

MATH 223B (GALOIS COHOMOLOGY AND CLASS FIELD THEORY)

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1. INTRODUCTION

Let \mathbb{Q} denote the rational numbers with algebraic closure $\overline{\mathbb{Q}}$. A basic goal in algebraic number theory is to understand the structure of the group $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$, known as the absolute Galois group of \mathbb{Q} . Roughly speaking, this is the collection of symmetries of the following sets

$$(1.1) \quad \{\alpha \in \overline{\mathbb{Q}} \mid p(\alpha) = 0\}$$

for $p(x) \in \mathbb{Q}[x]$ an irreducible polynomial. For example, when $p(x) = x^2 - 5$, we have the solutions $\{\sqrt{5}, -\sqrt{5}\}$ and a corresponding surjection $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}) \rightarrow \text{Gal}(\mathbb{Q}(\sqrt{5})/\mathbb{Q}) \simeq \mathbb{Z}/2\mathbb{Z} = \langle -1 \rangle$, where $-1 \in \mathbb{Z}/2\mathbb{Z}$ acts via the reflection $\sqrt{5} \leftrightarrow -\sqrt{5}$. More interestingly, for the equation $p(x) = x^q - 1$ for q a prime number, we have the solutions $\{\zeta_q^i \mid 0 \leq i \leq q-1\}$ for ζ_q a non-trivial q th root of unity and a surjection $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}) \rightarrow \text{Gal}(\mathbb{Q}(\zeta_q)/\mathbb{Q}) \simeq (\mathbb{Z}/q\mathbb{Z})^*$, where $a \in (\mathbb{Z}/q\mathbb{Z})^*$ acts via $\sigma_a : \zeta_q^i \mapsto \zeta_q^{ia}$.

More precisely, the absolute Galois group is the inverse limit in the category of groups of

$$(1.2) \quad \text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}) := \varprojlim_L \text{Gal}(L/\mathbb{Q}),$$

where L/\mathbb{Q} ranges over finite Galois extensions of \mathbb{Q} , and the maps, for an inclusion $\mathbb{Q} \subset L' \subset L$, are given by the natural restriction map $\text{Gal}(L/\mathbb{Q}) \rightarrow \text{Gal}(L'/\mathbb{Q})$. As we will discuss in the next lectures, such a projective limit of finite groups gives examples of what are known as pro-finite groups.

One of the basic reasons for wanting to understand the group $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ is that it provides us information about the structure of solutions to the equation $p(x)$. E.g from Galois theory we know that if the action of $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ on the solutions of $p(x)$ factors through a finite solvable group then

the solutions can be computed in terms of the coefficients and radicals. In this way, the group $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ together with its action on (1.1) provides some kind of systematic generalization for the notion of solvability of polynomial among radicals.

Another (perhaps more compelling reason) is that the group $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ is intimately related to many interesting arithmetic phenomena. For example, let's consider the polynomial $p(x) = x^2 - 5$ again. We may ask ourselves the following basic arithmetic question.

Question 1.1. *When does $x^2 = 5$ have a solution modulo a prime number p ?*

This is the content of quadratic reciprocity; often phrased in terms of the Legendre symbol.

Definition 1.2. Let p be an odd prime. The *Legendre symbol*

$$\left(\frac{a}{p}\right)$$

is defined for any integer a by

$$\left(\frac{a}{p}\right) = \begin{cases} 0 & \text{if } p \mid a, \\ 1 & \text{if there exists } x \in \mathbb{Z} \text{ such that } x^2 \equiv a \pmod{p}, \\ -1 & \text{otherwise.} \end{cases}$$

This symbol can be completely understood in terms of quadratic reciprocity.

Theorem 1.3 (Quadratic Reciprocity). *Let p and q be distinct odd primes. Then we have an equality*

$$\left(\frac{p}{q}\right) = (-1)^{\frac{(p-1)(q-1)}{4}} \left(\frac{q}{p}\right).$$

Moreover, for any odd prime p , we have equalities:

$$\left(\frac{-1}{p}\right) = (-1)^{\frac{p-1}{2}}, \quad \left(\frac{2}{p}\right) = (-1)^{\frac{p^2-1}{8}}.$$

Specialized to the case of interest, this gives us the following.

Example 1.4. Let $p \neq 5$ be an odd prime then we have that

$$(1.3) \quad \left(\frac{p}{5}\right) = \left(\frac{5}{p}\right).$$

In particular, if we look at the squares mod 5 then we have that $\{1^2, 2^2, 3^2, 4^2\} \cong \{1, -1, -1, 1\}$ mod 5, which allows us to conclude.

Corollary 1.5. *For $p \neq 5$ an odd prime number*

$$\left(\frac{5}{p}\right) = 1 \iff p \cong \pm 1 \pmod{5}.$$

We claim that Corollary 1.5 and indeed Theorem 1.3 is a consequence of understanding the action of the group $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ on the set of solutions $\{\sqrt{5}, -\sqrt{5}\}$. To see this, we recall that we have an inclusion $\mathbb{Q}(\sqrt{5}) \subset \mathbb{Q}(\zeta_5)$, as witnessed by the identity

$$\zeta_5 + \zeta_5^{-1} = \cos\left(\frac{2\pi}{5}\right) = \frac{\sqrt{5}-1}{2}.$$

To proceed further, we recall some basic properties of the arithmetic of the cyclotomic fields $\mathbb{Q}(\zeta_q)/\mathbb{Q}$. In particular, we have the following.

Theorem 1.6. *Let q be an odd prime and $\zeta_q \in \overline{\mathbb{Q}}$ a non-trivial q th root of unity.*

(1) The extension $\mathbb{Q}(\zeta_q)/\mathbb{Q}$ is Galois with Galois group isomorphic to $(\mathbb{Z}/q\mathbb{Z})^*$ via the mapping

$$a \mapsto \sigma_a,$$

where $\sigma_a(\zeta_q) = \zeta_q^a$.

(2) The ring of integers of $\mathbb{Q}(\zeta_q)$ is given by $\mathbb{Z}[\zeta_q]$.

(3) A prime p in \mathbb{Z} is unramified in $\mathbb{Q}(\zeta_q)$ if and only if $p \neq q$.

(4) If $q \neq p$ then by (1)-(3), we have a factorization as prime ideals $(p)\mathbb{Z}[\zeta_q] = \mathfrak{p}_1 \cdots \mathfrak{p}_g$, and for all $i = 1, \dots, g$ that $\mathbb{Z}[\zeta_q]/\mathfrak{p}_i \simeq \mathbb{F}_{p^f}$ for some $f \geq 1$ such that

$$(1.4) \quad gf = q - 1$$

(5) For $q \neq p$ as in (4), for any $i = 1, \dots, g$, we may look at the decomposition group $\mathfrak{D}_{\mathfrak{p}_i} \subset \text{Gal}(\mathbb{Q}(\zeta_q)/\mathbb{Q})$ of elements fixing the prime ideal \mathfrak{p}_i . Then the natural map

$$(1.5) \quad \mathfrak{D}_{\mathfrak{p}_i} \rightarrow \text{Gal}((\mathbb{Z}[\zeta_q]/\mathfrak{p}_i)/(\mathbb{Z}/p)) \simeq \text{Gal}(\mathbb{F}_{p^f}/\mathbb{F}_p) = \langle \{x \mapsto x^p\} \rangle \simeq \mathbb{Z}/f\mathbb{Z},$$

In turn, we obtain a lift $\text{Frob}_{\mathfrak{p}_i} \in \mathfrak{D}_{\mathfrak{p}_i} \subset \text{Gal}(\mathbb{Q}(\zeta_q)/\mathbb{Q})$ of the p th power map $x \mapsto x^p$ on \mathbb{F}_{p^f} , which is given by σ_p in the parametrization of (1).

Implicitly, we were invoking the abstract structure theory of a Galois extension of number fields L/K specialized to the case of the $\mathbb{Q}(\zeta_q)/\mathbb{Q}$.

Exercise 1.7. Let L/K be a finite Galois extension of number fields with Galois group $G = \text{Gal}(L/K)$. Let $\mathfrak{p} \subset \mathcal{O}_K$ be a nonzero prime ideal and fix a prime ideal $\mathfrak{P} \subset \mathcal{O}_L$ lying above it (i.e. $\mathfrak{P} \cap \mathcal{O}_K = \mathfrak{p}$). Write $k_{\mathfrak{p}} = \mathcal{O}_K/\mathfrak{p}$ and $k_{\mathfrak{P}} = \mathcal{O}_L/\mathfrak{P}$ for the residue fields, and denote by $L_{\mathfrak{P}}$ and $K_{\mathfrak{p}}$ the completions of L and K at \mathfrak{P} and \mathfrak{p} respectively. We recall, since \mathcal{O}_L is Dedekind, we have a unique factorization

$$(1.6) \quad \mathfrak{p} \mathcal{O}_L = \prod_{i=1}^g \mathfrak{P}_i^{e_i}$$

into prime ideals \mathfrak{P}_i of \mathcal{O}_L for integers $e_i \geq 1$.

(1) Define the decomposition group of \mathfrak{P} by

$$D(\mathfrak{P}|\mathfrak{p}) = \{ \sigma \in G : \sigma(\mathfrak{P}) = \mathfrak{P} \}.$$

(a) Prove that $D(\mathfrak{P}|\mathfrak{p})$ is a subgroup of G .

(b) Show that G acts transitively on the set of primes of L above \mathfrak{p} and that the stabilizer of \mathfrak{P} is $D(\mathfrak{P}|\mathfrak{p})$. Deduce that

$$g = [G : D(\mathfrak{P}|\mathfrak{p})].$$

(2) Show that all the integers e_i in (1.6) equal to a single integer $e := e(\mathfrak{P}|\mathfrak{p})$. In particular, the decomposition (1.6) becomes

$$\mathfrak{p} \mathcal{O}_L = \prod_{i=1}^g \mathfrak{P}_i^e.$$

Show that there exists a single integer $f = f(\mathfrak{P}|\mathfrak{p})$ such that $[k_{\mathfrak{P}_i} : k_{\mathfrak{p}}] = f$ for all i . Deduce the fundamental relation

$$(1.7) \quad [L : K] = e f g.$$

(3) Consider the reduction map

$$\text{red}_{\mathfrak{P}} : \mathcal{O}_L \longrightarrow k_{\mathfrak{P}}.$$

(a) For $\sigma \in D(\mathfrak{P}|\mathfrak{p})$, show that σ induces a well-defined automorphism $\bar{\sigma}$ of $k_{\mathfrak{P}}$ by

$$\bar{\sigma}(\text{red}_{\mathfrak{P}}(x)) = \text{red}_{\mathfrak{P}}(\sigma(x)).$$

(b) Deduce a group homomorphism

$$\phi_{\mathfrak{P}} : D(\mathfrak{P}|\mathfrak{p}) \longrightarrow \text{Gal}(k_{\mathfrak{P}}/k_{\mathfrak{p}}).$$

(c) Define the inertia group by

$$I(\mathfrak{P}|\mathfrak{p}) = \ker(\phi_{\mathfrak{P}}) = \{ \sigma \in D(\mathfrak{P}|\mathfrak{p}) : \bar{\sigma} = \text{id on } k_{\mathfrak{P}} \}.$$

Prove that $I(\mathfrak{P}|\mathfrak{p})$ is a normal subgroup of $D(\mathfrak{P}|\mathfrak{p})$.

(4) Prove that $\phi_{\mathfrak{P}}$ is surjective and that there is a short exact sequence

$$1 \longrightarrow I(\mathfrak{P}|\mathfrak{p}) \longrightarrow D(\mathfrak{P}|\mathfrak{p}) \xrightarrow{\phi_{\mathfrak{P}}} \text{Gal}(k_{\mathfrak{P}}/k_{\mathfrak{p}}) \longrightarrow 1.$$

Deduce in particular that

$$|D(\mathfrak{P}|\mathfrak{p})| = e(\mathfrak{P}|\mathfrak{p}) f(\mathfrak{P}|\mathfrak{p}), \quad |I(\mathfrak{P}|\mathfrak{p})| = e(\mathfrak{P}|\mathfrak{p}), \quad |\text{Gal}(k_{\mathfrak{P}}/k_{\mathfrak{p}})| = f(\mathfrak{P}|\mathfrak{p}).$$

(5) (a) Show that the natural embedding $K \hookrightarrow K_{\mathfrak{p}}$ extends to an embedding $L \hookrightarrow L_{\mathfrak{P}}$ and that restriction induces a canonical isomorphism

$$D(\mathfrak{P}|\mathfrak{p}) \cong \text{Gal}(L_{\mathfrak{P}}/K_{\mathfrak{p}}).$$

(b) Under this identification, interpret $I(\mathfrak{P}|\mathfrak{p})$ as the subgroup of $\text{Gal}(L_{\mathfrak{P}}/K_{\mathfrak{p}})$ acting trivially on the residue field $k_{\mathfrak{P}}$.

(6) Assume \mathfrak{p} is unramified in L , i.e. $e(\mathfrak{P}|\mathfrak{p}) = 1$. Then $I(\mathfrak{P}|\mathfrak{p}) = 1$ and $\phi_{\mathfrak{P}}$ is an isomorphism. Let $\text{Frob}_{\mathfrak{p}} \in D(\mathfrak{P}|\mathfrak{p})$ be the unique element whose image in $\text{Gal}(k_{\mathfrak{P}}/k_{\mathfrak{p}})$ is the $|k_{\mathfrak{p}}|$ -power map.

(a) Show that $\text{Frob}_{\mathfrak{p}}$ is characterized by

$$\text{Frob}_{\mathfrak{p}}(x) \equiv x^{N_{\mathfrak{p}}} \pmod{\mathfrak{P}} \quad \text{for all } x \in \mathcal{O}_L.$$

(b) Show that if $\mathfrak{P}' = \tau(\mathfrak{P})$ for some $\tau \in G$, then

$$\text{Frob}_{\mathfrak{p}}(\mathfrak{P}') = \tau \text{Frob}_{\mathfrak{p}}(\mathfrak{P}) \tau^{-1}.$$

In particular, the conjugacy class of $\text{Frob}_{\mathfrak{p}}$ in G is independent of the choice of $\mathfrak{P}|\mathfrak{p}$.

(c) If L/K is abelian i.e. $\text{Gal}(L/K)$ is abelian, deduce that the Frobenius element $\text{Frob}_{\mathfrak{p}} \in G$ (for \mathfrak{p} unramified) is independent of the choice of $\mathfrak{P}|\mathfrak{p}$ as an element of G (not just up to conjugacy).

With this in hand, let's go back to the original problem. In particular, suppose we have a prime p , then we were interested in determining when $\left(\frac{5}{p}\right) = 1$ or equivalently when $x^2 = 5$ has a solution modulo p . We recall that the ring of integers of $\mathbb{Q}(\sqrt{5})$ is given by $\mathbb{Z}[\sqrt{5}]$ (since $5 \cong 1 \pmod{4}$). In particular, it follows that $x^2 = 5$ has a solution modulo p if and only if the prime p splits in $\mathbb{Z}[\sqrt{5}]$, which is equivalent to the g appearing in Theorem 1.6 (4) being equal 2 (resp. 4) or equivalently that f is equal to 2 (resp. 1). However, in light of 1.6 (5) this is equivalent to $p \cong \pm 1 \pmod{5}$. In particular, we see that this exactly recovers Corollary 1.5, and this perspective is powerful enough to capture the general picture.

Exercise 1.8. Use Theorem 1.6 to establish Theorem 1.3. Let $q \neq p$ be odd primes and set $K = \mathbb{Q}(\zeta_q)$, for ζ_q a non-trivial q th root of unity.

(1) Show that

$$\left(\frac{-1}{p}\right) = (-1)^{\frac{p-1}{2}}.$$

(2) Set $H \subset (\mathbb{Z}/q\mathbb{Z})^{\times}$ be the subgroup of squares, and let $K^+ = K^H$ denote the fixed field. Prove that

$$K^+ = \mathbb{Q}\left(\sqrt{(-1)^{\frac{q-1}{2}} q}\right).$$

(Hint: Compare discriminants.)

(3) Show that p splits completely in K^+ if and only if the image of Frob_p lies in H .

(4) Deduce that

$$\left(\frac{q}{p}\right) = 1 \iff p \text{ splits in } \mathbb{Q}\left(\sqrt{(-1)^{\frac{q-1}{2}}q}\right).$$

(5) Use (1) and (3), to show that

$$\left(\frac{q}{p}\right) = (-1)^{\frac{(p-1)(q-1)}{4}} \left(\frac{p}{q}\right).$$

In this way, we see that Corollary 1.3 is a consequence of understanding the structure of $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ and in particular its quotient $\text{Gal}(\mathbb{Q}(\zeta_p)/\mathbb{Q})$. More specifically, we may organize what happened above as follows. We view the Legendre symbol as giving rise to a map

$$\begin{aligned} \chi_q : \text{Gal}(\mathbb{Q}(\zeta_q)/\mathbb{Q}) \simeq (\mathbb{Z}/q\mathbb{Z})^* &\rightarrow \langle \pm 1 \rangle \subset \mathbb{C}^* \\ a &\mapsto \left(\frac{a}{q}\right) \end{aligned}$$

where we note that, it easily follows from Definition 1.2, we have an equality $\left(\frac{a}{q}\right)\left(\frac{b}{q}\right) = \left(\frac{ab}{q}\right)$ so this is indeed a multiplicative character. Then quadratic reciprocity follows by explicating the lifts of Frobenius $\text{Frob}_p \in \text{Gal}(\mathbb{Q}(\zeta_q)/\mathbb{Q})$ of the p th power map for $q \neq p$ and interpreting them in terms of the arithmetic of the cyclotomic field.

In the hopes of generalizing this arithmetic phenomenon, we fix a number field K/\mathbb{Q} with algebraic closure $K \subset \overline{K}$, and a homomorphism

$$\chi : \text{Gal}(\overline{K}/K) \rightarrow \mathbb{C}^*,$$

where $\text{Gal}(\overline{K}/K) := \varprojlim_{K \subset L} \text{Gal}(L/K)$ over finite Galois extensions L/K , as in (1.2). Since \mathbb{C}^* is abelian, the character χ will factor through the abelianization $\text{Gal}(\overline{K}/K)^{\text{ab}}$ of this group. This can be thought of as the Galois group of an algebraic extension $K \subset K^{\text{ab}} \subset \overline{K}$. In particular, K^{ab} is the union of finite Galois extensions $K \subset L \subset K^{\text{ab}}$ such that $\text{Gal}(L/K)$ is abelian, and is known as the maximal abelian extension of K . We may write

$$\varprojlim_L \text{Gal}(L/K) =: \text{Gal}(K^{\text{ab}}/K),$$

and one can check that the natural map $\text{Gal}(\overline{K}/K) \rightarrow \text{Gal}(K^{\text{ab}}/K)$ identifies with the abelianization of $\text{Gal}(\overline{K}/K)$. To our aim of generalizing the above story, we would now like to define Frobenius elements inside this group. In light of exercise 1.7 (6.c), we see that it is important to pass to the quotient $\text{Gal}(K^{\text{ab}}/K)$, as in general these will only be defined up to conjugacy. However, we still have a problem that in general the existence of Frobenius elements are only well-defined for unramified extensions, as seen in exercise 1.7 (6). For a finite set of prime ideals S of K , we may consider the quotients

$$\begin{aligned} \varprojlim_{L^S} \text{Gal}(L^S/K) &:= \text{Gal}(K^S/K), \\ (\text{resp. } \varprojlim_{L^S} \text{Gal}(L^S/K) &:= \text{Gal}(K^{S,\text{ab}}/K)) \end{aligned}$$

defined by the set of finite extensions $K \subset L^S \subset \overline{K}$ (resp. $K \subset L^S \subset K^{\text{ab}}$) such that, for all prime ideals $\mathfrak{p} \notin S$, \mathfrak{p} is unramified inside L^S . As before, the algebraic extension $K \subset K^S \subset \overline{K}$ (resp. $K \subset K^{S,\text{ab}} \subset \overline{K}$) is defined by the compositum of the collection of all the finite extensions appearing in the above limits, and we refer to them as the maximal unramified extension outside S (resp. maximal abelian unramified extension outside S). The groups $\text{Gal}(K^S/K)$ (resp. $\text{Gal}(K^{S,\text{ab}}/K)$) are the infinite Galois groups of these infinite extensions. As before, it is clear from the definition that there is a natural map $\text{Gal}(K^S/K) \rightarrow \text{Gal}(K^{S,\text{ab}}/K)$, which one can verify identifies with the abelianization of $\text{Gal}(K^S/K)$.

Inside these infinite Galois groups, we can now construct our Frobenius elements.

Construction 1.9. *For a number field K/\mathbb{Q} and a finite set of prime ideals S of K and all $\mathfrak{p} \notin S$, we construct a conjugacy class of elements $\text{Frob}_{\mathfrak{p}} \in \text{Gal}(K^S/K)$ (resp. element $\text{Frob}_{\mathfrak{p}} \in \text{Gal}(K^{S,\text{ab}}/K)$) as follows.*

- (1) *For all finite Galois extensions $K \subset L \subset K^S$, we fix an unramified prime $\mathfrak{P}(L)|\mathfrak{p}$ lying above \mathfrak{p} . We consider the conjugacy class of elements $[\text{Frob}_{\mathfrak{p}}(\mathfrak{P}(L))] \subset \text{Gal}(L/K)$ given by Exercise 1.7 6 (b).*
- (2) *We choose the prime ideals in (1) such that if we have an inclusion $K \subset L_1 \subset L_2 \subset K^S$, we have that $\mathfrak{P}(L_2)|\mathfrak{P}(L_1)$ then it follows that if we look at the restriction map*

$$\text{Gal}(L_2/K) \rightarrow \text{Gal}(L_1/K)$$

that the conjugacy class $[\text{Frob}_{\mathfrak{p}}(\mathfrak{P}(L_2))]$ maps to the conjugacy class $[\text{Frob}_{\mathfrak{p}}(\mathfrak{P}(L_1))]$.

- (3) *In light of (2), we may choose a choice of representatives $\{\text{Frob}_{\mathfrak{p}}(\mathfrak{P}(L))\}_{K \subset L \subset K^S} \in \varprojlim_{K \subset L \subset K^S} \text{Gal}(L/K) = \text{Gal}(K^S/K)$ of the conjugacy classes compatible under restriction. One can check that this is well-defined up to conjugacy in $\text{Gal}(K^S/K)$ (cf. the last part of the proof of Proposition 2.12).*
- (4) *As the natural map $\text{Gal}(K^S/K) \rightarrow \text{Gal}(K^{S,\text{ab}}/K)$ identifies with the abelianization, the construction in (3) gives rise to a well-defined element $\text{Frob}_{\mathfrak{p}} \in \text{Gal}(K^{S,\text{ab}}/K)$ which only depends on the prime ideal $\mathfrak{p} \notin S$.*

With the Frobenius elements now constructed, we might worry that we have departed too much from our original goal of explicating characters of the form

$$\chi : \text{Gal}(\overline{K}^{\text{ab}}/K) \rightarrow \mathbb{C}^*,$$

as we have only constructed Frobenius elements in a certain quotient of $\text{Gal}(K^{S,\text{ab}}/K)$ of the group $\text{Gal}(\overline{K}^{\text{ab}}/K)$. However, we recall that, for any finite extension L/K , it must be unramified outside of some finite set of prime ideals S (as any ramified prime ideal must occur in the factorization of the discriminant of the extension L/K). In particular, this formally implies that we have

$$\text{Gal}(\overline{K}/K) \xrightarrow{\cong} \varprojlim_S \text{Gal}(K^S/K)$$

and

$$\text{Gal}(K^{S,\text{ab}}/K) \xrightarrow{\cong} \varprojlim_S \text{Gal}(K^{S,\text{ab}}/K)$$

where the map is induced by the natural quotient maps, and we note that, for any inclusion $S \subset T$ of sets of prime ideals, we have a natural inclusion $K^T \subset K^S$ and therefore a natural map $\text{Gal}(K^S/K) \rightarrow \text{Gal}(K^T/K)$. In particular, all characters χ of arithmetic interest will always factor through $\text{Gal}(K^S/K)$ for some finite set of prime ideals S of K .

We now come to the main Theorem describing the structures of these groups in the case of $K = \mathbb{Q}$, which tells us that Theorem 1.6 is sufficient for completely understanding $\text{Gal}(\mathbb{Q}^{\text{ab}}/\mathbb{Q})$ and in turn a general character $\chi : \text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}) \rightarrow \mathbb{C}^*$, at least assuming it factors through $\text{Gal}(\mathbb{Q}^S/\mathbb{Q})$ for some finite set of primes S .

Theorem 1.10 (The Kronecker–Weber Theorem and Class Field Theory over \mathbb{Q}). *The following is true.*

- (1) *There is an equality of fields*

$$\mathbb{Q}^{\text{ab}} = \bigcup_{n \geq 1} \mathbb{Q}(\zeta_n),$$

where ζ_n is a primitive n -th root of unity. In particular, every finite abelian extension $\mathbb{Q} \subset L \subset \mathbb{Q}^{\text{ab}}$ is contained in a cyclotomic field.

(2) *In light of the identification*

$$\mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q}) \cong (\mathbb{Z}/n\mathbb{Z})^\times,$$

of Theorem 1.6 (1), passing to the inverse limit yields a canonical isomorphism of profinite groups

$$\mathrm{Gal}(\mathbb{Q}^{\mathrm{ab}}/\mathbb{Q}) \cong \varprojlim_n (\mathbb{Z}/n\mathbb{Z})^\times =: \widehat{\mathbb{Z}}^\times.$$

We note, by the Chinese remainder theorem, we have an identification

$$(1.8) \quad \widehat{\mathbb{Z}}^\times \simeq \prod_q \mathbb{Z}_q^*,$$

where \mathbb{Z}_q^ denotes the invertible elements in the q -adic integers, for q varying over prime numbers.*

(3) *Let S be a finite set of primes of \mathbb{Q} . For $n \in \mathbb{Z}$, we write $\mathrm{supp}(n)$ for the collection of primes dividing n . Then*

$$\mathbb{Q}^S = \bigcup_{\substack{n \geq 1 \\ \mathrm{supp}(n) \subset S}} \mathbb{Q}(\zeta_n),$$

and there is a canonical isomorphism

$$\mathrm{Gal}(\mathbb{Q}^S/\mathbb{Q}) \cong \varprojlim_{\substack{n \\ \mathrm{supp}(n) \subset S}} (\mathbb{Z}/n\mathbb{Z})^\times.$$

Equivalently,

$$(1.9) \quad \mathrm{Gal}(\mathbb{Q}^{S,\mathrm{ab}}/\mathbb{Q}) \cong \prod_{q \in S} \mathbb{Z}_q^\times,$$

under the identification of (1.8).

(4) *As in Theorem 1.6 (4), under the identification*

$$\mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q}) \cong (\mathbb{Z}/n\mathbb{Z})^\times,$$

the Frobenius element Frob_p corresponds to the residue class

$$\mathrm{Frob}_p \longleftrightarrow p \bmod n.$$

for $p \nmid n$.

Passing to the inverse limit, the Frobenius element at a prime $p \notin S$ corresponds in $\mathrm{Gal}(\mathbb{Q}^S/\mathbb{Q})$ to the element

$$(p)_q \in \prod_{q \in S} \mathbb{Z}_q^\times, \quad (p)_q = p \in \mathbb{Z}_q^\times.$$

In particular, we observe that the group $\mathrm{Gal}(\mathbb{Q}^{\mathrm{ab}}/\mathbb{Q})$ has a remarkably simple structure which is completely describable in terms of the multiplicative structure of certain completions attached to \mathbb{Q} (namely, \mathbb{Z}_q^* for varying primes q). Moreover, this is setup in such a way that passing to the Galois group $\mathrm{Gal}(\mathbb{Q}^{S,\mathrm{ab}}/\mathbb{Q})$ with restricted ramification corresponds to only looking at the completions for $q \in S$ and such that the Frobenius element at p corresponds to the q -adic unit $p \in \mathbb{Z}_q^*$.

As we will discuss in more detail later in the course, this is indeed a general phenomenon. In particular, for any number field K/\mathbb{Q} , the profinite group $\mathrm{Gal}(K^{\mathrm{ab}}/K)$ will be explicitly describable in terms of the multiplicative structure of the groups K_q , and $\mathrm{Gal}(K^{\mathrm{ab},S}/K)$ will be describable in terms of the completions K_q for $q \in S$. In such a way that the Frobenius elements Frob_p will correspond to certain units in \mathcal{O}_{K_q} . This comprises the main content of what is known as global class field theory. The goal of the course will be to explain the statement and proofs of these statements, and show how it can be used to illuminate arithmetic phenomenon such as quadratic reciprocity.

