

MA 45401-H01: Galois Theory Honors

Definitions and Results

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1 Introduction I

Definition 1 (Symmetric function). A function $\varphi(x_1, \dots, x_n)$ is called *symmetric* if

$$\varphi(x_1, \dots, x_n) = \varphi(x_{\omega(1)}, \dots, x_{\omega(n)})$$

for all $\omega \in S_n$.

Definition 2 (Elementary symmetric polynomial).

$$\begin{aligned}\sigma_1 &= \sigma_1(x_1, \dots, x_n) = x_1 + \dots + x_n \\ \sigma_2 &= \sigma_2(x_1, \dots, x_n) = x_1x_2 + \dots + x_1x_n + x_2x_3 + \dots + x_{n-1}x_n \\ &\vdots \\ \sigma_k &= \sigma_k(x_1, \dots, x_n) = \sum_{1 \leq i_1 < i_2 < \dots < i_k \leq n} x_{i_1} \dots x_{i_k} \\ &\vdots \\ \sigma_n &= \sigma_n(x_1, \dots, x_n) = \prod_{i=1}^n x_i\end{aligned}$$

Theorem 1.1. For any symmetric function $\psi(x_1, \dots, x_n)$, there exists a unique polynomial $P(t_1, \dots, t_n)$ such that $\psi(x_1, \dots, x_n) = P(\sigma_1, \dots, \sigma_n)$.

Definition 3 (Vieta formulae). Suppose $f(t) = t^n + a_{n-1}t^{n-1} + \dots + a_0$ has roots r_1, \dots, r_n . Then,

$$\begin{aligned}r_1 + r_2 + \dots + r_n &= -a_{n-1} \\ \sum_{1 \leq i < j \leq n} r_i r_j &= a_{n-2} \\ &\vdots \\ \sum_{1 \leq i_1 < i_2 < \dots < i_k \leq n} r_{i_1} r_{i_2} \dots r_{i_k} &= (-1)^k a_{n-k} \\ &\vdots \\ r_1 r_2 \dots r_n &= (-1)^n a_0\end{aligned}$$

Corollary 1. The discriminant D of $f \in R[x]$, where R is a ring and $f = x^n + a_1x^{n-1} + \dots + a_{n-1}x + a_n$, is a polynomial in a_1, \dots, a_n and coefficients from R (i.e. $D \in R[a_1, \dots, a_n]$).

Note: Any cubic equation can be converted to a depressed cubic by

$$x^3 + Ax^2 + Bx + c = \left(x + \frac{A}{3}\right)^3 + p\left(x + \frac{A}{3}\right) + q.$$

Theorem 1.2 (Vieta's method). Using the trigonometric identity $\cos 3\varphi = 4\cos^3\varphi - 3\cos\varphi$, we can solve certain cubic equations. For example, consider $4x^3 - 3x = -\frac{1}{2}$. Let $x = \cos\varphi$. Then

$$\begin{aligned}\cos 3\varphi = -\frac{1}{2} &\iff 3\varphi = \pm \frac{2\pi}{3} + 2\pi k \quad \text{for } k \in \mathbb{Z} \\ &\iff \varphi = \pm \frac{2\pi}{9} + 2\pi k \\ &\iff x \in \left\{ \cos \frac{2\pi}{9}, \cos \frac{4\pi}{9}, \cos \frac{8\pi}{9} \right\}.\end{aligned}$$

In general, we can use this method to solve $4x^3 - 3x = a \implies x = \cos \varphi$, $\cos 3\varphi$ and $\cos : \mathbb{C} \rightarrow \mathbb{C}$ is now a complex function. For $x^3 + px + q = 0$, set $x = ky$ such that $\frac{k^3}{pk} = \frac{-4}{3} \implies k = \pm \frac{\sqrt{-4p}}{3}$.

Definition 4 (Ferrari's resolvent). Let $f(x) = x^4 + ax^2 + bx + c$, and assume $b^2 - 4ac \neq 0$. Consider a parameter y . Then

$$\begin{aligned} f(x) &= \left(x^2 + \frac{y}{2}\right)^2 + (a - y)x^2 + bx + c - \frac{y^2}{4} \\ \implies D &= b^2 - 4(a - y)\left(c - \frac{y^2}{4} = 0\right) \end{aligned}$$

and hence we obtain *Ferrari's resolvent*:

$$y^3 - ay^2 - 4cy + 4ac - b^2 = 0.$$

Solving the resolvent allows one to reduce solving f to solving a system of quadratics.

2 Introduction II

Theorem 2.1 (Lagrange). Let $\varphi = \varphi(x_1, \dots, x_n)$ and

$$\text{orb}(\varphi) = \{\varphi^\omega = \varphi(x_{\omega(1)}, \dots, x_{\omega(n)}) \mid \omega \in S_n\}.$$

Then y_1, \dots, y_k are roots of some polynomial with degree $\leq k$ whose coefficients depend on elementary symmetric polynomials $\sigma_1, \dots, \sigma_n$ in a polynomial way.

Theorem 2.2 (Lagrange). Let $\varphi, \psi \in K[x_1, \dots, x_n]$ and $G_\varphi = \{\omega \in S_n \mid \varphi^\omega = \varphi\} \leq G_\psi$. Then $\psi = R(\varphi)$ where R is a rational function whose coefficients are symmetric functions on x_1, \dots, x_n .

Definition 5 (Group action). Let G be a group and X be a set. The (left) group action of G on X is the map $\cdot : G \times X \rightarrow X$ such that

1. $e_G \cdot x = x, \quad \forall x \in X$
2. $g \cdot (h \cdot x) = (g \cdot h) \cdot x, \quad \forall x \in X, \forall g, h \in G$

Definition 6 (Orbit). Let G be a group, X be a set, and $x \in X$. Then we define *the orbit* of x , $G \cdot x = \text{orb}(x)$, as $\{g \cdot x \mid g \in G\}$. Moreover, $\text{orb}(x) \subseteq X$.

Definition 7 (Stabilizer). Let G be a group, X be a set, and $x \in X$. Then we define *the stabilizer* of x , $\text{stab}(x)$, as $\{g \in G \mid g \cdot x = x\}$. Moreover, $\text{stab}(x) \leq G$.

Theorem 2.3. Let G be a finite group that acts on X . Then for all $x \in X$, $|\text{orb}(x)| \cdot |\text{stab}(x)| = |G|$.

Definition 8 (Polynomial ring). Let R be a commutative ring. Then the ring of polynomials with coefficients in R is

$$R[t] = \left\{ \sum_{i=0}^n c_i t^i : n \in \mathbb{Z}_+, c_i \in R \right\}$$

3 Field Extensions I

Definition 9 (Integral domain). Let R be a commutative ring. Then R is an *integral domain* if $ab = 0$ implies that $a = 0$ or $b = 0$ for all $a, b \in R$.

Definition 10 (Euclidean domain). Let R be an integral domain. Then R is a *Euclidean domain* if there exists some function $f : R \setminus \{0\} \rightarrow \mathbb{Z}_{\geq 0}$ such that for all $a, b \neq 0 \in R$, there exist elements $q, r \in R$ such that $a = qb + r$ where $r = 0$ or $f(r) < f(b)$.

Theorem 3.1 (Bézout's Identity). Let R be a Euclidean domain. For $a, b \in R$, there exists $\alpha, \beta \in R$ such that $\gcd(a, b) = \alpha a + \beta b$

Definition 11 (Irreducible). Let F be a field, and $f \in F[t] \setminus F$. Then f is *irreducible* if $\nexists g, h \in F[t] \setminus F$ of strictly smaller degree such that $f = gh$.

