20 The Kronecker-Weber theorem

In the previous lecture we established a relationship between finite groups of Dirichlet characters and subfields of cyclotomic fields. Specifically, we showed that there is a one-to-one-correspondence between finite groups H of primitive Dirichlet characters of conductor dividing m and subfields K of $\mathbb{Q}(\zeta_m)$ under which H can be viewed as the character group of the finite abelian group $\mathrm{Gal}(K/\mathbb{Q})$ and the Dedekind zeta function of K factors as

$$\zeta_K(s) = \prod_{\chi \in H} L(s,\chi).$$

Now suppose we are given an arbitrary finite abelian extension $K/\mathbb{Q}$. Does the character group of $\mathrm{Gal}(K/\mathbb{Q})$ correspond to a group of Dirichlet characters, and can we then factor the Dedekind zeta function $\zeta_K(s)$ as a product of Dirichlet L-functions?

The answer is yes! This is a consequence of the *Kronecker-Weber theorem*, which states that every finite abelian extension of $\mathbb{Q}$ lies in a cyclotomic field. This theorem was first stated in 1853 by Kronecker [2], who provided a partial proof for extensions of odd degree. Weber [7] published a proof 1886 that was believed to address the remaining cases; in fact Weber's proof contains some gaps (as noted in [5]), but in any case an alternative proof was given a few years later by Hilbert [1]. The proof we present here is adapted from [6, Ch. 14]

20.1 Local and global Kronecker-Weber theorems

We now state the (global) Kronecker-Weber theorem.

Theorem 20.1. *Every finite abelian extension of $\mathbb{Q}$ lies in a cyclotomic field $\mathbb{Q}(\zeta_m)$.*

There is also a local version.

Theorem 20.2. *Every finite abelian extension of $\mathbb{Q}_p$ lies in a cyclotomic field $\mathbb{Q}_p(\zeta_m)$.*

We first show that the local version implies the global one.

Proposition 20.3. *The local Kronecker-Weber theorem implies the global Kronecker-Weber theorem.*

Proof. Let $K/\mathbb{Q}$ be a finite abelian extension. For each ramified prime p of $\mathbb{Q}$, pick a prime $\mathfrak{p}|p$ and let $K_\mathfrak{p}$ be the completion of K at $\mathfrak{p}$ (the fact that $K/\mathbb{Q}$ is Galois means that every $\mathfrak{p}|p$ is ramified with the same ramification index; it makes no difference which $\mathfrak{p}$ we pick). We have $\mathrm{Gal}(K_\mathfrak{p}/\mathbb{Q}_p) \simeq D_\mathfrak{p} \subseteq \mathrm{Gal}(K/\mathbb{Q})$, by Theorem 11.23, so $K_\mathfrak{p}$ is an abelian extension of $\mathbb{Q}_\mathfrak{p}$ and the local Kronecker-Weber theorem implies that $K_\mathfrak{p} \subseteq \mathbb{Q}_p(\zeta_{m_p})$ for some $m_p \in \mathbb{Z}_{\geq 1}$. Let $n_p := v_p(m_p)$, put $m := \prod_p p^{n_p}$ (this is a finite product), and let $L = K(\zeta_m)$. We will show $L = \mathbb{Q}(\zeta_m)$, which implies $K \subseteq \mathbb{Q}(\zeta_m)$.

The field $L = K \cdot \mathbb{Q}(\zeta_m)$ is a compositum of Galois extensions of $\mathbb{Q}$, and is therefore Galois over $\mathbb{Q}$ with $\mathrm{Gal}(L/\mathbb{Q})$ isomorphic to a subgroup of $\mathrm{Gal}(K/\mathbb{Q}) \times \mathrm{Gal}(\mathbb{Q}(\zeta_m)/\mathbb{Q})$, hence abelian (as recalled below, the Galois group of a compositum $K_1 \cdots K_r$ of Galois extensions K_i/F is isomorphic to a subgroup of the direct product of the $\mathrm{Gal}(K_i/F)$). Let $\mathfrak{q}$ be a prime of L lying above a ramified prime $\mathfrak{p}|p$; as above, the completion $L_\mathfrak{q}$ of L at $\mathfrak{q}$ is a finite abelian extension of $\mathbb{Q}_p$, since $L/\mathbb{Q}$ is finite abelian, and we have $L_\mathfrak{q} = K_\mathfrak{p} \cdot \mathbb{Q}_p(\zeta_m)$. Let $F_\mathfrak{q}$ be the maximal unramified extension of $\mathbb{Q}_p$ in $L_\mathfrak{q}$. Then $L_\mathfrak{q}/F_\mathfrak{q}$ is totally ramified and $\mathrm{Gal}(L_\mathfrak{q}/F_\mathfrak{q})$ is isomorphic to the inertia group $I_p := I_\mathfrak{q} \subseteq \mathrm{Gal}(L/\mathbb{Q})$, by Theorem 11.23 (the $I_\mathfrak{q}$ all coincide because $L/\mathbb{Q}$ is abelian).

