Galois Theory notes

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Abstract

Notes taken while studying Galois Theory, mostly from Ian Stewart's book "Galois Theory" [1].

Usually while reading books and papers I take handwritten notes in a notebook, this document contains some of them re-written to $LaTeX$.

The notes are not complete, don't include all the steps neither all the proofs.

Contents

1 Recap on the degree of field extensions

(Definitions, theorems, lemmas, corollaries and examples enumeration follows from Ian Stewart's book [1]).

Definition 4.10. A *simple extension* is $L : K$ such that $L = K(\alpha)$ for some $\alpha \in L$.

Example 4.11. Beware, $L = \mathbb{Q}(i, -i, \sqrt{5}, -\sqrt{5}) = \mathbb{Q}(i, \sqrt{5}) = \mathbb{Q}(i + \sqrt{5})$.

Definition 5.5. Let $L : K$, suppose $\alpha \in L$ is algebraic over K. Then, the *minimal polynomial* of α over K is the unique monic polynomial m over K, $m(t) \in K[t]$, of smallest degree such that $m(\alpha) = 0$.
eg.: $i \in \mathbb{C}$ is algebraic over $\mathbb{R}$. The minimal polynomial of i over $\mathbb{R}$ is $m(t) = t^2 + 1$, so that $m(i) = 0$.

Lemma 5.9. Every polynomial $a \in K[t]$ is congruent modulo m to a unique polynomial of degree $< \delta m$.

Proof. Divide a/m with remainder, $a = qm + r$, with $q, r \in K[t]$ and $\delta r < \delta m$. Then, $a - r = qm$, so $a \equiv r \pmod{m}$.

It remains to prove uniqueness.

Suppose $\exists\ r \equiv s \pmod{m}$, with $\delta r, \delta s < \delta m$. Then, $r - s$ is divisible by m, but has smaller degree than m.

Therefore, $r - s = 0$, so $r = s$, proving uniqueness. □

Lemma 5.14. Let $K(\alpha) : K$ be a simple algebraic extension, let m be the minimal polynomial of α over K, let $\delta m = n$.

Then $\{1, \alpha, \alpha^2, \ldots, \alpha^{n-1}\}$ is a basis for $K(\alpha)$ over K. In particular, $[K(\alpha) : K] = n$.

Definition 6.2. The degree $[L : K]$ of a field extension $L : K$ is the dimension of L considered as a vector space over K.

Equivalently, the dimension of L as a vector space over K is the number of terms in the expression for a general element of L using coefficients from K.

Example 6.3.
1. $\mathbb{C}$ elements are 2-dimensional over $\mathbb{R}$ ($p + qi \in \mathbb{C}$, with $p, q \in \mathbb{R}$), because a basis is $\{1, i\}$, hence $[\mathbb{C} : \mathbb{R}] = 2$.
2. $[\mathbb{Q}(i, \sqrt{5}) : \mathbb{Q}] = 4$, since the elements $\{1, \sqrt{5}, i, i\sqrt{5}\}$ form a basis for $\mathbb{Q}(i, \sqrt{5})$ over $\mathbb{Q}$.

Theorem 6.4. *(Short Tower Law)* If $K, L, M \subseteq \mathbb{C}$, and $K \subseteq L \subseteq M$, then $[M : K] = [M : L] \cdot [L : K]$.

Proof. Let $(x_i)_{i \in I}$ be a basis for L over K, let $(y_j)_{j \in J}$ be a basis for M over L.
$\forall i \in I, j \in J$, we have $x_i \in L, u_j \in M$.
Want to show that $(x_i y_j)_{i \in I, j \in J}$ is a basis for M over K.

i. prove linear independence:
   Suppose that
$$\sum_{ij} k_{ij} x_i y_j = 0 \ (k_{ij} \in K)$$
   rearrange
$$\sum_j (\underbrace{\sum_i k_{ij} x_i}_{\in L}) y_j = 0 \ (k_{ij} \in K)$$

Since $\sum_i k_{ij} x_i \in L$, and the $y_j \in M$ are linearly independent over L, then $\sum_i k_{ij} x_i = 0$.
Repeating the argument inside $L \longrightarrow k_{ij} = 0 \;\; \forall i \in I, j \in J$.
So the elements $x_i y_j$ are linearly independent over K.

ii. prove that $x_i y_j$ span M over K:
Any $x \in M$ can be written $x = \sum_j \lambda_j y_j$ for $\lambda_j \in L$, because y_j spans M over L. Similarly, $\forall j \in J, \;\lambda_j = \sum_i \lambda_{ij} x_i y_j$ for $\lambda_{ij} \in K$.
Putting the pieces together, $x = \sum_{ij} \lambda_{ij} x_i y_j$ as required.