Definition 12 (Unique factorization domain). Let R be an integral domain. Then R is a *unique factorization domain* (UFD) if for irreducible $p_i \in R$, any nonzero $x \in R$ can be written uniquely (up to ordering) as $x = p_1 p_2 \cdots p_k$, $k \geq 1$.

Fact: If R is an Euclidean domain, then R is a UFD (and PID)

Corollary 2. Let $f \in \mathbb{F}[t]$ be a monic polynomial with $\deg f \geq 1$. Then we can write $f = f_1 f_2 \cdots f_k$ uniquely (up to ordering) for irreducible monic polynomials f_j .

Definition 13. Let R be a UFD. When $a_0, \dots, a_n \in R$ are not all 0, we can generalize the *greatest common divisor* of a_0, \dots, a_n (written $\gcd(a_0, \dots, a_n)$) any element $c \in R$ satisfying

- (i) $c \mid a_i$ ($0 \leq i \leq n$), and
- (ii) if $d \mid a_i$ ($0 \leq i \leq n$), then $d \mid c$.

When $f = \sum_{j=0}^d a_j x^j \in R[x]$ is a non-zero polynomial, we define a *content* of f to be any $\gcd(a_0, \dots, a_d)$ and $\gcd(f) = \gcd(a_0, \dots, a_d)$. We say that $f \in R[X]$ is *primitive* if $f \neq 0$ and the content of f is divisible only by units of R .

Lemma 3.2 (Gauss). $\gcd(fg) = \gcd f \cdot \gcd g$

Corollary 3. $f \in \mathbb{Z}[t]$ is irreducible $\iff f$ is irreducible over $\mathbb{Q}[t]$

Corollary 4. If R is a UFD with field of fractions Q and $f \in R[X]$ with $\deg f > 0$, then f is irreducible in $R[X] \iff f$ is irreducible in Q .

Theorem 3.3 (Eisenstein's Criterion). Let R be a UFD with field of fractions Q and let $f = a_0 + a_1 X + \dots + a_n X^n \in R[X]$ with $\gcd(f) = 1$. Suppose there exists an irreducible element $p \in R$ such that

- (i) $p \mid a_i$ for $0 \leq i < n$,
- (ii) $p^2 \nmid a_0$, and
- (iii) $p \nmid a_n$,

then f is irreducible in $R[X]$ (and hence also in $Q[X]$).

Definition 14 (Field extension). Let L and K be fields. Then L is an *extension* of K if there exists a homomorphism $\varphi : K \rightarrow L$. Then we write $L : K$ or L/K , $\varphi(K) \cong K$ and identify $\varphi(K)$ with K .

Fact: Suppose that L is a field extension of K with associated embedding $\varphi : K \rightarrow L$. Then L forms a vector space over K , under the operations

$$\begin{aligned} & \text{(vector addition)} \quad \psi : L \times L \rightarrow L \quad \text{given by} \quad (v_1, v_2) \mapsto v_1 + v_2 \\ & \text{(scalar multiplication)} \quad \tau : K \times L \rightarrow L \quad \text{given by} \quad (k, v) \mapsto \varphi(k)v. \end{aligned}$$

Definition 15 (Degree, finite extension). Let $L : K$. Then the *degree* of $L : K$ is $[L : K] = \dim L$ over K as a vector space. We say that $L : K$ is a *finite extension* if $[L : K] < \infty$.

Definition 16 (Tower, intermediate field). We say that $M : L : K$ is a *tower* of field extensions if $M : L$ and $L : K$ are field extensions, and in this case we say that L is an *intermediate field* (relative to the extension $M : K$)

Theorem 3.4 (The Tower Law). Suppose that $M : L : K$ is a tower of field extensions. Then $M : K$ is a field extension, and $[M : K] = [M : L][L : K]$.

Corollary 5. Suppose that $L : K$ is a field extension for which $[L : K]$ is a prime number. Then whenever $L : M : K$ is a tower of field extensions with $K \subseteq M \subseteq L$, one has either $M = L$ or $M = K$.

4 Field Extensions II

Definition 17 (Smallest subring/subfield). Let $L : K$ with $K \subseteq L$.

- (i) When $\alpha \in L$, we denote by $K[\alpha]$ the *smallest subring of L containing K and α* , and by $K(\alpha)$ the *smallest subfield of L containing K and α* ;
- (ii) More generally, when $A \subseteq L$, we denote by $K[A]$ the *smallest subring of L containing K and A* , and by $K(A)$ the *smallest subfield of L containing K and A* .

Then

$$K[\alpha] = \left\{ \sum_{i=0}^d c_i \alpha^i : d \in \mathbb{Z}_{\leq 0}, c_0, \dots, c_d \in K \right\}$$

$$K(\alpha) = \{f/g : f, g \in K[\alpha], g \neq 0\}.$$

Definition 18 (Algebraic/transcendental element). Suppose that $L : K$ is a field extension with $K \subseteq L$ and $\alpha \in L$.

- (i) We say α is *algebraic over K* if $\exists f \neq 0 \in K[t]$ such that $f(\alpha) = 0$.
- (ii) If α is not algebraic over K , then we say α is *transcendental over K* .
- (iii) When every element of L is algebraic over K , we say that L is *algebraic over K* .

Definition 19 (Evaluation map). Suppose that $L : K$ is a field extension with $K \subseteq L$, and that $\alpha \in L$. We define the *evaluation map* $E_\alpha : K[t] \rightarrow L$ by putting $E_\alpha(f) = f(\alpha)$ for each $f \in K[t]$.

Definition 20 (Minimal polynomial). Suppose that $L : K$ is a field extension with $K \subseteq L$, and suppose that $\alpha \in L$ is algebraic over K . Then the minimal polynomial of α over K is the unique monic polynomial μ_α^K such that $\ker(E_\alpha) = (\mu_\alpha^K)$.

Lemma 4.1. 1. μ_α^K is irreducible over K ;

2. If $f \in K[t]$ such that $f(\alpha) = 0$, then $\mu_\alpha^K \mid f$;

3. If $f \in K[t]$ such that $f(\alpha) = 0$ and f is irreducible over K , then $\exists k \in K$ such that $f = k\mu_\alpha^K$.

Theorem 4.2. Let $L : K$ with $K \subseteq L$, and suppose that $\alpha \in L$ is algebraic over K .

- (i) $K[\alpha]$ is a field, and $K[\alpha] = K(\alpha)$;
- (ii) If $n = \deg \mu_\alpha^K$, then $\{1, \alpha, \alpha^2, \dots, \alpha^{n-1}\}$ is a basis for $K(\alpha)$ over K ($\implies [K(\alpha) : K] = \deg \mu_\alpha^K$).

Theorem 4.3 (Rational Root Theorem). Let $\frac{p}{q}$ be a root of $f = a_0 t^n + \dots + a_{n-1} t^{n-1} + a_n$, for $a_j \in \mathbb{Z}$, where p and q are coprime. Then $p \mid a_n$ and $q \mid a_0$.

Note: If α is transcendental over K , then $K(\alpha) \cong K(x)$ (where x is a formal variable).

Corollary 6. Let $L : K$ with $K \subseteq L$, and suppose that $\alpha \in L$ is algebraic over K . Then every element of $K(\alpha)$ is algebraic over K .

Corollary 7. Let $L : K$ with $K \subseteq L$. Then $[L : K] < \infty \iff L = K(\alpha_1, \dots, \alpha_n)$ for $\alpha_j \in L$.