It follows from Corollary 10.20 that $K_\mathfrak{p} \subseteq F_\mathfrak{q}(\zeta_{p^{n_p}})$, since $K_\mathfrak{p} \subseteq \mathbb{Q}_p(\zeta_{m_p})$ and $\mathbb{Q}_p(\zeta_{m_p/p^{n_p}})$ is unramified, and that $L_\mathfrak{q} = F_\mathfrak{q}(\zeta_{p^{n_p}})$, since $\mathbb{Q}_p(\zeta_{m/p^{n_p}})$ is unramified. Moreover, we have $F_\mathfrak{q} \cap \mathbb{Q}_p(\zeta_{p^{n_p}}) = \mathbb{Q}_p$, since $\mathbb{Q}_p(\zeta_{p^{n_p}})/\mathbb{Q}_p$ is totally ramified, and it follows that

$$I_p \simeq \mathrm{Gal}(L_\mathfrak{q}/F_\mathfrak{q}) \simeq \mathrm{Gal}(\mathbb{Q}_p(\zeta_{p^{n_p}})/\mathbb{Q}_p) \simeq (\mathbb{Z}/p^{n_p}\mathbb{Z})^\times.$$

Now let I be the group generated by the union of the groups $I_p \subseteq \mathrm{Gal}(L/\mathbb{Q})$ for $p|m$. Since $\mathrm{Gal}(L/\mathbb{Q})$ is abelian, we have $\bigcup I_p \subseteq \prod I_p$, thus

$$\#I \le \prod_{p|m} \#I_p = \prod_{p|m} \#(\mathbb{Z}/p^{n_p}\mathbb{Z})^\times = \prod_{p|m} \phi(p^{n_p}) = \phi(m) = [\mathbb{Q}(\zeta_m) : \mathbb{Q}].$$

Each inertia fields L^{I_p} is unramified at p (see Proposition 7.12), as is $L^I \subseteq L^{I_p}$. So $L^I/\mathbb{Q}$ is unramified, and therefore $L^I = \mathbb{Q}$, by Corollary 14.21. Thus

$$[L : \mathbb{Q}] = [L : L^I] = \#I \le [\mathbb{Q}(\zeta_m) : \mathbb{Q}],$$

and $\mathbb{Q}(\zeta_m) \subseteq L$, so $L = \mathbb{Q}(\zeta_m)$ as claimed and $K \subseteq L = \mathbb{Q}(\zeta_m)$. □

To prove the local Kronecker-Weber theorem we first reduce to the case of cyclic extensions of prime-power degree. Recall that if L_1 and L_2 are two Galois extensions of a field K then their compositum $L \coloneqq L_1L_2$ is Galois over K with Galois group

$$\mathrm{Gal}(L/K) \simeq \{(\sigma_1, \sigma_2) : \sigma_1|_{L_1\cap L_2} = \sigma_2|_{L_1\cap L_2}\} \subseteq \mathrm{Gal}(L_1/K) \times \mathrm{Gal}(L_2/K).$$

The inclusion on the RHS is an equality if and only if $L_1 \cap L_2 = K$. Conversely, if $\mathrm{Gal}(L/K) \simeq H_1 \times H_2$ then by defining $L_2 := L^{H_1}$ and $L_1 := L^{H_2}$ we have $L = L_1L_2$ with $L_1 \cap L_2 = K$, and $\mathrm{Gal}(L_1/K) \simeq H_1$ and $\mathrm{Gal}(L_2/K) \simeq H_2$.

It follows from the structure theorem for finite abelian groups that we may decompose any finite abelian extension L/K into a compositum $L = L_1 \cdots L_n$ of linearly disjoint cyclic extensions L_i/K of prime-power degree. If each L_i lies in a cyclotomic field $\mathbb{Q}(\zeta_{m_i})$, then so does L. Indeed, $L \subseteq \mathbb{Q}(\zeta_{m_1}) \cdots \mathbb{Q}(\zeta_{m_n}) = \mathbb{Q}(\zeta_m)$, where $m \coloneqq m_1 \cdots m_n$.

To prove the local Kronecker-Weber theorem it thus suffices to consider cyclic extensions $K/\mathbb{Q}_p$ of prime power degree ℓ^r. There two distinct cases: $\ell \ne p$ and $\ell = p$.

20.2 The local Kronecker-Weber theorem for $\ell \ne p$

Proposition 20.4. *Let $K/\mathbb{Q}_p$ be a cyclic extension of degree ℓ^r for some prime $\ell \ne p$. Then K lies in a cyclotomic field $\mathbb{Q}_p(\zeta_m)$.*

Proof. Let F be the maximal unramified extension of $\mathbb{Q}_p$ in K; then $F = \mathbb{Q}_p(\zeta_n)$ for some $n \in \mathbb{Z}_{\ge 1}$, by Corollary 10.19. The extension K/F is totally ramified, and it must be tamely ramified, since the ramification index is a power of $\ell \ne p$. By Theorem 11.10, we have $K = F(\pi^{1/e})$ for some uniformizer π, with $e = [K : F]$. We may assume that $\pi = -pu$ for some $u \in \mathcal{O}_F^\times$, since $F/\mathbb{Q}_p$ is unramified: if $\mathfrak{q}|p$ is the maximal ideal of $\mathcal{O}_F$ then the valuation $v_\mathfrak{q}$ extends v_p with index $e_\mathfrak{q} = 1$ (by Theorem 8.20), so $v_\mathfrak{q}(-pu) = v_p(-p) = 1$. The field $K = F(\pi^{1/e})$ lies in the compositum of $F((-p)^{1/e})$ and $F(u^{1/e})$, and we will show that both fields lie in a cyclotomic extension of $\mathbb{Q}_p$.

