1 Algebraic Closure I

Definition 1 (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 1.1. 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 2 (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 $m \leq b \Longrightarrow b = m$).

Corollary 1. Any proper ideal A of a commutative ring R is contained in a maximal ideal.

Lemma 1.2. Let K be a field. Then there exists an algebraic extension $E : K$, with $K \subseteq E$, such that E contains a root of every irreducible $f \in K[t]$, and hence also every $g \in K[t] \setminus K$.

Theorem 1.3 (Existence of Algebraic Closures)**.** Suppose that K is a field. Then there exists an algebraic extension $\overline{K}$ of K such that $\overline{K}$ is algebraically closed.

Definition 3 (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 $\varphi_i : K_i \to L_i$. Suppose that $\sigma : K_1 \to K_2$ and $\tau : L_1 \to L_2$ 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.*

$$\begin{tikzcd} L_1 \arrow[r, "\tau"] & L_2 \\ K_1 \arrow[u, "\varphi_1"] \arrow[r, "\sigma"] \arrow[ur, dashed] & K_2 \arrow[u, "\varphi_2"'] \end{tikzcd}$$

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

Definition 4 (K-homomorphism)**.** Let $L : K$ be a field extension relative to the embedding $\varphi : K \to L$, and let M be a subfield of L containing $\varphi(K)$. Then, when $\sigma : M \to L$ 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 1.4. Suppose that $L : K$ is a field extension with $K \subseteq L$, and that $\tau : L \to L$ 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 $f(\alpha) = 0 \Longleftrightarrow f(\tau(\alpha)) = 0$.

Theorem 1.5. Let $\sigma : K_1 \to K_2$ 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 $\tau : K_1(\alpha) \to K_2(\beta)$ in such a manner that $\tau(\alpha) = \beta$ if and only if $\mu_\beta^{K_2} = \sigma(\mu_\alpha^{K_1})$.

$$\begin{tikzcd}
K_2 \arrow[r, "\varphi_2"] \arrow[d, "\sigma"] & K_2(\beta) \arrow[r, hook, "\iota_2"] \arrow[d, "\tau"] & L_2 \\
K_1 \arrow[r, "\varphi_1"] & K_1(\alpha) \arrow[r, hook, "\iota_1"] & L_1
\end{tikzcd}$$

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

Corollary 2. Let $L : M$ be a field extension with $M \subseteq L$. Suppose that $\sigma : M \to L$ is a homomorphism, and $\alpha \in L$ is algebraic over M. Then the number of ways we can extend σ to a homomorphism $\tau : M(\alpha) \to L$ is equal to the number of distinct roots of $\sigma(\mu_\alpha^M)$ that lie in L.