Theorem 4.4. Let $L : K$ be a field extension, and define

$$L^{\text{alg}} = \{\alpha \in L : \alpha \text{ is algebraic over } K\}.$$

Then L^{alg} is a subfield of L .

5 Algebraic Conjugates

Lemma 5.1. Let \mathbb{F} be a field with $f \in \mathbb{F}[t]$ irreducible. Then $\mathbb{F}[t] / (f)$ is a field.

Corollary 8. If $L : K$ with $\alpha \in L$ algebraic over K , then $K[t] / (\mu_\alpha^K)$ is a field.

Theorem 5.2. Let K be a field, and suppose that $f \in K[t]$ is irreducible. Then there exists a field extension $L : K$, with associated embedding $\varphi : K[t] \rightarrow L[y]$, such that L contains a root of $\varphi(f)$.

Definition 21 (Algebraic conjugate). Suppose α is algebraic over K and μ_α^K factors as a product of linear polynomials over a field $L \supseteq K$:

$$\mu_\alpha^K(x) = (x - \alpha_1) \cdots (x - \alpha_n), \quad \alpha_1, \dots, \alpha_n \in L.$$

Then $\alpha_1, \dots, \alpha_n$ are *algebraic conjugates* of α .

Lemma 5.3. Let $(x - \alpha_1) \cdots (x - \alpha_n) \in K[x]$ and $f(\bar{y}, x_1, \dots, x_n) \in K[\bar{y}, x_1, \dots, x_n]$ be symmetric polynomial in x_1, \dots, x_n . Then $f(\bar{y}, x_1, \dots, x_n) \in K[\bar{y}]$.

Theorem 5.4. Let α be algebraic over K with algebraic conjugates $\alpha = \alpha_1, \dots, \alpha_n$. Then for all $f \in K[x]$, the conjugates of $f(\alpha)$ are exactly $f(\alpha_1), \dots, f(\alpha_n)$.

6 Ruler and Compass Constructions

Definition 22 (Constructible points/angles). Let $P_0 = (0, 0)$ and $P_1 = (1, 0)$, and let $\mathcal{S}_n = (P_0, \dots, P_n)$. Then P_{n+1} is a constructible point if it is the intersection of either

1. two lines containing points in \mathcal{S}_n ;
2. two circles with centers in \mathcal{S}_n ;
3. a circle and line with center and endpoints in \mathcal{S}_n .

Similarly, an angle θ is constructible if for some $a \in \mathbb{R}$, there exists some constructible point x such that $x^2 = a^2$.

Lemma 6.1. If n -gon constructible, then $2n$ -gon is constructible.

Lemma 6.2. If a, b, c constructible (or polyquadratic), then $a \pm b$, $\frac{ab}{c}$, and \sqrt{ab} constructible.

Fact 1. If m -gon and n -gon are constructible for coprime m, n , then mn -gon is constructible.

Fact 2. If $p \geq$ prime, then p^k -gon constructible for $k \in \mathbb{N}$.

Theorem 6.3 (Gauss).

$$\cos \frac{2\pi}{17} = \frac{-1 + \sqrt{17} + \sqrt{34 - 2\sqrt{17}} + 2\sqrt{17 + 3\sqrt{17} - \sqrt{34 - 2\sqrt{17}}}}{16}$$

Corollary 9. The 17-gon is constructible.

Corollary 10. If $a \in \mathbb{R}$ is constructible, then $[\mathbb{Q}(a) : \mathbb{Q}] = 2^n$ for some $n \geq$

Corollary 11. Given a cube C_1 with volume V_1 , it is impossible to construct a cube C_2 with volume $2V_1$ by ruler and compass. That is, the volume of a cube can not be duplicated by ruler and compass.

Corollary 12. An arbitrary angle cannot be trisected by ruler and compass.

Theorem 6.4 (Gauss-Wantzel). A regular n -gon is constructible $\iff n = 2^r p_1 p_2 \cdots p_s$ for $r \in \mathbb{Z}_{\geq 0}$ and Fermat primes $p_j = 2^{(2^k)} + 1$ for $k \in \mathbb{Z}_{\geq 0}$.

7 Cyclotomic Polynomials

Theorem 7.1. For prime p , we have $x^p - 1 = (x - 1)(x^{p-1} + \cdots + 1)$ and $\mu_{\varepsilon_p}^{\mathbb{Q}} = x^{p-1} + \cdots + 1$.

Definition 23 (n^{th} cyclotomic polynomial).

$$\Phi_n(x) = \prod_{\substack{\varepsilon \in \sqrt[n]{1} \\ |\varepsilon|=n}} (x - \varepsilon) = \frac{x^n - 1}{\prod_{d|n, d < n} \Phi_d(x)}$$

Theorem 7.2. Φ_n is irreducible over \mathbb{Q} .

Corollary 13. (a) $[\mathbb{Q}(\exp(\frac{2\pi i}{n})) : \mathbb{Q}] = \varphi(n)$ (where φ is Euler's totient function);

(b) $[\mathbb{Q}(\cos(\frac{2\pi}{n})) : \mathbb{Q}] = \frac{1}{2}\varphi(n)$. Furthermore, all algebraic conjugates of $\cos \frac{2\pi}{n}$ are $\cos \frac{2\pi k}{n}$ for $\gcd(k, n) = 1$.

(c) Let $c = \frac{a+bi}{a-bi} \in \sqrt[n]{1}$, where $a, b \in \mathbb{Z}$. Then $c \in \{\pm i, \pm 1\}$

Lemma 7.3. Let \mathbb{F} be a finite field. Then $\mathbb{F}^\times = \mathbb{F} \setminus \{0\}$ is a cyclic group.

8 Splitting Fields, Abel-Ruffini

Definition 24 (Splitting field). Let $L : K$ with embedding $\varphi : K \rightarrow L$ and $f \in K[t] \setminus K$. We say f *splits over* L if $\varphi(f) = c \prod_{j=1}^n (x - \alpha_j)$ for $\alpha_j \in L$ and $c \in \varphi(K)$. We say that $M : K$ is a *splitting field extension* for f if f splits over L , $\varphi(K) \subseteq M \subseteq L$, and M is the smallest subfield of L containing $\varphi(K)$ over which f splits.

Lemma 8.1. Let $L : K$ be a splitting field extension for $f \in K[t]$ relative to the embedding $\varphi : K \rightarrow L$, and let $\alpha_j \in L$ be roots of $\varphi(f)$. Then $L = \varphi(K)(\alpha_1, \dots, \alpha_n)$.

Lemma 8.2. Let $L : K$ be a splitting field extension for $f \in K[t] \setminus K$. Then $[L : K] \leq (\deg f)!$.

Lemma 8.3. Let $L : K$ and $M : K$ be splitting field extensions for $f \in K[t] \setminus K$. Then $L \cong M$ (in particular, $[L : K] = [M : K]$).

Definition 25 (Radical, radical extension, solvability by radicals). Let $L : K$ and $\beta \in L$. We say that β is *radical over* K when $\beta^n \in K$ for some $n \in \mathbb{N}$ (so $\beta = \alpha^{1/n}$ for some $\alpha \in K$ and some $n \in \mathbb{N}$). We say that $L : K$ is an *extension by radicals* when there is a tower of field extensions $L = L_r : L_{r-1} : \cdots : L_0 = K$ such that $L_i = L_{i-1}(\beta_i)$ with β_i radical over L_{i-1} (for $1 \leq i \leq r$). We say $f \in K[t]$ is *solvable by radicals* if there is a radical extension of K over which f splits.