The extension $F(u^{1/e})/F$ is unramified, since $v_{\mathfrak{q}}(\operatorname{disc}(x^e - u)) = 0$ for $p \nmid e$, so $F(u^{1/e})/\mathbb{Q}_p$ is unramified and $F(u^{1/e}) = \mathbb{Q}_p(\zeta_k)$ for some $k \in \mathbb{Z}_{\geq 1}$. The field $K(u^{1/e}) = K \cdot \mathbb{Q}_p(\zeta_k)$ is a compositum of abelian extensions, so $K(u^{1/e})/\mathbb{Q}_p$ is abelian, and it contains the subextension $\mathbb{Q}_p((-p)^{1/e})/\mathbb{Q}_p$, which must be Galois (since it lies in an abelian extension) and totally ramified (by Theorem 11.5, since it is an Eisenstein extension). The field $\mathbb{Q}_p((-p)^{1/e})$ contains ζ_e (take ratios of roots of $x^e + p$) and is totally ramified, but $\mathbb{Q}_p(\zeta_e)/\mathbb{Q}_p$ is unramified (since $p \nmid e$), so we must have $\mathbb{Q}_p(\zeta_e) = \mathbb{Q}_p$. Thus $e|(p-1)$, and by Lemma 20.5 below,

$$\mathbb{Q}_p((-p)^{1/e}) \subseteq \mathbb{Q}_p((-p)^{1/(p-1)}) = \mathbb{Q}_p(\zeta_p),$$

It follows that $F((-p)^{1/e}) = F \cdot \mathbb{Q}_p((-p)^{1/e}) \subseteq \mathbb{Q}_p(\zeta_n) \cdot \mathbb{Q}_p(\zeta_p) \subseteq \mathbb{Q}_p(\zeta_{np})$. We then have $K \subseteq F(u^{1/e}) \cdot F((-p)^{1/e}) \subseteq \mathbb{Q}(\zeta_k) \cdot \mathbb{Q}(\zeta_{np}) \subseteq \mathbb{Q}(\zeta_{knp})$ and may take $m = knp$. □

Lemma 20.5. *For any prime p we have $\mathbb{Q}_p\big((-p)^{1/(p-1)}\big) = \mathbb{Q}_p(\zeta_p)$.*

Proof. Let $\alpha = (-p)^{1/(p-1)}$. Then α is a root of the Eisenstein polynomial $x^{p-1} + p$, so the extension $\mathbb{Q}_p((-p)^{1/(p-1)}) = \mathbb{Q}_p(\alpha)$ is totally ramified of degree $p-1$, and α is a uniformizer (by Lemma 11.4 and Theorem 11.5). Let $\pi = \zeta_p - 1$. The minimal polynomial of π is

$$f(x) := \frac{(x+1)^p - 1}{x} = x^{p-1} + px^{p-2} + \cdots + p,$$

which is Eisenstein, so $\mathbb{Q}_p(\pi) = \mathbb{Q}_p(\zeta_p)$ is also totally ramified of degree $p-1$, and π is a uniformizer. We have $u := -\pi^{p-1}/p \equiv 1 \bmod \pi$, so u is a unit in the ring of integers of $\mathbb{Q}_p(\zeta_p)$. If we now put $g(x) = x^{p-1} - u$ then $g(1) \equiv 0 \bmod \pi$ and $g'(1) = p - 1 \not\equiv 0 \bmod \pi$, so by Hensel's Lemma 9.15 we can lift 1 to a root β of $g(x)$ in $\mathbb{Q}_p(\zeta_p)$.

We then have $p\beta^{p-1} = pu = -\pi^{p-1}$, so $(\pi/\beta)^{p-1} + p = 0$, and therefore $\pi/\beta \in \mathbb{Q}_p(\zeta_p)$ is a root of the minimal polynomial of α. Since $\mathbb{Q}_p(\zeta_p)$ is Galois, this implies that $\alpha \in \mathbb{Q}_p(\zeta_p)$, and since $\mathbb{Q}_p(\alpha)$ and $\mathbb{Q}_p(\zeta_p)$ both have degree $p-1$, the two fields coincide. □

To complete the proof of the local Kronecker-Weber theorem, we need to address the case $\ell = p$. Before doing so, we first recall some background on Kummer extensions.

20.3 A brief introduction to Kummer theory

Let n be a positive integer and let K be a field of characteristic prime to n that contains a primitive nth root of unity ζ_n. While we are specifically interested in the case where K is a local or global field, in this section K can be any field that satisfies these conditions.

For any $a \in K$, the field $L = K(\sqrt[n]{a})$ is the splitting field of $f(x) = x^n - a$ over K; the notation $\sqrt[n]{a}$ denotes a particular nth root of a, but it does not matter which root we pick because all the nth roots of a lie in L (if $f(\alpha) = f(\beta) = 0$ then $\alpha/\beta \in \zeta_n^i \in K$ for some $0 \leq i < n$ and $K(\alpha) = K(\beta)$). The polynomial $f(x)$ is separable, since n is prime to the characteristic of K, so L is a Galois extension of K, and $\operatorname{Gal}(L/K)$ is cyclic, since we have an injective homomorphism

$$\begin{aligned} \operatorname{Gal}(L/K) &\hookrightarrow \langle \zeta_n \rangle \simeq \mathbb{Z}/n\mathbb{Z} \\ \sigma &\mapsto \frac{\sigma(\sqrt[n]{a})}{\sqrt[n]{a}}. \end{aligned}$$

This homomorphism is an isomorphism if and only if $x^n - a$ is irreducible.