2. GALOIS COHOMOLOGY, REFERENCE: [SER94; MIL20A; NSW08; KED02; NEU99]

We saw in the §1 that of utmost interest for us will be groups of the form

$$G := \varprojlim_{i \in I} G_i,$$

which are projective limits of finite groups G_i , as in (1.2). This is what is known as a pro-finite group. In particular, we were interested in understanding the abelianization

$$G^{\text{ab}} := G/[G, G]$$

of such a group where $[G, G] \subset G$ denotes the subgroup of commutators. In §1, the interest in the abelianization came from the technical requirement to have well-defined Frobenius elements, as in 1.9 (6)-(c). However, the passage to this abelianization will accomplish much more. In particular, as we will see, the abelianization of the group may be re-expressed

$$G^{\text{ab}} \simeq H_{1, \text{cont}}(G, \mathbb{Z})$$

where the RHS will be the 1st continuous homology group of the profinite group G , where \mathbb{Z} will be the integers equipped with the trivial G -action and the discrete topology¹. As the notation suggests, this group is part of a family $H_{i, \text{cont}}(G, \mathbb{Z})$ for $i \in \mathbb{N}_{\geq 0}$. These will be known as the continuous homology groups of G , which will provide us the essential computation tool for computing $H_1^{\text{cont}}(G, \mathbb{Z})$ and in turn proving the main results of class field theory. To this aim, we begin by describing the structure of profinite groups and building up this algebraic machine known as group (co)-homology.

2.1. Preliminaries.

2.1.1. *Profinite Groups.* We start with the basic definition.

Definition 2.1. A topological group G is said to be *profinite* if it is the projective limit of finite groups

$$\varprojlim_{i \in I} G_i = G,$$

where each of the groups is endowed with the discrete topology, and the inverse limit is computed in the category of topological groups (so that G is endowed with the minimal topology such that the projection maps $G \rightarrow G_i$ are continuous for all $i \in I$).

One of the basic reasons to keep track of the topology is the following alternative characterization of such groups.

Proposition 2.2. *A topological group G is profinite if and only if it is compact, totally disconnected, and Hausdorff.*

Proof. We prove the two implications separately.

(\Rightarrow) It follows from the definition of profinite, that there exists some directed set (I, \geq) such that we have a continuous map

$$\alpha : G \rightarrow \prod_{i \in I} G_i,$$

where the target is endowed with the product topology, and the image is identified with the set of tuples $(g_i)_{i \in I}$ such that $f_{jk}(g_k) = g_j$ for all $j \leq k$ in I . Here $f_{jk} : G_k \rightarrow G_j$ denotes the transition maps in a presentation of $G := \varprojlim_{i \in I} G_i$ as a projective limit with respect to the directed set (I, \geq) .

¹As we will discuss later, the homology of a pro-finite group will not be well-behaved if the group is not finite. This will make it more natural to consider the dual notion or what is known as the cohomology. However, we ignore this technical point for the introduction.

In particular, for varying $j \leq k$ in I , the image of α is the intersection of the $A_{jk} := \{(g_i)_{i \in I} \mid f_{jk}(g_k) = g_j\}$. However, A_{jk} is the preimage of diagonal in $X_j \times X_j$ under the topologically continuous map $\prod_{i \in I} G_i \xrightarrow{p_j \times p_k} G_j \times G_k \xrightarrow{\text{id} \times f_{jk}} G_j \times G_j$. In particular, A_{jk} is closed inside $\prod_{i \in I} G_i$ and therefore so is G . By the Tychonoff theorem, we know that $\prod_{i \in I} G_i$ is compact, and therefore G is as well. Similarly, $\prod_{i \in I} G_i$ is easily checked to be Hausdorff and totally disconnected so that G is as well.

(\Leftarrow) Let G be a compact totally disconnected Hausdorff topological group. For any locally compact totally disconnected group, it follows (e.g. by van-Dantzig's theorem) that the identity element has a basis of open neighborhoods given by open subgroups $U \subset G$. We consider such a $U \subset G$. This automatically has finite index since G is compact. Hence, its conjugates gUg^{-1} are finite in number and therefore their intersection $V \subset G$ is an open normal subgroup. Therefore, we conclude the set of open normal subgroups $V \subset G$ form a basis of open neighborhoods of the identity element. We consider the natural continuous map

$$G \rightarrow \varprojlim G/V,$$

where V ranges over all such subgroups. The map is injective continuous, and has dense image, and therefore it is an isomorphism. Indeed, both sides are easily verified to be compact Hausdorff by the argument given above (see Lemma 2.3 (1)), so the map is automatically closed. \square

Note that in the proof we also exhibited proofs of the following claims, which we record for future use.

Lemma 2.3. *The following is true.*

- (1) A projective limit $X := \varprojlim_{i \in I} X_i$ of compact (resp. totally disconnected, Hausdorff) topological spaces X_i endowed with the inverse limit topology is also compact (resp. totally disconnected, Hausdorff).
- (2) For a profinite group G , the identity element has a basis of open neighborhoods $U_i \subset G$ for some directed set (I, \geq) given by open (hence of finite index) normal subgroups and the ordering is determined by inclusion. In particular, we can always find an isomorphism

$$G \xrightarrow{\cong} \varprojlim_{i \in I} G/U_i,$$

of topological groups.

Remark 2.4. For (2), we note that, given a presentation

$$G = \varprojlim_{i \in I} G_i,$$

we may simply take $U_i := \text{Ker}(G \xrightarrow{\pi_i} G_i)$.

We have the following basic examples.

Example 2.5. (1) Let L/K be an extension of fields which can be written as the union of its finite Galois subextensions $K \subset L_i \subset L$. We then define the infinite Galois group

$$\text{Gal}(L/K) := \varprojlim_{i \in I} \text{Gal}(L_i/K),$$

where the limit is over finite Galois extensions $K \subset L_i \subset L$ and the ordering on I is determined by inclusion. Since the compositum of two finite Galois extension is again finite Galois, the set I is directed and therefore $\text{Gal}(L/K)$ is a profinite group.

- (2) We recall that the p -adic numbers \mathbb{Z}_p are a profinite group with presentation

$$\mathbb{Z}_p \simeq \varprojlim_{n \rightarrow 1} \mathbb{Z}/p^n\mathbb{Z}.$$

Similarly, if we consider the group $\mathrm{GL}_n(\mathbb{Z}_p)$ of $n \times n$ invertible matrices with coefficients in \mathbb{Z}_p then this is also a profinite group with presentation given by

$$\mathrm{GL}_n(\mathbb{Z}_p) \simeq \varprojlim_{n \geq 1} \mathrm{GL}_n(\mathbb{Z}/p^n \mathbb{Z}_p).$$

- (3) Let G be a discrete topological group, and let \hat{G} be the projective limit of the finite quotients of G . The group \hat{G} is known as the *pro-finite* completion of G . We note that there is a natural map

$$G \rightarrow \hat{G}$$

with kernel given by the intersection of all groups of finite index. If we apply this to the group \mathbb{Z} then we obtain what is known as the Prüfer ring

$$\hat{\mathbb{Z}} := \varprojlim_{n \in \mathbb{Z}} \mathbb{Z}/n\mathbb{Z}$$

which by the Chinese remainder theorem is isomorphic to a direct product

$$(2.1) \quad \hat{\mathbb{Z}} \simeq \prod_p \mathbb{Z}_p$$

indexed by all prime numbers p .

We also have the following important examples of profinite groups coming from duality.

Exercise 2.6. *If M is an abelian group then we define its Pontryagin dual to be $M^* := \mathrm{Hom}(M, \mathbb{Q}/\mathbb{Z})$.*

- (1) *Construct isomorphisms of the form*

$$\begin{aligned} (\mathbb{Z}/n\mathbb{Z})^\vee &\simeq \mathbb{Z}/n\mathbb{Z} \\ (\mathbb{Q}_p/\mathbb{Z}_p)^\vee &\simeq \mathbb{Z}_p, \end{aligned}$$

for p a prime number and $n \geq 1$ an integer. Show that

$$\mathbb{Q}^\vee \simeq 0.$$

- (2) *Suppose that M is a torsion abelian group endowed with the discrete topology. Endow M^* with topology given by pointwise convergence (I.e consider the embedding $M \hookrightarrow M^{\mathbb{Q}/\mathbb{Z}}$, where $M^{\mathbb{Q}/\mathbb{Z}}$ is given the product topology and M is given the subspace topology). Prove that M^* is a commutative profinite group (Hint: write M^* as a directed limit or union of its finite subgroups).*

- (3) *For M a torsion abelian group check that the natural evaluation map*

$$\begin{aligned} \mathrm{ev}_M : M &\rightarrow (M^*)^* \\ m &\mapsto (\chi \mapsto \chi(m)) \end{aligned}$$

is an isomorphism of abelian groups. We let \mathbf{TorAb} be the category of discrete torsion abelian groups. Let $\mathbf{ProFinAb}$ be the category of profinite (equivalently: compact, Hausdorff, totally disconnected topological) abelian groups (with morphisms being continuous homomorphisms). The above duality upgrades to a contravariant equivalence

$$\mathbf{TorAb}^{\mathrm{op}} \simeq \mathbf{ProFinAb}.$$

of categories. This is known as Pontryagin duality.

- (4) *Prove that Pontryagin dual of a torsion-free profinite abelian group is a divisible abelian group.*
- (5) *Combine (1), (4), and Exercise 2.7 below, to deduce that any commutative torsion free profinite group is isomorphic to a (possibly-infinite) product of copies of \mathbb{Z}_p for some prime numbers p .*

Exercise 2.7. Let A be a divisible abelian group, i.e. for every $a \in A$ and every integer $n \geq 1$ there exists $b \in A$ with $nb = a$.

- (1) Show that a finite divisible abelian group is trivial.
- (2) Show that A a divisible abelian group is a \mathbb{Q} -vector space if and only if it is torsion-free.
- (3) Let

$$A_{\text{tors}} := \{a \in A \mid \exists n \geq 1 \text{ with } na = 0\}.$$

Show that A_{tors} is a divisible subgroup of A .

- (4) Prove that A_{tors} decomposes canonically as a direct sum of its p -primary components

$$A_{\text{tors}} = \bigoplus_p A[p^\infty], \quad A[p^\infty] := \{a \in A \mid \exists n \text{ with } p^n a = 0\}.$$

- (5) Fix a prime p . Show that every divisible p -primary (in the sense that for every element a there exists $n \geq 0$ such that $p^n a = 0$) abelian group D contains a nonzero element of order p^n for all $n \geq 1$ unless $D = 0$.
- (6) Show that $\mathbb{Q}_p/\mathbb{Z}_p$ is a divisible p -primary group.
- (7) Prove that any divisible p -primary abelian group is a direct sum of copies of $\mathbb{Q}_p/\mathbb{Z}_p$.
- (8) Show that there exists a (non-canonical) decomposition

$$A \cong A_{\text{tors}} \oplus A/A_{\text{tors}}.$$

- (9) Show that A/A_{tors} is torsion-free and divisible, hence a \mathbb{Q} -vector space by (3).
- (10) Deduce that there exist cardinals κ and $\{\lambda_p\}_p$ such that

$$A \cong \mathbb{Q}^{(\kappa)} \oplus \bigoplus_p (\mathbb{Q}_p/\mathbb{Z}_p)^{(\lambda_p)},$$

where p varies over all prime numbers.

(Hint: Use that divisible abelian groups are injective objects (See Definition 2.21) in the category of abelian groups, so short exact sequences with divisible terms split. For the p -primary case, reduce to showing that a nonzero divisible p -group contains a copy of $\mathbb{Q}_p/\mathbb{Z}_p$ and then use Zorn's lemma to obtain a maximal direct sum of such copies.)

With the basic examples out of the way, let's turn towards the structure of the subgroups profinite groups

Lemma 2.8. Let $H \subset G$ be a subgroup of a pro-finite G . Then the following is true.

- (1) If $H \subset G$ is an open subgroup then it is also closed.
- (2) If $H \subset G$ is a closed subgroup then H is also profinite.

Proof. For (1) is an easy consequence of the fact that since G is compact any open H is of finite index. In particular, we can write H as the complement of its finitely many non-trivial translates implying it is closed.

For (2), we consider a presentation

$$G = \varprojlim_{i \in I} G/U_i,$$

as in Lemma 2.3 (2). We then have a natural map

$$H \rightarrow \varprojlim_{i \in I} H/(H \cap U_i),$$

which is easily checked to be continuous and injective with dense image. However, since $H \subset G$ is closed, this is a map of compact Hausdorff spaces using Lemma 2.3 (1), so we conclude that is an isomorphism. \square

We now have the following technical lemma, which will play an important technical role in explicating the cohomology of groups.

Proposition 2.9. *Suppose $K \subset H \subset G$ are an inclusion of two closed subgroups of G . Then the natural map $G/K \rightarrow G/H$ admits a continuous section $s : G/H \rightarrow G/K$.*

Proof. We start out with the following special case.

Lemma 2.10. *Suppose that $K \subset H$ is an inclusion of closed subgroups such that K has finite index in H then $G/K \rightarrow G/H$ admits a continuous section.*

Proof. Let U be an open normal subgroup of G such that $U \cap H \subset K$. The restriction of the map $G/K \rightarrow G/H$ to the image of U in G/K will then be injective. Its inverse map is therefore a section over the image of U inside G/H which is open by the finite index assumption. One may then extend to a section over all of G/H by translation. \square

For the general case, first note that, by replacing G with G/K , we may assume without loss of generality that $K = 1$.

Let X be the set of pairs (S, s) , where $S \subset H$ is a closed subgroup of H and s is a continuous section of $G/H \rightarrow G/S$. This is equipped with a natural partial ordering $(S, s) \geq (S', s')$ if $S \subset S'$ and the induced diagram

$$s : G/H \xrightarrow{s'} G/S' \rightarrow G/S$$

commutes. Suppose we have a totally ordered family (S_i, s_i) of elements of X with respect to the partial ordering defined above. We set $S = \bigcap_{i \in I} S_i$. We note that $S \subset G$ is closed and the natural map

$$G/S \rightarrow \varprojlim_{i \in I} G/S_i$$

is an isomorphism of topological groups. Indeed, it is injective and continuous with dense image, and all the spaces are compact Hausdorff using Lemma 2.3 (2). Using this, we may find an element (S, s) that lies above all the (S_i, s_i) in the partial ordering.

We are therefore in a position in which we may invoke Zorn's lemma. We let (S, s) be the resulting maximal element. Let us show that $S = 1$. Suppose that this is not the case. Then, by Lemma 2.3 (2) and Lemma 2.8 (2), this would imply that there exists an open subgroup $U \subset G$ such that $U \cap S \neq S$. We apply Lemma 2.10 $G/(S \cap U) \rightarrow G/S$ to deduce a section of the natural map, and composing this with the section $s : G/H \rightarrow G/S$ gives a contradiction to maximality of (S, s) in light of Lemma 2.8 (1). \square

A prototypical example of a closed subgroup which is not open is the subgroup $\mathbb{Z}_p \subset \hat{\mathbb{Z}}$ given by the inclusion of the p th coordinate in the isomorphism (2.1). The notion of index of course does not make sense for such a subgroup in any kind of naive way. However, as profinite groups are built out of limits of finite groups, this does make sense up to modifying our expectations in a controlled way.

Definition 2.11. We define the following.

- (1) A *supernatural number* is a formal product $\prod_p p^{n_p}$, where p ranges over all prime numbers and n_p is an integer that is ≥ 0 or is equal to ∞ . We note that we may define the lcm and gcd of such numbers in the obvious way.
- (2) For $H \subset G$, the inclusion of a closed subgroup into a profinite group G . We define the index $[G : H]$ to be the supernatural number defined as the lcm of the indices $[G/U : H/(H \cap U)]$ as U runs over the set of open normal subgroups of G . We define the order of a profinite G to be $[G : 1]$.
- (3) We say a group G is *pro- p* if the supernatural number given by its order is a power of p . Equivalently, if it is a projective limit of finite p -order groups.

- (4) We say a closed subgroup $H \subset G$ is a p -Sylow subgroup if it is pro- p and the index $[G : H]$ is of order prime to p .

We can now bootstrap the usual Sylow theorems to the profinite context.

Proposition 2.12. *Every profinite subgroup G has Sylow p -Sylow subgroup, and these are all conjugate.*

Proof. The key will be to use the following lemma, which is of manifold use when bootstrapping claims from the finite context to the pro-finite context.

Lemma 2.13. *A projective limit $X := \varprojlim_{i \in I} X_i$ for a directed set (I, \geq) of non-empty finite sets is non empty.*

Proof. Recall, as in the proof of the forward implication of Proposition 2.2, we have that X may be identified with the intersection of the closed subsets

$$A_{jk} := \{(x_i)_i \in X \mid f_{jk}(x_k) = x_j\}.$$

For all $j \leq k$ in I inside $\prod_{i \in I} X_i$, where X_i is endowed with the discrete topology and $\prod_{i \in I} X_i$ is endowed with the product topology. The claim is reduced to showing that the intersection of all these sets is non-empty.

As in 2.2, $\prod_{i \in I} X_i$ is compact by Tychonoff and therefore so is A_{jk} . By a standard compactness argument, the claim is therefore reduced to showing that given finitely many $A_{j_1 k_1}, \dots, A_{j_r k_r}$ their intersection is non-empty. Let J be the finite set of indices appearing. Since I is directed, there exists $m \in I$ with $m \geq k$ for all $j \in J$. Choose any $x_m \in X_m$. For each $k \in J$ define $x_k := f_{mk}(x_m)$, and choose arbitrary elements in $\prod_{i \in I} X_i$ for indices outside J . This defines an element in the intersection $A_{j_1 k_1} \cap \dots \cap A_{j_r k_r}$, showing the claim. \square

Now let I be the directed set determined by a family of open normal subgroups $\{U_i\}_{i \in I}$ of G as in Lemma 2.3 (2). For each $i \in I$, let $P(U_i)$ be the set of Sylow p -subgroups in the finite group G/U_i . We consider the inverse system $\varprojlim_{i \in I} P(U_i)$ noting that this is well-defined as the transition morphisms $G/U_i \rightarrow G/U_j$ are all surjective maps of finite groups, which therefore carries p -Sylow subgroups to p -Sylow subgroups. By applying Lemma 2.13 and invoking the usual Sylow theorems, we obtain a subgroup $H = \varprojlim_{i \in I} H_i$, which one easily checks will be a p -Sylow subgroup of H . Given any two such choices H and H' of such a p -Sylow subgroup, we consider, for $i \in I$, the set $Q(U_i)$ of elements which conjugate the image of H in G/U_i to H' . By applying Lemma 2.13 to the inverse system $\varprojlim_{i \in I} Q(U_i)$ and invoking the usual Sylow theorems, we construct an element $x \in G$ such that $xHx^{-1} = H'$, as desired. \square

We now want to review the following situation in which profinite groups will show up for us in full force.

2.1.2. *Aside on Infinite Galois Theory.* We recall the following basic assertion of Galois theory.

Theorem 2.14. *Let L/K be a finite Galois extension. Then the normal subgroups $H \subset G$ correspond to Galois subextensions $M \subset L$. The correspondence is given by taking a subgroup H to the fixed field L^H and $L/M/K$ to $\text{Gal}(L/M)$.*

As we have already seen in Example 2.5 (1) and in §1, for an infinite Galois extension L/K we may write L as the compositum of finite Galois extensions L_i/K in some index set $i \in I$ and form the inverse limit

$$\text{Gal}(L/K) = \lim_{i \in I} \text{Gal}(L_i/K)$$

to endow the Galois group of this infinite extension with the structure of a profinite group. If $L = K^{\text{sep}}$ denotes the separable closure of the field K (which agrees with the algebraic closure if K is a perfect field) then it is the inverse limit

$$\lim_{i \in I} \text{Gal}(K_i/K),$$

where K_i runs over all finite Galois extensions of K . We refer to the resulting profinite group $\text{Gal}(K^{\text{sep}}/K)$, as the absolute Galois group of K .

Example 2.15. We set $q = p^f$ for p a prime. We let \mathbb{F}_q be the unique finite extension of \mathbb{F}_p of degree f . Similarly, for all $n \geq 1$, recall that \mathbb{F}_q has exactly one finite extension of degree n which we denote by \mathbb{F}_{q^n} . Moreover, the Galois group $\text{Gal}(\mathbb{F}_{q^n}/\mathbb{F}_q)$ is isomorphic to $\mathbb{Z}/n\mathbb{Z}$ and is generated by the Frobenius element Frob_p sending $x \mapsto x^p$. The absolute Galois group of \mathbb{F}_q in this case is given by

$$\text{Gal}(\overline{\mathbb{F}_q}/\mathbb{F}_q) \simeq \lim_{n \geq 1} \text{Gal}(\mathbb{F}_{q^n}/\mathbb{F}_q) \simeq \lim_{n \geq 1} \mathbb{Z}/n\mathbb{Z} =: \hat{\mathbb{Z}},$$

where the RHS is the Prüfer ring introduced in 2.5 (3).

We now want to formulate a version of Galois theory that applies to infinite extensions. In particular, we want to say that subgroups of $\text{Gal}(L/K)$ should correspond to (possibly) infinite subextensions of $L/L'/K$. However, we clearly need to be a bit careful. In particular, the Galois groups of the subextensions should correspond to these subgroups, and therefore they should also be profinite. A simple way of guaranteeing this in light of Lemma 2.8, is to only look at closed subgroups of $\text{Gal}(L/K)$. This leads to the fundamental Theorem of infinite Galois theory.

Theorem 2.16. *Let L/K be a (not necessarily finite) Galois extension. Then there is a correspondence between Galois subextensions $M \subset L$ and normal closed subgroups $H \subset \text{Gal}(L/K)$ given by*

$$H \mapsto L^H$$

and $L/M/K$ to

$$M \mapsto \text{Gal}(L/M).$$

Moreover, the resulting extension L^H is finite if and only if the subgroup $H \subset \text{Gal}(L/K)$ is open. Moreover, if M is the fixed field of a normal subgroup H , we have an isomorphism $\text{Gal}(M/K) \simeq \text{Gal}(L/K)/H$.

Proof. See [Neu99, Chapter 4, Section 1, Theorem 1.2] □

Instead of giving a proof, we give some flavor for what this is saying by working out an important example.

Exercise 2.17. *Consider the infinite Galois extension $\text{Gal}(\mathbb{Q}^{\text{ab}}/\mathbb{Q})$. We recall that we have an isomorphism $\text{Gal}(\mathbb{Q}^{\text{ab}}/\mathbb{Q}) \simeq \hat{\mathbb{Z}}^*$ by Theorem 1.10 (2). We now work out what infinite Galois theory is telling us in this particular case.*

- (1) *Show that we have an isomorphism $\mathbb{Z}_p^* \simeq \mathbb{Z}/(p-1)\mathbb{Z} \times \mathbb{Z}_p$ if p is odd and that $\mathbb{Z}_2^* \simeq \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}_2$. Deduce the existence of a surjective continuous map $\hat{\mathbb{Z}}^* \rightarrow \hat{\mathbb{Z}}$ of profinite groups (Hint: use the p -adic exponential map).*
- (2) *Classify all closed subgroups of $\hat{\mathbb{Z}}^*$ using part (1) and the isomorphism $\hat{\mathbb{Z}}^* \simeq \prod_p \mathbb{Z}_p^*$. Deduce that $1 + n\hat{\mathbb{Z}}$, $\prod_p 1 + p^{e_p}\mathbb{Z}_p$ for $e_p \geq 1$, and $\langle \pm 1 \rangle$ define closed subgroups of $\hat{\mathbb{Z}}^*$.*
- (3) *Identify the (possibly infinite abelian extensions) that correspond to the closed subgroups $1 + n\hat{\mathbb{Z}}$, $\prod_p 1 + p^{e_p}\mathbb{Z}_p$ for $e_p \geq 1$, and $\langle \pm 1 \rangle$ described in (2) under infinite Galois Theory.*

We now turn to the cohomology of groups. We begin first with the finite case.

2.2. Cohomology of Finite Groups. For the rest of this subsection, we will let G denote a finite group.

2.2.1. *A Bit of Abstract Nonsense.* We write Mod_G for the abelian category with objects given by abelian groups $(A, +)$ with a left action $G \times A \rightarrow A$ $(g, a) \mapsto g.a$ of the group G , and morphisms given by G -equivariant maps $f : A \rightarrow B$.

Remark 2.18. We can consider the group ring $\mathbb{Z}[G]$ which is given by the collection of formal linear combinations $\sum_{g \in G} a_g g$, where $a_g \in \mathbb{Z}$ and $g \in G$ is an element. This has an obvious addition operation given by adding the coordinates and an obvious (not necessarily commutative) multiplication induced by the multiplication on G . We note that we can identify Mod_G with the category of left $\mathbb{Z}[G]$ -modules under this ring.

We will be interested in the functor

$$(2.2) \quad (-)^G : \text{Mod}_G \rightarrow \text{Ab}$$

of G -invariants, where Ab denotes the category of abelian groups. I.e. $A^G := \{a \in A \mid g.a = a\}$ is the subgroup of elements which are fixed under the action of G . The cohomology of groups arises by considering how this functor interacts with the notion of short exact sequences

$$(2.3) \quad 0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$$

in the category Mod_G . These are just usual short exact sequences in the category of abelian groups, but we insist that the morphisms are in the category Mod_G . In particular, given such a short exact sequence, we obtain an induced left exact sequence

$$(2.4) \quad 0 \rightarrow A^G \rightarrow B^G \rightarrow C^G,$$

where injectivity of the map $A^G \rightarrow B^G$ is clear; however, surjectivity of the map $B^G \rightarrow C^G$ does not hold in general.

Exercise 2.19. Let $G = C_p$ be the cyclic group of order p , and let $k = \mathbf{F}_p$. We consider the G -modules

$$M = k[G] \quad N = k,$$

where $k[G]$ is the group ring of G introduced above. We consider the natural map.

$$\varepsilon : k[G] \rightarrow k, \quad \varepsilon \left(\sum_{g \in G} a_g g \right) = \sum_{g \in G} a_g.$$

which is known as the augmentation morphism

- (1) Show that ε is surjective.
- (2) Show that M^G is one-dimensional and is spanned by

$$s = \sum_{g \in G} g.$$

- (3) Compute the induced map on G -invariants

$$\varepsilon^G : M^G \longrightarrow N^G$$

and show that it is the zero map.

Our main goal will be to extend the sequence (2.4) to a long exact sequence of abelian groups. The main tool will be to use the following, which is the basic building block of all homological algebra.

Lemma 2.20. (*Snake Lemma*) Consider a commutative diagram of abelian groups with exact rows:

$$(2.5) \quad \begin{array}{ccccccc} A & \xrightarrow{f} & B & \xrightarrow{g} & C & \longrightarrow & 0 \\ & & \downarrow \alpha & & \downarrow \beta & & \\ 0 & \longrightarrow & A' & \xrightarrow{f'} & B' & \xrightarrow{g'} & C' \\ & & & & \downarrow \gamma & & \end{array}$$

Then there exists a connecting homomorphism

$$\delta: \ker(\gamma) \longrightarrow \operatorname{coker}(\alpha)$$

such that the following sequence is exact:

$$(2.6) \quad \ker(\alpha) \longrightarrow \ker(\beta) \longrightarrow \ker(\gamma) \xrightarrow{\delta} \operatorname{coker}(\alpha) \longrightarrow \operatorname{coker}(\beta) \longrightarrow \operatorname{coker}(\gamma)$$

Moreover, if f is injective then this is exact on the left and if g' is surjective then this is exact on the right.

Proof. This is a standard diagram chase. In particular, we can construct the map δ by taking an element $c \in \operatorname{Ker}(\gamma) \subset C$ and lifting it to an element in B and then pushing to an element B' by the map β . By the commutativity of the diagram and the fact that $c \in \operatorname{Ker}(\gamma)$, this element will vanish upon applying g' and therefore lie in $\operatorname{Im}(f')$ (cf. [Wei80]). By similar arguments, one may check it is well-defined and gives rise to a sequence with the claimed exactness properties. \square

The basic idea is now that we can use Lemma 2.20 to build up further terms of left exact sequence (2.4) of abelian groups, by embedding the terms of the original sequence (2.3) in Mod_G into another sequence defined by objects that behave in a simpler way with respect to taking invariants, and then using the snake lemma to conclude some consequences for the sequence (2.4) by taking invariants. More precisely, we want to consider the following.

