i \right)^p.$$

But this equation contradicts the assumption that  $f$  is irreducible in  $F[T]$ .

$\Rightarrow$ : Suppose that  $F$  is perfect and let  $x \in F$ . Consider the polynomial

$$f = T^p - x$$

and let  $g$  denote a monic irreducible factor of  $f$  in  $F[T]$ . Find a root  $\alpha$  of  $g$  in some extension field of  $F$ .

Then  $\alpha$  is also a root of  $f$ , so that  $\alpha^p = x$ . In  $F(\alpha)[T]$  we have the identity

$$f = T^p - x = T^p - \alpha^p = (T - \alpha)^p.$$

By unique factorization in  $E[T]$  – see Theorem 5.2.1 –, we find that  $g = (T - \alpha)^m$  for some  $1 \leq m \leq p$ . But  $g$  is irreducible, so the assumption that  $F$  is perfect means  $g$  has no repeated roots in the extension field  $E$ . Thus  $m = 1$  so that  $g = (T - \alpha)$ . This implies that  $\alpha \in F$  so indeed  $x$  has a  $p$ -th root in  $F$ .  $\square$

We can now prove the following important fact:

**Proposition 13.3.5.** *A finite field is perfect.*

*Proof.* Let  $F$  be a finite field, and recall that the Frobenius mapping  $\mathcal{F}(x) = x^p$  is a ring homomorphism  $F \rightarrow F$  – see Lemma 12.4.3. Moreover,  $\ker \mathcal{F} = \{0\}$  since  $x^p = 0 \implies x = 0$ ; this shows that  $\mathcal{F}$  is *injective*.

Since  $F$  is finite and  $\mathcal{F}$  is injective, one knows that  $\mathcal{F}$  is also *surjective*. This proves that  $F = F^p$ ; thus the field  $F$  is perfect by Proposition 13.3.4.  $\square$

*Remark 13.3.6.* Observe that the proof shows that  $\mathcal{F}$  is always injective for a field of characteristic  $p$ . Moreover, the image  $\mathcal{F}(F)$  coincides with  $F^p$ , which is therefore a *subfield* of  $F$ .

We see that the following are equivalent:

- i)  $F$  is *perfect*,
- ii) the Frobenius mapping  $\mathcal{F}$  is *onto*,
- iii) the Frobenius mapping  $\mathcal{F}$  is bijective, i.e. an *automorphism* of  $F$ .

## 14 Automorphisms of algebraic objects

Consider an algebraic object  $\mathcal{X}$  – e.g. a *group*, or a *ring*, or a *field*, or a *field extension*, or a *vector space over a field*.

Within the family of algebraic objects of the same type, there is a notion of *isomorphism*.

For the above list, probably the only case that raises eyebrows is the question: “what is an isomorphism of a field extension?”

Though a related question is: what is the right notion for isomorphism of “vector spaces over fields”? We’ll have more to say on this in the examples, below.

Once one has agreed on a notion of isomorphism, then for a fixed object  $\mathcal{X}$  one can consider the collection of all isomorphisms

$$\mathcal{X} \rightarrow \mathcal{X}$$

This collection is a group

$$\text{Aut}(\mathcal{X}),$$

the group of *automorphisms* of  $\mathcal{X}$ .

### 14.1 Automorphism examples

- Vector spaces

For a field  $F$  and an  $n$ -dimensional vector space  $V$  over  $F$ , the automorphism group

$$\text{Aut}(V) = \text{GL}(V) \simeq \text{GL}_n(F)$$

identifies with the group of invertible  $n \times n$  matrices with coefficients in  $F$ .

- Automorphisms of some finite abelian groups

Let  $m \geq 1$  and consider the group

$$A = \mathbb{Z}_m \times \mathbb{Z}_m,$$

a group with  $|A| = m^2$ .

Let’s represent elements  $x$  of  $A$  as column vectors:

$$x = \begin{bmatrix} a \\ b \end{bmatrix} \quad \text{for } a, b \in \mathbb{Z}_m.$$

Any matrix

$$M = \begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix} \quad \text{for } \alpha, \beta, \delta, \gamma \in \mathbb{Z}_m$$

determines a *group homomorphism*

$\phi_M : A \rightarrow A$  given by the rule

$$\phi_M(x) = \begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = a \begin{bmatrix} \alpha \\ \gamma \end{bmatrix} + b \begin{bmatrix} \beta \\ \delta \end{bmatrix}$$

and  $\phi_M$  is an *automorphism* if and only if the determinant of  $M$  is a unit in  $\mathbb{Z}_m$  – i.e.  $\det M \in (\mathbb{Z}_m)^\times$ .