Kummer's key observation is that the converse holds. In order to prove this we first recall a basic (but often omitted) lemma from Galois theory, originally due to Dedekind.

Lemma 20.6. *Let L/K be a finite extension of fields. The set $\mathrm{Aut}_K(L)$ is a linearly independent subset of the L-vector space of functions $L \to L$.*

Proof. Suppose not. Let $f := c_1\sigma_1 + \cdots + c_r\sigma_r = 0$ with $c_i \in L$, $\sigma_i \in \mathrm{Aut}_K(L)$, and r minimal; we must have $r > 1$, the c_i nonzero, and the σ_i distinct. Choose $\alpha \in L$ so $\sigma_1(\alpha) \neq \sigma_r(\alpha)$ (possible since $\sigma_1 \neq \sigma_r$). We have $f(\beta) = 0$ for all $\beta \in L$, and the same applies to $f(\alpha\beta) - \sigma_1(\alpha)f(\beta)$, which yields a shorter relation $c_2'\sigma_2 + \cdots + c_r'\sigma_r = 0$, where $c_i' = c_i\sigma_i(\alpha) - c_i\sigma_1(\alpha)$ with $c_1' = 0$, which is nontrivial because $c_r' \neq 0$, a contradiction. □

Corollary 20.7. *Let L/K be a cyclic field extension of degree n with Galois group $\langle\sigma\rangle$ and suppose L contains an nth root of unity ζ_n. Then $\sigma(\alpha) = \zeta_n\alpha$ for some $\alpha \in L$.*

Proof. The automorphism σ is a linear transformation of L with characteristic polynomial $x^n - 1$; by Lemma 20.6, this must be its minimal polynomial, since $\{1, \sigma^1, \ldots, \sigma^{n-1}\}$ is linearly independent. Therefore ζ_n is eigenvalue of σ, and the lemma follows. □

Remark 20.8. Corollary 20.7 is a special case of Hilbert's Theorem 90, which replaces ζ_n with any element u of norm $\mathrm{N}_{L/K}(u) = 1$; see [4, Thm. VI.6.1], for example.

Lemma 20.9. *Let K be a field, let $n \geq 1$ be prime to the characteristic of K, and assume $\zeta_n \in K$. If L/K is a cyclic extension of degree n then $L = K(\sqrt[n]{a})$ for some $a \in K$.*

Proof. Let L/K be a cyclic extension of degree n with $\mathrm{Gal}(L/K) = \langle\sigma\rangle$. By Corollary 20.7, there exists an element $\alpha \in L$ for which $\sigma(\alpha) = \zeta_n\alpha$. We have

$$\sigma(\alpha^n) = \sigma(\alpha)^n = (\zeta_n\alpha)^n = \alpha^n,$$

thus $a = \alpha^n$ is invariant under the action of $\langle\sigma\rangle = \mathrm{Gal}(L/K)$ and therefore lies in K. Moreover, the orbit $\{\alpha, \zeta_n\alpha, \ldots, \zeta_n^{n-1}\alpha\}$ of α under the action of $\mathrm{Gal}(L/K)$ has order n, so $L = K(\alpha) = K(\sqrt[n]{a})$ as desired. □

Definition 20.10. Let K be a field with algebraic closure $\overline{K}$, let $n \geq 1$ be prime to the characteristic of K, and assume $\zeta_n \in K$. The *Kummer pairing* is the map

$$\begin{aligned} \langle\cdot,\cdot\rangle\colon \mathrm{Gal}(\overline{K}/K) \times K^\times &\to \langle\zeta_n\rangle \\ \langle\sigma, a\rangle &\mapsto \frac{\sigma(\sqrt[n]{a})}{\sqrt[n]{a}} \end{aligned}$$

where $\sqrt[n]{a}$ is any nth root of a in $\in \overline{K}^\times$. If α and β are two nth roots of a, then $(\alpha/\beta)^n = 1$, so $\alpha/\beta \in \langle\zeta_n\rangle \subseteq K$ is fixed by σ and $\sigma(\beta)/\beta = \sigma(\beta)/\beta \cdot \sigma(\alpha/\beta)/(\alpha/\beta) = \sigma(\alpha)/\alpha$, so the value of $\langle\sigma, a\rangle$ does not depend on the choice of $\sqrt[n]{a}$. If $a \in K^{\times n}$, then $\langle\sigma, a\rangle = 1$ for all $\sigma \in \mathrm{Gal}(\overline{K}/K)$, so the Kummer pairing depends only on the image of a in $K^\times/K^{\times n}$; thus we may also view it as a pairing on $\mathrm{Gal}(\overline{K}/K) \times K^\times/K^{\times n}$.

Theorem 20.11. *Let K be a field, let $n \geq 1$ be prime to the characteristic of K with $\zeta_n \in K$. The Kummer pairing induces an isomorphism*

$$\begin{aligned} \Phi\colon K^\times/K^{\times n} &\to \mathrm{Hom}\big(\mathrm{Gal}(\overline{K}/K), \langle\zeta_n\rangle\big) \\ a &\mapsto \big(\sigma \mapsto \langle\sigma, a\rangle\big). \end{aligned}$$

Proof. For each $a \in K^\times - K^{\times n}$, if we pick an nth root $\alpha \in \overline{K}$ of a then the extension $K(\alpha)/K$ will be non-trivial and some $\sigma \in \operatorname{Gal}(\overline{K}/K)$ must act nontrivially on α. For this σ we have $\langle \sigma, a\rangle \neq 1$, so $a \notin \ker \Phi$; thus Φ is injective.