Theorem 8.4 (Abel-Ruffini). Let $K = \mathbb{C}(a_1, \dots, a_n)$ where a_1, \dots, a_n are formal variables. Let $f(x) = x^n + a_1 x^{n-1} + \cdots + a_n \in K[x]$ be the generic polynomial of degree $n \geq 5$ over K . Then $f(x)$ is not solvable by radicals.

9 Algebraic Closure I

Definition 26 (Algebraically closed field, algebraic closure). Let M be a field.

- (i) We say that M is *algebraically closed* if every non-constant polynomial $f \in M[t]$ has a root in M .
- (ii) We say that M is an algebraic closure of K if $M : K$ is an algebraic field extension such that M is algebraically closed.

Lemma 9.1. Let M be a field. The following are equivalent:

- (i) The field M is algebraically closed;
- (ii) every non-constant polynomial $f \in M[t]$ factors in $M[t]$ as a product of linear factors;

- (iii) every irreducible polynomial in $M[t]$ has degree 1;
- (iv) the only algebraic extension of M containing M is itself.

Definition 27 (Chain). Suppose that X is a nonempty, partially ordered set with \leq denoting the partial ordering. A *chain* C in X is a collection of elements $\{a_i\}_{i \in I}$ of X such that for every $i, j \in I$, either $a_i \leq a_j$ or $a_j \leq a_i$.

Zorn's Lemma: Suppose that X is a nonempty, partially ordered set with \leq the partial ordering. If every non-empty chain C in X has an upper bound in X , then X has at least one maximal element m (i.e. $b \in X$ with $m \leq b \implies b = m$).

Corollary 14. Any proper ideal A of a commutative ring R is contained in a maximal ideal.

Lemma 9.2. Let K be a field. Then there exists an algebraic extension $E : K \subseteq E$, such that E contains a root of every irreducible $f \in K[t]$, and hence also every $g \in K[t] \setminus K$.

Theorem 9.3 (Existence of Algebraic Closures). Suppose that K is a field. Then there exists an algebraic extension \bar{K} of K such that \bar{K} is algebraically closed.

Definition 28 (Extension of field homomorphism, isomorphic field extensions). For $i = 1$ and 2 , let $L_i : K_i$ be a field extension relative to the embedding $\varphi_i : K_i \rightarrow L_i$. Suppose that $\sigma : K_1 \rightarrow K_2$ and $\tau : L_1 \rightarrow L_2$ are isomorphisms. We say that τ *extends* σ if $\tau \circ \varphi_1 = \varphi_2 \circ \sigma$. In such circumstances, we say that $L_1 : K_1$ and $L_2 : K_2$ are *isomorphic field extensions*.

$$\begin{array}{ccc} L_1 & \xrightarrow{\tau} & L_2 \\ \varphi_1 \uparrow & \nearrow & \uparrow \varphi_2 \\ K_1 & \xrightarrow{\sigma} & K_2 \end{array}$$

When $\sigma : K_1 \rightarrow K_2$ and $\tau : L_1 \rightarrow L_2$ are homomorphisms (instead of isomorphisms), then τ *extends* σ as a *homomorphism of fields* when the isomorphism $\tau : L_1 \rightarrow L'_1 = \tau(L_1)$ extends the isomorphism $\sigma : K_1 \rightarrow K'_1 = \sigma(K_1)$.

Definition 29 (K -homomorphism). Let $L : K$ be a field extension relative to the embedding $\varphi : K \rightarrow L$, and let M be a subfield of L containing $\varphi(K)$. Then, when $\sigma : M \rightarrow L$ is a homomorphism, we say that σ is a K -homomorphism if σ leaves $\varphi(K)$ pointwise fixed, which is to say that for all $\alpha \in \varphi(K)$, one has $\sigma(\alpha) = \alpha$.

Lemma 9.4. Suppose that $L : K$ is a field extension with $K \subseteq L$, and that $\tau : L \rightarrow L$ is a K -homomorphism. Suppose that $f \in K[t]$ has the property that $\deg f \geq 1$, and additionally that $\alpha \in L$.

- (i) if $f(\alpha) = 0$, one has $f(\tau(\alpha)) = 0$;
- (ii) if τ is a K -automorphism of L , then $f(\alpha) = 0 \iff f(\tau(\alpha)) = 0$.

Theorem 9.5. Let $\sigma : K_1 \rightarrow K_2$ be a field isomorphism. Suppose that L_i is a field with $K_i \subseteq L_i$ ($i = 1, 2$). Suppose also that $\alpha \in L_1$ is algebraic over K_1 , and that $\beta \in L_2$ is algebraic over K_2 . Then we can extend σ to an isomorphism $\tau : K_1(\alpha) \rightarrow K_2(\beta)$ in such a manner that $\tau(\alpha) = \beta$ if and only if $\mu_\beta^{K_2} = \sigma(\mu_\alpha^{K_1})$.

$$\begin{array}{ccccc} K_2 & \xrightarrow{\varphi_2} & K_2(\beta) & \xhookrightarrow{\iota_2} & L_2 \\ \downarrow \sigma & & \downarrow \tau & & \\ K_1 & \xrightarrow{\varphi_1} & K_1(\alpha) & \xhookrightarrow{\iota_1} & L_1 \end{array}$$

Note: When $\tau : K_1(\alpha) \rightarrow K_2(\beta)$ is a homomorphism, and τ extends the homomorphism $\sigma : K_1 \rightarrow K_2$, then τ is completely determined by σ and the value of $\tau(\alpha)$.

Corollary 15. Let $L : M$ be a field extension with $M \subseteq L$. Suppose that $\sigma : M \rightarrow L$ is a homomorphism, and $\alpha \in L$ is algebraic over M . Then the number of ways we can extend σ to a homomorphism $\tau : M(\alpha) \rightarrow L$ is equal to the number of distinct roots of $\sigma(\mu_\alpha^M)$ that lie in L .

10 Algebraic Closure II

Theorem 10.1. Let $L : K$ be an algebraic extension with $K \subseteq L$ and $\varphi : K \rightarrow \overline{K}$ be a homomorphism. Then there exists an extension of φ to a homomorphism $\psi : L \rightarrow \overline{K}$.

Theorem 10.2. If L and M are both algebraic closures of K , then $L \cong M$.

Corollary 16. Let $L : K$ be an extension with $K \subseteq L$. Suppose that $g \in L[t]$ is irreducible over L , and that $g \mid f$ in $L[t]$, where $f \in K[t] \setminus \{0\}$. Then g divides a factor of f that is irreducible over K .

Thus, there exists an irreducible $h \in K[t]$ such that $h \mid f$ in $K[t]$, and $g \mid h$ in $L[t]$.

Definition 30 (Normal extension). The extension $L : K$ is *normal* if it is algebraic, and every irreducible polynomial $f \in K[t]$ either splits over L or has no root in L .

Theorem 10.3. $K(\alpha) : K$ is normal \iff all conjugates of α are contained in $K(\alpha)$.

Theorem 10.4. A finite extension $L : K$ is normal $\iff L$ is a splitting field extension for some $f \in K[t] \setminus K$.