Definition 2.21. An object $M \in \operatorname{Mod}_G$ is said to be *injective* if, for every commutative diagram

$$\begin{array}{ccc} A & \xrightarrow{\phi} & M \\ \downarrow i & & \\ B & & \end{array},$$

in Mod_G where $i: A \hookrightarrow B$ is an injective map of G -modules, there exists a map $\psi: B \rightarrow M$ such that the diagram commutes.

Remark 2.22. We note that we may equivalently think of injectivity as saying that the natural map

$$\operatorname{Hom}(B, M) \rightarrow \operatorname{Hom}(A, M)$$

induced by an injection $i: A \rightarrow B$ is always surjective, where we note that the injectivity is automatic by the injectivity of i .

Now suppose we have a short exact sequence

$$0 \rightarrow A \xrightarrow{i} B \rightarrow C \rightarrow 0,$$

where the object A is assumed to be injective. Then, by taking $i = \operatorname{id}_A$ in Definition 2.21, we note that injectivity allows us to deduce the existence of a splitting

$$0 \longrightarrow A \xrightarrow{i} B \longrightarrow C \longrightarrow 0$$

$\longleftarrow \underbrace{\hspace{1.5cm}}_s$

which gives us an isomorphism $B \simeq A \oplus C$. Similarly, if we take G -invariants then we get a diagram

$$0 \longrightarrow A^G \xrightarrow{i^G} B^G \longrightarrow C^G$$

$$\quad \quad \quad \longleftarrow \underbrace{\hspace{1.5cm}}_{s^G}$$

which would in turn gives us a splitting $B^G \simeq A^G \oplus C^G$. In turn applying, this a priori only left exact sequence is right exact for injective objects. Therefore, by embedding a general short exact sequence (2.3) into a short exact sequence involving injective objects, we will obtain an interesting structure by taking G -invariants and using Lemma 2.20. We now have the following basic fact which tells us that we can always do this.

Exercise 2.23. *Show that, for every $A \in \text{Mod}_G$, there exists an injection $A \hookrightarrow M$ in Mod_G such that M is injective (Hint: first think about the case of usual abelian groups (e.g when G is trivial). We already discussed examples of injective objects in this category in Exercise 2.7).*

This exercise allows us to deduce the existence of the following.

Definition 2.24. We say an injective resolution of $M \in \text{Mod}_G$ is a long exact sequence

$$(2.7) \quad 0 \rightarrow M \rightarrow I^0 \xrightarrow{d^0} I^1 \xrightarrow{d^1} I^2 \xrightarrow{d^2} \dots,$$

in Mod_G , where the objects I^j are all injective in the sense of Definition 2.21. We note that the existence of such a resolution is guaranteed by iteratively applying Exercise 2.23. We will denote such a resolution by the notation $M \rightarrow I^*$.

We now have the following sequence of invariants attached to any $M \in \text{Mod}_G$.

Definition 2.25. Given $M \in \text{Mod}_G$, we consider the injective resolution

$$I^0 \xrightarrow{d^0} I^1 \xrightarrow{d^1} I^2 \xrightarrow{d^2} \dots,$$

of M , and apply $(-)^G : \text{Mod}_G \rightarrow \text{Ab}$. This gives us a sequence of maps

$$(I^0)^G \xrightarrow{(d^0)^G} (I^1)^G \xrightarrow{(d^1)^G} (I^2)^G \xrightarrow{(d^2)^G} \dots,$$

however this is not exact. Nonetheless, we still have, for all $i \geq 0$, an inclusion $\text{Im}((d^i)^G) \subset \text{Ker}((d^{i+1})^G)$, where we set $(d^{-1})^G$ to be the natural map $0 \rightarrow (I^0)^G$. We form the cohomology groups

$$H^i(G, M) := \text{Ker}((d^i)^G) / \text{Im}((d^{i-1})^G) \in \text{Ab}$$

which are known as the *group cohomology groups* of M . We observe, by the exactness of the sequence (2.7) defining the notion of injective resolution and the left exactness of the functor $(-)^G$, that we have a canonical identification

$$H^0(G, M) \simeq M^G.$$

We note that a priori this depends on the choice $M \rightarrow I^*$ of injective resolution. We will come back to this point in a second. For now, let us consider a G -module map $f : M \rightarrow N$, and suppose that we have an injective resolutions $0 \rightarrow M \rightarrow I^*$ and $0 \rightarrow N \rightarrow J^*$. We note that, by the lifting property of injective objects 2.21, we may inductively lift f to a map $f^i : I^i \rightarrow J^i$ for all $i \geq 0$, giving rise to a commutative diagram

$$(2.8) \quad \begin{array}{ccccccc} 0 & \longrightarrow & M & \longrightarrow & I^0 & \xrightarrow{d^0} & I^1 & \xrightarrow{d^1} & \dots \\ & & \downarrow f & & \downarrow f^0 & & \downarrow f^1 & & \\ 0 & \longrightarrow & N & \longrightarrow & J^0 & \xrightarrow{d^0} & J^1 & \xrightarrow{d^1} & \dots \end{array}$$

If we take G -invariants then we note that this induces for us a morphism

$$H^i(f) : H^i(G, M) \rightarrow H^i(G, N)$$

on group cohomology. We now have the following basic lemma checking that this is well-defined.

Lemma 2.26. *The map $H^i(f)$ only depends on f and not on the choice of injective resolutions or of lifts f^i filling in the commutative diagram 2.8.*

Proof. It suffices to check that if $f = 0$ then $H^i(f) = 0$ for all $i \geq 0$, regardless of the choice of the lifts f^i . If $f = 0$ then for any choice of lifts f^i , we may, by exercise 2.27 construct morphisms $g^i : I^{i+1} \rightarrow J^i$ satisfying the identity

$$f^i = g^i \circ d^i + d^{i-1} \circ g^{i-1}.$$

In particular, if we take G -invariants and evaluate this on $a \in \text{Ker}((d^i)^G) \subset (I^i)^G$ representing a class in $H^i(G, M)$ then we see that

$$(f^i)^G(a) = (d^{i-1} \circ g^{i-1})^G(a) \in \text{Im}((d^{i-1})^G)$$

which implies that it vanishes in $H^i(G, N)$. □

In the above proof, we implicitly used the following which we leave as an exercise.

Exercise 2.27. *Show that if we are given a map $f : M \rightarrow N$ in Mod_G such that $f = 0$ then, for any lifts f^i filling in a commutative diagram*

$$\begin{array}{ccccccc} 0 & \longrightarrow & M & \longrightarrow & I^0 & \xrightarrow{d^0} & I^1 & \xrightarrow{d^1} & \dots \\ & & \downarrow f & & \downarrow f^0 & & \downarrow f^1 & & \\ 0 & \longrightarrow & N & \longrightarrow & J^0 & \xrightarrow{d^0} & J^1 & \xrightarrow{d^1} & \dots \end{array}$$

between injective resolutions $M \rightarrow I^*$ and $N \rightarrow I^*$, we may construct morphisms $g^i : I^{i+1} \rightarrow J^i$ such that

$$f^i = g^i \circ d^i + d^{i-1} \circ g^{i-1}.$$

(Hint: Proceed by induction on i and use the lifting property for injective objects).

We now have the following promised Corollary of this.

Corollary 2.28. *For $M \in \text{Mod}_G$, the cohomology groups $H^i(G, M)$ do not depend on the choice of injective resolution $M \rightarrow I^*$.*

Proof. We apply Lemma 2.26 to $M = N$, the identity map, and two different injective resolutions of M . We see that the resulting map must give the identity on $H^i(G, M)$. □

In particular, as a consequence of the above discussion, we obtain well-defined functors

$$H^i(G, -) : \text{Mod}_G \rightarrow \text{Ab}$$

extending the functor of G -invariants. These are known as the right derived functors of $(-)^G$. We now have the following important property, which is easy consequence of Lemma 2.20.

Proposition 2.29. *Suppose we have a short exact sequence*

$$0 \rightarrow A \xrightarrow{f} B \xrightarrow{g} C \rightarrow 0$$

in Mod_G . Then we have a long exact sequence

$$0 \rightarrow H^0(G, A) \xrightarrow{H^0(f)} H^0(G, B) \xrightarrow{H^0(g)} H^0(G, C) \xrightarrow{\delta_0} H^1(G, A) \xrightarrow{H^1(f)} \dots H^i(G, C) \xrightarrow{\delta_i} H^{i+1}(G, A) \rightarrow \dots$$

in Ab .

These cohomology groups will be of utmost importance for us. We now turn our attention to computing with them.

2.2.2. *From the Abstract to the Concrete.* In order to render the cohomology groups computable, we note that they can be computed in terms of the following.

Definition 2.30. We define the following.

- (1) We say that $M \in \text{Mod}_G$ is *acyclic* if $H^i(G, M) = 0$ is trivial for all $i \geq 1$.
- (2) We say an *acyclic resolution* of $M \in \text{Mod}_G$ is a long exact sequence

$$0 \rightarrow M \rightarrow M_0 \xrightarrow{d^0} M_1 \xrightarrow{d^1} \dots,$$

in Mod_G , where each M_i for $i \geq 0$ is acyclic in the sense of (1).

We now have the following, which essentially tells us that acyclic resolutions are sufficient for computing cohomology.

Exercise 2.31. *Show the following.*

- (1) *Show that if $M \in \text{Mod}_G$ is injective then it is acyclic. I.e that*

$$H^i(G, M) = 0.$$

(Hint: We discussed how an injective map from an injective module must split, so apply this to the injective resolution.)

- (2) *Let $M \rightarrow M_*$ be an acyclic resolution of $M \in \text{Mod}_G$. We apply G -invariants to the terms of the resolution and consider the resulting complex*

$$M_0^G \xrightarrow{(d^0)^G} M_1^G \rightarrow \dots M_i^G \xrightarrow{(d^i)^G} M_{i+1}^G \rightarrow \dots$$

and consider, for all $i \geq 0$, the resulting cohomology

$$\text{Ker}((d^i)^G) / \text{Im}((d^{i-1})^G).$$

where we set $d_{-1}^G : 0 \rightarrow M_0^G$. Show that this is isomorphic to $H^i(G, M)$ (Hint: inductively apply the long exact cohomology sequence).

We will now be interested in constructing an acyclic resolution of a general G -module M . The recipe for doing this will be using the following functors.

Definition 2.32. Let $H \subset G$ be a subgroup. We define the following.

- (1) We consider the functor

$$\begin{aligned} \text{Ind}_H^G : \text{Mod}_H &\rightarrow \text{Mod}_G \\ M &\mapsto \mathbb{Z}[G] \otimes_{\mathbb{Z}[H]} M, \end{aligned}$$

where we have implicitly used the description of G and H -modules described in Remark 2.18.

- (2) We consider the functor

$$\text{Res}_H^G : \text{Mod}_G \rightarrow \text{Mod}_H$$

given by remembering the H -action and forgetting the rest of the action.

Remark 2.33. Alternatively, we may identify $\text{Ind}_H^G(M)$ as the set of functions $\phi : G \rightarrow M$ such that $\phi(hg) = h.\phi(g)$ together with the G -action given by translation on the left. In particular, we may think of elements in $\mathbb{Z}[G] \otimes_{\mathbb{Z}[H]} M$ in terms of sums of elements

$$[g] \otimes m \in \mathbb{Z}[G] \otimes_{\mathbb{Z}[H]} M,$$

where $[g]$ denotes a coset representative of $g \in G$ inside G/H . Given such a element, it corresponds to the function $\phi_{[g],m}$ taking an $g' \in G$ to $(g'.g).m$ if $g'.g \in H$ and 0 otherwise.

Remark 2.34.

We now have the following fundamental property of these operations, which effectively say they are an adjoint pair.

Proposition 2.35. (Frobenius Reciprocity) *Let $H \subset G$ be a subgroup, M a G -module, and N an H -module. Then we have the following isomorphisms between G -equivariant and H -equivariant Hom spaces*

$$(2.9) \quad \mathrm{Hom}_G(M, \mathrm{Ind}_H^G(N)) \simeq \mathrm{Hom}_H(\mathrm{Res}_H^G(M), N)$$

and

$$(2.10) \quad \mathrm{Hom}_G(\mathrm{Ind}_H^G(N), M) \simeq \mathrm{Hom}_H(N, \mathrm{Res}_H^G(M)),$$

which are natural in both M and N .

Proof. We first consider the case where $N = \mathrm{Res}_H^G(M)$. Then the statement says that the identity map $\mathrm{Res}_H^G(M) \rightarrow \mathrm{Res}_H^G(M)$ is supposed to correspond to maps

$$\mathrm{Ind}_H^G \mathrm{Res}_H^G(M) \rightarrow M$$

and

$$M \rightarrow \mathrm{Ind}_H^G \mathrm{Res}_H^G(M).$$

We write down these maps explicitly. The map

$$(2.11) \quad \mathrm{Ind}_H^G \mathrm{Res}_H^G(M) \rightarrow M$$

is given by

$$\sum_{[g] \in G/H} [g] \otimes m_g \mapsto \sum_{g \in G} g \cdot m_g,$$

where we use the description of $\mathrm{Ind}_H^G(-)$ as a tensor product over group rings spelled out in Remark 2.33. Moreover, the map

$$(2.12) \quad M \rightarrow \mathrm{Ind}_H^G \mathrm{Res}_H^G(M)$$

is given by

$$m \mapsto \sum_{[g] \in G/H} [g^{-1}] \otimes g_i \cdot m.$$

We see that, this is independent of the set of coset representatives of H in G . In particular, for a set of cosets representatives $g_i \in G$ for $i \in I$ and $g \in G$, we can use $g_i g$ instead to see that

$$g \cdot m \mapsto \sum_i [g_i^{-1}] \otimes (g_i g) \cdot m = [g] \cdot \left(\sum_{i \in I} [(g_i g)^{-1}] \otimes (g_i g) \cdot m \right)$$

which shows us that this map is indeed G -equivariant.

Now let N be general. Given a homomorphism $\mathrm{Res}_H^G M \rightarrow N$ of H -modules, we can apply Ind_H^G to obtain a homomorphism

$$\mathrm{Ind}_H^G \mathrm{Res}_H^G M \rightarrow \mathrm{Ind}_H^G N$$

which we can then precompose with the map (2.12) to get a map

$$M \rightarrow \mathrm{Ind}_H^G \mathrm{Res}_H^G M \rightarrow \mathrm{Ind}_H^G N,$$

as desired. In summary, we have constructed a map

$$\mathrm{Hom}_H(\mathrm{Res}_H^G M, N) \rightarrow \mathrm{Hom}_G(M, \mathrm{Ind}_H^G N).$$

We now need to see that we have an inverse map. Consider a homomorphism $M \rightarrow \mathrm{Ind}_H^G N$ and apply Res_H^G to obtain a map

$$\mathrm{Res}_H^G M \rightarrow \mathrm{Res}_H^G \mathrm{Ind}_H^G N.$$

Using Remark 2.33, we may identify $\mathrm{Res}_H^G \mathrm{Ind}_H^G N$ with functions $\phi : G \rightarrow N$, therefore we have a natural map $\mathrm{Res}_H^G \mathrm{Ind}_H^G N \rightarrow N$ taking ϕ to $\phi(e)$. In particular, postcomposing with this we obtain a map $\mathrm{Res}_H^G M \rightarrow N$, as desired. This establishes the isomorphism (2.9).

For (2.10), we proceed similarly. In particular, we consider a homomorphism $N \rightarrow \text{Res}_H^G M$ of H -modules and apply Ind_H^G to it. This gives us a map

$$\text{Ind}_H^G N \rightarrow \text{Ind}_H^G \text{Res}_H^G M,$$

which we may postcompose with the map (2.11) to get a morphism

$$\text{Ind}_H^G N \rightarrow \text{Ind}_H^G \text{Res}_H^G M \rightarrow M.$$

Therefore, we have given a map

$$\text{Hom}_H(N, \text{Res}_H^G M) \rightarrow \text{Hom}_G(\text{Ind}_H^G N, M).$$

To exhibit an inverse, we consider a map $\text{Ind}_H^G N \rightarrow M$ of G -modules and then apply Res_H^G to get a morphism $\text{Res}_H^G \text{Ind}_H^G N \rightarrow \text{Res}_H^G M$. Now we note that we have a natural map $N \rightarrow \text{Res}_H^G \text{Ind}_H^G N$ given by sending $n \mapsto [e] \otimes n$, where e is the identity element. \square

Remark 2.36. We note that for $M \in \text{Mod}_G$ the natural maps

$$M \rightarrow \text{Ind}_1^G \text{Res}_1^G(M)$$

and

$$\text{Ind}_1^G \text{Res}_1^G(M) \rightarrow M$$

are injective and surjective, respectively. In particular, we always obtain short exact sequences.

$$0 \rightarrow M \rightarrow \text{Ind}_1^G \text{Res}_1^G(M) \rightarrow N \rightarrow 0$$

and

$$0 \rightarrow N' \rightarrow \text{Ind}_1^G \text{Res}_1^G(M) \rightarrow M \rightarrow 0$$

in Mod_G . These short exact sequences will be important for us later. In particular, the point is that the middle term will be acyclic in the sense of 2.31, by Schapiro's Lemma below. In particular, Proposition 2.29, will give us natural isomorphisms

$$H^i(G, N) \xrightarrow{\cong} H^{i+1}(G, M)$$

and

$$H^i(G, M) \xrightarrow{\cong} H^{i+1}(G, N')$$

for any $M \in \text{Mod}_G$, which will allow us to move claims on cohomology groups in higher degree to lower degree and vice-versa.

This in particular implies that Res_H^G and Ind_H^G are both left and right adjoints of one another. In other words, we have a repeating sequence of adjunctions

$$\cdots \dashv \text{Ind}_H^G \dashv \text{Res}_H^G \dashv \text{Ind}_H^G \dashv \cdots$$

To deduce something interesting from this, we have the following basic categorical lemma which now helps us out.

Lemma 2.37. *Suppose \mathcal{C} and \mathcal{D} are locally small categories (in the sense that the set of maps between objects X and Y is a set) and that we have a pair of adjoint functors*

$$F \dashv G.$$

Then F commutes with colimits and G commutes with limits.

Proof. Suppose we have a colimit $\text{colim}_{i \in I} c_i$ in \mathcal{C} for some index set I then we want to show that the natural map

$$F(\text{colim}_{i \in I} c_i) \rightarrow \text{colim}_{i \in I} F(c_i)$$

induced by the universal property of the colimit is an isomorphism. The Yoneda lemma now tells us that to check this is an isomorphism, it suffices to show the induced map

$$\text{Hom}(\text{colim}_{i \in I} F(c_i), d) \rightarrow \text{Hom}(F(\text{colim}_{i \in I} c_i), d)$$

for all $d \in \mathcal{D}$ is an isomorphism. However, now note that we can rewrite the RHS, as

$$\mathrm{Hom}(\mathrm{colim}_{i \in I} c_i, G(d)) \simeq \lim_{i \in I} \mathrm{Hom}(c_i, G(d)) \simeq \lim_{i \in I} \mathrm{Hom}(F(c_i), d) \simeq \mathrm{Hom}(\mathrm{colim}_{i \in I} F(c_i), d),$$

which implies the desired claim for F . The proof for the claim for G is completely analogous. \square

In particular, given a map $f : A \rightarrow B$ in Mod_G , we note that the kernel is the limit with respect to the following diagram

$$\begin{array}{ccc} & & 0 \\ & & \downarrow \\ A & \xrightarrow{f} & B \end{array}$$

and the cokernel is the colimit with respect to the diagram

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ \downarrow & & \\ 0 & & \end{array}$$

In particular, any functor that commutes with colimits will be right exact, and any functor that commutes with limits will be left exact. In particular as a consequence of Lemma 2.37, we deduce the following Corollary of Proposition 2.35.

Corollary 2.38. *For $H \subset G$ an inclusion of finite groups, the functors Ind_H^G and Res_H^G are exact.*

We also have the following basic consequence.

Corollary 2.39. *Suppose I is an injective H -module then $\mathrm{Ind}_H^G(I)$ is an injective G -module.*

Proof. This immediately follows from combining Remark 2.22 with Proposition 2.35. \square

We now have the following basic result, which is known as Schapiro's lemma, and will provide us our main source of acyclic resolutions of G -modules M .

Lemma 2.40. *For a subgroup $H \subset G$, there is a canonical isomorphism for all H -modules N*

$$H^i(G, \mathrm{Ind}_H^G(N)) \xrightarrow{\simeq} H^i(H, N).$$

Proof. Choose an injective resolution

$$(2.13) \quad 0 \rightarrow N \rightarrow I^0 \rightarrow I^1 \rightarrow \dots$$

of N as a H -module. Now apply the functor Ind_H^G ,

$$0 \rightarrow \mathrm{Ind}_H^G N \rightarrow \mathrm{Ind}_H^G I^0 \rightarrow \mathrm{Ind}_H^G I^1 \rightarrow \dots,$$

which, by Corollaries 2.39 and 2.38, we note is an injective resolution of $\mathrm{Ind}_H^G N$. Hence, after taking G -invariants, the resulting complex

$$(2.14) \quad (\mathrm{Ind}_H^G I^0)^G \rightarrow (\mathrm{Ind}_H^G I^1)^G \rightarrow \dots$$

computes $H^i(G, \mathrm{Ind}_H^G(N))$. However, now for any G -module N , we note that we have an identification $\mathrm{Ind}_H^G(N)^G \simeq N^H$. Indeed, this follows from identifying Ind_H^G with a subspace of functions $f : G \rightarrow N$, as in Remark 2.33. This tells us that (2.14) identifies with $(-)^H$ applied to (2.13), implying the desired claim after taking cohomology. \square

This gives us the following example of acyclic objects.

Definition 2.41. We say an object $M \in \mathrm{Mod}_G$ is induced if it is isomorphic to $\mathrm{Ind}_e^G(N)$ for N an abelian group. Here $e \in G$ is the identity element.

Remark 2.42. Suppose we have a subgroup $H \subset G$, and we take an induced module $\text{Ind}_{\{e\}}^G(N)$ for the group G . Then one can check that

$$\text{Res}_H^G \text{Ind}_{\{e\}}^G(N) \simeq \text{Ind}_{\{e\}}^H(N^{\oplus [G:H]}).$$

Indeed, giving a function $\phi : G \rightarrow N$ is the same as giving on each one of the cosets of H in G , which is the same as giving $[G : H]$ functions on H .

Such acyclic objects come up very naturally in the study of the group cohomology of Galois groups.

Now the following is a consequence of Lemma 2.40 and the fact that $H^i(\{e\}, M) = 0$ tautologically for any $i > 0$.

Corollary 2.43. *If M is an induced G -module then we have that*

$$H^i(G, M) = 0$$

for all $i > 0$.

This finally allows us to answer the question of how to explicitly compute $H^i(G, M)$ for a G -module M . Indeed, in light of Corollary 2.43 and 2.31 (2), we see that it suffices to resolve M by induced G -modules. To this end, we consider for all $n \geq 0$ the set of functions

$$\phi : G^{n+1} \rightarrow M$$

with G -action given by

$$(g \cdot \phi)(g_0, \dots, g_n) = g \cdot \phi(g^{-1} \cdot g_0, \dots, g^{-1} \cdot g_n).$$

We denote the set of all such functions by $C^n(G, M)$. This is equipped with a natural differential

$$(2.15) \quad d^n : C^n(G, M) \rightarrow C^{n+1}(G, M)$$

$$d^n(\phi)(g_0, \dots, g_{n+1}) = \sum_{i=0}^{n+1} (-1)^i \phi(g_0, \dots, \hat{g}_i, \dots, g_{n+1}),$$

where \hat{g}_j means you omit the coordinate. We can check that this does indeed have all the properties we would like for an acyclic resolution.

Exercise 2.44. *Show that the following is true.*

- (1) *Show that the G -module $C^n(G, M)$ is expressible as $\text{Ind}_e^G(C^n(G, M)_0)$, where $C^n(G, M)_0$ is the subset of $C^n(G, M)$ of functions for which $\phi(g_0, \dots, g_n) = 0$ when $g_0 \neq e$. In particular, we have that $C^0(G, M) = \text{Ind}_e^G(M)$ which using Frobenius reciprocity is equipped with a natural G -equivariant embedding $M \rightarrow \text{Ind}_e^G(M)$.*
- (2) *Check that map the d^n is indeed G -equivariant for the above G -action on $C^n(G, M)$.*
- (3) *Show that for all $n \geq 0$, we have that*

$$d^{n+1} \circ d^n = 0.$$

- (4) *Check that we have an exact complex of G -modules*

$$0 \rightarrow M \rightarrow C^0(G, M) \xrightarrow{d^0} C^1(G, M) \xrightarrow{d^1} \dots,$$

and deduce that we have an isomorphism

$$H^n(G, M) \simeq \text{Ker}((d^n)^G) / \text{Im}((d^{n-1})^G).$$

for all $n \geq 0$, where we set $(d^{-1})^G : 0 \rightarrow C^0(G, M)^G$.

(5) Show, for all $n \geq 0$, that we have an isomorphism

$$C^n(G, M)^G \simeq C(G^n, M),$$

where $C(G^n, M)$ denotes the space of all functions $\phi : G^n \rightarrow M$. Show that, under this isomorphism, we have an identification of

$$(d^n)^G : C(G^n, M) \rightarrow C(G^{n+1}, M)$$

with

(2.16)

$$(d^n)^G(\phi)(g_1, \dots, g_{n+1}) = g_1 \cdot \phi(g_2, \dots, g_n) + \sum_{i=1}^n (-1)^i \phi(g_1, \dots, g_i g_{i+1}, \dots, g_{n+1}) + (-1)^{n+1} \phi(g_1, \dots, g_n).$$

Remark 2.45. We call the functions $\phi(g_1, \dots, g_n) \in C(G^n, M)$ which lie in the kernel of $(d^n)^G$ cocycles. In particular the condition that

$$g_1 \cdot \phi(g_2, \dots, g_n) + \sum_{i=1}^n (-1)^i \phi(g_1, \dots, g_i g_{i+1}, \dots, g_{n+1}) + (-1)^{n+1} \phi(g_1, \dots, g_n) = 0$$

is known as the cocycle condition. Similarly, we call the functions in $\text{Im}((d^{n-1})^G)$ the coboundaries. This leads to the terminology that $H^n(G, M)$ is the quotient of the cocycles by the coboundaries in $C(G^n, M)$. The space of functions $C(G^n, M)$ or equivalently $C^n(G, M)^G$ by Exercise 2.31 (5) are what are known as cochains. If we compute using $C(G^n, M)$ we will say we are using *inhomogeneous* cochains and if we compute using $C^n(G, M)^G =: C^n(G, M)_{\text{hom}}$ we will say we are using *homogeneous* cochains. We see that the form of the cocycle condition and the form of the coboundaries depends on which type of cochains we are using, and, depending on the precise application, it will be more desirable to work with one or the other.

To illustrate the utility of these resolutions, we now give an explicit interpretation of $H^1(G, M)$ and $H^2(G, M)$.

Example 2.46. Using Exercise 2.31 and in particular Exercise 2.31 (4), we may identify a class in $H^1(G, M)$ with a function $\phi : G \rightarrow M$ which satisfies, for all $h \in G$, the cocycle condition

$$h \cdot \phi(g) - \phi(hg) + \phi(h) = 0,$$

as in (2.16) or equivalently,

$$h \cdot \phi(g) = \phi(hg) - \phi(h).$$

Moreover, it is a coboundary if and only if there exists $m \in M$ such that

$$\phi(g) = g \cdot m - m$$

for all $m \in M$. For $m \in M$, we write ϕ_m for the function defined by this relationship. In summary, we have an isomorphism

$$H^1(G, M) \simeq \{\phi : G \rightarrow M \mid h \cdot \phi(g) - \phi(hg) + \phi(h) = 0\} / (\phi_m, m \in M)$$

We now specialize to the case where $M = \mathbb{Z}$ is the trivial G -module. In this case, we see that $\phi_m = 0$ and we are simply looking at functions $\phi : G \rightarrow \mathbb{Z}$ such that $\phi(hg) = \phi(h) + \phi(g)$. In other words, homomorphisms, in summary we have

$$H^1(G, \mathbb{Z}) = \text{Hom}(G, \mathbb{Z}) \simeq \text{Hom}(G^{\text{ab}}, \mathbb{Z}).$$

This tells us that $H^1(G, \mathbb{Z})$ is dual as an abelian group to the abelianization G^{ab} of G . This is what was alluded to in the introduction, where there we were discussing homology which is the dual to the cohomology we are discussing here.