Now let $f\colon \operatorname{Gal}(\overline{K}/K) \to \langle \zeta_n\rangle$ be a homomorphism, and put $d := \#\operatorname{im} f$, $H := \ker f$, and $L := \overline{K}^H$. Then $\operatorname{Gal}(L/K) \simeq \operatorname{Gal}(\overline{K}/K)/H \simeq \mathbb{Z}/d\mathbb{Z}$, so L/K is a cyclic extension of degree d, and Lemma 20.9 implies that $L = K(\sqrt[d]{a})$ for some $a \in K$. If we put $e = n/d$ and consider the homomorphisms $\Phi(a^{me})$ for $m \in (\mathbb{Z}/d\mathbb{Z})^\times$, these homomorphisms are all distinct (because the a^{me} are distinct modulo $K^{\times n}$ and Φ is injective), and they all have the same kernel and image as f (their kernels have the same fixed field L because L contains all the dth roots of a). There are $\#(\mathbb{Z}/d\mathbb{Z})^\times = \#\operatorname{Aut}(\mathbb{Z}/d\mathbb{Z})$ distinct isomorphisms $\operatorname{Gal}(\overline{K}/K)/H \simeq \mathbb{Z}/d\mathbb{Z}$, one of which corresponds to f, and each corresponds to one of the $\Phi(a^{me})$. It follows that $f = \Phi(a^{me})$ for some $m \in (\mathbb{Z}/d\mathbb{Z})^\times$, thus Φ is surjective. □

Given a finite subgroup A of $K^\times/K^{\times n}$, we can choose $a_1, \ldots, a_r \in K^\times$ so that the images $\bar{a}_i$ of the a_i in $K^\times/K^{\times n}$ form a basis for the abelian group A; this means

$$A = \langle \bar{a}_1\rangle \times \cdots \times \langle \bar{a}_r\rangle \simeq \mathbb{Z}/n_1\mathbb{Z} \times \cdots \times \mathbb{Z}/n_r\mathbb{Z},$$

where $n_i|n$ is the order of $\bar{a}_i$ in A. For each a_i, the fixed field of the kernel of $\Phi(\bar{a}_i)$ is a cyclic extension of K isomorphic to $L_i := K(\sqrt[n_i]{a_i})$, as in the proof of Theorem 20.11. The fields L_i are linearly disjoint over K (because the a_i correspond to independent generators of A), and their compositum $L = K(\sqrt[n_1]{a_1}, \ldots \sqrt[n_r]{a_r})$ has Galois group $\operatorname{Gal}(L/K) \simeq A$, an abelian group whose exponent divides n; such fields L are called *n-Kummer extensions* of K.

Conversely, given an n-Kummer extension L/K, we can iteratively apply Lemma 20.9 to put L in the form $L = K(\sqrt[n_1]{a_1}, \ldots, \sqrt[n_r]{a_r})$ with each $a_i \in K^\times$ and $n_i|n$, and the images of the a_i in $K^\times/K^{\times n}$ then generate a subgroup A corresponding to L as above. We thus have a 1-to-1 correspondence between finite subgroups of $K^\times/K^{\times n}$ and (finite) n-Kummer extensions of K (this correspondence also extends to infinite subgroups provided we put a suitable topology on the groups).

So far we have been assuming that K contains all the nth roots of unity. To help handle situations where this is not necessarily the case, we rely on the following lemma, in which we restrict to the case that n is a prime (or an odd prime power) so that $(\mathbb{Z}/n\mathbb{Z})^\times$ is cyclic (the definition of ω in the statement of the lemma does not make sense otherwise).

Lemma 20.12. *Let n be a prime (or an odd prime power), let F be a field of characteristic prime to n, let $K = F(\zeta_n)$, and let $L = K(\sqrt[n]{a})$ for some $a \in K^\times$. Define the homomorphism $\omega\colon \operatorname{Gal}(K/F) \to (\mathbb{Z}/n\mathbb{Z})^\times$ by $\zeta_n^{\omega(\sigma)} = \sigma(\zeta_n)$. If L/F is abelian then $\sigma(a)/a^{\omega(\sigma)} \in K^{\times n}$ for all $\sigma \in \operatorname{Gal}(K/F)$.*

Proof. Let $G = \operatorname{Gal}(L/F)$, let $H = \operatorname{Gal}(L/K) \subseteq G$, and let A be the subgroup of $K^\times/K^{\times n}$ generated by a. The Kummer pairing induces a bilinear pairing $H \times A \to \langle \zeta_n\rangle$ that is compatible with the Galois action of $\operatorname{Gal}(K/F) \simeq G/H$. In particular, we have

$$\langle h, a^{\omega(\sigma)}\rangle = \langle h, a\rangle^{\omega(\sigma)} = \sigma(\langle h, a\rangle) = \langle h^\sigma, \sigma(a)\rangle = \langle h, \sigma(a)\rangle$$

for all $\sigma \in \operatorname{Gal}(K/F)$ and $h \in H$; the Galois action on H is by conjugation (lift σ to G and conjugate there), but it is trivial because G is abelian (so $h^\sigma = h$). The isomorphism Φ induced by the Kummer pairing is injective, so $a^{\omega(\sigma)} \equiv \sigma(a) \bmod K^{\times n}$. □

20.4 The local Kronecker-Weber theorem for $\ell = p > 2$

We are now ready to prove the local Kronecker-Weber theorem in the case $\ell = p > 2$.