11 Galois Groups I

Definition 31 (Galois group of polynomial). Let $L = K(\alpha_1, \dots, \alpha_n)$ and let $P(\alpha_1, \dots, \alpha_n)$ where $P \in K[\alpha_1, \dots, \alpha_n]$ is an element of L . Then we define

$$\text{Gal}_K(f) = \{\sigma \in S_n \mid \forall P \in K[\alpha_1, \dots, \alpha_n], \text{ if } P(\alpha_1, \dots, \alpha_n) = 0 \text{ then } P(\alpha_{\sigma(1)}, \dots, \alpha_{\sigma(n)}) = 0\}$$

Lemma 11.1. 1. $\text{Gal}_K(f) \leq S_n$;

2. If $K_1 : K$, then $\text{Gal}_{K_1}(f) \leq \text{Gal}_K(f)$.

Definition 32. Let $L : K$ be a field extension. Then

$$\text{Gal}_K(L) = \text{Gal}(L : K) = \{\varphi \in \text{Aut}(L) : \varphi \text{ is a } K\text{-homomorphism}\}$$

Definition 33 (Galois automorphism on splitting field). Let $\sigma \in \text{Gal}_K f$ where L is a splitting field for f over K , and define $\hat{\sigma} \in \text{Aut}_K(L)$ such that $\hat{\sigma}(P(\alpha_1, \dots, \alpha_n)) = P(\alpha_{\sigma(1)}, \dots, \alpha_{\sigma(n)})$.

Lemma 11.2. The map $\psi(\sigma) = \hat{\sigma}$ is a group isomorphism.

Theorem 11.3. If $L : K$ is an algebraic extension and $\sigma : L \rightarrow L$ is a K -homomorphism, then $\sigma \in \text{Aut}(L)$

Lemma 11.4. Suppose that $M : K$ is a normal extension. Then:

- (a) for any $\sigma \in \text{Gal}(M : K)$ and $\alpha \in M$, we have $\mu_{\sigma(\alpha)}^K = \mu_\alpha^K$;
- (b) for any $\alpha, \beta \in M$ with $\mu_\alpha^K = \mu_\beta^K$, there exists $\tau \in \text{Gal}(M : K)$ such that $\tau(\alpha) = \beta$.

12 Galois Groups II

Lemma 12.1. Suppose that $L : K$ is a normal extension with $K \subseteq L \subseteq \overline{K}$. Then for any K -homomorphism $\tau : L \rightarrow \overline{K}$, we have $\tau(L) = L$.

Lemma 12.2. For $n \geq 2$, S_n is generated by

- 1. transpositions (ij) ;
- 2. transpositions $(1i)$;
- 3. adjacent transpositions $(12), (23), \dots, (n-1, n)$;
- 4. (12) and $(12 \dots n)$;

5. (12) and $(23 \dots n)$;
6. (ij) and $(i \dots i_p)$ where p is prime.

Lemma 12.3. Let $(i_1 \dots i_k) \in S_n$. Then for all $\sigma \in S_n$, one has $\sigma(i_1 \dots i_k)\sigma^{-1} = (\sigma(i_1) \dots \sigma(i_k))$.

Note: $|\text{Gal}_K(f)| = [L : K]$ where $L : K$ is a splitting field extension for f .

13 Galois Groups III

Theorem 13.1 (Kronecker). Let $p \geq 3$ be a prime and $f \in \mathbb{Q}[x]$ be irreducible over \mathbb{Q} with $\deg f = p$. If the equation $f(x) = 0$ is solvable by radicals, then the number of real roots of f is 1 or p .

Lemma 13.2. Let p be prime and $G \leq S_p$ such that G acts transitively on $\{1, \dots, p\}$. Then G contains a cycle of order p .

Theorem 13.3. If $L : K$ is a finite extension, then $|\text{Gal}_K(L)| \leq [L : K]$.

14 Separability

Definition 34 (Separable). Let K be a field.

- (i) An irreducible polynomial $f \in K[t]$ is *separable over K* if it has no multiple roots, meaning that $f = \lambda(t - \alpha_1)(t - \alpha_2) \dots (t - \alpha_d)$, where $\alpha_1, \dots, \alpha_d \in \overline{K}$ are distinct.
- (ii) A non-zero polynomial $f \in K[t]$ is *separable over K* if its irreducible factors in $K[t]$ are separable over K .
- (iii) When $L : K$ is a field extension, we say that $\alpha \in L$ is *separable over K* when α is algebraic over K and μ_α^K is separable.
- (iv) An algebraic extension $L : K$ is a *separable extension* if every $\alpha \in L$ is separable over K .

Lemma 14.1. Suppose that $L : M : K$ is a tower of algebraic field extensions. Assume that $K \subseteq M \subseteq L \subseteq \overline{K}$, and suppose that $f \in K[t] \setminus K$ satisfies the property that f is separable over K . If $g \in M[t] \setminus M$ has the property that $g \mid f$, then g is separable over M . Thus, if $\alpha \in L$ is separable over K then α is separable over M , and if $L : K$ is separable then so is $L : M$.

Lemma 14.2. 1. If $L : M$ is an algebraic field extension, $\alpha \in L$ and $\sigma : M \rightarrow \overline{M}$ is a homomorphism, then $\sigma(\mu_\alpha^M)$ is separable over $\sigma(M) \iff \mu_\alpha^M$ is separable over M .

2. If $L : K$ is a splitting field extension for $f \in K[t]$ and f is separable over K , then $L : K$ is separable.

Theorem 14.3. Let $L : K$ be a finite extension with $K \subseteq L \subseteq \overline{K}$, whence $L = K(\alpha_1, \dots, \alpha_n)$ for some $\alpha_1, \dots, \alpha_n \in L$. Put $K_0 = K$, and for $1 \leq i \leq n$, set $K_i = K_{i-1}(\alpha_i)$. Finally, let $\sigma_0 : K \rightarrow \overline{K}$ be the inclusion map.

- (i) If α_i is separable over K_{i-1} for $1 \leq i \leq n$, then there are $[L : K]$ ways to extend σ_0 to a homomorphism $\tau : L \rightarrow \overline{K}$.
- (ii) If α_i is not separable over K_{i-1} for some i with $1 \leq i \leq n$, then there are fewer than $[L : K]$ ways to extend σ_0 to a homomorphism $\tau : L \rightarrow \overline{K}$.

Theorem 14.4. Let $L : K$ be a finite extension with $L = K(\alpha_1, \dots, \alpha_n)$. Set $K_0 = K$, and for $1 \leq i \leq n$, inductively define K_i by putting $K_i = K_{i-1}(\alpha_i)$. Then the following are equivalent:

- (i) the element α_i is separable over K_{i-1} for $1 \leq i \leq n$;
- (ii) the element α_i is separable over K for $1 \leq i \leq n$;
- (iii) the extension $L : K$ is separable.

Corollary 17. Suppose that $L : K$ is a finite extension. If $L : K$ is a separable extension, then the number of K -homomorphism $\sigma : L \rightarrow \overline{K}$ is $[L : K]$, and otherwise the number is smaller than $[L : K]$.

Corollary 18. Suppose that $f \in K[t] \setminus K$ and that $L : K$ is a splitting field extension for f . Then $L : K$ is a separable extension $\iff f$ is separable over K . More generally, suppose that $L : K$ is a splitting field extension for $S \subseteq K[t] \setminus K$. Then $L : K$ is a separable extension \iff each $f \in S$ is separable over K .

15 The Primitive Element Theorem

Definition 35 (Simple extension). Suppose $L : K$ is a field extension relative to the embedding $\varphi : K \rightarrow L$. We say that $L : K$ is a *simple extension* if there is some $\gamma \in L$ such that $L = \varphi(K)(\gamma)$.

Theorem 15.1 (The Primitive Element Theorem). If $L : K$ is a finite, separable extension with $K \subseteq L$, then $L : K$ is a simple extension.