Thus

$$\text{Aut}(A) \simeq \text{GL}_2(\mathbb{Z}_m).$$

So, for example the matrix

$$M = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$$

has determinant  $-2 \equiv m - 2 \pmod{m}$ , and so it defines an automorphism of  $A$  whenever

$$\gcd(m, m - 2) = 1$$

i.e. whenever  $m$  is *odd*.

## 14.2 Automorphisms of field extensions

Our real interest in this course is in automorphisms of a field extension  $F \subset E$ . Here, an automorphism of the field extension is an automorphism  $\phi : E \rightarrow E$  such that  $\phi(a) = a$  for all  $a \in F$ .

To remind ourself of the “bottom field” of the field extension  $F \subset E$  ( $F$  is sometimes called the “ground field” or “base field”) we write

$$\text{Aut}_F(E) \quad \text{or} \quad \text{Aut}(E/F)$$

for the automorphism group of this field extension.

- Example: quadratic extensions when the characteristic is not 2

Suppose that  $[E : F] = 2$  and that the characteristic of  $F$  is not 2.

Then  $E = F(\beta)$  for some element  $\beta \in E$ ,  $\beta \notin F$ ,  $\beta^2 \in F$ .

Indeed, we may choose a basis of  $E$  as an  $F$  vector space of the form  $1, \gamma$ . Then linear independence implies that  $\gamma \notin F$ . Let

$$f(T) = T^2 + aT + b \in F[T]$$

be the monic minimal polynomial of  $\gamma$  over  $F$ .

For any  $s \in F$ , we claim that the minimal polynomial of the element  $\gamma - s \in E$  has the form

$$\begin{aligned} f(T + s) &= (T + s)^2 + a(T + s) + b \\ &= T^2 + (a + 2s)T + s^2 + as + b \end{aligned}$$

Taking  $s = \frac{-a}{2}$ , we find that  $g(T) = f(T + s)$  has the form

$$g(T) = T^2 - c$$

for some  $c \in F$ , so that  $\beta = \gamma - s$  satisfies  $\beta^2 = c$ . Now it just remains to observe that

$$F(\gamma) = F(\gamma + s) = F(\beta).$$

Now, notice that every element of  $E$  has the form

$$a + b\beta \quad \text{for} \quad a, b \in F.$$

Now, the roots of  $T^2 - c$  in  $E$  are  $\pm\beta$ . Since  $T^2 - c$  is irreducible over  $F$ , it follows that there is an isomorphism

$$\phi : E = F(\beta) \rightarrow E = F(\beta)$$

for which  $\phi(\beta) = -\beta$  and  $\phi(s) = s$  for all  $s \in F$ .

Thus

$$\phi(a + b\beta) = a - b\beta \quad \text{for } a, b \in F.$$

**Proposition 14.2.1.** *Suppose that the characteristic of  $F$  not equal 2. For  $E = F(\gamma) = F(\beta)$  a quadratic extension as above,  $\text{Aut}_F(E) = \langle \phi \rangle$  and in particular  $|\text{Aut}_F(E)| = 2$ .*

- Example: quadratic extensions in characteristic 2.

Suppose that the characteristic of  $F$  is 2, and consider a polynomial of the form  $T^2 - c \in F[T]$ . If  $\beta$  is a root of this polynomial then

$$T^2 - c = T^2 - \beta^2 = (T - \beta)^2$$

since the characteristic is 2.

Just for emphasis, let's double check this:

$$(T - \beta)^2 = T^2 - 2\beta T + (-\beta)^2 = T^2 + c = T^2 - c.$$

Thus the polynomial  $T^2 - c$  has a single root  $\beta$  which is repeated twice. It is irreducible over  $F$  if and only if  $\beta \notin F$ .

However, in general at least, there are irreducible quadratic polynomials with distinct roots in characteristic 2.

Consider a polynomial of the form

$$f = T^2 + T + a \quad \text{for } a \in F$$

and suppose that  $\beta$  is a root of  $f$ ; thus

$$\beta^2 + \beta + a = 0.$$

We claim that also  $\beta + 1$  is a root of  $f$ . Indeed,

$$\begin{aligned} f(\beta + 1) &= (\beta + 1)^2 + (\beta + 1) + a \\ &= \beta^2 + 1 + \beta + 1 + a \\ &= \beta^2 + \beta + a + 2 \\ &= \beta^2 + \beta + a \\ &= f(\beta) = 0. \end{aligned}$$

It follows that

$$f = T^2 + T + a = (T + \beta)(T + \beta + 1)$$

i.e.  $\beta$  and  $\beta + 1$  are the distinct roots of  $f$ . Recall that  $\mathbb{F}_4 = \mathbb{F}_2(\beta)$  where  $\beta^2 + \beta = 1$ .