Theorem 20.13. *Let $K/\mathbb{Q}_p$ be a cyclic extension of odd degree p^r. Then K lies in a cyclotomic field $\mathbb{Q}_p(\zeta_m)$.*

Proof. There are two obvious candidates for K, namely, the cyclotomic field $\mathbb{Q}_p(\zeta_{p^{p^r}-1})$, which by Corollary 10.19 is an unramified extension of degree p^r, and the index $p-1$ subfield of the cyclotomic field $\mathbb{Q}_p(\zeta_{p^{r+1}})$, which by Corollary 10.20 is a totally ramified extension of degree p^r (the p^{r+1}-cyclotomic polynomial $\Phi_{p^{r+1}}(x)$ has degree $\phi(p^{r+1}) = p^r(p-1)$ and remains irreducible over $\mathbb{Q}_p$). If K is contained in the compositum of these two fields then $K \subseteq \mathbb{Q}_p(\zeta_m)$, where $m := (p^{p^r}-1)(p^{r+1})$ and the theorem holds. Otherwise, the field $K(\zeta_m)$ is a Galois extension of $\mathbb{Q}_p$ with

$$\mathrm{Gal}(K(\zeta_m)/\mathbb{Q}_p) \simeq \mathbb{Z}/p^r\mathbb{Z} \times \mathbb{Z}/p^r\mathbb{Z} \times \mathbb{Z}/(p-1)\mathbb{Z} \times \mathbb{Z}/p^s\mathbb{Z},$$

for some $s > 0$; the first factor comes from the Galois group of $\mathbb{Q}_p(\zeta_{p^{p^r}-1})$, the second two factors come from the Galois group of $\mathbb{Q}_p(\zeta_{p^{r+1}})$ (note $\mathbb{Q}_p(\zeta_{p^{r+1}}) \cap \mathbb{Q}_p(\zeta_{p^{p^r}-1}) = \mathbb{Q}_p$), and the last factor comes from the fact that we are assuming $K \not\subseteq \mathbb{Q}_p(\zeta_m)$, so $\mathrm{Gal}(K(\zeta_m)/\mathbb{Q}_p(\zeta_m))$ is nontrivial and must have order p^s for some $s \in [1, r]$.

It follows that the abelian group $\mathrm{Gal}(K(\zeta_m)/\mathbb{Q}_p)$ has a quotient isomorphic to $(\mathbb{Z}/p\mathbb{Z})^3$, and the subfield of $K(\zeta_m)$ corresponding to this quotient is an abelian extension of $\mathbb{Q}_p$ with Galois group isomorphic $(\mathbb{Z}/p\mathbb{Z})^3$. By Lemma 20.14 below, no such field exists. □

To prove that $\mathbb{Q}_p$ admits no $(\mathbb{Z}/p\mathbb{Z})^3$-extensions our strategy is to use Kummer theory to show that the corresponding subgroup of $\mathbb{Q}_p(\zeta_p)^\times/\mathbb{Q}_p(\zeta_p)^{\times p}$ given by Theorem 20.11 must have p-rank 2 and therefore cannot exist. For an alternative proof that uses higher ramification groups instead of Kummer theory, see Problem Set 10.

Lemma 20.14. *For $p > 2$ no extension of $\mathbb{Q}_p$ has Galois group isomorphic to $(\mathbb{Z}/p\mathbb{Z})^3$.*

Proof. Suppose for the sake of contradiction that K is an extension of $\mathbb{Q}_p$ with Galois group $\mathrm{Gal}(K/\mathbb{Q}_p) \simeq (\mathbb{Z}/p\mathbb{Z})^3$. Then $K/\mathbb{Q}_p$ is linearly disjoint from $\mathbb{Q}_p(\zeta_p)/\mathbb{Q}_p$, since the order of $G := \mathrm{Gal}(\mathbb{Q}_p(\zeta_p)/\mathbb{Q}_p) \simeq (\mathbb{Z}/p\mathbb{Z})^\times$ is not divisible by p, and $\mathrm{Gal}(K(\zeta_p)/\mathbb{Q}_p(\zeta_p)) \simeq (\mathbb{Z}/p\mathbb{Z})^3$ is a p-Kummer extension. There is thus a subgroup $A \subseteq \mathbb{Q}_p(\zeta_p)^\times/\mathbb{Q}_p(\zeta_p)^{\times p}$ isomorphic to $(\mathbb{Z}/p\mathbb{Z})^3$, for which $K(\zeta_p) = \mathbb{Q}_p(\zeta_p, A^{1/p})$, where $A^{1/p} := \{\sqrt[p]{a} : a \in A\}$ (here we identify elements of A by representatives in $\mathbb{Q}_p(\zeta_p)^\times$ that are determined only up to pth powers).