□

Lemma 6.6. *(Tower Law)*
If $K_0 \subseteq K_1 \subseteq \ldots \subseteq K_n$ are subfields of $\mathbb{C}$, then

$$[K_n : K_0] = [K_n : K_{n-1}] \cdot [K_{n-1} : K_{n-2}] \cdot \ldots \cdot [K_1 : K_0]$$

Proof. From 6.4. □

[...] TODO: pending to add key parts up to Chapter 15.

2 Tools

This section contains tools that I found useful to solve Galois Theory related problems, and that don't appear in Stewart's book.

2.1 De Moivre's Theorem and Euler's formula

Useful for finding all the roots of a polynomial.

Euler's formula:

$$e^{i\psi} = cos\psi + i \cdot sin\psi$$

The n-th roots of a complex number $z = x + iy = r(cos\theta + i \cdot sin\theta)$ are given by

$$z_k = \sqrt[n]{r} \cdot \left(cos(\frac{\theta + 2k\pi}{n}) + i \cdot sin(\frac{\theta + 2k\pi}{n}) \right)$$

for $k = 0, \ldots, n-1$.

So, by Euler's formula:

$$z_k = \sqrt[n]{r} \cdot e^{i(\frac{\theta+2k\pi}{n})}$$

Usually we will set $\alpha = \sqrt[n]{r}$ and $\zeta = e^{\frac{2\pi i}{n}}$, and find the $\mathbb{Q}$-automorphisms from there (see 3.1 for examples).

2.2 Einsenstein's Criterion

reference: Stewart's book

Let $f(t) = a_0 + a_1 t + \ldots + a_n t^n$, suppose there is a prime q such that

1. $q \nmid a_n$
2. $q | a_i$ for $i = 0, \ldots, n-1$
3. $q^2 \nmid a_0$

Then, f is irreducible over $\mathbb{Q}$.

TODO proof & Gauss lemma.

2.3 Elementary symmetric polynomials

TODO from orange notebook, page 36

2.4 Cyclotomic polynomials

2.4.1 From Elmyn Berlekamp's "Algebraic Coding Theory" book

The notes in this section are from the book "Algebraic Coding Theory" by Elmyn Berlekamp [3].

Some times we might find polynomials that have the shape of $t^n - 1$, those are *cyclotomic polynomials*, and have some properties that might be useful.

Observe that in a finite field of order q, factoring $x^q - x$ gives

$$x^q - x = x(x^{q-1} - 1)$$

The factor $x^{q-1} - 1$ is a special case of $x^n - 1$: if we assume that the field contains an element α of order n, then the roots of $x^n - 1 = 0$ are

$$1, \alpha, \alpha^2, \alpha^3, \ldots, \alpha^{n-1}$$

and $\deg(x^n - 1) = n$, thus $x^n - 1$ has at most n roots in any field, henceforth the powers of α must include all the n-th roots of unity.

There fore, in any field which contains a primitive n-th root of unity we have:

Theorem 4.31.

$$x^n - 1 = \prod_{i=0}^{n-1} (x - \alpha^i) = \prod_{i=1}^{n} (x - \alpha^i)$$

If $n = k \cdot d$, then $\alpha^k, \alpha^{2k}, \alpha^{3k}, \ldots, \alpha^{dk}$ are all roots of $x^d - 1 = 0$

Every element with order dividing n, must be a power of α, since an element of order d is a d-th root of unity.

Every power of α has order which divides n, and every field element whose order divides n is a power of α. This suggests that we partition the powers of α according to their orders:

$$x^n - 1 = \prod_{\substack{d,\\ d|n}} \prod_{\beta} (x - \beta)$$

where at each iteration, β is a field element of order d for each d.

The polynomial whose roots are the field elements of order d is called the *cyclotomic polynomial*, denoted by $Q^{(d)}(x)$.

Theorem 4.32.

$$x^n - 1 = \prod_{\substack{d,\\ d|n}} Q^{(d)}(x)$$

2.4.2 From Ian Stewart's "Galois Theory" book

Notes from Ian Stewart's book [1].

Consider the case $n = 12$, let $\zeta = e^{\pi i/6}$ be a primitive 12-th root of unity. Classify its powers (ζ^j) according to their minimal power d such that $(\zeta^j)^d = 1$ (ie. when they are primitive d-th roots of unity).