Note that the for any  $F$  of char. 2, the polynomial  $f = T^2 + T + a$  is irreducible if and only if  $\beta \notin F$  – this follows from Proposition 7.1.4.

Suppose  $f$  is irreducible and let  $E = F(\beta)$ . Recall that an element of  $E$  has the form

$$a + b\beta \quad \text{for } a, b \in F.$$

Since  $\beta$  and  $\beta + 1$  are the roots of  $f$ , there is a automorphism

$$\phi : E = F(\beta) \rightarrow E = F(\beta + 1) = F(\beta)$$

for which  $\phi(\beta) = \beta + 1$  and  $\phi(s) = s$  for  $s \in F$ .

Thus

$$\phi(a + b\beta) = a + b + b\beta.$$

*Remark 14.2.2.* When  $F = \mathbb{F}_2$  and  $\beta^2 + \beta = 1$ , notice that

$$(a + b\beta)^2 = \phi(a + b\beta) = a + b + b\beta.$$

## 15 The Fundamental Theorem of Galois Theory

Let  $F$  be a field and let  $E$  be the splitting field over  $F$  of some *separable* polynomial  $g \in F[T]$ . Loosely speaking, the fundamental theorem of Galois Theory relates two things:

- *intermediate fields*  $L$ , where  $F \subset L \subset E$ , and
- *subgroups*  $H$ , where  $H \subset \text{Gal}(E/F)$ .

### 15.1 Subfields from subgroups

**Proposition 15.1.1.** *Let  $K$  be any field and let  $H$  be any subgroup of the group  $\text{Aut}(K)$  of automorphisms of  $K$ . Then*

$$K^H = \{x \in K \mid h \cdot x = x \quad \forall h \in H\}$$

*is a subfield of  $K$ .*

*Proof.* If  $x, y \in K^H$  with  $x \neq 0$ , we must argue that  $x - y \in K^H$ , that  $x \cdot y \in K^H$  and that  $\frac{1}{x} \in K^H$ . But for each  $h \in H$  we have:

$$h(x - y) = h(x) - h(y) = x - y \implies x - y \in K^H$$

$$h(x \cdot y) = h(x) \cdot h(y) = x \cdot y \implies x \cdot y \in K^H$$

and

$$h\left(\frac{1}{x}\right) = \frac{1}{h(x)} = \frac{1}{x} \implies \frac{1}{x} \in K^H.$$

□

### 15.2 Splitting fields and Galois groups

The following result follows the proof of Lemma 11.3.1

**Proposition 15.2.1.** *Let  $g \in F[T]$  be a separable polynomial and let  $E$  be a splitting for  $g$  over  $F$ . Suppose that  $\phi : F \rightarrow F_1$  is a field isomorphism and write  $g_1 = \phi(g) \in F_1[T]$  and write  $E_1$  for a splitting field for  $g_1$  over  $F_1$ . Then there are exactly  $[E : F]$  isomorphisms  $\theta : E \rightarrow E_1$  such that  $\theta_F = \phi$ .*

*Proof.* We are going to essentially repeat the proof of Lemma 11.3.1 with a little more book-keeping.

Proceed by induction on  $\deg g$ . If  $g$  has degree 0 or 1 then  $F = E$  and  $F_1 = E_1$  and there is nothing to prove.

So suppose that  $d = \deg g > 1$  and that the result is known for all fields  $F$  and all polynomials of degree less than  $d$ . Let  $p$  be an irreducible factor of  $g$  of degree  $e \leq d$  and write  $p_1 = \phi(p)$  which is thus an irreducible factor of  $g_1$ . Of course,  $p$  splits over  $E$  and we choose a root  $\alpha \in E$  of  $p$ .

Since  $g$  has no repeated roots, the same is true for  $g_1$  and  $p_1$ . Thus there are  $e$  roots of  $p_1$  in  $E_1$ , and for any root  $\beta \in E_1$  of  $p_1$  Lemma 11.3.1 gives an isomorphism  $\phi' : F(\alpha) \rightarrow F_1(\beta)$  such that  $\phi'_F = \phi$  and such that  $\phi'(\alpha) = \beta$ . Thus, there are exactly  $d = [F(\alpha) : F]$  isomorphisms  $F(\alpha) \rightarrow F_1(\beta)$  whose restriction to  $F$  is  $\phi$ .