For any $a \in A$, the extension $\mathbb{Q}_p(\zeta_p, \sqrt[p]{a})/\mathbb{Q}_p$ is abelian, so by Lemma 20.12, we have

$$\sigma(a)/a^{\omega(\sigma)} \in \mathbb{Q}_p(\zeta_p)^{\times p} \tag{1}$$

for all $\sigma \in G$, where $\omega\colon G \xrightarrow{\sim} (\mathbb{Z}/p\mathbb{Z})^\times$ is the isomorphism defined by $\sigma(\zeta_p) = \zeta_p^{\omega(\sigma)}$.

The field $\mathbb{Q}_p(\zeta_p)$ is a totally tamely ramified extension of $\mathbb{Q}_p$ of degree $p-1$ with residue field $\mathbb{Z}/p\mathbb{Z}$; as shown in the proof of Lemma 20.5, we may take $\pi := \zeta_p - 1$ as a uniformizer. For each $a \in A$ we have

$$v_\pi(a) = v_\pi(\sigma(a)) \equiv \omega(\sigma)v_\pi(a) \bmod p,$$

thus $(1 - \omega(\sigma))v_\pi(a) \equiv 0 \bmod p$, for all $\sigma \in G$, hence for all $\omega(\sigma) \in \omega(G) = (\mathbb{Z}/p\mathbb{Z})^\times$; for $p > 2$, this implies $v_\pi(a) \equiv 0 \bmod p$. Now a is determined only up to pth-powers, so after multiplying by $\pi^{-v_\pi(a)}$ we may assume $v_\pi(a) = 0$, and after multiplying by a suitable power of $\zeta_{p-1}^p = \zeta_{p-1}$, we may assume $a \equiv 1 \bmod \pi$, since the image of ζ_{p-1} generates the multiplicative group $(\mathbb{Z}/p\mathbb{Z})^\times$ of the residue field.

We may thus assume that $A \subseteq U_1/U_1^p$, where $U_1 := \{u \equiv 1 \bmod \pi\}$. Each $u \in U_1$ can be written as a power series in π with integer coefficients in $[0, p-1]$ and constant coefficient 1.

We have $\zeta_p \in U_1$, since $\zeta_p = 1 + \pi$, and $\zeta_p^b = 1 + b\pi + O(\pi^2)$ for integers $b \in [0, p-1]$.[1] For $a \in A \subseteq U_1$, we can choose b so that for some integer $c \in [0, p-1]$ and $e \in \mathbb{Z}_{\geq 2}$ we have

$$a = \zeta_p^b(1 + c\pi^e + O(\pi^{e+1})).$$

For $\sigma \in G$ we have

$$\frac{\sigma(\pi)}{\pi} = \frac{\sigma(\zeta_p - 1)}{\zeta_p - 1} = \frac{\zeta_p^{\omega(\sigma)} - 1}{\zeta_p - 1} = \zeta_p^{\omega(\sigma)-1} + \cdots + \zeta_p + 1 \equiv \omega(\sigma) \bmod \pi,$$

since each term in the sum is congruent to 1 modulo $\pi = (\zeta_p - 1)$; here we are representing $\omega(\sigma) \in (\mathbb{Z}/p\mathbb{Z})^\times$ as an integer in $[1, p-1]$. Thus $\sigma(\pi) \equiv \omega(\sigma)\pi \bmod \pi$ and

$$\sigma(a) = \zeta_p^{b\omega(\sigma)}(1 + c\omega(\sigma)^e\pi^e + O(\pi^{e+1})).$$

We also have

$$a^{\omega(\sigma)} = \zeta_p^{b\omega(\sigma)}(1 + c\omega(\sigma)\pi^e + O(\pi^{e+1})).$$

As we showed for a above, any $u \in U_1$ can be written as $u = \zeta_p^b u_1$ with $u_1 \equiv 1 \bmod \pi^2$. Each interior term in the binomial expansion of $u_1^p = (1 + O(\pi^2))^p$ other than leading 1 is a multiple of $p\pi^2$ with $v_\pi(p\pi^2) = p - 1 + 2 = p + 1$, and it follows that $u^p = u_1^p \equiv 1 \bmod \pi^{p+1}$. Thus every element of U_1^p is congruent to 1 modulo π^{p+1}, and as you will show on the problem set, the converse holds, that is, $U_1^p = \{u \equiv 1 \bmod \pi^{p+1}\}$.

We know from (1) that $\sigma(a)/a^{\omega(\sigma)} \in U_1^p$, so $\sigma(a) = a^{\omega(\sigma)}(1 + O(\pi^{p+1}))$ and therefore

$$\sigma(a) \equiv a^{\omega(\sigma)} \bmod \pi^{p+1}.$$

For $e \leq p$ this is possible only if $\omega(\sigma) = \omega(\sigma)^e$ for every $\sigma \in G$, equivalently, for every $\omega(\sigma) \in \sigma(G) = (\mathbb{Z}/p\mathbb{Z})^\times$, but then $e \equiv 1 \bmod (p-1)$ and we must have $e \geq p$, since $e \geq 2$.