$d = 1, \quad 1$

$d = 2, \quad \zeta^6$

$d = 3, \quad \zeta^4, \zeta^8$

$d = 4, \quad \zeta^3, \zeta^9$

$d = 6, \quad \zeta^2, \zeta^{10}$

$d = 12, \quad \zeta, \zeta^5, \zeta^7, \zeta^{11}$

Observe that we can factorize $t^{12} - 1$ by grouping the corresponding zeros:

$$\begin{aligned} t^{12} - 1 = &(t-1)\times \\ &(t-\zeta^6)\times \\ &(t-\zeta^4)(t-\zeta^8)\times \\ &(t-\zeta^3)(t-\zeta^9)\times \\ &(t-\zeta^2)(t-\zeta^{10})\times \\ &(t-\zeta)(t-\zeta^5)(t-\zeta^7)(t-\zeta^{11}) \end{aligned}$$

which simplifies to

$$t^{12} - 1 = (t-1)(t+1)(t^2+t+1)(t^2+1)(t^2-t+1)F(t)$$

where $F(t) = (t-\zeta)(t-\zeta^5)(t-\zeta^7)(t-\zeta^{11}) = t^4 - t^2 + 1$ (this last step can be obtained either by multiplying $(t-\zeta)(t-\zeta^5)(t-\zeta^7)(t-\zeta^{11})$ together, or by dividing $t^{12} - 1$ by all the other factors).

Let $\Phi_d(t)$ be the factor corresponding to primitive d-th roots of unity, then we have proved that

$$t^{12} - 1 = \Phi_1\Phi_2\Phi_3\Phi_4\Phi_6\Phi_{12}$$

Definition 21.5. The polynomial $\Phi_d(t)$ defined by

$$\Phi_n(t) = \prod_{a \in \mathbb{Z}_n, (a,n)=1} (t - \zeta^a)$$

is the n-th *cyclotomic polynomial* over C.

Lemma 21.6. $\forall n \in \mathbb{N}$, the polynomial $\Phi_n(t)$ lies in $\mathbb{Z}[t]$ and is monic and irreducible.

Theorem 21.9.

1. The Galois group $\Gamma(\mathbb{Q}(\zeta) : \mathbb{Q})$ consists of the $\mathbb{Q}$-automorphisms ψ_j defined by

$$\psi_j(\zeta) = \zeta^j$$

   where $0 \leq j \leq n-1$ and j is prime to n.

2. $\Gamma(\mathbb{Q}(\zeta) : \mathbb{Q}) \overset{iso}{\cong} \mathbb{Z}_n^*$, and is an abelian group.
3. its order is $\phi(n)$
4. if n is prime, $\mathbb{Z}_n^*$ is cyclic

2.4.3 Examples

Examples of cyclotomic polynomials:

$$\Phi_n(x) = x^{n-1} + x^{n-2} + \ldots + x^2 + x + 1 = \sum_{i=0}^{n-1} x^i$$

$$\Phi_{2p}(x) = x^{p-1} + \ldots + x^2 - x + 1 = \sum_{i=0}^{p-1} (-x)^i$$

$$\Phi_m(x) = x^{m/2} + 1, \quad \text{when } m \text{ is a power of 2}$$

2.5 Lemma 1.42 from J.S.Milne's book

Lemma from J.S.Milne's book [2].

Useful for when dealing with $x^p - 1$ with p prime.

Observe that

$$x^p - 1 = (x-1)(x^{p-1} + x^{p-2} + \ldots + 1)$$

Notice that

$$\Phi_p(x) = x^{p-1} + x^{p-2} + \ldots + 1$$

is the p-th Cyclotomic polynomial.

Lemma 1.42. If p prime, then $x^{p-1} + \ldots + 1$ is irreducible; hence $\mathbb{Q}[e^{2\pi i/p}]$ has degree $p-1$ over $\mathbb{Q}$.

Proof. Let $f(x) = (x^p - 1)/(x-1) = x^{p-1} + \ldots + 1$ then

$$f(x+1) = \frac{(x+1)^p - 1}{x+1-1} = \frac{(x+1)^p - 1}{x} = x^{p-1} + \ldots + a_i x^i + \ldots + p$$

with $a_i = \binom{p}{i+1}$.

We know that $p|a_i$ for $i = 1, \ldots, p-2$, therefore $f(x+1)$ is irreducibe by Einsenstein's Criterion.