Now, we may write  $g = (T - \alpha)s$  for  $s \in F(\alpha)[T]$ , and  $g_1 = (T - \beta)s_1$  for  $s_1 \in F_1(\beta)[T]$ . Since  $g_1 = \phi(g)$  we have  $s_1 = \phi'(s)$ . It is clear that  $E$  is a splitting field for  $s$  over  $F$  and that  $E_1$  is a splitting field for  $s_1$  over  $F_1$ .

Since  $\deg s = d - 1$ , for any isomorphism  $\theta'$  as in the preceding paragraph, the induction hypothesis guarantees that there are precisely  $[E : F(\alpha)]$  isomorphisms  $\theta : E \rightarrow E'$  for which  $\theta_{F(\alpha)} = \phi'$ .

It therefore follows that there are  $[E : F(\alpha)] \cdot [F(\alpha) : F] = [E : F]$  isomorphisms  $\theta : E \rightarrow E_1$  with  $\theta_F = \phi$ , as required.  $\square$

As an immediate consequence of Proposition 15.2.1 we obtain the following:

**Corollary 15.2.2.** *Let  $g \in F[T]$  be a separable polynomial, and let  $E$  denote a splitting field of  $g$  over  $F$ . Then  $|\text{Gal}(E/F)| = [E : F]$ .*

**Proposition 15.2.3.** *Suppose that  $E$  is the splitting field over  $F$  of a separable polynomial  $g \in F[T]$ . Let  $\Gamma = \text{Gal}(E/F)$ . Then  $F = E^\Gamma$ .*

*Proof.* Let  $L = E^\Gamma$ , so that  $L$  is an intermediate field:

$$F \subset L = E^\Gamma \subset E.$$

Viewing  $g$  as a polynomial in  $L[T]$ , it is clear that  $E$  is a splitting field of  $g$  over  $L$ .

Now Corollary 15.2.2 guarantees that

$$[E : L] = |\text{Gal}(E/L)| \quad \text{and} \quad [E : F] = |\text{Gal}(E/F)|.$$

Since  $F \subset L$ , we have  $\text{Gal}(E/L) \subset \Gamma = \text{Gal}(E/F)$ . The assumption  $L = E^\Gamma$  shows that any automorphism of  $E$  which is the identity on  $F$  is the identity on  $L$ ; this shows that

$$\Gamma = \text{Gal}(E/F) = \text{Gal}(E/L).$$

It now follows that  $[E : L] = [E : F]$  and hence that  $L = F$ .  $\square$

### 15.3 Fixed fields and some linear algebra

The correspondence between subgroups  $H \subset \text{Gal}(E/F)$  and intermediate fields  $F \subset L \subset E$  will be given by the assignment

$$H \mapsto E^H$$

(we'll formulate the statement more precisely later on).

We are ultimately going to argue that this assignment determines a one-to-one correspondence between the subgroups and the intermediate fields. For this, we require some numerical estimates relating the degrees  $[E : E^H]$  and the orders  $|H|$ . These estimates are obtained using a result of E. Artin:

## Proposition (Artin).

**Proposition 15.3.1.** *Let  $G$  be a finite group of automorphisms of a field  $K$  and let  $L = K^G$ . Then  $[K : L] \leq |G|$ .*

*Proof.* If  $|G| = n$ , let us write

$$G = \{\theta_1, \theta_2, \dots, \theta_n\}$$

where  $\theta_1 = 1_G$ .



We must argue that  $[K : L] \leq n$ . Suppose the contrary, and choose  $n + 1$  elements  $u_1, u_2, \dots, u_{n+1} \in K$  which are linearly independent over  $L$ .

Now form the following  $n \times (n + 1)$  matrix with entries in  $K$ :

$$M = \begin{pmatrix} \theta_1(u_1) & \theta_1(u_2) & \cdots & \theta_1(u_{n+1}) \\ \theta_2(u_1) & \theta_2(u_2) & \cdots & \theta_2(u_{n+1}) \\ \vdots & \vdots & \ddots & \vdots \\ \theta_n(u_1) & \theta_n(u_2) & \cdots & \theta_n(u_{n+1}) \end{pmatrix} \in \text{Mat}_{n \times (n+1)}(K).$$

Since  $M$  has  $n$  rows, we know that the *rank* of  $M$  satisfies

$$\text{rk}(M) \leq n.$$

On the other hand, linear algebra tells us that

$$\dim_K \text{Null}(M) + \text{rk}(M) = n + 1 = \# \text{ of columns of } M.$$

Thus

$$\dim_K \text{Null}(M) = n + 1 - \text{rk}(M) \geq n + 1 - n = 1$$

and we conclude that there is a non-zero solution  $\mathbf{x} = \mathbf{a} \in K^{n+1}$  to the matrix equation

$$(\clubsuit) \quad M \cdot \mathbf{x} = \mathbf{0}.$$

Among all possible non-zero solutions

$$\mathbf{0} \neq \mathbf{a} = (a_1 \ a_2 \ \cdots \ a_{n+1})^T$$

to  $(\clubsuit)$ , choose one with the smallest number of non-zero coefficients  $a_i \in K$ .