We can similarly find an interpretation for the H^2 .

Example 2.47. Suppose that M is finite. Then we claim that $H^2(G, M)$ can be interpreted as extensions

$$0 \rightarrow M \rightarrow E \rightarrow G \rightarrow 1$$

in the category of G -modules, where we note that E is it not necessarily abelian. In particular, it is the space of such extensions up to equivalence, where we say two such extensions are equivalent if there exists a commutative diagram

$$(2.17) \quad \begin{array}{ccccccc} 0 & \longrightarrow & M & \longrightarrow & E & \xrightarrow{\pi} & G \longrightarrow 1 \\ & & \downarrow \text{id}_M & & \downarrow & & \downarrow \text{id}_G \\ 0 & \longrightarrow & M & \longrightarrow & E' & \xrightarrow{\pi'} & G \longrightarrow 1. \end{array}$$

We note (e.g by the Snake Lemma (Lemma 2.20)) that this guarantees that $E \simeq E'$. However, even if we fix the isomorphism class of the central term, there may be multiple extensions. In particular, we note that there are $p - 1$ equivalent extensions of abelian groups

$$0 \rightarrow \mathbb{Z}/p\mathbb{Z} \rightarrow \mathbb{Z}/p^2\mathbb{Z} \rightarrow \mathbb{Z}/p\mathbb{Z} \rightarrow 0$$

given by sending $1 \mapsto ap$, where $a \in (\mathbb{Z}/p\mathbb{Z})^*$ is a unit. Indeed, if we consider $G = M = \mathbb{Z}/p\mathbb{Z}$ where the G -action is trivial then we have an isomorphism $H^2(G, M) \simeq \mathbb{Z}/p\mathbb{Z}$, where $(\mathbb{Z}/p\mathbb{Z})^* \subset \mathbb{Z}/p\mathbb{Z}$ corresponds to the extensions described above, and $0 \in \mathbb{Z}/p\mathbb{Z}$ corresponds to the split extension

$$0 \rightarrow \mathbb{Z}/p\mathbb{Z} \rightarrow (\mathbb{Z}/p\mathbb{Z})^{\oplus 2} \rightarrow \mathbb{Z}/p\mathbb{Z} \rightarrow 0.$$

To see why such extensions are parametrized by classes in $H^2(G, M)$, we choose a set-theoretic section $s : G \rightarrow E$ (e.g using Proposition 2.9). This gives rise to a function

$$\phi(g, h) = s(g)s(h)s(gh)^{-1}$$

which a priori defines a function $\phi : G^2 \rightarrow E$. However, now we note that if we apply the map $\pi : G \rightarrow E$ then this maps to 1, which implies that the function lands in $M \hookrightarrow E$. In particular, we get a well-defined function $\phi : G^2 \rightarrow E$ which will represent the class in $H^2(G, M)$. One can check that the associativity of the group law in E will guarantee that the function $\phi(g, h)$ satisfies the cocycle condition. Moreover, note that this a priori depends on the choice of section s . In particular, suppose we have two sections s and s' , and let ϕ' be the analogous function as constructed above. We may then consider the function

$$b(g) := s'(g)s(g)^{-1} \in \text{Ker}(\pi) = M.$$

Then one may check that

$$\phi'(g, h) = \phi(g, h) + g.b(h) - b(gh) + b(g)$$

where we note that the RHS is precisely given by applying $(d^1)^G$ to b . In particular, the class in $H^2(G, M)$ represented by $\phi(g, h)$ does not depend on s . Moreover, if we are given a section $s : G \rightarrow E$ and an equivalent extension given by a commutative diagram (2.17) that if we consider the induced section $G \xrightarrow{s} E \rightarrow E'$ the resulting function in $C(G^2, M)$ will be the same by the commutativity of the diagram. Conversely, we have the following.

Exercise 2.48. Suppose we are given a two cocycle $\phi(g, h) : G^2 \rightarrow M$ for $M \in \text{Mod}_G$ then we can produce an extension $0 \rightarrow M \rightarrow E \rightarrow G \rightarrow 0$, as follows. As a set, we define $E := M \times G$. However, we endow E with the binary operation

$$(m, g).(m', h) := (m + g.m' + \phi(g, h), gh).$$

Check the following, by using the two cocycle condition on M . Explicitly, for $g_1, g_2, g_3 \in G$ this says that

$$(2.18) \quad g_1\phi(g_2, g_3) - \phi(g_1g_2, g_3) + \phi(g_1, g_2g_3) - \phi(g_1, g_2) = 0,$$

as in (2.16).

- (1) Show that the element $(-\phi(e, e), e)$ is a two side identity element for the group operation described above.
- (2) Show that the binary operation is associative.
- (3) Check that $(-g^{-1}.m - \phi(g^{-1}, g) - \phi(e, e), g^{-1})$ is a 2-sided inverse to (m, g) .

In particular, by (1)-(3) E is a group. We note that there are natural maps

$$\begin{aligned} E &\rightarrow G \\ (m, g) &\mapsto g \end{aligned}$$

and natural maps

$$\begin{aligned} M &\rightarrow E \\ m &\mapsto (m - \phi(e, e), e) \end{aligned}$$

which will sit in a short exact sequence

$$0 \rightarrow M \rightarrow E \rightarrow G \rightarrow 0$$

of groups.

- (4) Suppose that $\phi'(g, h) = \phi(g, h) + g.b(h) - b(gh) + b(g)$ for some function $b : G \rightarrow M$ and let E' be the group attached to ϕ' as above. Show that the map

$$\alpha : E \rightarrow E'$$

defined by $(m, g) \mapsto (m - b(g), g)$ is an isomorphism and that we have a commutative diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & M & \longrightarrow & E & \longrightarrow & G \longrightarrow 1 \\ & & \downarrow \text{id}_M & & \downarrow \alpha & & \downarrow \text{id}_G \\ 0 & \longrightarrow & M & \longrightarrow & E' & \longrightarrow & G \longrightarrow 1. \end{array}$$

Before returning to an abstract study of group cohomology, let's briefly reconnect this to the arithmetic of fields that we want to study.

Theorem 2.49. (Hilbert Theorem 90) Let L/K be a Galois extension we consider the multiplicative group $L^* \in \text{Mod}_{\text{Gal}(L/K)}$ then we have an isomorphism

$$H^1(\text{Gal}(L/K), L^*) \simeq 0$$

Proof. We first start out with the following basic lemma.

Lemma 2.50. Let $\sigma_1, \dots, \sigma_n$ be distinct automorphisms of a field E . Then if $c_1, \dots, c_n \in E$ such that

$$c_1\sigma_1(x) + \dots + c_n\sigma_n(x) = 0$$

for all $x \in E$ then $c_i = 0$.

Proof. Without loss of generality, we assume that all the $c_i \neq 0$. We proceed by induction. If $n = 1$ then by evaluating on $x = 1$ we deduce that $c_1 = 0$ showing the claim. Let $n > 1$. Replacing x by ax for any $a \in E$, we obtain

$$c_1\sigma_1(a)\sigma_1(x) + \dots + c_n\sigma_n(a)\sigma_n(x) = 0$$

We may now multiply the equation $\sum_{i=1}^n c_i\sigma_i(x)$ equation by $\sigma_n(a)$ and subtract the result off from the previous equation to deduce that

$$c_1(\sigma_1(a) - \sigma_n(a))\sigma_1(x) + c_{n-1}(\sigma_{n-1}(a) - \sigma_n(a))\sigma_{n-1}(x) = 0.$$

However, since the σ_i are distinct, we may choose a such that $\sigma_1(a) - \sigma_n(a) \neq 0$. In particular, our inductive hypothesis tells us that $c_1 = 0$, and then we may apply our inductive hypothesis again, to show that the remaining $c_i = 0$. \square

Now, using the interpretation of H^1 provided in Example 2.46 and switching to multiplicative notation, we deduce that we are tasked with showing that, for every function $\phi : \text{Gal}(L/K) \rightarrow L^*$ satisfying the condition that

$$(2.19) \quad \phi(\sigma \circ \tau) = \phi(\sigma)\sigma(\phi(\tau))$$

for all $\sigma, \tau \in \text{Gal}(L/K)$ that there exists $\gamma \in L^*$ such that

$$\phi(\sigma) = \sigma(\gamma)\gamma^{-1}.$$

To see this, note that by Lemma 2.50,

$$\sum_{\tau \in \text{Gal}(L/K)} \phi(\tau)\tau(-) : L \rightarrow L$$

is not the zero map, since $\phi(\tau) \in L^*$ is non-zero by definition. In particular, there exists some $l \in L^*$ such that

$$\gamma^{-1} := \sum_{\tau \in \text{Gal}(L/K)} \phi(\tau)\tau(l) \in L^*$$

We claim that this is the sought after γ . Indeed, for all $\sigma \in \text{Gal}(L/K)$, we have that

$$\sigma(\gamma)^{-1} = \sum_{\tau \in \text{Gal}(L/K)} \sigma(\phi(\tau))\sigma(\tau(l))$$

which we may rewrite using (2.19) as

$$\sum_{\tau \in \text{Gal}(L/K)} \phi(\sigma)^{-1}\phi(\sigma \circ \tau)\sigma(\tau(l)) = \phi(\sigma)^{-1} \sum_{\tau \in \text{Gal}(L/K)} \phi(\sigma \circ \tau)\sigma(\tau(l)) = \phi(\sigma)^{-1}\gamma^{-1},$$

which gives us

$$\phi(\sigma) = \sigma(\gamma)\gamma^{-1},$$

as desired. □

In the additive case, we have a much more definitive answer.

Exercise 2.51. *Let L/K be a Galois extension. Consider the additive group $(L, +) \in \text{Mod}_{\text{Gal}(L/K)}$ show the following is true.*

- (1) *Show, using the explicit description of H^1 provided in Example 2.46, that one has $H^1(\text{Gal}(L/K), L) = 0$ (Hint: Your replacement for Lemma 2.50 should be normal basis theorem which says that there exists $\alpha \in L$ such that its conjugates under $\text{Gal}(L/K)$ form a basis for L as a K -vector space).*
- (2) *Prove that L is actually an induced $\text{Gal}(L/K)$ -module and conclude that*

$$H^i(\text{Gal}(L/K), L) = 0$$

for all $i \geq 1$.

2.2.3. Aside on the Brauer Group. In light of Exercise 2.51 and Theorem 2.49, one might wonder about $H^2(\text{Gal}(L/K), L^*)$? In particular, is this always trivial? The answer is no and the structure of this cohomology group is one of the most important invariants of the extension L/K . To explain this, we consider the following a priori unrelated notion.

Definition 2.52. Let k be a field.

- (1) A (not necessarily non-commutative) ring D is said to be a division algebra if every non-zero element $d \in D$ has a two sided inverse d^{-1} .
- (2) We say that a division algebra D is a division algebra over k if its center is isomorphic to k . In particular, D is a module over k , and we say it is finite-dimensional over k if it is finite-dimensional as a vector space.

- (3) A central simple algebra over k is a (not necessarily non-commutative) ring A with no non-trivial two sided ideals and center isomorphic to k .
- (4) We note that a central simple algebra has the structure of a vector space over k , by multiplication by the center, and we say that A is a finite dimensional central simple algebra if it is finite-dimensional as a vector space over k .
- (5) We note that given a finite dimensional central simple algebra A over k . We can define another finite dimensional central simple algebra A over k , denoted A^{op} , by reversing the order of the multiplication.

Observe that a division algebra D over k is a particular example of a central simple algebra over k . Indeed, any non-zero right or left ideal $I \subset D$ must contain 1 by the existence of two sided inverses and therefore is equal to D . We can push this even further.

Example 2.53. Let $M_n(D)$ be the matrix algebra of a division algebra D over k . We claim that this is a central simple algebra over k . We need to check that it has no non-zero two sided ideals and that its center is equal to k . To see this, as in usual linear algebra we note that we have matrices $E_{ij} \in M_n(D)$ which are 1 in the i th row and j th column and 0 everywhere else. Suppose we have $X \in M_n(D)$ with entries given by (X_{ij}) . Then the relationship

$$E_{ij}X = XE_{ij}$$

will tell us that $x_{ij} = 0$ unless $i = j$. In particular, X is a diagonal matrix. If X acts on the right it will scale the columns of a matrix, and if it acts on the left then it will scale the rows. This forces the relationship that all the diagonal entries of X are the same. In particular, X lies in the image of the natural map $D \rightarrow M_n(D)$ given by the diagonal embedding. However, now it clearly must lie in the image of the center of D , so that we have an isomorphism

$$(2.20) \quad Z(M_n(D)) \simeq Z(D)$$

of centers. Now by assumption that D is a division algebra over k , we have an isomorphism $Z(D) \simeq k$, by the assumption that D is a division algebra over k .

For the statement on two-sided ideals, we suppose X is a non-zero matrix in some two-sided ideal $I \subset M_n(D)$ with non-zero entry x_{pq} for some $1 \leq p, q \leq n$. Then we have that

$$E_{ip}XE_{qj} = x_{pq}E_{ij}$$

lies inside I for all $1 \leq i, j \leq n$. By acting via the diagonal matrices, this tells us that I contains $(x_{pq})E_{ij}$, where (x_{pq}) is the two sided ideal generated by x_{pq} inside D , which must be given by (1) as explained above. Since i and j were arbitrary, this tells us that $I = M_n(D)$, as desired.

In fact, this example captures all finite dimensional central simple algebras over a field k (In fact, the finite dimensionality hypothesis is also not necessary, but we do not address this for simplicity).

Theorem 2.54. (Wedderburn's Theorem) *Let A be a finite dimensional central simple algebra over k then there exists $n \geq 1$ and a finite dimensional division algebra D over k such that*

$$M_n(D) \simeq A.$$

Proof. We may choose a non-zero minimal left ideal $I \subset A$. Then the left multiplication of A on I defines a natural non-zero map

$$A \rightarrow \text{End}_k(I)$$

which will be necessarily injective. Indeed, the kernel of this map generates a two-sided ideal which must therefore be 0 or (1) by the simplicity of A . Let D be the centralizer of A in $\text{End}_k(I)$. We claim that this is a division algebra. Indeed, by definition we have an identification $D = \text{End}_A(I)$, and any $f : I \rightarrow I \in \text{End}_A(I)$ must be injective, since otherwise its kernel would generate a non-zero minimal ideal of A properly contained in I . However, it must also be surjective by rank-nullity (note I is a finite dimensional k -vector space and f is a k -linear map). Therefore, f is invertible. In

particular, this endows I with the structure of a left D -module, which must necessarily be free, since, as noted above, any non-zero ideal of D is isomorphic D , so that $I \simeq D^{\oplus n}$. Now, by Lemma 2.55 below, the centralizer of D in $\text{End}_k(I)$ is isomorphic to A . In particular, this gives an identification $M_n(D^{\text{op}}) \simeq \text{End}_D(I) \simeq A$, as desired. By the finite-dimensionality of A , the division algebra D must be finite dimensional, and by (2.20) it must have center equal to k . \square

We used the following Lemma in the proof, which is a hard exercise in linear algebra.

Lemma 2.55. *Let A be a k -algebra and V be a semisimple A -module such that the map*

$$A \rightarrow \text{End}_k(V)$$

is injective. Then the double centralizer of A in $\text{End}_k(V)$ is equal to A .

Proof. See [Mil20a, Theorem 1.14]. \square

Indeed, this tells us that central simple algebras are a straightforward extension of division algebras given by taking matrix algebras. However, we have yet to provide any interesting examples of division algebras.

Example 2.56. (1) If $D = k$ then it is of course a division algebra over k .

- (2) The first interesting example of a non-commutative division algebra is the Hamilton quaternions. In particular, we set \mathbb{H} to be the \mathbb{R} -algebra $\mathbb{R} \oplus \mathbb{R}i \oplus \mathbb{R}j \oplus \mathbb{R}k$, where i, j, k are subject to the relationships

$$\begin{aligned} i^2 = j^2 = k^2 &= -1 \\ ij = -ji &= k. \end{aligned}$$

Given an element $q = a + ib + cj + dk$, we may define its conjugate $\bar{q} = a - bi - cj - dk$. We have an equality

$$N(q) := q\bar{q} = a^2 + b^2 + c^2 + d^2 \in \mathbb{R}.$$

so that $\bar{q}/N(q)$ gives a well-defined inverse to q . In particular, \mathbb{H} has the structure of a division algebra! Moreover, one easily checks the center is equal to \mathbb{R} via the embedding $\mathbb{R} \rightarrow \mathbb{H}$ given by the first coordinate, which extends to an embedding $\mathbb{C} \rightarrow \mathbb{H}$ via the first and second coordinate. The field \mathbb{C} defines a maximal commutative subfield of \mathbb{H} .

- (3) A more interesting family of examples occurs in the case of a finite cyclic extension L/K . We write σ for the generator of the Galois group. For $a \in K^*$, we define the cyclic algebra

$$A = (L/K, \sigma, a)$$

as follows. We consider the K -algebra

$$A := \bigoplus_{i=0}^{n-1} Lu^i$$

generated by L and the symbol u subject to the relationship that

$$u^n = a,$$

and, for all $x \in L$, we have that

$$ux = \sigma(x)u.$$

We can check that this does indeed give a central simple algebra over K , and in certain good situations also division algebras.

Exercise 2.57. *Show the following claims.*

- (1) (**Basic properties**)

- (a) *Show that $A = (L/K, \sigma, a)$ is a central simple K -algebra of dimension n^2 over K .*
 (b) *Show that the natural inclusion $L \hookrightarrow A$ defines a maximal commutative subfield of A .*

(c) Prove that

$$A \otimes_K L \cong M_n(L).$$

of central simple L -algebras. (Hint: Recall that we have an isomorphism $L \otimes_K L \simeq \prod_{\tau \in \text{Gal}(L/K)} L$ for any Galois extension L/K . In the case of a cyclic extension, this takes the form of sending $x \otimes y \mapsto (\sigma^i(x)y)_{i=0}^{n-1}$ in the case of a cyclic extension. Use this map to define the isomorphism $A \otimes_K L \simeq M_n(L)$.)

(2) (**Relationship to the Hamilton Quaternions**) Let $K = \mathbb{R}$ and $L = \mathbb{C}$, and let σ be complex conjugation. Consider the cyclic algebra

$$A = (\mathbb{C}/\mathbb{R}, \sigma, -1)$$

(a) Let $u \in A$ be the adjoined generator, so that $u^2 = -1$ and $uz = \bar{z}u$ for $z \in \mathbb{C}$. Define elements

$$i := \sqrt{-1} \in \mathbb{C} \subset A, \quad j := u, \quad k := ij.$$

Show that $i^2 = j^2 = k^2 = -1$ and that

$$ij = k, \quad ji = -k,$$

(b) Show that every element of A can be written uniquely as

$$a + bi + cj + dk \quad (a, b, c, d \in \mathbb{R}),$$

and conclude that A is isomorphic to the classical Hamilton quaternion division algebra \mathbb{H} .

(3) (**The Splitting Criterion.**) We will now be interested in showing the following Theorem. We let $\text{Nm}_{L/K} : L^* \rightarrow K^*$ denote the norm map.

Theorem 2.58. *The central simple algebra $A = (L/K, \sigma, a)$ is isomorphic to $M_n(K)$ if and only if $a = \text{Nm}_{L/K}(b)$ for some $b \in L^*$.*

Assume that $a = \text{Nm}_{L/K}(b)$, for some $b \in L^\times$.

(a) Set $v := b^{-1}u \in A$. Compute v^i for $i = 0, \dots, n-1$ and show that $v^n = 1$.

(b) Consider the element $e = \sum_{i=0}^{n-1} v^i \in A$. Show that Ae is a nonzero left ideal of A of K -dimension n . Deduce that $A \cong M_n(K)$, by arguing similarly to the proof of Wedderburn's theorem. Conclude the converse direction of Theorem 2.58.

We now establish the forward direction. Suppose that $A \simeq M_n(K)$.

(c) Let V be a simple left A -module. Show that $\dim_K V = n$ and that, via the embedding $L \hookrightarrow A$, the space V becomes a 1-dimensional vector space over L .

(d) Choose $0 \neq v \in V$. Since $u^n = a \in K \subset L$, show that

$$u^n v = av.$$

(e) Because V is 1-dimensional over L , there exists $\lambda \in L^\times$ with $uv = \lambda v$. Using the relation $ux = \sigma(x)u$, prove that

$$u^n v = \lambda \sigma(\lambda) \cdots \sigma^{n-1}(\lambda) v = \text{Nm}_{L/K}(\lambda) v.$$

(f) Combine the two previous steps to deduce that $a = \text{Nm}_{L/K}(\lambda)$.

(4) Combine Theorem 2.58 with Wedderburn's theorem to conclude that $A = (L/K, \sigma, a)$ is a division algebra if and only if $a \neq \text{Nm}_{L/K}(b)$ for some $b \in L^*$.

In particular, we see that there is an interesting relationship between the structure of these division algebras and the surjectivity of the maps $\text{Nm}_{L/K} : L^* \rightarrow K^*$, which is measured by the group $K^*/\text{Nm}_{L/K}(K^*)$, at least in the case of a cyclic extension. Indeed, we see that if $L = \mathbb{C}$ and $K = \mathbb{R}$ then we have that $\mathbb{R}^*/\text{Nm}_{L/K}(\mathbb{C}^*) = \mathbb{R}^*/\mathbb{R}_{>0} \simeq \langle -1 \rangle$. Moreover, the non-trivial element -1 gives rise to a the non-trivial division algebra \mathbb{H} over the field \mathbb{R} . As we will see later,

this is because the group $K^*/\text{Nm}_{L/K}(K^*)$ classifies such division algebras in the case of a cyclic extension. This suggested relationship will come full circle after we discuss Tate cohomology later in the course. For now, we begin by linking the classification of division algebras with the cohomology group $H^2(\text{Gal}(L/K), L^*)$. To this aim, we introduce the following.

Definition 2.59. Fix a field K , we define the following.

- (1) We say two finite dimensional central simple algebras A, B over K are equivalent $A \sim B$ if there exists a finite-dimensional division algebra D over K and positive integers $n, m \geq 1$ such that

$$A \simeq M_n(D)$$

and

$$B \simeq M_m(D),$$

where we note that such a D always exists by Wedderburn's Theorem (Theorem 2.54). We denote the equivalence class of such a finite dimensional central simple algebra A over k by $[A]$.

- (2) We write $\text{Br}(k)$ for the set of equivalence classes of finite central simple algebras over k .
- (3) For a finite extension L/K , we write $\text{Br}(L/K) \subset \text{Br}(K)$ for the subset of $[A]$ such that $A \otimes_K L \simeq M_n(L)$ for some $n \geq 1$. This is referred to as the Brauer group of the finite extension L/K .

Remark 2.60. We note that, every finite-dimensional division algebra D over K , gives rise to a class in $\text{Br}(K)$. In particular, by Wedderburn's Theorem (Theorem 2.54), if we vary over the isomorphism classes of such division algebras D over K , this gives rise to every class in $\text{Br}(K)$. In particular, we see that we have bijection of sets:

$$\text{Br}(K) \leftrightarrow \{D \text{ a finite-dimensional division algebra over } K\} / \simeq .$$

Similarly, for a finite extension L/K , we say that a division algebra D splits over K if there exists $n \geq 1$ and an isomorphism

$$D \otimes_K L \simeq M_n(L),$$

and we similarly have a bijection

$$\text{Br}(L/K) \leftrightarrow \{D \text{ a finite-dimensional division algebra over } K \text{ split over } L\} / \simeq$$

In fact, every finite dimensional division algebra D/K can be shown to split over some finite extension L . This is given by a maximal commutative subfield $L \hookrightarrow D$ (cf. Exercise 2.57 (1b,1c)). This gives us an equality

$$(2.21) \quad \text{Br}(K) := \varinjlim_{L/K} \text{Br}(L/K),$$

where L/K ranges over all finite extensions of K .

The terminology "group" here is not just for show.

Exercise 2.61. Let K be a field. Show that the following is true.

- (1) If A, B are two finite dimensional central simple algebras over K . Show that $A \otimes_K B$ is again a finite dimensional central simple algebra over K .
- (2) Check that the map

$$\begin{aligned} \text{Br}(K) \times \text{Br}(K) &\rightarrow \text{Br}(K) \\ ([A], [B]) &\mapsto [A \otimes_K B] \end{aligned}$$

gives rise to a well-defined binary, commutative, and associative operation on the set of equivalence classes of finite-dimensional central simple algebras over K with identity element K .

(3) Given a finite-dimensional central simple algebra A of dimension n over K , show that

$$A \otimes A^{\text{op}} \simeq M_n(K).$$

Conclude that $\text{Br}(K)$ is a commutative group. For a finite extension L/K , prove that $\text{Br}(L/K) \subset \text{Br}(K)$ is a subgroup.

We now want to connect the group $\text{Br}(L/K)$ to the group cohomology $H^2(\text{Gal}(L/K), L^*)$ for a finite Galois extension L/K . We may do this through a generalization of Example 2.56 (3).

Example 2.62. We let L/K be a finite Galois extension. We consider the L -algebra

$$\bigoplus_{\sigma \in \text{Gal}(L/K)} x_{\sigma} L$$

with multiplication for $\alpha \in L^{*2}$ defined by

$$(2.22) \quad \alpha x_{\sigma} = x_{\sigma} \sigma(\alpha)$$

and

$$x_{\sigma} x_{\tau} = \phi(\sigma, \tau) x_{\sigma\tau},$$

for some $\phi(\sigma, \tau) \in L^*$. The associativity of the multiplication forces the relationship

$$(2.23) \quad \rho(\phi(\sigma, \tau)) \phi(\rho\sigma, \tau) = \phi(\rho, \sigma) \phi(\rho\sigma, \tau)$$

for all $\rho, \sigma, \tau \in \text{Gal}(L/K)$, which we readily identify with the condition that $\phi : \text{Gal}(L/K)^2 \rightarrow L^*$ is an inhomogeneous cocycle in the multiplicative notation, as described in the additive notation in (2.18). Given a cocycle $\phi : \text{Gal}(L/K)^2 \rightarrow L^*$, we denote this central simple K -algebra by $A := (L/K, \phi)$. It is referred to as the cross-product algebra with respect to ϕ . By using the isomorphism, $L \otimes_K L \simeq \prod_{\tau \in \text{Gal}(L/K)} L$ one may check that

$$A \otimes_K L \simeq M_n(L)$$

(cf. Exercise 2.57 (1c)). In particular, this gives rise to a well-defined element $[(L/K, \phi)] \in \text{Br}(L/K)$! We now would like to claim that we can upgrade this to an isomorphism

$$H^2(\text{Gal}(L/K), L^*) \simeq \text{Br}(L/K)$$

of abelian groups. To this aim, we will first need to check that we have a well defined map

$$H^2(\text{Gal}(L/K), L^*) \rightarrow \text{Br}(L/K)$$

$$\phi \mapsto [(L/K, \phi)].$$

In other words, we need to check if we multiply ϕ by a coboundary

$$\frac{\sigma(b(\tau))b(\sigma)}{b(\sigma\tau)}$$

for some function $b : \text{Gal}(L/K) \rightarrow L^*$ to get some new ϕ' then we have an isomorphism

$$(L/K, \phi) \simeq (L/K, \phi')$$

of central simple algebras over K . We may do this as follows. We define a natural map

$$\begin{aligned} \Phi_b : \bigoplus_{\sigma} x_{\sigma} L &\rightarrow \bigoplus_{\sigma} x'_{\sigma} L \\ x_{\sigma} &\mapsto b(\sigma) x_{\sigma'}, \end{aligned}$$

²Note that we have put the copy of L on the right this time, so we need to apply $(-)^{\text{op}}$ when comparing with Example 2.56 (3)!

which, since $b(\sigma) \in L^*$ will define an isomorphism, assuming that it respects the multiplication. To see what this means, we note that

$$\Phi_b(x_\sigma x_\tau) = b(\sigma\tau)\phi(\sigma, \tau)x'_{\sigma\tau}$$

and that

$$\Phi_b(x_\sigma)\Phi_b(x_\tau) = b(\sigma)x'_\sigma b(\tau)x'_\tau$$

and by (2.22) the RHS identifies with

$$b(\sigma)\sigma(b(\tau))\phi'(\sigma, \tau)x'_{\sigma\tau}.$$

In particular, if we have that $\Phi_b(x_\sigma x_\tau) = \Phi_b(x_\sigma)\Phi_b(x_\tau)$, we recover precisely the relationship

$$\frac{\sigma(b(\tau))b(\sigma)}{b(\sigma\tau)}\phi'(\sigma, \tau) = \phi(\sigma, \tau),$$

which was precisely the condition that ϕ and ϕ' differ by a coboundary. In summary, we see that we have a well-defined map

$$(2.24) \quad H^2(\text{Gal}(L/K), L^*) \rightarrow \text{Br}(L/K).$$

We now come to the key claim which gives us the desired link between the Brauer group and the group cohomology $H^2(\text{Gal}(L/K), L^*)$.