This implies that $f(x)$ is irreducible. □

2.6 Dihedral groups - Groups of symmetries

Source: Wikipedia and [4].

Dihedral groups ($\mathbb{D}_n$) represent the symmetries of a regular n-gon.

Properties:

- are non-abelian (for $n > 2$), ie. $rs \neq sr$
- order $2n$
- generated by a rotation r and a reflection s

- $r^n = s^2 = id, \quad (rs)^2 = id$

Subgroups of $\mathbb{D}_n$:

- rotation form a cyclic subgroup of order n, denoted as $< r >$
- for each d such that $d|n$, $\exists$ $\mathbb{D}_d$ with order $2d$
- normal subgroups
  - for n odd: $\mathbb{D}_n$ and $< r^d >$ for every $d|n$
  - for n even: 2 additional normal subgroups
- Klein four-groups: $\mathbb{Z}_2 \times \mathbb{Z}_2$, of order 4

Total number of subgroups in $\mathbb{D}_n$: $d(n) + s(n)$, where $d(n)$ is the number of positive disivors of n, and $s(n)$ is the sum of those divisors.

Example . For $\mathbb{D}_6$, we have $\{1, 2, 3, 6\}|6$, so $d(n) = d(6) = 4$, and $s(6) = 1+2+3+6 = 12$; henceforth, the total amount of subgroups is $d(n)+s(n) = 4+12 = 16$.

For $n \geq 3, \quad \mathbb{D}_n \subseteq \mathbb{S}_n$ (subgroup of the Symmetry group).

3 Exercises

3.1 Galois groups

3.1.1 $t^6 - 7 \in \mathbb{Q}$

This exercise comes from a combination of exercises 12.4 and 13.7 from [1].

First let's find the roots. By De Moivre's Theorem (2.1), $t_k = \sqrt[6]{7} \cdot e^{i\frac{2\pi k}{6}}$.

From which we denote $\alpha = \sqrt[6]{7}$, and $\zeta = e^{\frac{2\pi i}{6}}$, so that the roots of the polynomial are $\{\alpha, \alpha\zeta, \alpha\zeta^2, \alpha\zeta^3, \alpha\zeta^4, \alpha\zeta^5\}$, ie. $\{\alpha\zeta^k\}_0^5$.

Hence the *splitting field* is $\mathbb{Q}(\alpha, \zeta)$.

Degree of the extension

In order to find $[\mathbb{Q}(\alpha, \zeta) : \mathbb{Q}$, we're going to split it in tow parts. By the Tower Law (6.6),

$$[\mathbb{Q}(\alpha, \zeta) : \mathbb{Q}] = [\mathbb{Q}(\alpha, \zeta) : \mathbb{Q}(\alpha)] \cdot [\mathbb{Q}(\alpha) : \mathbb{Q}]$$

To find each degree, we will find the minimal polynomial of the adjoined term over the base field of the extension:

i. minimal polynomial of α over $\mathbb{Q}$
   By Einsenstein's Criterion (2.2), with $q = 7$ we have that $q \nmid 1$, $7 | -7, 0, 0, \ldots$, and $7^2 \nmid -7$, hence $f(t)$ is irreducibe over $\mathbb{Q}$, thus is the minimal polynomial

   $$m_i(t) = f(t) = t^6 - 7$$

   which has roots $\{\alpha\zeta^k\}_0^5$.

ii. minimal polynomial of ζ over $\mathbb{Q}(\alpha)$
   Since ζ is the primitive 6th root of unity, we know that the minimal polynomial will be the 6th cyclotomic polynomial (2.4):

   $$m_{ii}(t) = \Phi_6(t) = t^2 - t + 1$$

   which has roots $\zeta, -\zeta$.
   Since $\mathbb{Q}(\alpha) \subseteq \mathbb{R}$, and the roots of $\Phi_6(t) = t^2 - t + 1$ are in $\mathbb{C}$, $\Phi_6(t)$ remains irreducible over $\mathbb{Q}(\alpha)$.

Therefore, by the tower of law,

$$[\mathbb{Q}(\alpha, \zeta) : \mathbb{Q}] = \deg \Phi_6(t) \cdot \deg f(t) = 2 \cdot 6 = 12$$

and by the Fundamental Theorem of Galois Theory, we know that

$$|\Gamma(\mathbb{Q}(\alpha, \zeta) : \mathbb{Q})| = [\mathbb{Q}(\alpha, \zeta) : \mathbb{Q}] = 12$$

which tells us that there exist 12 $\mathbb{Q}$-automorphisms of the Galois group.