After renumbering the indices on the  $u_i$  and the  $x_j$ , we may suppose that  $a_1 \neq 0$ . Since the vector  $\left(\frac{1}{a_1}\right) \cdot \mathbf{a}$ , remains a solution to  $(\clubsuit)$ , we may and will suppose that  $a_1 = 1$ .

Recall that  $\theta_1 = 1_G = \text{id}_K$ . The first coefficient in the vector equation

$$\mathbf{0} = M \cdot \mathbf{a}$$

gives

$$0 = \sum_{i=1}^{n+1} a_i \theta_1(u_i) = \sum_{i=1}^{n+1} a_i u_i.$$

Since the  $u_i$  are linearly independent over  $L$  by assumption, some  $a_j$  must be in  $K$  and not in  $L = K^G$ .

Renumbering again, we may and will suppose that  $a_2 \in K$ ,  $a_2 \notin L = K^G$ .

Of course,  $a_2 \notin K^G \implies ga_2 \neq a_2$  for some  $g \in G$ , and in turn we recall that  $g = \theta_i$  for some  $i > 1$  hence we have

$$\theta_i(a_2) \neq a_2.$$

Consider the matrix  $\theta_i(M) \in \text{Mat}_{n \times (n+1)}(K)$  given by

$$\theta_i(M) = \begin{pmatrix} \theta_i \cdot \theta_1(u_1) & \theta_i \cdot \theta_1(u_2) & \cdots & \theta_i \cdot \theta_1(u_{n+1}) \\ \theta_i \cdot \theta_2(u_1) & \theta_i \cdot \theta_2(u_2) & \cdots & \theta_i \cdot \theta_2(u_{n+1}) \\ \vdots & \vdots & \ddots & \vdots \\ \theta_i \cdot \theta_n(u_1) & \theta_i \cdot \theta_n(u_2) & \cdots & \theta_i \cdot \theta_n(u_{n+1}) \end{pmatrix}.$$

Since  $G$  is group, the rows of  $\theta_i(M)$  are the same as those of  $M$ , but in a different *order*. In particular,

$$\text{Null}(M) = \text{Null}(\theta_i(M)).$$

On the other hand, it is clear that

$$\mathbf{0} = \theta_i(\mathbf{0}) = \theta_i(M \cdot \mathbf{a}) = \theta_i(M) \cdot \theta_i(\mathbf{a}).$$

This proves that both  $\mathbf{a}$  and  $\theta_i(\mathbf{a})$  are solutions to  $(\clubsuit)$ , hence  $\mathbf{v} = \mathbf{a} - \theta_i(\mathbf{a})$  is a solution to  $(\clubsuit)$ , as well.

Now

$$\mathbf{a} = (1 \quad a_2 \quad \cdots \quad a_{n+1})^T$$

and

$$\theta_i(\mathbf{a}) = (1 \quad \theta_i(a_2) \quad \cdots \quad \theta_i(a_{n+1}))^T.$$

Since  $a_2 \neq \theta_i(a_2)$ ,  $\mathbf{v} = \mathbf{a} - \theta_i(\mathbf{a})$  is non-zero. On the other hand, the first coefficient of  $\mathbf{v} = \mathbf{a} - \theta_i(\mathbf{a})$  is 0, hence  $\mathbf{v}$  has more non-zero terms than does  $\mathbf{a}$ . This contradicts the choice of  $\mathbf{a}$ , and completes the proof.  $\square$

## 15.4 Normal extensions

Let  $E$  be an algebraic extension of the field  $F$ . We will say that  $E$  is a *normal extension* of  $F$  if every polynomial that contains a root in  $E$  actually *splits* over  $E$ .

In order to check that  $E$  is a normal extension of  $F$ , it is enough to verify that each *irreducible* polynomial with a root in  $E$  actually splits over  $E$ .