Corollary 19. Suppose that $L : K$ is an algebraic, separable extension, and suppose that for every $\alpha \in L$, the polynomial μ_α^K has degree at most n over K . Then $[L : K] \leq n$.

Fact: Let $L : K$ be a normal extension and let $\deg(\mu_\alpha^K) \leq n$ for all $\alpha \in L$. Then $[L : K] \leq n$.

Corollary 20. If $f \in K[t]$ is irreducible over K , then $\text{Gal}_K(f)$ acts transitively on the roots of f .

16 Galois Fields I

Definition 36 (Formal derivative). We define the *derivative operator* $\mathcal{D} : K[t] \rightarrow K[t]$ by

$$\mathcal{D} \left(\sum_{k=0}^n a_k t^k \right) = \sum_{k=1}^n k a_k t^{k-1}.$$

Theorem 16.1. Let $f \in K[t] \setminus K$, and let $L : K$ be a splitting field extension for f with $K \subseteq L$. Then the following are equivalent:

- (i) f has a repeated root over L ;
- (ii) There exists $\alpha \in L$ such that $f(\alpha) = 0 = (\mathcal{D}f)(\alpha)$;
- (iii) There exists $g \in K[t]$ with $\deg g \geq 1$ such that $g \mid f$ and $g \mid \mathcal{D}f$.

Definition 37 (Inseparable). A polynomial $f \in K[t]$ is *inseparable over K* if f is not separable over K , i.e. f has an irreducible factor $g \in K[t]$ such that g has fewer than $\deg g$ distinct roots in K .

Theorem 16.2. Suppose $f \in K[t]$ is irreducible over K . Then f is inseparable over $K \iff \text{char } K = p > 0$ and $f \in K[t^p]$.

Definition 38 (Frobenius map). Suppose that $\text{char } K = p > 0$. The *Frobenius map* $\varphi : K \rightarrow K$ is defined by $\varphi(\alpha) = \alpha^p$.

Theorem 16.3. Suppose that $\text{char } K = p > 0$, and put $F = \{c \cdot 1_K : c \in \mathbb{Z}\}$. Then F is a subfield (called the prime subfield) of K , and $F \cong \mathbb{Z}/p\mathbb{Z}$.

Definition 39 (Fixed field). Let $L : K$ be a field extension and $G \leq \text{Aut}(L)$. We define the *fixed field of G* as

$$\text{Fix}_L(G) = \{\alpha \in L : \sigma(\alpha) = \alpha \text{ for all } \sigma \in G\}.$$

Theorem 16.4. Suppose that $\text{char } K = p > 0$, and let F be the prime subfield of K . Let $\varphi : K \rightarrow K$ denote the Frobenius map. Then φ is an injective homomorphism, and $\text{Fix}_\varphi(K) = F$.

Corollary 21. Suppose that $\text{char } K = p > 0$ and K is algebraic over its prime subfield. Then the Frobenius map is an automorphism of K .

Corollary 22. Suppose that $\text{char } K = p > 0$ and K is algebraic over its prime subfield. Then all polynomials in $K[t]$ are separable over K .

Corollary 23 ().** Suppose that $\text{char } K = 0$. Then all polynomials in $K[t]$ are separable over K .

Theorem 16.5. Suppose that $\text{char } K = p > 0$. Let

$$f(t) = g(t^p) = a_0 + a_1 t^p + \cdots + a_{n-1} t^{(n-1)p} + t^{np}$$

be a non-constant monic polynomial over K . Then $f(t)$ is irreducible in $K[t]$ if and only if $g(t)$ is irreducible in $K[t]$ and not all the coefficients a_i are p -th powers in K .

17 Galois Fields II

Theorem 17.1. Let p be a prime, and let $q = p^n$ for some $n \in \mathbb{N}$. Then:

- (a) There exists a field \mathbb{F}_q of order q , and this field is unique up to isomorphism.
- (b) All elements of \mathbb{F}_q satisfy the equation $t^q = t$, and hence $\mathbb{F}_q : \mathbb{F}_p$ is a splitting field extension for $t^q - t$.
- (c) There is a unique copy of \mathbb{F}_q inside any algebraically closed field containing \mathbb{F}_p .

Theorem 17.2. Let p be a prime, and suppose that $q = p^n$ for some $n \in \mathbb{N}$. Then:

- (a) $\text{Gal}(\mathbb{F}_q : \mathbb{F}_p) \cong \mathbb{Z}/n\mathbb{Z}$;
- (b) The field \mathbb{F}_q contains a subfield of order p^d if and only if $d \mid n$. When $d \mid n$, moreover, there is a unique subfield of \mathbb{F}_q of order p^d .

Definition 40 (Norm, Trace). Let p be a prime and let $\alpha \in F_q$ where $q = p^n$ for some $n \in \mathbb{N}$. Then we define

$$\begin{aligned} \text{Tr}(\alpha) &= \alpha + \alpha^p + \cdots + \alpha^{p^{n-1}} \\ &= \alpha + \varphi(\alpha) + \cdots + \varphi^{n-1}(\alpha) \end{aligned}$$

and

$$\begin{aligned} \text{Norm}(\alpha) &= \alpha \cdot \alpha^p \cdots \alpha^{p^{n-1}} = \alpha^{\frac{p^n-1}{p-1}} \\ &= \alpha \cdot \varphi(\alpha) \cdots \varphi^{n-1}(\alpha) \end{aligned}$$

Lemma 17.3. Let p be a prime and let $\alpha \in F_q$ where $q = p^n$ for some $n \in \mathbb{N}$.

- 1. For all $\alpha \in \mathbb{F}_q$, one has $\text{Tr}(\alpha), \text{Norm}(\alpha) \in \mathbb{F}_p$;
- 2. If $p \neq 2$, then $\exists \alpha_1$ such that $\text{Tr}(\alpha_1) \neq 0$ and $\exists \alpha_2 (\neq 0)$ such that $\text{Norm}(\alpha_2) \neq 1$.

19 Fixed Fields

Definition 41 (Fixed field). Let $L : K$ be a field extension and $G \leq \text{Aut}(L)$. Then the *fixed field* of G is

$$\text{Fix}_L(G) = L^G = \{\alpha \in L : g\alpha = \alpha \ \forall g \in G\}$$

Theorem 19.1. Let $K, M \subseteq L$ be fields and $G, H \leq \text{Aut}(L)$. Then

- 1) if $K \subseteq M$, then $\text{Gal}(L : K) \supseteq \text{Gal}(L : M)$;
- 2) if $G \leq H$, then $\text{Fix}_L(G) \supseteq \text{Fix}_L(H)$;
- 3) $K \subseteq \text{Fix}_L(\text{Gal}(L : K))$;
- 4) $G \leq \text{Gal}(L : \text{Fix}_L(G))$;

$$5) \text{ Gal}(L : K) = \text{Gal}(L : \text{Fix}_L(\text{Gal}(L : K)));$$

$$6) \text{ Fix}_L(G) = \text{Fix}_L(\text{Gal}(L : \text{Fix}_L(G))).$$

Definition 42 (Galois Extension). Let $L : K$ be a field extension. Then $L : K$ is a *Galois extension* if it is normal and separable.

Theorem 19.2. Let $L : K$ be algebraic. Then $L : K$ is Galois $\iff K = \text{Fix}_L(\text{Gal}_K(L))$

Theorem 19.3. Suppose that L is a field, $G \leq \text{Aut}(L)$ such that $|G| < \infty$, and put $K = \text{Fix}_L(G)$. Then $L : K$ is a finite Galois extension with $[L : K] = |\text{Gal}(L : K)|$, and furthermore $G = \text{Gal}_K(L)$.