Theorem 2.63. *For L/K a finite Galois extension, the natural map (2.24) is an isomorphism of groups.*

Proof. (Proof Sketch) Giving a complete proof of this fact, will take us to far a field. Instead, we content ourselves with explaining how to construct an inverse map. To do this, we will invoke the following result.

Theorem 2.64. (Stokelm-Noether Theorem) *Let k be a field and let $f, g : A \rightarrow B$ be a morphism of k -algebras. Suppose that A over k^3 and that B is central simple over k . Then there exists an invertible $b \in B$ such that $f(a) = bg(a)b^{-1}$.*

Proof. See [Mil20a, Theorem 2.10]. □

We now start with a class in $\text{Br}(L/K)$. By Remark 2.60, this will be represented by a finite dimensional division algebra D/K which is split over L . In particular, there will be an isomorphism

$$\psi : M_n(L) \xrightarrow{\cong} D \otimes_K L.$$

Each $\sigma \in \text{Gal}(L/K)$ will act on the RHS, this will define a natural map

$$\text{Gal}(L/K) \rightarrow \text{Aut}_L(M_n(L))$$

$$\sigma \mapsto \psi^{-1} \circ (\text{id} \otimes \sigma) \circ \psi,$$

However, by Theorem 2.64, we have an isomorphism $\text{Aut}_L(M_n(L)) \simeq \text{PGL}_n(L)$. Here $\text{PGL}_n(L)$ is the group defined by the short exact sequence

$$(2.25) \quad 0 \rightarrow L^* \rightarrow \text{GL}_n(L) \rightarrow \text{PGL}_n(L) \rightarrow 0,$$

where $\text{GL}_n(L)$ is the set of $n \times n$ invertible matrices and $L^* \rightarrow \text{GL}_n(L)$ maps via the diagonal matrices. In particular, Theorem 2.64 tells us that we have a surjective map $\text{GL}_n(L) \rightarrow \text{Aut}_L(M_n(L))$ given by conjugation and it is easy to check the kernel will be the diagonal matrices. We therefore have a map

$$\text{Gal}(L/K) \rightarrow \text{Aut}_L(M_n(L)) \simeq \text{PGL}_n(L),$$

³ie it is k -algebra with no non-trivial two sided ideals, but its center is not necessarily k .

and one may verify that this defines a 1-cocycle in the group cohomology $H^1(\text{Gal}(L/K), \text{GL}_n(L))^4$. Attached to the sequence (2.25), by an analogue of Proposition 2.29 one obtains a boundary map

$$\delta : H^1(\text{Gal}(L/K), \text{PGL}_n(L)) \rightarrow H^2(\text{Gal}(L/K), L^*),$$

and the image of the 1-cocycle will be the desired inverse. \square

We now have a good feeling for the structure of the cohomology groups $H^i(G, M)$, so we will return to verifying some additional functorialities of group cohomology in the finite case before proceeding to treat profinite groups.

2.2.4. Additional Functoriality. We already saw that if we have a map $f : M \rightarrow N$ of G -modules that we obtain a well-defined functor

$$H^i(f) : H^i(G, M) \rightarrow H^i(G, N)$$

on the cohomology groups. We now want to ask about functoriality with respect to a homomorphism $\alpha : G \rightarrow G'$ of groups. To this end, we have the following definition.

Definition 2.65. Let G, G' be finite groups and $M \in \text{Mod}_G$ and $M' \in \text{Mod}_{G'}$. Suppose that we have a homomorphism $\alpha : G' \rightarrow G$ and $\beta : M \rightarrow M'$. We say that these are compatible if

$$\beta(\alpha(g').m) = g'.\beta(m)$$

for all $g' \in G'$ and $m \in M$.

Now in this situation, we construct a natural map $H^i(G, M) \rightarrow H^i(G', M')$.

Construction 2.66. Suppose we are in the situation of Definition 2.65 then we claim that we obtain a map

$$(2.26) \quad H^i(G, M) \rightarrow H^i(G', M')$$

as follows. We first have a map

$$H^i(G, M) \rightarrow H^i(G', M),$$

where M is regarded as a G' -module via the map $\alpha : G' \rightarrow G$. In terms of the description of cohomology given in 2.31 (4), this may be described in terms of the restriction map

$$C(G^n, M) \rightarrow C((G')^n, M)$$

taking a function $G^n \rightarrow M$ to the function $(G')^n \xrightarrow{\alpha^n} G^n \rightarrow M$. In particular, one checks that this commutes in the obvious sense with the differentials (2.15), giving rise to a natural map

$$H^i(G, M) \rightarrow H^i(G', M)$$

by taking cohomology. We then compose this with the natural map

$$H^i(G', M) \rightarrow H^i(G', M')$$

induced by $H^i(\beta)$ or equivalently the map induced by looking at the natural map $C(G^n, M) \rightarrow C(G^n, M')$ induced by β' and taking cohomology.

Now we study various examples of this construction, where it gives rise to various important maps.

⁴We note that we only defined group cohomology for abelian groups with an action of a (possibly non-abelian) group. However, with a bit of care one may check that the discussion extends to (possibly) non-abelian groups with an action of a (possibly) non-abelian group. For now, we ask the reader to suspend disbelief.

Example 2.67. Consider a subgroup $H \subset G$. We specialize (2.66) to the case where $M' = M$, β is the identity map, and $\alpha : H \rightarrow G$ is the inclusion of the subgroup. Then we obtain a natural map

$$\text{Res}_H^G : H^i(G, M) \rightarrow H^i(H, \text{Res}_H^G(M))$$

known as the restriction maps. Alternatively, we may construct this as follows. We consider the natural adjunction map

$$M \rightarrow \text{Ind}_H^G \text{Res}_H^G(M)$$

given by applying Proposition 2.35 to the identity map. We then obtain a map

$$H^i(G, M) \rightarrow H^i(G, \text{Ind}_H^G \text{Res}_H^G(M)) \simeq H^i(G, \text{Res}_H^G(M)),$$

where the last isomorphism is Lemma 2.40.

We similarly obtain the following dual notion, which comes from the alternative description of the restriction map in 2.67 using Schapiro's Lemma and the adjunction morphisms of Proposition 2.35.

Example 2.68. For M a G -module, we consider the natural map

$$\text{Ind}_H^G \text{Res}_H^G(M) \rightarrow M$$

given by Proposition 2.35. By Lemma 2.40, this gives rise to a natural map

$$\text{CoRes}_H^G : H^i(H, \text{Res}_H^G(M)) \xrightarrow{\simeq} H^i(G, \text{Ind}_H^G \text{Res}_H^G(M)) \rightarrow H^i(G, M)$$

known as the corestriction homomorphism. This definition might appear a bit obtuse as it was constructed using Schapiro's Lemma. To further elucidate this, we first ask what is the induced map for $i = 0$. It is a map of the form

$$M^H \rightarrow M^G,$$

which may be described as follows.

Definition 2.69. For $M \in \text{Mod}_G$, we define the norm map

$$\begin{aligned} \text{Nm}_{G/H} : M^H &\rightarrow M^G \\ m &\mapsto \sum_{[g] \in G/H} g.m, \end{aligned}$$

where the sum runs over a set of left coset representatives of G/H .

We may now use this map to give an alternative construction of CoRes_H^G . We do this by choosing a resolution $M \rightarrow I_*$ which is acyclic for M as both a H and a G -module (e.g if M is induced by Remark 2.42), and then looking at the induced map

$$\begin{array}{ccccc} I_0^H & \xrightarrow{(d^0)^H} & I_1^H & \xrightarrow{(d^1)^H} & \dots \\ \downarrow \text{Nm}_{G/H} & & \downarrow \text{Nm}_{G/H} & & \\ I_0^G & \xrightarrow{(d^0)^G} & I_1^G & \xrightarrow{(d^1)^G} & \dots \end{array}$$

and passing to cohomology. Indeed, one may see this from using that the above construction of CoRes_H^G on $i = 0$ agrees with $\text{Nm}_{G/H}$ and the fact that CoRes_H^G as constructed above commutes with the natural boundary maps

$$\delta_i : H^i(G, C) \rightarrow H^{i+1}(G, A)$$

for an exact triangle of $0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$ of G -modules. We may use this perspective to also compute in a different way. In particular, we consider the map

$$\text{cor} : C^n(H, M)^H \rightarrow C^n(G, M)^G$$

defined by

$$(2.27) \quad \text{cor}(\phi)(x_0, \dots, x_n) = \sum_{[g] \in G/H} g\phi(g^{-1}x_0gx_0^{-1}, \dots, gx_ngx_n^{-1}).$$

and considered the induced map on cohomology, which we easily verify is well-defined. One can indeed check this also agrees with CoRes_H^G by observing that it gives the norm map in degree 0 and it respects the boundary maps δ_i in an obvious way, as before, by using the dimension shifting principle mentioned in Remark 2.36.

The corestriction and restriction homomorphism are very useful tools for gaining some basic insight into the structure of the groups $H^i(G, M)$. In particular, we have the following.

Lemma 2.70. *Suppose $H \subset G$ is a subgroup of a finite group G . Then the natural map*

$$\text{CoRes}_H^G \circ \text{Res}_H^G : H^i(G, M) \rightarrow H^i(G, M)$$

is given by multiplication by $[G : H]$.

Proof. We recall from the proof of Proposition 2.35 that the natural adjunction map

$$M \rightarrow \text{Ind}_H^G \text{Res}_H^G M$$

is given by

$$m \mapsto \sum_{[g] \in G/H} [g^{-1}] \otimes g.m,$$

where the sum is over coset representatives $[g]$ of G/H for $i \in I$. The natural adjunction map

$$\text{Ind}_H^G \text{Res}_H^G M \rightarrow M$$

is given by

$$\sum_{[g] \in G/H} [g] \otimes m_{[g]} \mapsto \sum_{g \in G} g.m_{[g]}.$$

In particular, we see that the composite

$$M \rightarrow \text{Ind}_H^G \text{Res}_H^G M \rightarrow M$$

is given by

$$m \mapsto \sum_{[g] \in G/H} m = [G : H]m.$$

Therefore, by the description of $\text{Cor} \circ \text{Res}$ provided in Examples 2.67 and 2.68, this identifies with the natural map on $H^i(G, M)$ induced by multiplication by $[G : H]$ on M . \square

We now deduce the following nice consequence of this.

Corollary 2.71. *For G a finite group, the cohomology groups*

$$H^i(G, M)$$

are torsion of order dividing $|G|$ for $i \geq 1$.

Proof. We apply lemma 2.70 to the case where $H = \{e\}$ is the trivial group. In this case, we observe that $\text{Cor} \circ \text{Res}$ is given by multiplication by $|G|$ on $H^i(G, M)$. On the other hand, it factors through

$$H^i(G, M) \rightarrow H^i(G, \text{Ind}_H^G \text{Res}_H^G(M)) \simeq H^i(\{e\}, \text{Res}_H^G(M)) \rightarrow H^i(G, M).$$

However, $H^i(\{e\}, \text{Res}_H^G(M)) = 0$ tautologically. \square

By combining this with Theorem 2.63, we have the following consequence, which is a priori not clear from the definition of the Brauer group (Definition 2.59) and its group structure (Exercise 2.61).

Corollary 2.72. *Let L/K be a finite Galois extension, and let D be a finite dimensional division algebra over K of dimension n which is split over L . Then we have an isomorphism*

$$D^{\otimes_K [L:K]} \simeq M_{n[L:K]}(K)$$

of central simple algebras over K .

Another useful consequence of this is the following acyclicity result.

Lemma 2.73. *For G a finite group and let \mathbb{Q} be equipped with the trivial G -action then it is acyclic in the sense of 2.31. In particular, we have that*

$$H^i(G, \mathbb{Q}) = 0$$

for all $i > 0$.

Proof. We note that multiplication by $|G|$ induces an isomorphism on $H^i(G, \mathbb{Q})$, as it induces an isomorphism on \mathbb{Q} . However, by Corollary 2.71, the group $H^i(G, \mathbb{Q})$ is $|G|$ -torsion and therefore it must be 0. \square

We now leave off with one more important example of Construction 2.66.

Example 2.74. Let $H \subset G$ be a normal subgroup of G and let $\alpha : G \rightarrow G/H$ be associated surjection. We let $\beta : M^H \hookrightarrow M$ be the injection of the H -invariants and note that G/H acts on M^H . In this case, Construction 2.66 yields a map

$$\text{Inf}_{G/H}^G : H^i(G/H, M^H) \rightarrow H^i(G, M)$$

which is known as the inflation map.

These functors satisfy the following basic compatibilities with one another.

Proposition 2.75. *Let G be a finite group, let $N \subset G$ be a normal subgroup, and let $N \subset H \subset G$ be a subgroup. Then, for each $n \geq 0$, the following is true.*

(1) *The diagram*

$$\begin{array}{ccc} H^n(H/N, A^N) & \xrightarrow{\text{CoRes}_{H/N}^{G/N}} & H^n(G/N, A^N) \\ \text{Inf}_{H/N}^H \downarrow & & \downarrow \text{Inf}_{G/N}^G \\ H^n(H, A) & \xrightarrow{\text{CoRes}_H^G} & H^n(G, A). \end{array}$$

commutes.

(2) *The diagram*

$$\begin{array}{ccc} H^n(H/N, A^N) & \xleftarrow{\text{Res}_{H/N}^{G/N}} & H^n(G/N, A^N) \\ \text{Inf}_{H/N}^H \downarrow & & \downarrow \text{Inf}_{G/N}^G \\ H^n(H, A) & \xleftarrow{\text{Res}_H^G} & H^n(G, A). \end{array}$$

commutes.

This one may check, by using that all the functors commute with the boundary maps δ_n , as alluded to in Example 2.67, and that the diagram commutes in the case of $n = 0$.

Exercise 2.76. *Show that Proposition 2.75 is true in the case of $n = 0$.*

We are now in good shape to bootstrap to the profinite case.

2.3. Cohomology of Profinite Groups. In this section, we explain how the theory of group cohomology described in the finite case is bootstrapped to the profinite case. We let G be a profinite group for the rest of this subsection.

2.3.1. *Déviissage to the Finite Case.* We write $\text{Mod}_{G,\text{cont}}$ for the category of discrete abelian groups on which G acts continuously with its profinite topology. In particular, an object of $\text{Mod}_{G,\text{cont}}$ is an abelian group equipped with an action of G such that, for every $m \in M$, the set of elements in G stabilizing m is an open subgroup of $U \subset G$. In particular, we have that

$$(2.28) \quad M = \bigcup_{U \subset G} M^U,$$

where M^U denotes the subspace of elements fixed by an open subgroup $U \subset G$ and the union runs over all such open subgroups (equivalently, open normal subgroups). We want to define groups $H^n(G, M)$ which generalize the groups introduced in §2.2 and enjoy some of the same formal properties. To do this, we take the perspective of the definition of these groups provided by Exercise 2.44. In particular, we may consider

$$C_{\text{cont}}(G^n, M),$$

which will be the space of continuous functions $G^n \rightarrow M$, where M has the discrete topology. In particular, this is the same as locally constant functions. We equip this with the differential

$$\partial_n : C(G^n, M) \rightarrow C(G^{n+1}, M)$$

given by the identity

$$(\partial_n)(\phi)(g_1, \dots, g_{n+1}) = g_1 \cdot \phi(g_2, \dots, g_n) + \sum_{i=1}^n (-1)^i \phi(g_1, \dots, g_i g_{i+1}, \dots, g_{n+1}) + (-1)^{n+1} \phi(g_1, \dots, g_n),$$

as in (2.15). This will satisfy the identity $\partial_n \circ \partial_{n-1} = 0$ and therefore we can define

$$H^n(G, M) := \text{Ker}(\partial_n) / \text{Im}(\partial_{n-1}),$$

as before.

Remark 2.77. We note that it is also possible to show that the category $\text{Mod}_{G,\text{cont}}$ possesses enough injective objects, as shown in the finite case in Exercise 2.23. In particular, the discussion in §2.2.1 will also allow us to identify $H^n(G, M)$ as the right derived functors of invariants $(-)^G$. However, as the category $\text{Mod}_{G,\text{cont}}$ will not have enough projective objects unless G is finite, this will mean the discussion of homology and Tate cohomology that we will see later will not extend to this profinite case in any naive way. This is one of the reasons that cohomology is more desirable than homology when setting up the theory.

In light of Exercise 2.44, this recovers the usual definition of group cohomology if G is finite, and we may formally reduce to this case as follows.

Let $(G_i)_{i \in I}$ be a projective system of profinite groups with respected to a directed set (I, \geq) , and let $(M_i)_{i \in I}$ be an inductive system of discrete G_i -modules so that the transition morphisms $f_{ij} : M_j \rightarrow M_i$ and $g_{ij} : A_j \rightarrow A_i$ are compatible in the sense of Definition 2.65. By applying the analogue of Construction 2.66, this gives rise to a directed system

$$\varinjlim_{i \in I} H^n(G_i, A_i).$$

We now have the following.

Lemma 2.78. *For $(G_i)_{i \in I}$ and $(M_i)_{i \in I}$ as above, we set $G := \varinjlim_{i \in I} G_i$ and $M = \varprojlim M_i$ then we have a natural isomorphism*

$$H^n(G, M) \xrightarrow{\cong} \varinjlim_{i \in I} H^n(G_i, M_i)$$

for all $n \geq 0$.

Proof. By taking cohomology, this follows from the fact that the natural map

$$C_{\text{cont}}(G^n, M) \rightarrow \varinjlim_{i \in I} C_{\text{cont}}(G_i^n, M_i)$$

is an isomorphism, since every locally constant function $f : G^n \rightarrow M$ factors through $G_i^n \rightarrow M_i$ for some $i \in I$. \square

We deduce the following consequence of this. Namely, by Lemma 2.3 (2), we have a basis of open neighborhoods of the identity element given by the open normal subgroups U_i of G indexed by $i \in I$, and we see that, as in (2.28) that, for any $M \in \text{Mod}_{G, \text{cont}}$, we can write $M := \varinjlim_{i \in I} M^{U_i} = \bigcup_{i \in I} M^{U_i}$ and that this has a compatible action of the inverse system of finite groups $G \simeq \varprojlim_{i \in I} G/U_i$ (cf. Example 2.74). In particular, we deduce the following from Lemma 2.78.

Corollary 2.79. *We have an isomorphism*

$$H^n(G, M) \simeq \varinjlim_{i \in I} H^n(G/U_i, M^{U_i}),$$

where $\{U_i\}$ is the inductive system of open normal subgroups of G and the transition morphisms on the RHS are given by the inflation map described in Example 2.74.

This in particular tells us that we may express the cohomology of any $M \in \text{Mod}_{G, \text{cont}}$ as an inductive limit of cohomology of finite groups on abelian groups. In particular, we deduce the following finiteness result even in this profinite case, by combining Corollary 2.79 with Corollary 2.71.

Corollary 2.80. *For all $n \geq 1$, the cohomology groups*

$$H^n(G, M)$$

are torsion of order dividing $|G|$, where we recall that this is a supernatural number, as in Definition 2.11.

We also have the standard interpretations of these groups.

Example 2.81. As one can see directly from the definition (cf. Example 2.46), we have the following for $M \in \text{Mod}_{G, \text{cont}}$.

- (1) $H^0(G, M) \simeq M^G$ is the set of G -invariants
- (2) We have an identification

$$H^1(G, M) := \{\phi : G \rightarrow M \in C_{\text{cont}}(G, M) \mid h \cdot \phi(g) - \phi(hg) + \phi(h) = 0\} / (\phi_m, m \in M)$$

where $\phi_m(g) := g \cdot m - m$.

- (3) If M is finite then, by arguing as in Example 2.47, we may interpret this as the space of extensions

$$0 \rightarrow M \rightarrow E \rightarrow G \rightarrow 0,$$

where E is a G -module with a continuous E -action up to equivalence as defined in (2.17). Here we note that E has naturally the structure of a profinite group by the finiteness of M . Indeed, the exact same argument will work. However, we need to ensure that the set-theoretic section $s : G \rightarrow E$ used there is continuous, but this was already explained in this profinite context in Proposition 2.9.

- (4) If K is a perfect field with algebraic closure \overline{K} then we have the absolute Galois group $\text{Gal}(\overline{K}/K) := \varprojlim_{L/K} \text{Gal}(L/K)$ as in (1.2) where L/K runs over finite Galois extensions

with its natural structure as a profinite group. The group \overline{K}^* of units defines an object in $\text{Mod}_{\text{Gal}(\overline{K}/K), \text{cont}}$, and we have an identification

$$(2.29) \quad H^2(\text{Gal}(\overline{K}/K), \overline{K}^*) \simeq \varprojlim_{L/K} H^2(\text{Gal}(L/K), L^*) \simeq \varprojlim_{L/K} \text{Br}(L/K) \simeq \text{Br}(K),$$

where the inverse limit is over finite Galois extensions L/K . Here the first isomorphism follows from Corollary 2.79, the second isomorphism is Theorem 2.63, and the last isomorphism follows from (2.21).

We now bootstrap some of the discussion of functoriality and Schapiro's Lemma to the profinite case.

2.3.2. Extended Functoriality in the Profinite Case. We now bootstrap the examples of functoriality described in §2.2.4.

In particular, we may consider two profinite groups G' and G with $M' \in \text{Mod}_{G', \text{cont}}$ and $M \in \text{Mod}_{G, \text{cont}}$. We consider a continuous homomorphism $\alpha : G' \rightarrow G$ and a map $\beta : M \rightarrow M'$, which are compatible in the sense of Definition 2.65. Just as in Construction 2.66, we obtain a natural map

$$H^i(G, M) \rightarrow H^i(G', M')$$

by using the explicit complex computing these objects in terms of $C_{\text{cont}}(G^n, M)$ and the natural maps $C_{\text{cont}}(G^n, M) \rightarrow C_{\text{cont}}((G')^n, M)$.

Example 2.82. Suppose that $H \subset G$ is an *closed* subgroup then the inclusion map $H \subset G$ is continuous. Therefore, we get a natural restriction map

$$\text{Res}_H^G : H^i(G, M) \rightarrow H^i(H, M)$$

extending Example 2.67.

We now turn to the corestriction map.

Example 2.83. Note that the construction in Example 2.68 involved Schapiro's Lemma, which we don't necessarily have. However, we also saw that we could also give a definition using Norm maps (Definition 2.69), which would make sense assuming that the subgroup $H \subset G$ has finite index. Indeed, we can construct the corestriction map assuming that $H \subset G$ is an *open* subgroup of G . Instead of using the norm map, we will construct it from the finite case by using some categorical maneuvers.

In particular, we consider a family of open normal subgroups $\{U_i\}_{i \in I}$ of G forming a basis of open neighborhoods of the identity element. We may consider the G/U_i -module M^{U_i} and the presentation

$$\varprojlim_{i \in I} H^n(G/U_i, M^{U_i}) \simeq H^n(G, M)$$

guaranteed by Corollary 2.79, where the transition morphisms are given by the inflation maps. Similarly, we have a presentation

$$\varprojlim_{i \in I} H^n(H/U_i \cap H, M^{U_i \cap H}) \simeq H^n(H, M),$$

where we note that $U_i \cap H$ is open and normal in H . By applying Example 2.68, we obtain a natural map

$$\text{CoRes}_i : H^i(G/U_i, M^{U_i}) \rightarrow H^i(H/U_i \cap H, M^{U_i \cap H}).$$

By Proposition 2.75 (1), these give rise to an induced map on the colimit

$$\text{CoRes}_H^G : H^n(G, M) \rightarrow H^n(H, M),$$

which is precisely the desired corestriction map.

In a similar fashion, by using Proposition 2.75 (2), when $H \subset G$ is open, we may construct Res_H^G as the colimit of the restriction maps for finite index subgroups. When $H \subset G$ is closed, we may write $H = \bigcap_{i \in I} U_i$ for some open normal subgroups

$$\text{Res}_{U_i}^G : H^n(G, M) \rightarrow H^n(U_i, M)$$

and then consider the induced map

$$H^n(G, M) \rightarrow \varinjlim_{i \in I} H^n(U_i, M),$$

where the transition morphisms on the RHS are defined restriction. By Lemma 2.78, this gives a map

$$H^n(G, M) \rightarrow H^n(H, M),$$

which is precisely the restriction map.

In particular, this allows us to deduce the following formally from Lemma 2.70.

Lemma 2.84. *For $H \subset G$ an open subgroup of finite index, we have that*

$$\text{CoRes} \circ \text{Res} = [G : H].$$

In general, we can use this to get something non-trivial in the pro- p case.

Lemma 2.85. *Suppose that $H \subset G$ is a closed subgroup such that the supernatural number $[G : H]$ is prime to p (e.g if H is the p -Sylow subgroup constructed in Proposition 2.12), as defined in 2.7 (4), then, for $M \in \text{Mod}_{G, \text{cont}}$ the natural map*

$$\text{Res}_H^G : H^n(G, M) \rightarrow H^n(H, M)$$

is injective on the p -primary component (as defined in Exercise 2.7 (4)) of $H^n(G, M)$.

Proof. If $[G : H]$ is finite then this is an immediate consequence of Lemma 2.70. In general, we may write H as an intersection of open subgroups containing H and then use Lemma 2.78 to reduce the case of finite index as explained above. \square

We can now have some fun with this in the profinite case.

Exercise 2.86. *[Ser94, Section 2.4] Let $f : G \rightarrow G'$ be any continuous morphism of profinite groups and p be a prime number.*

(1) *Show the equivalence of the following two properties.*

- *The index of $f(G)$ in G' is prime to p*
- *For any G' -module M equal to its p -primary part, the homomorphism*

$$H^1(G', M) \rightarrow H^1(G, M)$$

is injective.

(2) *Show the equivalence of the following properties.*

- *f is surjective.*
- *For any G' -module M , the homomorphism*

$$H^1(G', M) \rightarrow H^1(G, M)$$

is injective.

- *For any finite G' -module M , the homomorphism*

$$H^1(G', M) \rightarrow H^1(G, M)$$

is injective.

We leave off with a discussion of Schapiro's Lemma and induced modules in this case.

2.3.3. *Schapiro's Lemma and (co-)Induced Modules.* We saw in Remark 2.33 that there were two independent interpretations of the functors $\text{Ind}_H^G(M)$ in the finite case. One was in terms of functions $f : G \rightarrow M$ and the other one was in terms of a tensor product over the group $M \otimes_{\mathbb{Z}[H]} \mathbb{Z}[G]$. In the profinite case, these two interpretations are different from one another and only one will give rise to the correct form of Schapiro's Lemma.

Definition 2.87. Let $H \subset G$ be a closed subgroup. For $N \in \text{Mod}_{G,\text{cont}}$, we define the co-induced module $\text{coInd}_H^G(N)$ to be the space of continuous functions

$$f : G \rightarrow N,$$

where G has the profinite topology and M has the discrete topology such that $f(hg) = h.f(g)$.