**Proposition 15.4.1.** *Let  $E$  be an extension field of  $F$ , and let  $\Gamma = \text{Gal}(E/F)$ .*

*a. If  $F = E^\Gamma$ , then  $E$  is a normal, separable extension of  $F$ .*

*b. ::Let  $E$  be the splitting field over  $F$  of some separable polynomial  $g \in F[T]$ . Then  $E$  is a normal (and separable) extension of  $F$*

*Proof.* According to the [Proposition on splitting fields and fixed fields](#splitting-fields-and-fixed-fields), the field extension  $E \supset F$  in b. satisfies the condition in a. So b. is an immediate consequence of a.

To prove a., let  $h \in F[T]$  be an *irreducible* polynomial, and suppose that  $\alpha \in E$  is a root of  $h$ . We must argue that  $h$  is separable and actually *splits* over  $E$ .

Consider the *orbit*  $\mathcal{O}$  of the root  $\alpha$  under the action of  $\Gamma$ :

$$\mathcal{O} = \{g\alpha \mid g \in G/H\}$$

where  $H = \text{Stab}_\Gamma(\alpha)$ .

If  $g_1, \dots, g_m$  is a system of coset representatives for  $H$  in  $\Gamma$ , there are  $m = [\Gamma : H]$  distinct elements of  $\mathcal{O}$ :

$$\mathcal{O} = \{g_1\alpha, g_2\alpha, \dots, g_m\alpha\}.$$

Form the polynomial

$$h_1 = \prod_{\beta \in \mathcal{O}} (T - \beta) = \prod_{g \in \Gamma/H} (T - g\alpha) \in E[T].$$

Note that by construction  $h_1$  has  $m$  distinct roots in  $E$ . We first claim that in fact  $h_1 \in F[T]$ .

Of course, for any polynomial  $\ell \in E[T]$ , we know that

$$\ell \in F[T] = E^\Gamma[T] \iff x\ell = \ell \text{ for all } x \in \Gamma.$$

Thus, we must argue for each  $x \in \Gamma$  that  $xh_1 = h_1$ .

Well, for  $x \in \Gamma$ , we have

$$xh_1 = x \cdot \left( \prod_{g \in \Gamma/H} (T - g\alpha) \right) = \prod_{g \in \Gamma/H} (T - xg\alpha) = (\diamond).$$

Now using the substitution  $h = xg$ , note that

$$(\diamond) = \prod_{h \in \Gamma/H} (T - h\alpha) = h_1.$$

This proves that  $h_1 \in F[T]$ .

Since  $h$  is the *minimal polynomial* of  $\alpha$  over  $F$ , since  $h_1 \in F[T]$ , and since  $h_1$  has  $\alpha$  as a root by construction, we conclude that  $h \mid h_1$ . Since  $h_1$  splits over  $E$ , unique factorization in  $E[T]$  shows that  $h$  splits over  $E$ . Since  $h_1$  is separable, also  $h$  is separable. This completes the proof that  $E$  is a normal, separable extension of  $F$ .  $\square$

**Proposition 15.4.2.** *Let  $E$  be a finite, normal, separable extension of  $F$ . Then  $E$  is the splitting field over  $F$  of a separable polynomial  $g \in F[T]$ .*

*Proof.* Let  $\alpha_1, \dots, \alpha_n \in E$  be elements such that  $E = F(\alpha_1, \dots, \alpha_n)$ . For  $1 \leq i \leq n$ , write  $f_i \in F[T]$  for the minimal polynomial over  $F$  of the element  $\alpha_i$ .

Since  $f_i$  has the root  $\alpha_i$  in  $E$  and since  $E$  is normal over  $F$ , the polynomial  $f_i$  splits over  $E$ . Since  $E$  is generated over  $F$  by the roots of the  $f_i$ , it follows that  $E$  is a splitting field of the separable polynomial

$$f = \prod_{i=1}^n f_i \in F[T].$$

$\square$

*Remark 15.4.3.* It is actually true that any finite separable extension  $F \subset E$  is *primitive*; namely, there is an element  $\alpha \in E$  such that  $E = F(\alpha)$  – this result is known as the *Primitive Element Theorem*. We don't require this fact, and so I haven't given a proof. The proof of the previous Proposition would be slightly more streamlined using the Primitive Element Theorem.

## 15.5 The Fundamental Theorem

Before stating the main theorem of Galois theory, observe that results so far enable us to recognize Galois groups in some useful situations:

**Proposition 15.5.1.** *Suppose that  $F \subset E$  is an extension field, that  $G \subset \text{Aut}(E)$  is a finite group of automorphisms, and that  $F = E^G$ . Then*

$$G = \text{Gal}(E/F).$$

*Proof.* According to the [Proposition](#normal-as-fixed-field) above,  $E$  is a separable and normal extension of  $F$ , and  $[E : F] = |\text{Gal}(E/F)|$ .