Theorem 19.4. Let $L : K$ be finite.

1. If $L : K$ is a Galois extension, then $|\text{Gal}(L : K)| = [L : K]$ and $K = \text{Fix}_L(\text{Gal}(L : K))$.
2. If $L : K$ is not Galois, then $|\text{Gal}(L : K)| < [L : K]$ and K is a proper subfield of $\text{Fix}_L(\text{Gal}(L : K))$.

Corollary 24. Let $L : M : K$ be a tower such that $L : K$ is Galois. Then $L : M$ is Galois.

20 Fundamental Theorem of Galois Theory I

Theorem 20.1 (Fundamental Theorem of Galois Theory, Part 1). Let $L : K$ be a Galois extension with $G = \text{Gal}(L : K)$. Define $\mathcal{I}(K, L)$ and $\mathcal{S}(G)$ as the set of all intermediate fields of $L : K$ and the set of all subgroups of G , respectively. For all $P \in \mathcal{I}(K, L)$, we have $P = L^{G_P}$ where $G_P = \text{Aut}_P(L)$. Then

$$\begin{aligned} \forall P \in \mathcal{I}(K, L), \quad L^{G_P} &= P, \\ \forall H \in \mathcal{S}(G), \quad G_{L^H} &= H, \end{aligned}$$

$$\text{Also, } P_1 \subseteq P_2 \iff G_{P_1} \supseteq G_{P_2} \text{ and } H_1 \leq H_2 \iff L^{H_1} \supseteq L^{H_2}.$$

21 Fundamental Theorem of Galois Theory II

Theorem 21.1 (Fundamental Theorem of Galois Theory, Part 2). For all $P \in \mathcal{I}(K, L)$, we have $P : K$ is a normal extension $\iff G_P \triangleleft G$. Then, $\text{Gal}_K P \cong G/G_P$.

Lemma 21.2. Let $K - P - L$ be a tower of fields and $g \in \text{Aut } L$. Then $G_{gP} = gG_P g^{-1}$.

Remark 1. Let $L : P : K$ be a tower of fields, where $[L : K] = [L : P][P : K]$. Then $\text{Id.} : G_P : G$ is a tower of groups, where $[G : G_P] \cdot |G_P|$. That is, for all $P \leq L$ we have $[P : K] = [G : G_P]$ and $[L : P] = |G_P|$.

22 Composita

Remark 2. Let A, B be sets. Then $A \cap B$ can be expressed using only the operation \subseteq . Notice $A \cap B \subseteq A, B$ and $A \cap B$ is the maximal set with this property:

$$\forall C \text{ such that } C \subseteq A, B \implies C \subseteq A \cap B.$$

Let $H_1, H_2 \leq G$. Then $H_1 \cap H_2 \leq G$ is the *maximal* subgroup contained in both H_1 and H_2 . Hence by the Galois correspondence we have $L^{H_1 \cap H_2}$ is the *minimal* subfield of L containing both L^{H_1} and L^{H_2} .

Definition 43 (Compositum). Let K_1 and K_2 be fields contained in some field L . The *compositum* of K_1 and K_2 in L (or the *composite field*), denoted by $K_1 K_2$, is the smallest subfield of L containing both K_1 and K_2 .

Lemma 22.1. Let $K, E, F \subseteq L$. Then

1. $E : K, F : K$ finite $\implies EF : K$ finite;
2. $E : K, F : K$ normal $\implies E \cap F : K$ normal;

3. $E : K, F : K$ finite and $E : K$ normal $\implies EF : F$ normal;
4. $E : K, F : K$ finite and normal $\implies EF : K, E \cap F : K$ normal;
5. $E : K, F : K$ normal $\implies EF : E \cap F$ normal.

23 Soluble Groups I

Definition 44 (Soluble group). A group G is *soluble* if there exists a finite series of subgroups

$$\{Id.\} = G_n \leq G_{n-1} \leq \cdots \leq G_0 = G$$

such that

1. $G_j \triangleleft G_{j-1} \forall 1 \leq j \leq n$ and
2. G_{j-1}/G_j is cyclic $\forall 1 \leq j \leq n$.

Definition 45 (Simple group). A group G is *simple* if G has no non-trivial normal subgroups.

Lemma 23.1. For $n \geq 5$ the group A_n is simple (and hence not soluble).

Lemma 23.2. Let G be a group with $H \trianglelefteq G$ and $A \leq G$. Then

1. $(A \cap H) \trianglelefteq A$ and $A/(A \cap H) \cong (HA)/H$
2. if $H \subseteq A$ and $A \trianglelefteq G$, then $H \trianglelefteq A$, $(A/H) \trianglelefteq (G/H)$ and $(G/H)/(A/H) \cong G/A$.

Theorem 23.3. 1. If G is a soluble group with $A \leq G$, then A is soluble.

2. Let $H \trianglelefteq G$. Then G is soluble $\iff H$ and G/H are soluble.

Corollary 25. S_n is not soluble for $n \geq 5$.

Corollary 26. All p -groups are soluble (i.e. groups G such that $|G| = p^n$ for some prime p)

24 Soluble Groups II

Theorem 24.1 (Theorem - Definition). Let G be a group. Then the following are equivalent:

0. G is a (finite) soluble group;
1. There exists some $n \in \mathbb{Z}^+$ such that $G^{(n)} = \{e\}$;
2. There exists a normal series

$$\{Id.\} = G_n \triangleleft G_{n-1} \triangleleft \cdots \triangleleft G_1 \triangleleft G_0 = G$$

such that all quotients G_{j-1}/G_j are abelian;

3. There exists a subnormal series such that quotients G_{j-1}/G_j are abelian.

Definition 46 (Derived group). Let G be a group. Then the *derivative of G* is $G' = \langle [x, y] : x, y \in G \rangle = [G, G]$ where $[x, y] = xyx^{-1}y^{-1}$ is the *commutator* of x and y , and $(G')' = G''$.

Definition 47 (Derived series). The *derived series* of G is $G^{(n)} = (G^{(n-1)})'$ and $\{Id.\} = G^{(n)} \triangleleft G^{(n-1)} \triangleleft \cdots \triangleleft G' \triangleleft G$ (not to be confused with $G_{n+1} = [G_n, G]$, the *lower central series*).

Lemma 24.2. Let $\varphi : G \mapsto H$ be an epimorphism. Then $\varphi(G') = H'$.

Definition 48 (Composition series). Let G be a group. Then a *composition series* of G is a subnormal series of finite length

$$\{Id.\} = G_0 \triangleleft G_1 \triangleleft \cdots \triangleleft G_{\ell-1} \triangleleft G_{\ell} = G$$

such that G_j/G_{j-1} is a simple group for all j .

Theorem 24.3 (Jordan-Hölder). Any 2 composition series of some group G are equivalent up to permutation and isomorphism.

Theorem 24.4. Let K be a field with $\text{char } K \neq 2$ and let $f \in K[t]$ be a separable polynomial with splitting field L . Then $f = 0$ is solvable by *quadratic* radicals $\iff [L : K] = 2^t$.

25 Solvability by radicals and Galois theory I

Theorem 25.1. Let K be a field with $\text{char } K = 0$. Then $f \in K[t]$ is solvable by radicals $\iff \text{Gal}_K(f)$ is soluble.