This map will satisfy the property

$$(2.30) \quad \text{Hom}_G(M, \text{coInd}_H^G(N)) \simeq \text{Hom}_H(\text{Res}_H^G(M), N),$$

for $M \in \text{Mod}_{G,\text{cont}}$ and $N \in \text{Mod}_{H,\text{cont}}$, by analogous argument the proof of Proposition 2.35 and the other induction operation Ind_H^G (which we don't define for simplicity) will satisfy the other adjunction relationship

$$(2.31) \quad \text{Hom}_G(\text{Ind}_H^G(N), M) \simeq \text{Hom}_H(N, \text{Res}_H^G(M))$$

of Proposition 2.35. If $H \subset G$ has finite index (e.g in the finite case of 2.35) then they agree by an analogous argument to Remark 2.33, and we recover a generalization of Proposition 2.35. However, only one of these functors will have the desired categorical properties required for Schapiro's Lemma.

Lemma 2.88. *The functor coInd_H^G preserves injective objects in $\text{Mod}_{G,\text{cont}}$ and is exact.*

Proof. (Sketch) We note that the preservation of injective objects follows from (2.30) and the left exactness of the functor follows from Lemma 2.37 and the preceding discussion. However, we note that the functor Res_H^G is actually exact and will preserve some generators of categories of $\text{Mod}_G^{\text{cont}}$ (namely, the induced modules (cf. Remark 2.42)), which one can use to reverse the logic. \square

In particular, now by the same argument as in 2.40, we deduce Schapiro's Lemma in the profinite case, where we recall we can argue using injective resolutions in the profinite case using Remark 2.77.

Lemma 2.89. *Let $H \subset G$ be an inclusion of a closed subgroup. Then, for all $M \in \text{Mod}_{H,\text{cont}}$ and $n \geq 0$, we have a natural isomorphism*

$$H^n(G, \text{coInd}_H^G(N)) \simeq H^n(H, N)$$

of abelian groups.

In particular, we may apply this in the case that $H = \{e\}$ which gives us a notion of (co-)induced modules in the profinite case with the same formal properties as the finite case. We now turn our attention to the dual notion of cohomology, which will see the abelianization of profinite groups G^{ab} that we want to see.

2.4. Tate Cohomology.

2.4.1. *Homology of Finite Groups.* We let G be a finite group and write Mod_G for the category of left G -modules. As described in §2.2, the cohomology of finite groups arised as certain functors measuring the failure of the functor

$$(-)^G : \text{Mod}_G \rightarrow \text{Ab}$$

of invariants to be right exact. These were the higher derived functors of invariants. In this section, we want to study the dual notion. Namely, we want to study the failure of the following functor to be left exact and define certain left derived functors measuring this.

Definition 2.90. For $M \in \text{Mod}_G$, we define M_G the coinvariants of G to be the quotient of M by the abelian group generated by $g.m - m$ for $g \in G$. Alternatively, we may think of this in terms of the augmentation ideal of the group ring introduced in Remark 2.18 this is the subset

$$I_G := \left\{ \sum_{g \in G} a_g g \in \mathbb{Z}[G] \mid \sum_{g \in G} a_g = 0 \right\}$$

and it is preserved under the action of G -by left translation. In other words, it is the kernel of the natural map

$$\begin{aligned} \varepsilon : \mathbb{Z}[G] &\rightarrow \mathbb{Z} \\ \sum_{g \in G} a_g g &\mapsto \sum_{g \in G} a_g \end{aligned}$$

which is the augmentation map already described in 2.19. We then have a natural isomorphism

$$(2.32) \quad M_G \simeq \mathbb{Z} \otimes_{\mathbb{Z}[G]} M,$$

where the tensor product is formed using this map (See Exercise 2.100 (2)). In particular, this presentation makes it clear that this defines a functor

$$(-)_G : \text{Mod}_G \rightarrow \text{Ab}$$

which is the functor of G -coinvariants.

The tensor product is a left adjoint functor and therefore it commutes with colimits and is right exact, by Lemma 2.37 and the discussion proceeding it. Similarly, the functor of invariants may be interpreted as $\text{Hom}_{\mathbb{Z}[G]}(\mathbb{Z}, -)$, which is a right adjoint functor and therefore commutes with limits and is left exact. In particular, one easily checks that given a short exact sequence

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$$

the induced sequence

$$A_G \rightarrow B_G \rightarrow C_G \rightarrow 0$$

is right exact, but is not always left exact. As before, we want to complete this to a long exact sequence. As one might expect, this can be accomplished by the dual notion to the injective resolutions described in Definition 2.24. In particular, we have the following.

Definition 2.91. A G -module $P \in \text{Mod}_G$ is said to be projective if, for any diagram

$$\begin{array}{ccc} & & P \\ & & \downarrow p \\ A & \xrightarrow{f} & B \end{array}$$

in Mod_G , for f is surjectiv, there exists a lift $p' : P \rightarrow A$ such that the diagram commutes.

Remark 2.92. If we compare this with the definition of injective (Definition 2.21) we see that what we essentially did was just reverse the direction of the arrows and replace injection with surjection. In the sense, we can think of projective and injective as dual notions to one another, as duality normally reverses the direction of the arrows.

We have the following basic example of a projective $\mathbb{Z}[G]$ -module.

Example 2.93. Suppose we have an $B \in \text{Mod}_G$ and a map $p : \mathbb{Z}[G] \rightarrow B$. Since p is a map of G -modules, it is completely determined by where it sends 1. Indeed, if $p(1) = b \in B$ then we must have that $p(\sum_{g \in G} a_g g) = \sum_{g \in G} a_g g.b \in B$. In particular, if we now have a surjection, $f : A \rightarrow B$ then we may choose a lift of $p(1) \in B$ to some $a \in A$. We may then define a map $p' : \mathbb{Z}[G] \rightarrow A$ by sending $p'(\sum_{g \in G} a_g g) = \sum_{g \in G} a_g g.a$. In this way, we see that $\mathbb{Z}[G]$ is a projective G -module. Similarly, any (possibly infinite) direct sum $\bigoplus_{i \in I} \mathbb{Z}[G]$ of projective G -modules will also be projective.

In particular, we see that it is fairly easy to find examples of projective G -modules by taking direct sums of $\mathbb{Z}[G]$. Moreover, if we are given any G -module M then may fix a set of generators $m_i \in M$ for some index set $i \in I$ such that taking-translates under G and linear combinations of the m_i generates all of M . We may then define a surjection

$$\bigoplus_{i \in I} \mathbb{Z}[G] \rightarrow M$$

characterized by the property that 1 in the i th coordinate of the above direct sum maps to the generator m_i , as in Example 2.93. In particular, this shows the following analogue of Exercise 2.23.

Proposition 2.94. *The category Mod_G has enough projective objects. In particular, for any $M \in \text{Mod}_G$, there exists a surjection $P \rightarrow M$ from a projective object P .*

As in §2.2, we may now define the following.

Definition 2.95. For $M \in \text{Mod}_G$, a projective resolution of M is a long exact sequence

$$\cdots \rightarrow P_{i+1} \xrightarrow{d_i} P_i \rightarrow \cdots \rightarrow P_2 \xrightarrow{d_1} P_1 \xrightarrow{d_0} P_0 \rightarrow M \rightarrow 0,$$

where P_i for $i \geq 0$ is projective. We will denote such a resolution by $P_* \rightarrow M$, and denote the map $P_0 \rightarrow M$ by d_{-1} .

As before, Proposition 2.94 tells us that such a resolution always exists, and in turn we may define the following.

Definition 2.96. For $M \in \text{Mod}_G$, we fix a projective resolution $P_* \rightarrow M$. We then apply the functor of G -coinvariants

$$\cdots \rightarrow (P_2)_G \xrightarrow{(d_2)_G} (P_1)_G \xrightarrow{(d_1)_G} (P_0)_G$$

and then define

$$H_i(G, M) := \text{Ker}((d_{i-1})_G) / \text{Im}((d_i)_G) \in \text{Ab}.$$

We refer to this as the group homology of M .

By essentially the same arguments as in §2.2, we obtain the following.

Proposition 2.97. *The following is true.*

- (1) *The group homology groups do not depend on the choice of projective resolution.*
- (2) *Given a map $f : A \rightarrow B$, there is a natural induced map*

$$H_i(f) : H_i(G, A) \rightarrow H_i(G, B)$$

for all $i \geq 0$.

- (3) *For $M \in \text{Mod}_G$, we have an isomorphism*

$$H_0(G, M) \simeq M_G.$$

- (4) *For a short exact sequence*

$$0 \rightarrow A \xrightarrow{f} B \xrightarrow{g} C \rightarrow 0,$$

there exists natural boundary maps $\delta_i : H_i(G, C) \rightarrow H_{i-1}(G, A)$ for all $i \geq 1$ which sit in a long exact sequence

$$\cdots \rightarrow H_i(G, C) \xrightarrow{\delta_i} H_{i-1}(G, A) \xrightarrow{H_{i-1}(f)} H_{i-1}(G, B) \xrightarrow{H_{i-1}(g)} H_{i-1}(G, C) \xrightarrow{\delta_{i-1}}$$

extending the right exact sequence

$$A_G \rightarrow B_G \rightarrow C_G \rightarrow 0$$

in light of (3).

(5) For an inclusion of subgroups $H \subset G$ and $N \in \text{Mod}_H$, we have an isomorphism

$$H_i(H, N) \simeq H_i(G, \text{Ind}_H^G(N)).$$

Similarly, we may define the following.

Definition 2.98. We say that $M \in \text{Mod}_G$ is homologically acyclic if, for all $i \geq 1$, we have that

$$H_i(G, M) = 0.$$

Remark 2.99. As before, we may easily check that the analogue of Exercise 2.31 holds. In particular, projective modules are acyclic, and to compute group homology it suffices to find a resolution by homologically acyclic modules.

We would also like some concrete understanding of the higher homology groups, as was done for cohomology in Example 2.46. To this end, we have the following.

Exercise 2.100. Consider the short exact sequence in Mod_G

$$(2.33) \quad 0 \rightarrow I_G \rightarrow \mathbb{Z}[G] \xrightarrow{\varepsilon} \mathbb{Z} \rightarrow 0$$

defined by the augmentation map, as in Definition 2.90. Here \mathbb{Z} has the trivial action. Show the following.

- (1) By considering the long exact cohomology sequence of homology groups attached to (2.33) show that we have an isomorphism

$$H_1(G, \mathbb{Z}) \simeq I_G/I_G^2,$$

where I_G^2 is the ideal generated by products of elements in I_G with elements in I_G .

- (2) Show that I_G is generated as an ideal by the elements $(g - 1)$.
- (3) Consider the map

$$\phi : G \rightarrow I_G/I_G^2$$

sending $\phi(g)$ to $g - 1 \pmod{I_G^2}$. Show that this is a well-defined homomorphism where I_G/I_G^2 is equipped with its additive group structure.

- (4) Show that ϕ factors through $G^{\text{ab}} := G/[G, G]$, where $[G, G]$ is the subgroup of commutators and that the resulting map

$$\phi^{\text{ab}} : G^{\text{ab}} \rightarrow I_G/I_G^2$$

is an isomorphism. Conclude that $H_1(G, \mathbb{Z}) \simeq G^{\text{ab}}$ as abelian groups.

In particular, we see that indeed the 1st homology is computing the abelianization of the group G , as was alluded to in the introduction. We now turn to our next topic which will splice together this notion of homology and cohomology.

2.4.2. Tate Cohomology of Finite Groups. For a short exact sequence

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$$

in Mod_G . We have now seen two different long exact sequences we can attach to it. First is the cohomology long exact sequence which has the form

$$0 \rightarrow A^G \rightarrow B^G \rightarrow C^G \rightarrow H^1(G, A) \rightarrow \cdots,$$

and the second is the homology long exact sequence, which has the form

$$\rightarrow H_1(G, A) \rightarrow C_G \rightarrow B_G \rightarrow A_G \rightarrow 0.$$

Tate cohomology allows us to splice these two long exact sequences together into an infinite sequence in both directions. The key here is that for $M \in \text{Mod}_G$, we have the norm map

$$\text{Nm}_G : M \rightarrow M^G$$

$$m \mapsto \sum_{g \in G} g.m$$

as introduced in Definition 2.69. We note that this will send all the elements $h.m - m$ to 0 for $h \in G$. Indeed, $h. \sum_{g \in G} g.m = \sum_{g \in G} h.g.m = \sum_{g \in G} g.m$, as left multiplication permutes the elements of the group. Therefore, this induces a map

$$\overline{\text{Nm}}_G : M_G \rightarrow M^G$$

between the coinvariants and the invariants. This leads to the following definition.

Definition 2.101. For all $i \in \mathbb{Z}$, and $M \in \text{Mod}_G$, we define the Tate cohomology $H_T^i(G, M)$ as follows

$$H_T^i(G, M) := H^i(G, M)$$

if $i \geq 1$

$$H_T^i(G, M) := H_{-i-1}(G, M)$$

if $i < -1$, and

$$H_T^0(G, M) := M^G / \text{Nm}_G(M)$$

and

$$H_T^{-1}(G, M) := \text{Ker}(\text{Nm}_G) / I_G.M \simeq \text{Ker}(\overline{\text{Nm}}_G).$$

We record some additional properties of this which follow from our discussion of cohomology and homology together with a direct calculation for the $i = -1, 0$ Tate cohomology groups.

Proposition 2.102. *The following is true.*

(1) *For an inclusion of finite groups $H \subset G$ and $N \in \text{Mod}_H$, we have a natural isomorphism*

$$H_T^i(G, \text{Ind}_H^G(N)) \simeq H_T^i(H, N)$$

for all $i \in \mathbb{Z}$.

(2) *For any map $f : A \rightarrow B$ in Mod_G , we have, for all $i \in \mathbb{Z}$, a natural induced map*

$$H_T^i(f) : H_T^i(G, A) \rightarrow H_T^i(G, B)$$

extending the usual maps on cohomology and homology.

We also have the following most important property.

Exercise 2.103. *Suppose we have a short exact sequence $0 \rightarrow A \xrightarrow{f} B \xrightarrow{g} C \rightarrow 0$. Show the following.*

(1) *Check that we have a commutative diagram of the form*

(2.34)

$$\begin{array}{ccccccc}
 & & H_T^{-1}(G, A) & \longrightarrow & H_T^{-1}(G, B) & \longrightarrow & H_T^{-1}(G, C) \\
 & & \downarrow & & \downarrow & & \downarrow \\
 \cdots & \longrightarrow & H_{-1}(G, C) & \longrightarrow & A_G & \longrightarrow & B_G & \longrightarrow & C_G & \longrightarrow & 0 \\
 & & \downarrow \overline{\text{Nm}}_G & & \downarrow \overline{\text{Nm}}_G & & \downarrow \overline{\text{Nm}}_G & & & & \\
 0 & \longrightarrow & A^G & \longrightarrow & B^G & \longrightarrow & C^G & \longrightarrow & H^1(G, A) & \longrightarrow & \cdots \\
 & & \downarrow & & \downarrow & & \downarrow & & & & \\
 & & H_T^0(G, A) & \longrightarrow & H_T^0(G, B) & \longrightarrow & H_T^0(G, C) & & & & ,
 \end{array}$$

where the second and third row are given by the long exact sequence for homology and cohomology, respectively, and the remaining arrows are the obvious ones.

- (2) Check that by applying the snake lemma (Lemma 2.20) to the middle part of (2.34) that we obtain a long exact sequence

$$(2.35) \quad \cdots \rightarrow H_T^{i-1}(G, C) \rightarrow H_T^i(G, A) \xrightarrow{H_T^i(f)} H_T^i(G, B) \xrightarrow{H_T^i(g)} H_T^i(G, C) \rightarrow H_T^{i+1}(G, A) \rightarrow \cdots$$

for all $i \in \mathbb{Z}$.

In particular, Tate cohomology successfully "stiches together" the cohomology and the homology of a finite group G in a way that is compatible with the long exact sequences. As we will see, this provides a powerful tool that allows us to connect invariants such as the Brauer group of a field together with the abelianization of its Galois group and the multiplicative structure of the field, which will ultimately be the mechanism by which we prove the main results of local and global class field theory.

Before moving on to more interesting applications, we first discuss some examples of extended functoriality in the context of homology and Tate-cohomology. Let $\alpha : G' \rightarrow G$ be a homomorphism of finite groups and $M \in \text{Mod}_G$ and $M' \in \text{Mod}_{G'}$. We suppose we have a homomorphism $\beta : M \rightarrow M'$ which is α -compatible in the sense of Definition 2.65. We would like to say that this induces a map

$$H_i(G, M) \rightarrow H_i(G', M'),$$

as in Construction 2.66 for all $i \geq 0$. However, we note that Definition 2.65 is not enough to guarantee that β gives rise to a well-defined map $M_G \rightarrow M'_{G'}$ on coinvariants. Moreover, for Tate-cohomology, we would like to say that this induces a map

$$H_T^i(G, M) \rightarrow H_T^i(G', M')$$

for all $i \in \mathbb{Z}$. However, we also do not know that $M \rightarrow M'$ gives rise to a well defined map on $\text{Nm}_G(M) \rightarrow \text{Nm}_{G'}(M')$. In particular, we need to know that there exists (a necessarily unique) map $\beta_G : M_G \rightarrow M'_{G'}$ in Ab such that the diagram

$$(2.36) \quad \begin{array}{ccc} M & \xrightarrow{\beta} & M' \\ \downarrow (-)_G & & \downarrow (-)_{G'} \\ M_G & \xrightarrow{\beta_G} & M'_{G'} \end{array}$$

commutes to get a map on homology and similarly for projective resolutions of G . Similarly, for Tate cohomology, we need to know that there exists a map $\bar{\beta} : \text{Nm}_G(M) \rightarrow \text{Nm}_{G'}(M')$ such that

$$(2.37) \quad \begin{array}{ccc} \text{Nm}_G(M) & \xrightarrow{\bar{\beta}} & \text{Nm}_{G'}(M') \\ \downarrow & & \downarrow \\ M & \xrightarrow{\beta} & M'. \end{array}$$

commutes. This can be arranged in the following special cases.

Example 2.104. (1) We see that we can always construct such a map α_G filling (2.36) if β is surjective. Indeed, this follows from the fact that vertical arrows of (2.36) are surjective. Similarly, we may do this on projective resolutions. Therefore for (α, β) a compatible pair as in Definition 2.65, such that β is surjective we get a well-defined map

$$H_i(G, M) \rightarrow H_i(G', M')$$

on homology in this case.

- (2) We see that we can always construct such a map filling in the diagram (2.37) if β is injective. Therefore, for (α, β) a compatible pair, we get a well-defined map

$$H_T^i(G, M) \rightarrow H_T^i(G', M')$$

in this case for $i \geq -1$.

- (3) We see by (1) and (2) that if (α, β) are a compatible pair such that β is an isomorphism, we get a well-defined map

$$H_T^i(G, M) \rightarrow H_T^i(G', M')$$

for all $i \in \mathbb{Z}$.

- (4) We note that the situation of (3) is satisfied for the compatible pair (α, β) used in defining the restriction map for an inclusion of subgroups $H \subset G$, as in Example 2.67. In particular, we get a well-defined map

$$(2.38) \quad \text{Res}_H^G : H_T^i(G, M) \rightarrow H_T^i(H, \text{Res}_H^G(M)),$$

for all $i \in \mathbb{Z}$.

- (5) Since we know Schapiro's lemma for Tate-cohomology by Proposition 2.102 (2), we may apply the same logic as in Example 2.68, to deduce the existence of a map

$$(2.39) \quad \text{CoRes}_H^G : H_T^i(H, \text{Res}_H^G(M)) \rightarrow H_T^i(G, M)$$

for all $i \in \mathbb{Z}$, which will satisfy

$$\text{CoRes}_H^G \circ \text{Res}_H^G = [G : H]$$

as in Lemma 2.70. Similarly, as in Corollary 2.71, we may deduce that $H_T^i(G, M)$ is always $|G|$ -torsion.

- (6) If we consider the restriction map (2.38) for $i = -2$ and $M = \mathbb{Z}$ with the trivial G -action for $H \subset G$ an inclusion of subgroups then, by Exercise 2.100, we see that we obtain a map

$$G^{\text{ab}} \simeq H_T^{-2}(G, \mathbb{Z}) \rightarrow H^{\text{ab}} \simeq H_T^{-2}(H, \mathbb{Z})$$

from the abelianization of G to the abelianization of H . This is known as the Verlagerung (or transfer) morphism. We can describe this explicitly as follows. We write

$$G = Hg_1 \cup Hg_2 \cup \cdots \cup Hg_n.$$

for a set of coset representatives of $H \subset G$. We then consider the map sending $g \in G$ to g_i if $g \in Hg_i$. We then define

$$V : G \rightarrow H^{\text{ab}}$$

by

$$V(g) := \prod_{i=1}^n g_i g \phi(g_i g)^{-1} \text{ mod } [H, H]$$

where $[H, H] \subset H$ is the subgroup of commutators. One checks that this gives rise to a well-defined homomorphism, and therefore induces a map

$$G^{\text{ab}} \rightarrow H^{\text{ab}},$$

which is precisely the map described above.

We now analyze these Tate cohomology groups in the case of a cyclic group.

2.5. Tate Cohomology of a Cyclic Group. One of the most beautiful things about Tate cohomology is that it exhibits a remarkably simple structure when specialized to the case of a cyclic group.

Theorem 2.105. (Tate's Periodicity Theorem) *Let G be a finite cyclic group and $M \in \text{Mod}_G$. Then, for all $i \in \mathbb{Z}$, there is a natural in M isomorphism*

$$H_T^i(G, M) \xrightarrow{\cong} H_T^{i+2}(G, M)$$

determined by a generator of G .

Proof. We let m denote the order of G and choose a generator $\langle \sigma \rangle$ of G . We note that we have an identification

$$\mathbb{Z}[G] \simeq \mathbb{Z}[x]/(x^m - 1)$$

by sending σ to x . In particular, $\mathbb{Z}[G]$ is a commutative ring in this case. We can consider the multiplication by $(x - 1)$ map on $\mathbb{Z}[G]$. We recall the interpretation of induction as tensoring over the group ring 2.33. This tells us that the multiplication by $x - 1$ map gives rise to a map

$$\times(x - 1) : \text{Ind}_1^G \text{Res}_1^G M \simeq M \otimes_{\mathbb{Z}} \mathbb{Z}[G] \rightarrow M \otimes_{\mathbb{Z}} \mathbb{Z}[G] \simeq \text{Ind}_1^G \text{Res}_1^G M.$$

In light of the factorization $x^m - 1 = (x - 1)(x^{m-1} + \dots + x + 1)$, the kernel of the multiplication by $x - 1$ map on $\mathbb{Z}[G]$ is the image of multiplication of $x^{m-1} + \dots + 1$, while the image is the ideal generated by $x - 1$. This tells us that we get an exact sequence

$$(2.40) \quad 0 \rightarrow M \rightarrow \text{Ind}_1^G \text{Res}_1^G M \xrightarrow{\times(x-1)} \text{Ind}_1^G \text{Res}_1^G M \rightarrow M \rightarrow 0$$

where the outer arrows are given by adjunction maps coming from 2.35. Indeed, if we examine the construction of these maps provided in the proof of 2.35 we see that the first map is given by $m \mapsto \sum_{i=0}^{n-1} \sigma^i \otimes m$ and the last map is given by $\sum_{i=0}^{n-1} \sigma^i \otimes m_i \mapsto \sigma^i(m_i)$. We now can apply the following Lemma to (2.40) in light of Schapiro's Lemma for Tate cohomology (Proposition 2.102 (1)), which will give us the desired result.

Lemma 2.106. *For G a finite group, suppose we have an exact sequence*

$$0 \rightarrow A \xrightarrow{f} B \xrightarrow{g} C \xrightarrow{h} D \rightarrow 0$$

and B and C have vanishing Tate-cohomology for all $i \in \mathbb{Z}$. Then we have a natural isomorphism

$$H_T^{i+2}(G, A) \simeq H_T^i(G, D)$$

for all $i \in \mathbb{Z}$.

Proof. We consider the long exact cohomology sequence of (2.103) coming from the short exact sequence

$$0 \rightarrow A \rightarrow B \rightarrow B/\text{Im}(f) \rightarrow 0$$

then we deduce that we have an isomorphism

$$H_T^{i+2}(G, A) \simeq H_T^{i+1}(G, B/\text{Im}(f))$$

for all $i \in \mathbb{Z}$. Similarly, we apply the long exact cohomology sequence of (2.103) induced from the short exact sequence

$$0 \rightarrow B/\text{Ker}(g) \rightarrow C \rightarrow D \rightarrow 0$$

to deduce an isomorphism

$$H_T^{i+1}(G, B/\text{Ker}(g)) \simeq H_T^i(G, D).$$

However, we have that $B/\text{Ker}(g) \simeq B/\text{Im}(f)$ by exactness in the middle, so we get the desired result. □

□

Despite the remarkably elementary proof of this theorem, it has several amazing consequences especially when combined with Theorem 2.63. In particular, we deduce the following.

Corollary 2.107. *For L/K a finite cyclic Galois extension, we have an isomorphism*

$$\text{Br}(L/K) \simeq K^*/\text{Nm}_{L/K}(L^*).$$

In particular, by Remark 2.60, the set of isomorphism classes of division algebras over K split over L is in bijection with $K^/\text{Nm}_{L/K}(L^*)$*

Proof. Indeed, we have an identification

$$H_T^2(\mathrm{Gal}(L/K), L^*) = H^2(\mathrm{Gal}(L/K), L^*) \simeq \mathrm{Br}(L/K)$$

by Theorem 2.63. Similarly, we have an identification

$$H_T^0(\mathrm{Gal}(L/K), L^*) = (L^*)^{\mathrm{Gal}(L/K)} / \mathrm{Nm}_{\mathrm{Gal}(L/K)}(L^*) \simeq K^* / \mathrm{Nm}_{L/K}(L^*)$$

Therefore, the result is an immediate consequence of 2.105. \square

In particular, this allows us to very beautifully see the relationship already alluded to in Exercise 2.57. Namely, that the existence of a non-split division algebras attached to a cyclic extension L/K is intimately related to the surjectivity of the norm map $\mathrm{Nm}_{L/K} : L^* \rightarrow K^*$! We can use this to understand the structure of a division algebras in a wide variety of contexts.

Exercise 2.108 (Division Algebras over Finite and p -adic Fields). *Fix a prime p and let $q = p^f$ for some integer $f \geq 1$. Let $g \geq 1$ and consider the finite cyclic Galois extension $\mathbb{F}_{q^g}/\mathbb{F}_q$. We write $\mathrm{Frob}_q : \mathbb{F}_{q^g} \rightarrow \mathbb{F}_{q^g}$ for the q th power Frobenius $x \mapsto x^q$.*

Similarly, we consider $\mathbb{Q}_q/\mathbb{Q}_p$ to be an unramified extension of degree f (i.e the natural map $\mathrm{Gal}(\mathbb{Q}_{p^g}/\mathbb{Q}_p) \rightarrow \mathrm{Gal}(\mathbb{F}_{p^g}/\mathbb{F}_p)$) given by reduction mod p is an isomorphism (See §3.2.1 for a review). We let $\mathbb{Q}_{q^g}/\mathbb{Q}_q$ be the unramified extension of \mathbb{Q}_q of degree g , and write $\sigma \in \mathrm{Gal}(\mathbb{Q}_{q^g}/\mathbb{Q}_q)$ to be the natural lift of Frob_q under the isomorphism $\mathrm{Gal}(\mathbb{Q}_{q^g}/\mathbb{Q}_q) \rightarrow \mathrm{Gal}(\mathbb{F}_{q^g}/\mathbb{F}_q)$ given by mod p -reduction.

Recall that, for any finite extension K/\mathbb{Q}_p , with ring of integers \mathcal{O}_K and uniformizing element $\pi \in \mathcal{O}_K$, we have an isomorphism

$$(2.41) \quad K^* \simeq \mathcal{O}_K^* \times \langle \pi^{\mathbb{Z}} \rangle,$$

of abelian groups. Moreover, we have a short exact sequence

$$(2.42) \quad 0 \rightarrow U_K^1 \rightarrow \mathcal{O}_K^* \rightarrow (\mathcal{O}_K/\pi)^* \rightarrow 0$$

of abelian groups, where the last map is given by mod π -reduction. Show the following.