Since  $F = E^G$ , note that  $G \subset \text{Gal}(E/F)$ . Artin's Proposition implies that  $[E : F] \leq |G|$ , and we see that

$$[E : F] \leq |G| \leq |\text{Gal}(E/F)| = [E : F].$$

Thus equality holds everywhere, and we conclude that  $G = \text{Gal}(E/F)$  as required.  $\square$

**Theorem 15.5.2.** *Let  $E$  be a splitting field over  $F$  of a separable polynomial  $g \in F[T]$ , and let  $\Gamma = \text{Gal}(E/F)$ .*

*a. There is a one-to-one correspondence between subgroups of  $\Gamma$  and intermediate fields of the extension  $F \subset E$  given by  $H \mapsto E^H$ .*

*i. If  $H$  is a subgroup of  $\Gamma$ , we have*

$$H = \text{Gal}(E/E^H).$$

*ii. If  $F \subset K \subset E$  is an intermediate field, the corresponding subgroup is  $\text{Gal}(E/K) \subset \Gamma$ , and we have*

$$K = E^{\text{Gal}(E/K)}.$$

*b. For any subgroup  $H \subset \Gamma$ ,*

$$[E : E^H] = |H| \quad \text{and} \quad [E^H : F] = [\Gamma : H].$$

*c. :: Under the correspondence of a., the subgroup  $H$  is normal in  $\Gamma$  if and only if the subfield  $K = E^H$  is a normal extension of  $F$ . If this is the case, then*

$$\text{Gal}(E^H/F) = \Gamma/H \simeq \text{Gal}(E/F)/\text{Gal}(E/K).$$

*Proof.* For (a), write  $\mathcal{G}$  for the set of subgroups of  $\Gamma$  and write  $\mathcal{J}$  for the set of intermediate fields  $K$  (so  $F \subset K \subset E$ ).

We consider the mapping

$$\mathcal{G} \rightarrow \mathcal{J} \quad \text{given by } H \mapsto E^H$$

and the mapping

$$\mathcal{J} \rightarrow \mathcal{G} \quad \text{given by } K \mapsto \text{Gal}(E/K).$$

Let us pause to observe that if  $H_1, H_2 \subset G$  are subgroups with  $H_1 \subset H_2$ , then  $E^{H_2} \subset E^{H_1}$  – so the assignment  $H \mapsto E^H$  is *inclusion reversing*.

Similarly, if  $K_1 \subset K_2$  are intermediate fields, then  $\text{Gal}(E/K_2) \subset \text{Gal}(E/K_1)$ , so the assignment  $K \mapsto \text{Gal}(E/K)$  is inclusion reversing.

We observe that the statements of i. and ii. precisely confirm that these mappings are inverse to one another. So to prove a., we need to confirm that

$$\text{i.} \quad \text{Gal}(E/E^H) = H,$$

and that

$$\text{ii.} \quad K = E^{\text{Gal}(E/K)}$$

Now, i. is an immediate consequence of [Proposition (Recognition of Galois Groups)](#recognition-of-galois-groups).

On the other hand, suppose that  $K$  is an intermediate field:  $F \subset K \subset E$ . Since  $E$  is the splitting field of a separable polynomial over  $F$ , then also  $E$  is the splitting field over  $K$ . Thus the [Proposition on splitting fields and fixed fields](#splitting-fields-and-fixed-fields) implies that  $E^{\text{Gal}(E/K)} = K$  as required.

This completes the proof of a. As to b., let  $H$  be a subgroup of  $\Gamma$ . Since  $E$  is a splitting field over  $E^H$  of a separable polynomial, and since we've already seen that  $H = \text{Gal}(E/E^H)$ , [an earlier Theorem](10a-galois-first-steps.html##automorphisms-and-splitting-fields) shows that

$$[E : E^H] = |H|.$$

Now, the same reasoning shows that  $F = E^\Gamma$  and

$$[E : F] = [E : E^\Gamma] = |\Gamma|.$$

The remaining statement of b. now follows from a calculation:

$$[E^H : F] = \frac{[E : F]}{[E : E^H]} = \frac{|\Gamma|}{|H|} = [\Gamma : H].$$

This completes the proof b.

Finally, consider c. Let  $F \subset K \subset E$  be an intermediate extension, and let  $H = \text{Gal}(E/K) \subset \Gamma$ . We must argue that  $K$  is a normal extension of  $F$  if and only if  $H$  is a normal subgroup of  $\Gamma$ , and in case  $H$  is normal, we will argue that  $\Gamma/H$  is isomorphic to  $\text{Gal}(K/F)$ .