Lemma 25.2. Let $\text{char } K = 0$ and $R : K$ be a radical extension. Then there exists a tower $K = R_0 \subset R_1 \subset \dots \subset R_n = R$ such that $R_i : R_{i-1}$ is normal and radical.

Definition 49 (Cyclic extension). Let L be the splitting field of some polynomial f over K . If $\text{Gal}(L : K)$ is a cyclic group, then $L : K$ is a *cyclic* extension.

Lemma 25.3. Let $\text{char } K = 0$ and let n be a positive integer such that $t^n - 1$ splits over K , and let $L : K$ be the splitting field extension for $t^n - a$ for some $a \in K$. Then $\text{Gal}(L : K)$ is abelian.

Theorem 25.4. Let $\text{char } K = 0$ and $L : K$ be Galois. Suppose there exists some extension $M : L$ such that $M : K$ is normal. Then $\text{Gal}(L : K)$ is soluble.

Corollary 27. Let $\text{char } K = 0$. Then $f \in K[t]$ is SBR $\implies \text{Gal}_K(f)$ is soluble.

26 Solvability by radicals and Galois theory II

Lemma 26.1. Let p be prime and $G \leq S_p$ such that G acts transitively on $\{1, \dots, p\}$. Then G contains a cycle of order p .

Theorem 26.2. Let $\text{char } K = 0$ and $f \in K[t] \setminus K$. Then $\text{Gal}_K(f)$ is soluble $\implies f$ is SBR.

Lemma 26.3 (Wooley 14.8). Let $\text{char } K = 0$, and suppose that $L : K$ is a cyclic extension of degree n . Suppose also that K contains a primitive n -th root of 1. Then there exists $\theta \in K$ having the property that $t^n - \theta$ is irreducible over K , and $L : K$ is a splitting field for $t^n - \theta$. Further, if β is a root of $t^n - \theta$ over L , then $L = K(\beta)$.

Theorem 26.4 (Abel-Galois). Let $\text{char } K = 0$ and $f \in K[t]$ be irreducible over K with $\deg f = p$. Then following are equivalent

1. f is SBR over K ;
2. $\text{Gal}_K(f)$ is conjugated to a subgroup of $\text{Aff}(\mathbb{F}_p)$;
3. for the splitting field L of f , one has $L = K(\alpha_i, \alpha_j)$ where α_i, α_j are any two distinct roots of f .

Lemma 26.5. Let $\{\text{Id.}\} \neq N \trianglelefteq G \leq S_p$ for p prime. If G is a transitive group, then N is a transitive group.

27 Final remarks I

Definition 50 (Sylvester matrix). Let $f(x) = a_0 + a_1x + \dots + a_mx^m$ and $g(x) = b_0 + b_1x + \dots + b_nx^n$ be two polynomials in $\mathbb{K}[x]$. The *Sylvester matrix* of f and g , denoted $S(f, g)$, is the $(m+n) \times (m+n)$ matrix whose first n rows are the coefficients of f shifted right, and whose last m rows are the coefficients of g shifted

right. Concretely,

$$S(f, g) = \begin{pmatrix} a_m & a_{m-1} & \cdots & a_0 & 0 & \cdots & 0 \\ 0 & a_m & a_{m-1} & \cdots & a_0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \vdots & \ddots & 0 \\ 0 & \cdots & 0 & a_m & a_{m-1} & \cdots & a_0 \\ b_n & b_{n-1} & \cdots & b_0 & 0 & \cdots & 0 \\ 0 & b_n & b_{n-1} & \cdots & b_0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \vdots & \ddots & 0 \\ 0 & \cdots & 0 & b_n & b_{n-1} & \cdots & b_0 \end{pmatrix}.$$

Definition 51 (Resultant). The *resultant* of f and g is

$$R(f, g) = \det(S(f, g)).$$

Equivalently, if $\alpha_1, \dots, \alpha_m$ are the roots of f in an algebraic closure of \mathbb{K} , then

$$R(f, g) = a_m^n \prod_{i=1}^m g(\alpha_i).$$

Theorem 27.1. Let α_i be roots of f and β_j be roots of g . Then

$$\begin{aligned} R(f, g) &= a_0^m b_0^n \prod_i (\alpha_i - \beta_j) \\ &= a_0^m \prod_i g(\alpha_i) = b_0^n \prod_i f(\beta_i) \end{aligned}$$

Corollary 28. 1. $R(f, g) = (-1)^{\deg f \cdot \deg g} R(g, f)$

2. If $f = gq + r \implies R(f, g) = b_0^{\deg f - \deg R} R(r, g)$

3. $R(f, gh) = R(f, g)R(f, h)$

Corollary 29. Let $f(t) = a_0 t^n + \cdots + a_n$, $a_0 \neq 0$. Then $R(f, f') = (-1)^{\frac{n(n-1)}{2}} \prod_{i < j} (\alpha_i - \alpha_j)^2$

28 Final remarks II

Definition 52 (Resolvent invariant). Let $G \leq S_n$ and $P \in K[x_1, \dots, x_n]$. Then P is *resolvent invariant* for G if $P^g = P \iff g \in G$.

Lemma 28.1. Let P be resolvent invariant for G . Then

1. $P^a = P^b \iff ab^{-1} \in G$ (obvious: $P^a = P^b \iff P^{ab^{-1}} = P$)
2. P^a is resolvent invariant for $a^{-1}Ga$

Corollary 30. Let $S_n = \sqcup_j a_j G$. Then P is resolvent invariant for $G \iff P^{a_j}$ are distinct.

Definition 53 (Resolvent). Let P be a resolvent polynomial for $G \leq S_n$ and $S_n = \sqcup_{j=1}^s a_j G$. Then

$$R_G(z) = R_G(z, x_1, \dots, x_n) = (z - P^{a_1}) \cdots (z - P^{a_s})$$

is a *resolvent* for G (depends on P).

Lemma 28.2. Let $G \leq S_n$, $f \in K[t]$ be a separable polynomial. If $\text{Gal}_K(f) \leq G$ (and its conjugation), then $\exists j \in K$ such that $R_{G,f}(j) = 0$

Lemma 28.3. Let $|K| = \infty$ and $f \in K[t]$ be a separable polynomial. Then $\exists c_1, \dots, c_n \in K$ such that for all k ,

$$h_k(x_1, \dots, x_k) = c_1 x_1 + \dots + c_k x_k$$

has the property

$$h_k^a(\alpha_1, \dots, \alpha_k) = h_k^b(\alpha_1, \dots, \alpha_k) \iff x_i^a = x_i^b \text{ for } i = 1, \dots, k,$$

where $a, b \in S_n$ are any permutations.

Theorem 28.4. Let $|K| = \infty$, $f \in K[t]$ be a separable polynomial, and $G \leq S_n$. Then there exists a resultant $R_{G,f}(z)$ with no multiple roots.

Theorem 28.5. Let $|K| = \infty$ and $f \in K[t]$ be irreducible and separable with $\deg f = 4$. Then

1. $\sqrt{D} \notin K$ and $R_{V_4}^{(f)}$ has no roots in $K \implies G \cong S_4$ or $G \cong Z_4$
2. $\sqrt{D} \in K$ and $R_{V_4}^{(f)}$ has no roots in $K \implies G \cong A_4$
3. $\sqrt{D} \in K$ and $R_{V_4}^{(f)}$ has a roots in $K \implies G \cong V_4$
4. $\sqrt{D} \notin K$ and $R_{V_4}^{(f)}$ has no roots in $K \implies G \cong S_4$ or $G \cong D_4$