- (1) *Consider the norm map*

$$\begin{aligned} \mathrm{Nm}_{\mathbb{F}_{q^g}/\mathbb{F}_q} : \mathbb{F}_{q^g}^* &\rightarrow \mathbb{F}_q^* \\ x &\mapsto \prod_{i=0}^{g-1} (\mathrm{Frob}_q)^i(x). \end{aligned}$$

Show that $\mathrm{Nm}_{\mathbb{F}_{q^g}/\mathbb{F}_q}$ is surjective and compute the kernel. Describe the Tate cohomology groups $H_T^i(\mathrm{Gal}(\mathbb{F}_{q^g}/\mathbb{F}_q), \mathbb{F}_{q^g}^)$ for all $i \in \mathbb{Z}$.*

- (2) *Using part (2), deduce the following.*

Theorem 2.109. (Wedderburn's Little Theorem) *Let \mathbb{F}_q be a finite field then every finite-dimensional division algebra over \mathbb{F}_q splits over a finite extension of \mathbb{F}_q .*

- (3) *Show that the short exact sequence (2.42) when specialized to $K = \mathbb{Q}_{q^g}$ and $K = \mathbb{Q}_q$ gives rise to a commutative diagram*

$$(2.43) \quad \begin{array}{ccccccc} 0 & \longrightarrow & U_{\mathbb{Q}_{q^g}}^1 & \longrightarrow & \mathcal{O}_{\mathbb{Q}_{q^g}}^* & \longrightarrow & \mathbb{F}_{q^g}^* \longrightarrow 0 \\ & & \downarrow \mathrm{Nm}_{\mathbb{Q}_{q^g}/\mathbb{Q}_q} & & \downarrow \mathrm{Nm}_{\mathbb{Q}_{q^g}/\mathbb{Q}_q} & & \downarrow \mathrm{Nm}_{\mathbb{F}_{q^g}/\mathbb{F}_q} \\ 0 & \longrightarrow & U_{\mathbb{Q}_q}^1 & \longrightarrow & \mathcal{O}_{\mathbb{Q}_q}^* & \longrightarrow & \mathbb{F}_q^* \longrightarrow 0 \end{array}$$

of short exact sequences.

- (4) *Show that $\mathrm{Nm}_{\mathbb{Q}_{q^g}/\mathbb{Q}_q} : U_{\mathbb{Q}_{q^g}}^1 \rightarrow U_{\mathbb{Q}_q}^1$ is surjective (Hint: Use Hensel's Lemma).*

(5) Combine (1), (3), and (4) with the product decomposition 2.41 to deduce that

$$\mathbb{Q}_q^*/\text{Nm}_{\mathbb{Q}_{q^g}/\mathbb{Q}_q}(\mathbb{Q}_{q^g}^*) \simeq \mathbb{Z}/g\mathbb{Z}.$$

What can you conclude about division algebras over \mathbb{Q}_q ?

We now leave off with an important invariant that the periodic nature of Tate cohomology highlights for us. In particular, it tells us that the entire Tate-cohomology of a cyclic group is captured by two groups namely the H_T^{-1} and H_T^0 which are both very explicit invariants. We introduce the following invariant to keep track of this.

Definition 2.110. Let G be a finite cyclic group and $M \in \text{Mod}_G$. If the groups $H_T^i(G, M)$ are finite, we define the Herbrand quotient as the ratio

$$h(M) := |H_T^0(G, M)|/|H_T^{-1}(G, M)|,$$

where $|\cdot|$ denotes the cardinality of a set.

We have the following basic example.

Example 2.111. Suppose that G is a cyclic group and $M = \mathbb{Z}$ is equipped with the trivial G -action. Note that the norm map

$$\text{Nm}_G : \mathbb{Z} \rightarrow \mathbb{Z}^G = \mathbb{Z}$$

identifies with the multiplication by $|G|$ map. In particular, we have that

$$H_T^0(G, \mathbb{Z}) = \mathbb{Z}/|G|\mathbb{Z}$$

and

$$H_T^{-1}(G, \mathbb{Z}) = 0,$$

so in this case the Herbrand quotient $h(\mathbb{Z})$ exists and we have that $h(\mathbb{Z}) = \mathbb{Z}/|G|\mathbb{Z}$.

The key point behind this definition is that often times it will be easier to compute Herbrand quotient rather than each of the individual Tate cohomology groups. However, knowing the Herbrand quotient will cut our work in half telling us that if we compute the size of one of the cohomology groups we know the other. We have the following basic properties of this.

Proposition 2.112. *The following is true.*

(1) *Suppose we have a short exact sequence*

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$$

in Mod_G . If two out of three terms of the short exact sequence have Herbrand quotients then so does the third. Moreover, in this situation, we have the following relationship

$$h(B) = h(A)h(C)$$

of Herbrand quotients.

(2) *Suppose that M is finite then we have that*

$$h(M) = 1$$

Proof. In the situation of (1), we note that Theorem 2.105 tells us that the long exact cohomology sequence of 2.103 gives rise to an exact hexagon

$$\begin{array}{ccccc}
 & & H_T^{-1}(G, B) & \longrightarrow & H_T^{-1}(G, C) \\
 & \nearrow & & & \searrow \\
 H_T^{-1}(G, A) & & & & H_T^0(G, A) \\
 & \nwarrow & & & \swarrow \\
 & & H_T^0(G, C) & \longleftarrow & H_T^0(G, B)
 \end{array}$$

which in particular implies (1).

If M is finite then obviously $H_T^{-1}(G, M)$ and $H_T^0(G, M)$ are both finite and the Herbrand quotient exists. In order to see it is 1, we observe that we have exact sequences

$$0 \rightarrow M^G \rightarrow M \rightarrow M \rightarrow M_G \rightarrow 0,$$

where the middle map is given by $m \mapsto \sigma.m - m$ for a cyclic generator $\langle \sigma \rangle = G$ (See Exercise 2.100 (2) for the exactness on the right). Moreover, by definition, we have a short exact sequence

$$0 \rightarrow H_T^{-1}(G, M) \rightarrow M_G \xrightarrow{\overline{\text{Nm}}_G} M^G \rightarrow H_T^0(G, M) \rightarrow 0.$$

By the second exact sequence, we see that we have an equality

$$h(M) := |M^G|/|M_G|$$

which by the first exact sequence is equal to 1, as desired. \square

We now turn to some final compliments on cohomology before approaching the proof of local class field theory.

2.6. Final Compliments on Cohomology and Tate's Theorem. We start with the following notion.

2.6.1. *The Cup Product.* We recall the following.

Proposition 2.113. *Let G be a finite group and $M, N \in \text{Mod}_G$ then there are bilinear maps*

$$(-) \cup (-) : H^p(G, M) \times H^q(G, N) \rightarrow H^{p+q}(G, M \otimes_{\mathbb{Z}} N)$$

for all $p, q \geq 0$ and

$$(-) \cup (-) : H_T^p(G, M) \times H_T^q(G, N) \rightarrow H_T^{p+q}(G, M \otimes_{\mathbb{Z}} N)$$

for all $p, q \in \mathbb{Z}$, which are functorial in M and N . We refer to the operation $(-) \cup (-)$ as the "cup-product".

Proof. We first describe the construction of the cup product for cohomology and then deduce the claim for the Tate cohomology. We will construct this at the level of cochains. In particular, homogeneous cochains $C^n(G, M)_{\text{hom}}$, as in Remark 2.45. In particular, we define a natural map

$$(2.44) \quad \begin{aligned} C^p(G, M)_{\text{hom}} \otimes C^q(G, N)_{\text{hom}} &\rightarrow C^{p+q}(G, N \otimes M)_{\text{hom}} \\ f(x_0, \dots, x_p) \otimes g(x_0, \dots, x_q) &\mapsto (f \cup g)(x_0, \dots, x_{p+q}), \end{aligned}$$

where

$$(f \cup g)(x_0, \dots, x_{p+q}) := f(x_0, \dots, x_p) \otimes g(x_p, \dots, x_{p+q}).$$

We abuse notation and write $\partial : C^n(G, M)_{\text{hom}} \rightarrow C^{n+1}(G, M)_{\text{hom}}$ for the natural differential on homogenous cochains, as induced by (2.15). We then check the following.

Lemma 2.114. *We have an equality*

$$\partial(f \cup g) = \partial(f) \cup g + (-1)^p(f \cup \partial(g))$$

in $C^{p+q+1}(G, M \otimes N)_{\text{hom}}$

Proof. We have that

$$\partial(f \cup g)(x_0, \dots, x_{p+q+1}) = \sum_{i=0}^{p+q+1} (-1)^i (f \cup g)(x_0, \dots, \hat{x}_i, \dots, x_{p+q+1}),$$

which we may break up as

$$\sum_{i=0}^p (-1)^i f(x_0, \dots, \hat{x}_i, \dots, x_{p+1}) \otimes g(x_{p+1}, \dots, x_{p+q+1}) + \sum_{i=p+1}^{p+q+1} (-1)^i f(x_0, \dots, x_p) \otimes g(x_p, \dots, \hat{x}_i, \dots, x_{p+q+1}).$$

However, we readily identify the first term with $\partial(f) \cup g$ and the second term with $(-1)^p (f \cup \partial(g))$, as desired. \square

In particular, the lemma tells us that $f \cup g$ satisfies the cocycle condition if f and g are cocycles. Therefore, the map (2.44) restricts to a well-defined map on cocycles. Moreover, after restricting to cocycles, it tells us that $f \cup g$ is a coboundary if either f or g is a coboundary. Therefore, we get a well-defined map on cohomology. It is clear that this is functorial in M and N and is bi-linear. For the Tate-cohomology, we look at the natural map

$$0 \rightarrow M' \rightarrow \text{Ind}_1^G \text{Res}_1^G M \rightarrow M \rightarrow 0,$$

where the last map is given by adjunction and M' is the kernel. This in particular gives us an isomorphism $H_T^{i-1}(G, M) \simeq H_T^i(G, M)$ by (2.103) and Schapiro's Lemma 2.102 (1). This allows us to reduce to constructing the desired map to the case where the indices are given by $p \geq 1$ and $q \geq 1$ in which case it follows from the claim on cohomology described above. This is the dimension shifting principle mentioned in 2.36 and 2.68. \square

For many applications, one often considers the following variant of the cup product.

Construction 2.115. *Suppose we have $M, N, C \in \text{Mod}_G$ together with a bilinear pairing*

$$b : M \otimes_{\mathbb{Z}} N \rightarrow C$$

then we obtain a bilinear maps

$$H^p(G, M) \times H^q(G, N) \rightarrow H^{p+q}(G, M \otimes_{\mathbb{Z}} N) \xrightarrow{H^{p+q}(f)} H^{p+q}(G, C)$$

for all $p, q \geq 0$ and bilinear maps

$$H_T^p(G, M) \times H_T^q(G, N) \rightarrow H_T^{p+q}(G, M \otimes_{\mathbb{Z}} N) \xrightarrow{H_T^{p+q}(f)} H_T^{p+q}(G, C)$$

for all $p, q \in \mathbb{Z}$.

We will also refer to this as a cup-product. It has the following compatibilities whose verification is routine (See [NSW08, Section 4] for a very detailed discussion).

Proposition 2.116. *Suppose we have $M, N \in \text{Mod}_G$, and a bilinear pairing $M \otimes_{\mathbb{Z}} N \rightarrow C$, we consider the cup product as in 2.115 defined with respect to this datum. Let $f \in H^p(G, M)$, $g \in H^q(G, M)$, and $h \in H^r(G, M)$ be elements. Then the following is true.*

- (1) *The cup product is associative and symmetric up to the Koszul rule for signs. I.e we have*

$$(f \cup g) \cup h = f \cup (g \cup h)$$

in $H^{p+q+r}(G, C)$, and

$$(f \cup g) = (-1)^{pq} (g \cup f),$$

in $H^{p+q}(G, C)$. The analogous claims hold for Tate cohomology.

- (2) *The cup product is compatible with restriction. In other words, if we have an inclusion $H \subset G$ of finite groups there is a natural isomorphism*

$$\text{Res}_H^G(f \cup g) = \text{Res}_H^G(f) \cup \text{Res}_H^G(g)$$

in $H^{p+q}(H, \text{Res}_H^G(C))$, and similarly for Tate-cohomology.

We now turn to the following.

2.6.2. *Inflation-Restriction Exact Sequence.* We have the following fundamental result.

Proposition 2.117. *Let G be a finite group and $H \subset G$ a normal subgroup and $M \in \text{Mod}_G$. If $H^i(H, \text{Res}_H^G(M)) = 0$ for $i = 1, \dots, r-1$ then the sequence*

$$0 \rightarrow H^r(G/H, M^H) \xrightarrow{\text{Inf}_H^G} H^r(G, M) \xrightarrow{\text{Res}_H^G} H^r(H, M)$$

is exact, where we recall that the first map is the inflation map of 2.74.

Proof. We will proceed by induction on r using the dimension shifting principle of Remark 2.36. For $r = 1$, the condition is empty. We recall by 2.46 we may interpret classes in $H^1(G, M)$ as maps $\phi : G \rightarrow M$. If it lies in the image of Inf_H^G then up to changing by a coboundary it must factor through $\phi : G/H \rightarrow M$; in other words, ϕ is constant when restricted to H . Moreover, the value when restricted to H must lie inside M^H . In particular, if we look now at the cocycle condition

$$h.\phi(g) = \phi(hg) - \phi(h)$$

and assume that $h \in H$ and $g \in H$ then this becomes

$$\phi(g) + \phi(h) = \phi(hg)$$

and this forces ϕ to be trivial when restricted to H , since this is a homomorphism. Therefore, it lies in the kernel of the restriction map, as desired. Conversely, if we have some $m \in M$ such that $\phi(h) = h.m - m$ for all $h \in H$ then $\phi'(g) = \phi(g) - g.m + m$ represents the same class as ϕ inside $H^1(G, M)$, but it has value 0 on H . Indeed, for all $h \in H$ and $g \in G$, we have

$$\phi'(hg) = g\phi'(h) + \phi'(g) = \phi'(g),$$

by the cocycle condition since $\phi'(h) = 0$. However, this implies that ϕ' factors through $G \rightarrow G/H$. Similarly, for all $g \in G$ and $h \in H$, we have that

$$h\phi'(g) = \phi'(hg) - \phi'(h) = \phi'(g)$$

by the cocycle condition since $\phi'(h) = 0$, so ϕ' lies in M^H . Exactness on the left is similar. In general, we look at the sequence

$$(2.45) \quad 0 \rightarrow M \rightarrow \text{Ind}_1^G \text{Res}_1^G(M) \rightarrow N \rightarrow 0$$

where the first map is the adjunction map. The long exact sequence in cohomology (Proposition 2.29) and Schapiro's Lemma 2.40 gives us isomorphisms

$$H^i(G, N) \xrightarrow{\cong} H^{i+1}(G, M)$$

and

$$H^i(H, \text{Res}_H^G(N)) \xrightarrow{\cong} H^{i+1}(H, \text{Res}_H^G(M)),$$

where, for the second isomorphism, we have used that the restriction of an induced module is again an induced module (Remark 2.42) to apply Schapiro's Lemma. Moreover, we deduce that $H^i(H, \text{Res}_H^G(N))$ vanishes for $i = 1, \dots, r-2$, by our assumption on the vanishing of $H^{i+1}(H, \text{Res}_H^G(M))$. In particular, we may use these isomorphisms to fill in the following commutative diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & H^{r-1}(G/H, N^H) & \xrightarrow{\text{Inf}_H^G} & H^{r-1}(G, N) & \xrightarrow{\text{Res}_H^G} & H^{r-1}(H, \text{Res}_H^G(N)) \\ & & & & \downarrow \simeq & & \downarrow \simeq \\ & & H^r(G/H, M^H) & \xrightarrow{\text{Inf}_H^G} & H^r(G, M) & \xrightarrow{\text{Res}_H^G} & H^r(H, \text{Res}_H^G(M)), \end{array}$$

where we have used our inductive hypothesis to conclude exactness of the top row. Moreover, we note that we have used the compatibility of the restriction map with the boundary map in the long

exact sequence to see the commutativity of the right diagram. We would be finished if we could construct an isomorphism

$$H^{r-1}(G/H, N^H) \rightarrow H^r(G/H, M^H)$$

making the diagram commute, as exactness of the top row would imply exactness of the bottom row. We accomplish this as follows. We take invariants of (2.45) under H and apply the long exact sequence of cohomology to deduce the existence of a short exact sequence

$$0 \rightarrow M^H \rightarrow (\text{Ind}_1^G \text{Res}_1^G M)^H \rightarrow N^H \rightarrow H^1(H, \text{Res}_H^G(M)) = 0,$$

where here we have used our vanishing hypothesis on cohomology. We may now in turn consider the long exact cohomology sequence applied to G/H . We note that the boundary map in turn gives the desired isomorphism

$$H^{r-1}(G/H, N^H) \xrightarrow{\cong} H^r(G/H, M^H).$$

Indeed $(\text{Ind}_1^G \text{Res}_1^G(M))^H \simeq (\mathbb{Z}[G]^H \otimes_{\mathbb{Z}} M) \simeq \mathbb{Z}[G/H] \otimes_{\mathbb{Z}} M$ is an induced module for G/H . \square

We now combine this with the Tate-periodicity Theorem to deduce the following fundamental result, which essentially tells us that one version of the consequences of Tate-periodicity at least always holds for any group G .

Theorem 2.118. *Let $M \in \text{Mod}_G$ suppose that $H^i(H, \text{Res}_H^G(M)) = 0$ for $i = 1, 2$ and H any normal subgroup of G then $H_T^i(G, M) = 0$ for all $i \in \mathbb{Z}$.*

Proof. Note that if G was cyclic this would be an immediate consequence of the Tate periodicity theorem (Theorem 2.105).

We first assume that G is solvable and show the vanishing for all $H_T^i(G, M)$ for all $i \geq 0$. We use induction on the number of subgroups of G . If G is trivial there is nothing prove. In general, since G is solvable, we may find a proper normal subgroup $H < G$ for which G/H is cyclic. By the induction hypothesis, $H_T^i(H, \text{Res}_H^G(M)) = 0$ for all $i \geq 0$. Thus, by Proposition 2.117, we have a short exact sequence

$$(2.46) \quad 0 \rightarrow H^i(G/H, M^H) \rightarrow H^i(G, M) \rightarrow H^i(H, \text{Res}_H^G(M))$$

for all $i > 0$ and therefore we obtain an isomorphism $H^i(G/H, M^H) \xrightarrow{\cong} H^i(G, M) = 0$, for $i = 1, 2$. Since G/H is cyclic, we know that $H_T^i(G/H, M^H)$ is trivial for all $i \in \mathbb{Z}$. However, that then implies that $H^i(G, M) = 0$ for all $i > 0$ by the short exact sequence (2.46). It remains to show that $H_T^0(G, M) = 0$. The vanishing of $H_T^0(G/H, M^H)$ tells you that every $x \in M^G = (M^H)^{G/H}$ can be written in the form $\text{Nm}_{G/H}(y)$ for some $y \in M^H$ and the vanishing of $H_T^0(H, \text{Res}_H^G(M))$ by the inductive hypothesis tells you that $\text{Nm}_H(z) = y$ for some $z \in M$. One easily checks that $\text{Nm}_{G/H} \circ \text{Nm}_H = \text{Nm}_G$, implying the desired claim.

We let G be arbitrary, we prove that $H_T^i(G, M)$ for all $i \geq 0$ by induction on the size of the set $|G|$. We know that the groups $H_T^i(G, M)$ are $|G|$ -torsion, as described in Example 2.104 (5). In particular, it suffices to show its p -primary components are trivial for all p . We choose a p -Sylow subgroup $G_p \subset G$, and look at the restriction corestriction sequence

$$H_T^i(G, M) \xrightarrow{\text{Res}_{G_p}^G} H_T^i(G_p, \text{Res}_{G_p}^G(M)) \xrightarrow{\text{CoRes}_{G_p}^G} H_T^i(G, M)$$

which is given by multiplication by $[G : G_p]$, as in Lemma 2.85 this allows to conclude that the first map is an injective on p -primary parts. Moreover, we see that $H_T^i(G_p, \text{Res}_{G_p}^G(M))$ vanishes for $i = 1, 2$ by our assumption on M . Since this is a solvable group, we may use the above case to conclude that $H_T^i(G, \text{Res}_{G_p}^G(M))$ vanishes for all i which implies the p -primary part of $H_T^i(G, M)$ vanishes for all $i \geq 0$, as desired.

The case where $i < 0$ follows from dimension shifting. In particular, one analyzes the sequence

$$0 \rightarrow N \rightarrow \text{Ind}_1^G \text{Res}_1^G(M) \rightarrow M \rightarrow 0,$$

of Remark 2.36, where the last map is given by adjunction, as in the proof of Proposition 2.113. \square

We will need to following construction in what follows.

Exercise 2.119. Let $M \in \text{Mod}_G$ and e denote the identity element of G . Suppose we have a homogenous 2-cocycle $\phi : G^3 \rightarrow M$ representing a class in $H^2(G, M)$. We recall that this means that

$$\phi(gg_0, gg_1, g_2g) = g \cdot \phi(g_0, g_1, g_2)$$

and

$$\phi(g_1, g_2, g_3) - \phi(g_0, g_2, g_3) + \phi(g_0, g_1, g_3) - \phi(g_0, g_1, g_2) = 0$$

Moreover, this is a coboundary if and only if

$$(2.47) \quad \phi(g_0, g_1, g_2) = \rho(g_1, g_2) - \rho(g_0, g_2) + \rho(g_0, g_1)$$

for $\rho : G^2 \rightarrow M$ satisfying the condition that $\rho(gg_0, gg_1) = \rho(g_0, g_1)$. We let $M[\phi]$ be the splitting module of ϕ . As an abelian group, this is given by

$$M[\phi] := M \oplus \bigoplus_{g \in G \setminus \{e\}} \mathbb{Z}x_g$$

and we equip it with the G -action

$$(2.48) \quad g \cdot x_h = x_{gh} - x_g + \phi(e, g, gh)$$

where in this formula $x_e := \phi(e, e, e)$ and the usual G -action of M on the first coordinate. Show the following.

- (1) Check that (2.48) gives rise to a well-defined G -action.
- (2) Combine the above formulae to show that ϕ is a coboundary if and only if

$$\phi(e, g, gh) = g\rho(e, h) - \rho(e, gh) + \rho(e, g).$$

for some $\rho : G^2 \rightarrow M$ as above.

- (3) Show that the natural map $M \rightarrow M[\phi]$ given by the inclusion of M induces a natural map

$$H^2(G, M) \rightarrow H^2(G, M[\phi]),$$

which will send ϕ to 0, by using (2) and setting $\rho(e, g) = x_g$ for all $g \in G$.

- (4) Show that the natural map

$$\alpha : M[\phi] \rightarrow \mathbb{Z}[G]$$

sending x_g to $[g] - 1$ is a homomorphism of G -modules. Deduce the existence of a short exact sequence

$$(2.49) \quad 0 \rightarrow M \rightarrow M[\phi] \rightarrow I_G \rightarrow 0.$$

We now have the following, which will be essential for the proof of local class field theory. In particular, as we will see the proof will essentially reduce us to checking the assumptions of the theorem for $G = \text{Gal}(L/K)$ and $M = L^*$.

Theorem 2.120. (Tate-Nakayama Theorem) Let $M \in \text{Mod}_G$. Suppose that, for all normal subgroups $H \subset G$, the following holds:

- (1) We have that $H^1(H, \text{Res}_H^G(M)) = 0$.
- (2) We have that $H^2(H, \text{Res}_H^G(M))$ is cyclic of order $|H|$.

Then, for any generator γ of $H^2(G, M) = H_T^2(G, M)$ and $i \in \mathbb{Z}$, the cup product

$$\gamma \cup (-) : H_T^i(G, \mathbb{Z}) \rightarrow H_T^{i+2}(G, M)$$

of Proposition 2.113 is an isomorphism.

Proof. By Lemma 2.70, we know that $\text{Cor} \circ \text{Res} = [G : H]$. In particular, this implies that $\text{Res}(\gamma)$ also generates $H^2(H, \text{Res}_H^G(M))$ by (2). We choose a homogenous 2-cocycle $\phi : G^3 \rightarrow M$ representing γ . We let $M[\phi]$ be the G -module described in Exercise 2.119. We consider the short exact sequences

$$(2.50) \quad 0 \rightarrow M \rightarrow M[\phi] \rightarrow I_G \rightarrow 0$$

of (2.49) and

$$(2.51) \quad 0 \rightarrow I_G \rightarrow \mathbb{Z}[G] \rightarrow \mathbb{Z} \rightarrow 0.$$

of (2.33). The long exact sequence in Tate cohomology applied to (2.51) and Schapiro's Lemma gives us an isomorphism

$$H^1(H, \text{Res}_H^G I_G) \simeq H_T^0(H, \mathbb{Z}) = \mathbb{Z}/|H|\mathbb{Z},$$

where the second equality follows from the fact that the Norm map on a H -module with trivial action is just given by multiplication by $|H|$. Similarly, we have

$$H^2(H, \text{Res}_H^G I_G) \simeq H^1(H, \mathbb{Z}) = 0,$$

where the second equality follows since $H^1(H, \mathbb{Z}) = \text{Hom}(H^{\text{ab}}, \mathbb{Z})$ and H is finite, as in Example 2.46. Now, by applying the long exact cohomology sequence to (2.50), we obtain

$$\begin{aligned} 0 &= H^1(H, \text{Res}_H^G M) \rightarrow H^1(H, \text{Res}_H^G M[\phi]) \rightarrow H^1(H, \text{Res}_H^G I_G) \\ &\rightarrow H^2(H, \text{Res}_H^G M) \rightarrow H^2(H, \text{Res}_H^G M[\phi]) \rightarrow H^2(H, \text{Res}_H^G I_G) = 0 \end{aligned}$$

However, by construction $H^2(H, \text{Res}_H^G M)$ will be cyclic by assumption and the generator $\text{Res}_H^G(\gamma)$ will map to $\text{Res}_H^G \phi$ under $H^2(H, \text{Res}_H^G M) \rightarrow H^2(H, \text{Res}_H^G M[\phi])$, which will vanish by Exercise 2.119 (3). In particular, the map $H^2(H, \text{Res}_H^G M) \rightarrow H^2(H, \text{Res}_H^G M[\phi])$ is zero, so we deduce that $H^2(H, \text{Res}_H^G M[\phi]) = 0$. We now deduce that $H^1(H, \text{Res}_H^G(I_G)) \rightarrow H^2(H, \text{Res}_H^G M[\phi])$ is a surjective map between two cyclic groups of the same order, and is therefore an isomorphism implying that $H^1(H, \text{Res}_H^G M[\phi]) = 0$. In particular, we may now apply Theorem 2.118, to deduce that $H_T^i(H, \text{Res}_H^G M[\phi])$ for all subgroups $H \subset G$ and $i \in \mathbb{Z}$. We now splice the two short exact sequences (2.50) and (2.51) to deduce a long exact sequence

$$0 \rightarrow M \rightarrow M[\phi] \rightarrow \mathbb{Z}[G] \rightarrow \mathbb{Z} \rightarrow 0,$$

which, by applying Lemma 2.106, gives an isomorphism $H_T^i(G, \mathbb{Z}) \xrightarrow{\cong} H_T^{i+2}(G, M)$. Moreover, with a bit more work, one may verify this is the cup product with γ , as desired. \square

Now that we have built up our foundations in group cohomology and homology, we are ready to turn to one of the most beautiful applications of this theory: the proof of local class field theory.

3. LOCAL CLASS FIELD THEORY, REFERENCE: [MIL20A; KED02]

Let K/\mathbb{Q}_p be a finite extension of the p -adic numbers. We will refer to such fields as p -adic fields. In this section, we will use the machinery built up in the previous section to answer the following question: What is the profinite group $\text{Gal}(K^{\text{ab}}/K) := \lim_{L/K} \text{Gal}(L/K)$, where L/K runs over finite Galois extension with abelian Galois group or alternatively what is $\lim_{L/K} \text{Gal}(L/K)^{\text{ab}}$, where L/K runs over all finite Galois extensions? We first explain the answer to this question before proceeding to use our machinery of Tate cohomology to establish the statements.

3.1. The Statements. We fix K/\mathbb{Q}_p and let K^{ab}/K denote the maximal abelian extension. We write $\mathcal{O}_K \subset K$ for the ring of integers with uniformizing element π . The main result of class field theory is as follows.