$\Rightarrow$ : Suppose that  $K$  is a normal extension of  $F$ . To show that  $H$  is a normal subgroup of  $\Gamma$ , let  $\phi$  be an arbitrary element of  $\Gamma$ , and let  $\theta \in H = \text{Gal}(E/K)$ .

We must argue that  $\phi^{-1} \circ \theta \circ \phi \in H$ . For this, we must argue that  $\phi^{-1} \circ \theta \circ \phi$  is the identity on  $K$ .

Let  $u \in K$  and let  $p \in F[T]$  be the minimal polynomial of  $u$  over  $F$ . Since  $\phi \in \Gamma = \text{Gal}(E/F)$ , the element  $\phi(u)$  is again a root of  $p$ . Since  $K$  is a normal extension, it follows that  $\phi(u) \in K$ . Now,  $\theta|_K$  is the identity on  $K$ , so that

$$\theta(\phi(u)) = \phi(u) \implies \phi^{-1} \circ \theta \circ \phi(u) = u.$$

This proves that indeed  $H$  is normal in  $\Gamma$ .

$\Leftarrow$ : Suppose that  $H$  is a normal subgroup of  $\Gamma$ . We must argue that  $K$  is a normal extension of  $F$ .

We are first going to argue that  $\Gamma/H \simeq \text{Gal}(K/F)$ . To carry out this argument, we first contend that for any automorphism  $\phi$  in  $\Gamma$ , the restriction of  $\phi$  to  $K$  takes values in  $K$ . Let  $u \in K$ .

To argue that  $\phi(u) \in K = E^H$ , let  $\theta \in H$ . Since  $H$  is normal in  $\Gamma$ ,  $\theta_1 = \phi^{-1} \circ \theta \circ \phi \in H$ . Thus

$$\theta \circ \phi = \phi \circ \theta_1.$$

Now notice that

$$\theta(\phi(u)) = \phi(\theta_1(u)) = \phi(u)$$

since  $\theta_1$  is the identity on  $K$ . This shows that indeed  $\phi(u) \in E^H = K$ .

It now follows that the restriction of  $\phi$  to  $K$  takes values in  $K$ . Since  $\ker \phi = \{0\}$ ,  $\phi$  is a one-to-one mapping. Since  $\phi$  is an  $F$ -linear mapping and  $K$  is a finite dimensional vector space over  $F$ , conclude that  $\phi|_K$  is onto and thus determines an automorphism of  $K$ .

We have thus defined a *group homomorphism*

$$(\diamond) \quad \phi \mapsto \phi|_K : \text{Gal}(E/F) \rightarrow \text{Gal}(K/F).$$

The kernel of the group homomorphism  $(\diamond)$  consists in the automorphisms  $\phi$  whose restriction to  $K$  is the identity – i.e. the kernel is  $\text{Gal}(E/K) = H$ .

On the other hand, we claim that the homomorphism  $(\diamond)$  is *onto*. Indeed, since  $E$  is a splitting field over  $K$  of a (separable) polynomial, an earlier [Proposition on uniqueness of splitting fields](04c-Splitting-fields.html#uniqueness-of-splitting-fields) shows that for any automorphism  $\theta : K \rightarrow K$ , we may find an automorphism  $\hat{\theta} : E \rightarrow E$  with  $\hat{\theta}|_K = \theta$ .

It now follows that  $\Gamma/H \simeq \text{Gal}(K/F)$ .

To complete the proof that  $K$  is normal, note first that  $[\Gamma : H] = [K : F]$  by b. This proves that  $|\text{Gal}(K/F)| = [K : F]$ . Since  $\text{Gal}(K/F)$  is a finite group, the [Proposition on normal extensions as fixed fields](#normal-as-fixed-field) implies that  $K$  is a normal separable extension of  $K^{\text{Gal}(K/F)}$ .

But then

$$[K : K^{\text{Gal}(K/F)}] = |\text{Gal}(K/F)| = [K : F]$$

which implies that  $F = K^{\text{Gal}(K/F)}$  and we conclude that  $K$  is a normal separable extension of  $F$ . This completes the proof of c, and of the Theorem.  $\square$

## Bibliography

Artin, Michael. 2011. *Algebra*. 2nd ed. Pearson Education.

Friedberg, Stephen H., Arnold J. Insel, and Lawrence E. Spence. 2002. *Linear Algebra*. 4th edition. Upper Saddle River, NJ: Pearson.

Hoffman, Kenneth, and Ray Alden Kunze. 1971. *Linear Algebra*. 2nd ed. Prentice-Hall.