We have shown that every $a \in A$ is represented by an element $\zeta_p^b(1 + c\pi^p + O(\pi^{p+1})) \in U_1$ with $b, c \in \mathbb{Z}$, and therefore lies in the subgroup of U_1/U_1^p generated by ζ_p and $(1 + \pi^p)$, which is an abelian group of exponent p generated by 2 elements, hence isomorphic to a subgroup of $(\mathbb{Z}/p\mathbb{Z})^2$. But this contradicts $A \simeq (\mathbb{Z}/p\mathbb{Z})^3$. ☐

Remark 20.15. In the proof of Lemma 20.14 above, the elements of $\mathbb{Q}_p(\zeta_p)^\times/\mathbb{Q}_p(\zeta_p)^{\times p}$ that lie in A are quite special. For most $a \in \mathbb{Q}_p(\zeta_p)^\times$ the extension $\mathbb{Q}_p(\zeta_p, \sqrt[p]{a})/\mathbb{Q}_p$ will not be abelian, even though the extensions $\mathbb{Q}_p(\sqrt[p]{a})/\mathbb{Q}_p(\zeta_p)$ and $\mathbb{Q}_p(\zeta_p)/\mathbb{Q}_p$ both are, and we typically will not have $v_\pi(a) \equiv 0 \bmod p$ (consider $a = \pi$). The key point is that we started with an abelian extension $K/\mathbb{Q}_p$, so $K(\zeta_p) = K \cdot \mathbb{Q}_p(\zeta_p)$ is an abelian extension containing $A^{1/p}$; this ensures that for $a \in A$ the fields $\mathbb{Q}_p(\zeta_p, \sqrt[p]{a})$ are abelian.

Remark 20.16. There is an alternative proof to Lemma 20.14 that is much more explicit. One can show that for $p > 2$ the field $\mathbb{Q}_p$ admits exactly $p + 1$ cyclic extensions of degree p: the unramified extension $\mathbb{Q}_p(\zeta_{p^p-1})$ and the extensions $\mathbb{Q}_p[x]/(x^p + px^{p-1} + p(1 + ap))$, for integers $a \in [0, p-1]$; see [3, Prop. 2.3.1]. This implies that $\mathbb{Q}_p$ cannot have a $(\mathbb{Z}/p\mathbb{Z})^3$ extension, since this would imply the existence of $p^2 + p + 1$ cyclic extensions of degree p, one for each index p subgroup of $(\mathbb{Z}/p\mathbb{Z})^3$.

[1] The expression $O(\pi^n)$ denotes a power series in π that is divisible by π^n.

For $p = 2$ there is an extension of $\mathbb{Q}_2$ with Galois group isomorphic to $(\mathbb{Z}/2\mathbb{Z})^3$, the cyclotomic field $\mathbb{Q}_2(\zeta_{24}) = \mathbb{Q}_2(\zeta_3) \cdot \mathbb{Q}_2(\zeta_8)$, so the proof we used for $p > 2$ will not work. However we can apply a completely analogous argument.

Theorem 20.17. *Let $K/\mathbb{Q}_2$ be a cyclic extension of degree 2^r. Then K lies in a cyclotomic field $\mathbb{Q}_2(\zeta_m)$.*

Proof. The unramified cyclotomic field $\mathbb{Q}_2(\zeta_{2^{2^r}-1})$ has Galois group $\mathbb{Z}/2^r\mathbb{Z}$, and the totally ramified cyclotomic field $\mathbb{Q}_2(\zeta_{2^{r+2}})$ has Galois group $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2^r\mathbb{Z}$ (up to isomorphism). Let $m = (2^{2^r} - 1)(2^{r+2})$. If K is not contained in $\mathbb{Q}_2(\zeta_m)$ then

$$\operatorname{Gal}(K(\zeta_m)/\mathbb{Q}_2) \simeq \begin{cases} \mathbb{Z}/2\mathbb{Z} \times (\mathbb{Z}/2^r\mathbb{Z})^2 \times \mathbb{Z}/2^s\mathbb{Z} & \text{with } 1 \le s \le r \\ \text{or} & \\ (\mathbb{Z}/2^r\mathbb{Z})^2 \times \mathbb{Z}/2^s\mathbb{Z} & \text{with } 2 \le s \le r \end{cases}$$

and thus admits a quotient isomorphic to $(\mathbb{Z}/2\mathbb{Z})^4$ or $(\mathbb{Z}/4\mathbb{Z})^3$. By Lemma 20.18 below, no extension of $\mathbb{Q}_2$ has either of these Galois groups, thus K must lie in $\mathbb{Q}_2(\zeta_m)$. ☐

Lemma 20.18. *No extension of $\mathbb{Q}_2$ has Galois group isomorphic to $(\mathbb{Z}/2\mathbb{Z})^4$ or $(\mathbb{Z}/4\mathbb{Z})^3$.*

Proof. As you proved on Problem Set 4, there are exactly 7 quadratic extensions of $\mathbb{Q}_2$; it follows that no extension of $\mathbb{Q}_2$ has Galois group $(\mathbb{Z}/2\mathbb{Z})^4$, since this group has 15 subgroups of index 2 whose fixed fields would yield 15 distinct quadratic extension of $\mathbb{Q}_2$.

As you proved on Problem Set 5, there are only finitely many extensions of $\mathbb{Q}_2$ of any fixed degree d, and these can be enumerated by considering Eisenstein polynomials in $\mathbb{Q}_2[x]$ of degrees dividing d up to an equivalence relation implied by Krasner's lemma. One finds that there are 59 quartic extensions of $\mathbb{Q}_2$, of which 12 are cyclic; you can find a list of them here. It follows that no extension of $\mathbb{Q}_2$ has Galois group $(\mathbb{Z}/4\mathbb{Z})^3$, since this group has 28 subgroups whose fixed fields would yield 28 distinct cyclic quartic extensions of $\mathbb{Q}_2$. ☐

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