Let's find the 12 $\mathbb{Q}$-automorphisms. Start by defining σ which fixes ζ and acts on α, sending it to another of the roots of the minimal polynomial of α over $\mathbb{Q}$, $f(t)$, choose $\alpha\zeta$.

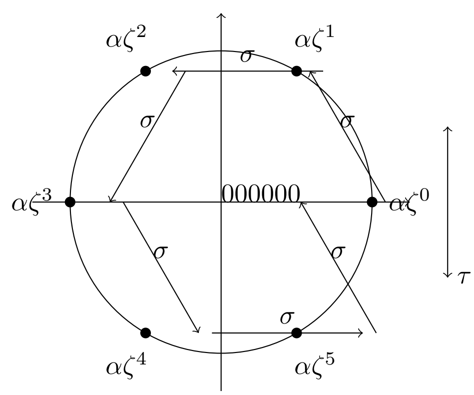
Now define τ which fixes α and acts on ζ, sending it into another root of the minimal polynomial of ζ over $\mathbb{Q}(\alpha)$, choose $-\zeta$.

$$\begin{aligned} \sigma : \alpha &\mapsto \alpha\zeta & \tau : \alpha &\mapsto \alpha \\ \zeta &\mapsto \zeta & \zeta &\mapsto -\zeta = \zeta^{-1} \end{aligned}$$

In other words, we have 12 $\mathbb{Q}$-automorphisms, which are the combination of σ and τ:

$$\sigma^k \tau^j : \begin{aligned} \alpha &\mapsto \alpha\zeta^k \\ \zeta &\mapsto \zeta^j \end{aligned}$$

for $0 \leq k \leq 5$ and $j = \pm 1$.



NOTE: WIP diagram.

Observe, that Γ is generated by the combination of σ and τ, and it is isomorphic to the group of symmetries of order 12, the dihedral group (2.6) of order 12, $\mathbb{D}_6$, ie. $\Gamma \cong \mathbb{D}_6$.

Let's find the subgroups of Γ, and the fixed fields of $\mathbb{Q}(\alpha, \zeta)$.

We know that $\Gamma \cong \mathbb{D}_6$, and we know from the properties of the dihedral group (2.6) that the number of subgroups of $\mathbb{D}_6$ will be $d(6) + s(6) = 4 + 12 = 16$ subgroups.

generators	order	group	fixed field	notes (check fixed field)
$\langle\rangle = \langle\sigma^6\rangle = \langle\tau^2\rangle$	1	id	$\mathbb{Q}(\alpha,\zeta)$	
$\langle\sigma\rangle = \langle\sigma^5\rangle$	6	$\mathbb{Z}_6$	$\mathbb{Q}(\zeta)$	
$\langle\sigma^2\rangle = \langle\sigma^4\rangle$	3	$\mathbb{Z}_3$	$\mathbb{Q}(\alpha^3,\zeta)$	$\sigma^2(\alpha^3) = \alpha^3\zeta^{3\cdot 2} = \alpha^3\zeta^6 = \alpha^3 \cdot 1 = \alpha^3$
$\langle\sigma^3\rangle$	2	$\mathbb{Z}_2$	$\mathbb{Q}(\alpha^2,\zeta)$	$\sigma^3(\alpha^2) = (\alpha\zeta^3)^2 = \alpha^2\zeta^6 = \alpha^2$
$\langle\tau\rangle$	2	$\mathbb{Z}_2$	$\mathbb{Q}(\alpha)$	
$\langle\sigma\tau\rangle$	2	$\mathbb{Z}_2$	$\mathbb{Q}(\alpha+\alpha\zeta)$	$\sigma\zeta(\alpha+\alpha\zeta) = \sigma(\alpha+\alpha\zeta^{-1}) = \alpha\zeta+\alpha\zeta^{-1}\zeta = \alpha\zeta+\alpha$
$\langle\sigma^2\tau\rangle$	2	$\mathbb{Z}_2$	$\mathbb{Q}(\alpha+\alpha\zeta^2), \mathbb{Q}(\alpha\zeta)$	$\sigma^2\tau(\alpha+\alpha\zeta^2) = \sigma(\alpha+\alpha\zeta^{-2}) = \alpha\zeta^2+\alpha\zeta^{-2}\zeta^2 = \alpha\zeta^2+\alpha$
$\langle\sigma^3\tau\rangle$	2	$\mathbb{Z}_2$	$\mathbb{Q}(\alpha+\alpha\zeta^3)$	$\sigma^3\tau(\alpha+\alpha\zeta^3) = \sigma(\alpha+\alpha\zeta^{-3}) = \alpha\zeta^3+\alpha\zeta^{-3}\zeta^3 = \alpha\zeta^3+\alpha$
$\langle\sigma^4\tau\rangle$	2	$\mathbb{Z}_2$	$\mathbb{Q}(\alpha+\alpha\zeta^4), \mathbb{Q}(\alpha\zeta^2)$	$\sigma^4\tau(\alpha+\alpha\zeta^4) = \sigma(\alpha+\alpha\zeta^{-4}) = \alpha\zeta^4+\alpha\zeta^{-4}\zeta^4 = \alpha\zeta^4+\alpha$
$\langle\sigma^5\tau\rangle$	2	$\mathbb{Z}_2$	$\mathbb{Q}(\alpha+\alpha\zeta^5)$	$\sigma^5\tau(\alpha+\alpha\zeta^5) = \sigma(\alpha+\alpha\zeta^{-5}) = \alpha\zeta^5+\alpha\zeta^{-5}\zeta^5 = \alpha\zeta^5+\alpha$
$\langle\sigma,\tau\rangle = \langle\sigma^5,\tau\rangle$	$6\cdot 2 = 12$	$\mathbb{D}_6$	$\mathbb{Q}$	
$\langle\sigma^2,\tau\rangle = \langle\sigma^4,\tau\rangle$	$3\cdot 2 = 6$	$\mathbb{D}_3$	$\mathbb{Q}(\alpha^3)$	$\sigma^2(\alpha^3) = \alpha^3\zeta^{3\cdot 2} = \alpha^3$ and $\tau(\alpha^3) = \alpha^3$
$\langle\sigma^3,\tau\rangle$	$2\cdot 2 = 4$	$\mathbb{D}_2$	$\mathbb{Q}(\alpha^2)$	$\sigma^3(\alpha^2) = \alpha^2\zeta^{2\cdot 2} = \alpha^2$ and $\tau(\alpha^2) = \alpha^2$
$\langle\sigma^2,\sigma\tau\rangle$	$3\cdot 2 = 6$	$\mathbb{D}_3$	$\mathbb{Q}(\alpha^3+\alpha^3\zeta^3)$	$\sigma^2(\alpha^3+\alpha^3\zeta^3) = \alpha^3\zeta^3+\alpha^3\zeta^3\zeta^3 = \alpha^3\zeta^3+\alpha^3\zeta^6 = \alpha^3\zeta^3+\alpha^3$
$\langle\sigma^3,\sigma\tau\rangle$	$2\cdot 2 = 4$	$\mathbb{Z}_2\times\mathbb{Z}_2$	$\mathbb{Q}(\alpha^2\zeta^2), \mathbb{Q}(\alpha^2+\alpha^2\zeta^2)$	$\sigma^3(\alpha^2+\alpha^2\zeta^2) = \alpha^2\zeta^{2\cdot 3}+\alpha^2\zeta^{2\cdot 3}\zeta^2 = \alpha^2+\alpha^2\zeta^2$ and $\sigma\tau(\alpha^2+\alpha^2\zeta^2) = \alpha^2\zeta^2+\alpha^2\zeta^{-2}\zeta^2 = \alpha^2\zeta^2+\alpha^2$
$\langle\sigma^3,\sigma^2\tau\rangle$	$2\cdot 2 = 4$	$\mathbb{Z}_2\times\mathbb{Z}_2$	$\mathbb{Q}(\alpha^2\zeta^4), \mathbb{Q}(\alpha^2+\alpha^2\zeta^4)$	$\sigma^2\zeta(\alpha^2\zeta^4) = \alpha^2\zeta^2\zeta^{-4} = \alpha^2\zeta^{-2} = \alpha^2\zeta^4$ and $\sigma^3(\alpha^2\zeta^4) = \alpha^2\zeta^{2\cdot 3}\zeta^4 = \alpha^2\zeta^4$

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[1] Ian Stewart. Galois Theory, Third Edition, 2004.

[2] James S. Milne. Fields and galois theory (v5.10), 2022. Available at `https://jmilne.org/math/`.

[3] Elmyn Berlekamp. Algebraic coding theory, 1984. Revised Edition from 1984.

[4] Gaurab Bardhan, Palash Nath, and Himangshu Chakraborty. Subgroups and normal subgroups of dihedral group up to isomorphism, 2010. `https://scipp.ucsc.edu/~haber/ph251/Dn_subgroups.pdf`.