Theorem 3.1. (The Local Reciprocity Law) *Let K/\mathbb{Q}_p be a finite extension then there exists a unique map*

$$\phi_K : K^* \rightarrow \text{Gal}(K^{\text{ab}}/K)$$

satisfying the following conditions:

- (1) *The image of the uniformizing element $\phi_K(\pi)$ is the Frobenius element, defined analogously to the global case, as in Construction 1.9 and Exercise 1.7.*
- (2) *For any finite abelian extension L/K , the composition*

$$K^* \xrightarrow{\phi_K} \text{Gal}(K^{\text{ab}}/K) \rightarrow \text{Gal}(L/K)$$

is a surjection with kernel isomorphic to $\text{Nm}_{L/K}(L^)$. In particular, we have an isomorphism*

$$\phi_{L/K} : K^*/\text{Nm}_{L/K}(L^*) \xrightarrow{\cong} \text{Gal}(L/K).$$

While we note that this essentially accomplishes our goal of describing the structure of all abelian extensions in terms of the multiplicative structure of our field, it is a bit lacking since we do not just have a clean description of the profinite group $\text{Gal}(K^{\text{ab}}/K)$. Indeed, the map ϕ_K is not an isomorphism, as the π -adic topology of $K^* \subset K$ is fundamentally incompatible with that of the profinite group $\text{Gal}(K^{\text{ab}}/K)$. In particular, K^* is locally compact (since it is a union of $\pi^i \mathcal{O}_K^*$ for all $i \in \mathbb{Z}$), but $\text{Gal}(K^{\text{ab}}/K)$ is compact, by virtue of being a profinite group (Proposition 2.2). To resolve this, we have the following.

Theorem 3.2. (Local Existence Theorem) *Let L/K be a finite extension of p -adic fields then, for every finite (not necessarily abelian extension) the subgroup $\text{Nm}_{L/K}(L^*) \subset K^*$ is open with respect to the π -adic topology and of finite index. Conversely, for every open subgroup $U \subset K^*$, there exists a finite abelian extension L of K such that $U = \text{Nm}_{L/K}(L^*)$.*

We note that the first part of the Theorem is a fairly routine calculation. Indeed, the norm subgroups (i.e the subgroups $\text{Nm}_{L/K}(L^*) \subset K^*$) are fairly explicit subgroups.

Exercise 3.3. *Let L/K be a finite extension of p -adic fields. Show that the following is true.*

- (1) *Show that $\text{Nm}_{L/K}(L^*) \subset K^*$ is an open subgroup of finite index.*
- (2) *Show that, for all $n \geq 1$, the subgroup $(K^*)^n \subset K^*$ is an open subgroup of finite index.*

In particular, we note by Theorem 3.2, Theorem 3.1, and 3.3 (2) that there exists a finite abelian extension L/K such that $\text{Nm}_{L/K}(L^*) = (K^*)^n \subset K^*$ and that we have an isomorphism $K^*/(K^*)^n \simeq \text{Gal}(L/K)$. The description of these abelian extensions fits into a more general paradigm known as Kummer Theory.

Exercise 3.4. (Kummer Theory) *Let K be a field of characteristic 0. Let \overline{K}/K denote the algebraic closure. We write $\mu_n \subset \overline{K}^*$ for the subgroup defined by the elements $x \in \overline{K}^*$ such that $x^n = 1$. We note that this has the natural structure of an object in $\text{Mod}_{\text{Gal}(\overline{K}/K), \text{cont}}$. We consider the short exact sequence*

$$(3.1) \quad 0 \rightarrow \mu_n \rightarrow \overline{K}^* \rightarrow \overline{K}^* \rightarrow 0,$$

in $\text{Mod}_{\text{Gal}(\overline{K}/K), \text{cont}}$, where the last map is given by the multiplication by n -map. We assume that $\mu_n \subset K^$.*

- (1) *Show that we have an isomorphism $\mu_n \simeq \mathbb{Z}/n\mathbb{Z}$ as $\text{Gal}(\overline{K}/K)$ -modules, where $\mathbb{Z}/n\mathbb{Z}$ has trivial Galois action.*

- (2) Use the long exact cohomology sequence attached to (3.1) to deduce the existence of an injective map

$$K^*/(K^*)^n \hookrightarrow \text{Hom}_{\text{cont}}(\text{Gal}(\overline{K}/K), \mu_n).$$

$$a \mapsto \left\{ \sigma \mapsto \frac{\sigma(\sqrt[n]{a})}{\sqrt[n]{a}} \right\},$$

- (3) If $a \in K^\times$ and $\alpha \in \overline{K}^*$, show that $\alpha^n = a$, show that for every $\sigma \in \text{Gal}(K(\alpha)/K)$

$$\sigma(\alpha) = \zeta \alpha \quad \text{for some } \zeta \in \mu_n.$$

Deduce that $K(\alpha)/K$ is abelian of exponent dividing n .

- (4) If $\Delta \subset K^\times$ contains $(K^\times)^n$, define

$$L_\Delta = K(\sqrt[n]{a} \mid a \in \Delta).$$

Show that L_Δ/K is abelian of exponent dividing n . Assume $\Delta/(K^\times)^n$ is finite. Prove that

$$\text{Gal}(L_\Delta/K) \simeq \Delta/(K^\times)^n$$

- (5) Conclude that finite abelian extensions of K of exponent dividing n correspond to finite-index subgroups of K^\times containing $(K^\times)^n$.
 (6) Let K/\mathbb{Q}_p be a p -adic field. Describe the extension corresponding to the open finite index subgroup $(K^*)^n \subset K^*$ in 3.3 (2) under local class field theory.
 (7) Let K/\mathbb{Q}_p be a p -adic field (not necessarily containing μ_ℓ) and let ℓ be a prime. Show that if $x \in \text{Nm}_{L/K}(L^*)$ for all finite extensions L/K then x is an ℓ th power.

In particular, from this we deduce the following Corollary by combining Theorems 3.1 and 3.2, which gives us a nice description of $\text{Gal}(K^{\text{ab}}/K)$.

Corollary 3.5. *The reciprocity map $\phi_K : K^* \rightarrow \text{Gal}(K^{\text{ab}}/K)$ induces an isomorphism*

$$\hat{\phi}_K : \hat{K}^* \xrightarrow{\simeq} \text{Gal}(K^{\text{ab}}/K),$$

where \hat{K}^* is the profinite completion of K^* , as defined in Example 2.5 (3).

Moreover, Theorem 3.2 tells us that actually every subgroup of $\text{Nm}_{L/K}(L^*) \subset K^*$ for a finite extension L/K arises from an abelian extension. However, it is natural to ask which one? This is the content of the norm limitation Theorem.

Theorem 3.6. (Norm Limitation Theorem) *Let L/K be a (not necessarily Galois) extension of p -adic fields. Let $K \subset M \subset L$ be the maximal abelian subextension of L/K . Then*

$$\text{Nm}_{L/K}(L^*) = \text{Nm}_{M/K}(M^*),$$

as desired.

Remark 3.7. We note that it is obvious by the identity $\text{Nm}_{L/K} = \text{Nm}_{M/K} \circ \text{Nm}_{L/M}$ that we have an inclusion

$$\text{Nm}_{L/K}(L^*) \subset \text{Nm}_{M/K}(M^*).$$

Moreover, as in (Exercise 3.3) is easy to see that $\text{Nm}_{L/K}(L^*)$ will be an open subgroup of finite index by direct calculation. In particular, by Theorem 3.2 we know that there exists some abelian extension $N \subset K$ such that $\text{Nm}_{N/K}(N^*) = \text{Nm}_{L/K}(L^*)$, and by Theorem 3.1 we know that we have an inclusion $N \subset M$. The key point is now to really show that $N = M$.

3.2. The Key Calculations. As already mentioned, the proof of Theorem 3.1 will follow from applying Theorem 2.120 to $M = L^*$ and $G = \text{Gal}(L/K)$ for L/K a finite Galois extension of local fields. To do this, for all Galois subextensions $K \subset M \subset L$ with associated subgroup $\text{Gal}(L/M)$, by Galois theory, we need to show the following.

- (1) $H^1(\text{Gal}(L/M), L^*) = 0$
- (2) $H^2(\text{Gal}(L/M), L^*)$ is cyclic of order $[L : M]$.

Here item (1) will follow by Theorem 2.49. We already essentially saw that $H^2(\text{Gal}(L/M), L^*)$ is cyclic of order $[L : M]$ in the case of the unramified extension $\mathbb{Q}_{q^g}/\mathbb{Q}_q$ in Exercise 2.108, and our goal will now be to push this claim further. Our goal is to extend this to any extension L/K . In particular, we want to show the following.

Goal 3.8. *For L/K finite Galois extensions of p -adic fields, we have an isomorphism*

$$H^2(\text{Gal}(L/K), L^*) \simeq \mathbb{Z}/[L : K]\mathbb{Z}.$$

Indeed, by the above discussion we have the following.

Theorem 3.9. *Assume L/K is a finite Galois extension of p -adic fields, then, assuming 3.8, we have an isomorphism*

$$\text{Gal}(L^{\text{ab}}/K) = \text{Gal}(L/K)^{\text{ab}} \simeq H_T^{-2}(\text{Gal}(L/K), \mathbb{Z}) \xrightarrow{\simeq} H_T^0(\text{Gal}(L/K), L^*) \simeq K^*/\text{Nm}_{L/K}(L^*),$$

induced by cupping with a generator $\langle u_{L/K} \rangle \simeq \mathbb{Z}/[L : K]\mathbb{Z} \simeq H^2(\text{Gal}(L/K), L^*)$.

Before trying to achieve Goal 3.8, we briefly review the structure of the Galois groups of local fields.

3.2.1. Brief Aside on The Structure of the Galois Group of a Local Field. For a finite extension K/\mathbb{Q}_p , we write \mathcal{O}_K for the ring of integers with uniformizing element $\pi_K \in \mathcal{O}_K$. We denote the residue field by $\kappa_K := \mathcal{O}_K/\pi_K$. We let $v_K(-) : K \rightarrow \mathbb{Z} \cup \{\infty\}$ denote the K -adic valuation. We recall that we may define this by

$$(3.2) \quad v_K := \frac{1}{f(K/\mathbb{Q}_p)} v_p(\text{Nm}_{K/\mathbb{Q}_p}(-)),$$

where v_p denotes the usual p -adic valuation on \mathbb{Q}_p and $\text{Nm}_{K/\mathbb{Q}_p} : K \rightarrow \mathbb{Q}_p$ is the norm map. Here $f_{K/\mathbb{Q}_p} \in \mathbb{N}_{\geq 1}$ is the ramification index, which we introduce below (See 3.6) We similarly set

$$|\cdot|_K : K \rightarrow \mathbb{R}$$

to be given by $p^{-v_K(-)}$ on K^* and we let it send 0 to 0. In particular, we note that, by the description of the Norm map for L/K is a finite Galois extension, we have that $|\sigma(\cdot)|_L = |\cdot|_L$ is invariant under the Galois action, and similarly for the valuations. Moreover, we may describe the ring of integers by the formula $\mathcal{O}_K = \nu_K^{-1}(\mathbb{N}_{\geq 0} \cup \{\infty\})$ and the maximal ideal of \mathcal{O}_K generated by the uniformizer π_K by the formula $\mathfrak{m}_K := (\pi_K) = \nu_K^{-1}(\mathbb{N}_{> 0} \cup \{\infty\})$.

As a consequence of this discussion we deduce that, for a finite Galois extension L/K the Galois group $\text{Gal}(L/K)$ preserves the extension of ring of integers $\mathcal{O}_L/\mathcal{O}_K$ and induces an automorphism of the extension of finite fields κ_L/κ_K . In particular, we deduce the existence of a well-defined map

$$\text{Gal}(L/K) \rightarrow \text{Gal}(\kappa_L/\kappa_K),$$

which as in 1.7 (4)-(5) will be a surjective map. This induces a short exact sequence

$$(3.3) \quad 0 \rightarrow I(L/K) \rightarrow \text{Gal}(L/K) \rightarrow \text{Gal}(\kappa_L/\kappa_K) \rightarrow 0,$$

where the kernel $I(L/K)$ of the surjection is referred to as the inertia group. The group $\text{Gal}(\kappa_L/\kappa_K)$ is cyclic as κ_L/κ_K is an extension of finite fields. In particular, this is the first step on a filtration on $\text{Gal}(L/K)$ where the graded pieces are cyclic. To proceed further, we need to analyze the group $I(L/K)$. To this end, we first note that one way of describing $I(L/K)$ is that it is the elements

of $\text{Gal}(L/K)$ which are trivial when one looks at their induced action on $\text{Aut}(\mathcal{O}_L/\mathfrak{m}_L \simeq \kappa_L)$. However, since $\text{Gal}(L/K)$ preserves the valuation, we note that it also preserves the subgroups \mathfrak{m}_L^n for all $n \geq 1$. In particular, we could also look at the homomorphism

$$\text{Gal}(L/K) \rightarrow \text{Aut}(\mathcal{O}_L/\mathfrak{m}_L^{n+1})$$

for all $n \geq 0$ and set $I_n(L/K)$ to be the kernel of this map. This defines for us the ramification filtration on $\text{Gal}(L/K)$ with the lower numbering

$$\cdots \subset I_{n+1}(L/K) \subset I_n(L/K) \subset \cdots \subset I_1(L/K) \subset I_0(L/K) = I(L/K) \subset \text{Gal}(L/K).$$

We note that if we have an element in the intersection of all the subgroups $\text{Gal}(L/K) := \bigcap_{n \geq 1} I_n(L/K)$ then the action of this element on $\mathcal{O}_L = \varprojlim_{n \geq 1} \mathcal{O}_L/\pi^n$ is also trivial which implies it must be the identity element. In particular, this filtration is exhaustive. Moreover, since $\text{Gal}(L/K)$ is finite we must have that $I_n(L/K) = \{e\}$ for sufficiently large n . Note that we can also alternatively view $I_n(L/K)$ as the subgroup of elements $\sigma \in \text{Gal}(L/K)$ such that $|\sigma(\pi_L) - \pi_L|_L < |\pi_L|_L^n$ by writing elements of \mathcal{O}_L as power series in π_L . Now, using this description, we can describe the graded pieces of this filtration. More precisely, recalling that $\mathfrak{m}_L^n/\mathfrak{m}_L^{n+1} \simeq \kappa_L$ for all $n \geq 0$, we note that we may define maps

$$(3.4) \quad \begin{aligned} I(L/K)/I_1(L/K) &\rightarrow \kappa_L^* \\ \sigma &\mapsto \frac{\sigma(\pi_L)}{\pi_L} \pmod{\mathfrak{m}_L} \end{aligned}$$

and

$$(3.5) \quad \begin{aligned} I_n(L/K)/I_{n+1}(L/K) &\rightarrow \mathfrak{m}_L^n/\mathfrak{m}_L^{n+1} \simeq \kappa_L \\ \sigma &\mapsto \frac{\sigma(\pi_L)}{\pi_L} - 1 \pmod{\mathfrak{m}_L^{n+1}} \end{aligned}$$

Now we have the following.

Proposition 3.10. *The maps (3.4) and (3.5) are injective. In particular, by combining with the short exact sequence (3.3) we deduce that $\text{Gal}(L/K)$ is solvable, for L/K a finite Galois extension of p -adic fields.*

Proof. See [Mil20b, Corollary 7.59]. □

We now want to endow this filtration with some more meaning. In particular, we recall that, since \mathcal{O}_L is a DVR, we have that

$$(3.6) \quad (\pi_K)\mathcal{O}_L = (\pi_L^{e(L/K)}),$$

where $e(L/K)$ is referred to as the ramification index of e in L/K . As in Exercise 1.7 (2), we have also have the invariant

$$(3.7) \quad f(L/K) := [\kappa_L : \kappa_K]$$

These two invariants will satisfy the relationship

$$(3.8) \quad f(L/K)e(L/K) = [L : K],$$

analogous to (1.7). In light of the short exact sequence (3.3) and the obvious identification $f(L/K) = |\text{Gal}(\kappa_L/\kappa_K)|$, this will give us an identification $e(L/K) = |I(L/K)|$. We now recall the following basic definitions.

Definition 3.11. Let L/K be a finite Galois extension of p -adic fields then we define the following.

- (1) We say the extension L/K is unramified if $e(L/K) = 1$ (equivalently $f(L/K) = [L : K]$ by 3.8) or equivalently if the natural map $\text{Gal}(L/K) \rightarrow \text{Gal}(\kappa_L/\kappa_K)$ appearing in (3.3) is an isomorphism.

- (2) We say the extension L/K is totally ramified if $f(L/K) = 1$ (equivalently $e(L/K) = [L : K]$ by 3.8) or equivalently if the natural map $I(L/K) \xrightarrow{\cong} \text{Gal}(L/K)$ appearing in (3.3) is an isomorphism.

We note that we always have the following consequence of the above discussion, by combining (3.3) with Galois theory.

Corollary 3.12. *For any finite extension L/K there exists a factorization*

$$K \subset M \subset L$$

where M/K is unramified and L/M is totally ramified. We have natural isomorphisms

$$(3.9) \quad \text{Gal}(M/L) \simeq I(L/K)$$

and

$$(3.10) \quad \text{Gal}(K/M) \simeq \text{Gal}(\kappa_L/\kappa_K)$$

Remark 3.13. We refer to $K \subset M$ as the maximal unramified subextension. We note that if we have two extensions $K \subset M$ and $K \subset L$ such that M/K is unramified and L/K is totally ramified then they must be disjoint from one another in the sense that, if ML/K denotes the compositum of the extension in the algebraic closure \overline{K} , then we have that the intersection of L/K and M/K inside ML is just K . Indeed, suppose the intersection $K \subset K' \subset M, L$ was non-trivial. Then we would have exhibited an unramified subextension $K \subset K' \subset L$, which, by the relationship $e(L/K) = e(K'/K)e(L/K')$, would contradict the fact that L/K is totally ramified.

In particular, we see that we can view $I(L/K)$ and the filtration by the subgroups $I_n(L/K)$ as capturing refined information about the totally ramified extensions of p -adic fields, which is why they are called the ramification subgroups. We also see that the structure of the Galois group of the unramified extensions mirrors that of extensions of finite fields. In particular, this relationship is tight.

Theorem 3.14. *The natural mapping*

$$\{L/K \text{ finite unramified extension}\} \rightarrow \{\kappa/\kappa_K \text{ a finite extension}\}$$

$$L \mapsto \kappa_L$$

is bijective.

Proof. See [Mil20b, Proposition 7.50]. The key point is that we may lift any minimal polynomial for the extension κ_L/κ_K using Hensel's lemma to get a minimal polynomial defining an unramified extension with the desired properties. \square

Now that we have the basic structural results on the Galois groups of local fields we may proceed with realizing our Goal 3.8. We begin with case of an unramified extension of fields L/K , which was essentially discussed already in Exercise 2.108.

3.2.2. Unramified Extensions. We now proceed with the verification of Goal 3.8 for an unramified extension L/K of p -adic fields. For the particular extensions $\mathbb{Q}_{q^g}/\mathbb{Q}_q$ this was essentially seen already in Exercise 2.108. As seen there, a key was the short exact sequence of $\text{Gal}(L/K)$ -modules.

$$(3.11) \quad 0 \rightarrow \mathcal{O}_{K^*} \rightarrow L^* \rightarrow \mathbb{Z} \rightarrow 0,$$

where the last map is the valuation and \mathbb{Z} is equipped with the trivial $\text{Gal}(L/K)$ -action. We note that this is a $\text{Gal}(L/K)$ -equivariant map, since the valuation on a local field is invariant under the action of the Galois group, by virtue of the formula (3.2) and the fact that the norm map is invariant under the action of the Galois group.

We now have the following special case of Goal 3.8.

Theorem 3.15. *Let L/K be an unramified extension of local fields L/K then we have that*

$$H^2(\text{Gal}(L/K), L^*) \simeq \mathbb{Z}/[L : K]\mathbb{Z}.$$

Proof. The key point is the following, which for the extension $\mathbb{Q}_{q^g}/\mathbb{Q}_q$ follows from Exercise 2.108 (1),(3),(4), and the argument in general is the same.

Lemma 3.16. *For L/K an unramified extension, the norm map $\text{Nm}_{L/K} : L^* \rightarrow K^*$ induces a surjective map $\mathcal{O}_{L^*} \rightarrow \mathcal{O}_{K^*}$ on the ring of integers.*

In particular, from this we deduce the following corollary.

Corollary 3.17. *For L/K an unramified extension, the Tate cohomology $H_T^i(\text{Gal}(L/K), \mathcal{O}_L^*)$ vanishes for all $i \in \mathbb{Z}$.*

Proof. Since the group $\text{Gal}(L/K)$ is cyclic as in Definition 3.11 (1), it follows by Theorem 2.105 that we only need to check this claim for $i = 0, 1$. The claim that $H_T^0(\text{Gal}(L/K), \mathcal{O}_L^*) = 0$ is an immediate consequence of Lemma 3.16. For $H_T^1(\text{Gal}(L/K), \mathcal{O}_L^*) = H^1(\text{Gal}(L/K), \mathcal{O}_{L^*})$, we note that the short exact sequence (3.11) is split in the case of an unramified extension. Indeed the uniformizing element $\pi_L = \pi_K$ is an element of K and so is fixed by the Galois group. In particular, we deduce that we have an isomorphism:

$$(3.12) \quad H_T^i(\text{Gal}(L/K), L^*) \simeq H_T^i(\text{Gal}(L/K), \mathcal{O}_L^*) \oplus H_T^i(\text{Gal}(L/K), \mathbb{Z})$$

for all $i \in \mathbb{Z}$. This implies that $H^1(\text{Gal}(L/K), \mathcal{O}_{L^*})$ is a direct summand of $H^1(\text{Gal}(L/K), L^*)$, which vanishes by Theorem 2.49. \square

Now we note that we have the following consequence of (3.12) for $i = 2$.

$$H^2(\text{Gal}(L/K), L^*) = H^2(\text{Gal}(L/K), \mathcal{O}_{L^*}) \oplus H^2(\text{Gal}(L/K), \mathbb{Z}) = H^2(\text{Gal}(L/K), \mathbb{Z}),$$

where we have used Corollary 3.17. Then we conclude using Theorem 2.105 that

$$H^2(\text{Gal}(L/K), \mathbb{Z}) \simeq H_T^0(\text{Gal}(L/K), \mathbb{Z}) \simeq \mathbb{Z}/[L : K]\mathbb{Z}.$$

\square

Remark 3.18. We note if K_n/K denotes the unique unramified extension of degree n guaranteed by Theorem 3.14, we have that $H^2(\text{Gal}(K_n/K), K_n^*) \simeq \mathbb{Z}/n\mathbb{Z}$ by Theorem 3.15. Moreover, by Tate-periodicity, we have that this is isomorphic to $K^*/\text{Nm}_{K_n/K}(K_n^*)$. Using the identification $K^* \simeq \mathcal{O}_K^* \times \mathbb{Z}$ given by the split (as $\text{Gal}(K_n/K)$ -modules) short exact sequence (3.11) for K_n^* and K^* together with Lemma 3.16 (as in 2.108), we may deduce that we may explicitly describe the norm subgroup $\text{Nm}_{K_n/K}(K_n^*) \subset K^*$ as the subgroup $n\mathbb{Z} \times \mathcal{O}_K^* \subset \mathbb{Z} \times \mathcal{O}_{K^*} \simeq K^*$. In particular, we note that $K^*/\text{Nm}_{K_n/K}(K_n^*)$ is generated by π_K .

Remark 3.19. We note that these identifications have the following compatibility as we vary the extension. For an unramified extension L/K , we note that we have a natural map

$$H^2(\text{Gal}(L/K), L^*) \simeq \mathbb{Z}/[L : K]\mathbb{Z} \simeq [L : K]\mathbb{Z}/\mathbb{Z} \hookrightarrow \mathbb{Q}/\mathbb{Z}.$$

We refer to this

$$(3.13) \quad \text{inv}_{L/K} : H^2(\text{Gal}(L/K), L^*) \rightarrow \mathbb{Q}/\mathbb{Z}$$

as the invariant map. If we have an unramified subextension $K \subset M \subset L$, we also have the natural inflation map

$$H^2(\text{Gal}(L/K), L^*) \rightarrow H^2(\text{Gal}(M/K), M^*).$$

This sits in a commutative diagram

$$(3.14) \quad \begin{array}{ccc} H^2(\mathrm{Gal}(L/K), L^*) & \xrightarrow{\mathrm{inv}_{L/K}} & \mathbb{Q}/\mathbb{Z} \\ \downarrow & & \downarrow \mathrm{id} \\ H^2(\mathrm{Gal}(M/K), M^*) & \xrightarrow{\mathrm{inv}_{M/K}} & \mathbb{Q}/\mathbb{Z} \end{array}$$

Indeed, we may see this by reinterpreting $\mathrm{inv}_{L/K}$ as follows. We have a natural isomorphism

$$H^2(\mathrm{Gal}(L/K), L^*) \simeq H_T^0(\mathrm{Gal}(L/K), L^*) \simeq H_T^0(\mathrm{Gal}(L/K), \mathbb{Z})$$

induced by fixing a generator $u_{L/K}$ of $H^2(\mathrm{Gal}(L/K), L^*)$. Now we look at the short exact sequence,

$$0 \rightarrow \mathbb{Z} \rightarrow \mathbb{Q} \rightarrow \mathbb{Q}/\mathbb{Z} \rightarrow 0$$

and invoke Lemma 2.73 to see that the boundary map in the long exact sequence induces an isomorphism

$$H_T^0(\mathrm{Gal}(L/K), \mathbb{Z}) \simeq H^1(\mathrm{Gal}(L/K), \mathbb{Q}/\mathbb{Z}) = \mathrm{Hom}(\mathrm{Gal}(L/K), \mathbb{Q}/\mathbb{Z}),$$

where the last identification is as in 2.46. We now note that we have a canonical map $\mathrm{Gal}(L/K) \rightarrow \mathbb{Q}/\mathbb{Z}$ given by evaluating on the Frobenius. In particular, the resulting map

$$H^2(\mathrm{Gal}(L/K), L^*) \rightarrow \mathbb{Q}/\mathbb{Z}$$

is $\mathrm{inv}_{L/K}$. Tracing through the identifications, this allows us to see the commutativity of the diagram (3.14) follows from the fact that the surjection $\mathrm{Gal}(L/K) \rightarrow \mathrm{Gal}(M/K)$ sends the Frobenius to the Frobenius. If we now consider the maximal unramified extension $K \subset K^{\mathrm{un}} \subset \overline{K}$ (i.e the compositum of all unramified extensions of K in \overline{K}) then we note this is an object in the category $\mathrm{Mod}_{\mathrm{Gal}(K^{\mathrm{un}}/K), \mathrm{cont}}$. We may form the cohomology

$$H^2(\mathrm{Gal}(K^{\mathrm{un}}/K), K^{\mathrm{un},*}),$$

which, by Corollary 2.79, is a direct limit of $H^2(\mathrm{Gal}(L/K), L^*)$ for L/K finite unramified over the inflation maps. Therefore, we obtain a map

$$(3.15) \quad \mathrm{inv} : H^2(\mathrm{Gal}(K^{\mathrm{un}}/K), K^{\mathrm{un},*}) \xrightarrow{\sim} \mathbb{Q}/\mathbb{Z}$$

which will now be an isomorphism by virtue of the fact that \mathbb{Q}/\mathbb{Z} is a direct limit over its finite torsion subgroups.

We now turn to the next level of generality

3.2.3. The Cyclic Case. We now consider a not necessarily unramified cyclic extension L/K . In this case, we will have to modify our approach slightly. Indeed, we note that the analogue of Lemma 3.16 does not hold in this case (Recall that \sqrt{p} is a uniformizer in $\mathbb{Q}_p(\sqrt{p})$ so that this extension is ramified, as in (3.6)) .

Exercise 3.20. Let $L = \mathbb{Q}_p(\sqrt{p})$ and $K = \mathbb{Q}_p$. Show the following.

(1) The natural map

$$\mathrm{Nm}_{L/K} : L^* \rightarrow K^*$$

induces an isomorphism $L^*/\mathcal{O}_L^* \simeq K^*/\mathcal{O}_K^*$.

(2) Compute the cohomology groups $H_T^i(\mathrm{Gal}(L/K), \mathcal{O}_L^*)$ for all $i \in \mathbb{Z}$. Show that $H_T^0(\mathrm{Gal}(L/K), \mathcal{O}_K^*) \neq 0$.

In particular, we will need some replacement for Lemma 3.16. The idea will be to first consider the additive case and then use the p -adic exponential map to move to the multiplicative case.

Lemma 3.21. Let L/K be a Galois extension of local fields then there is an open subgroup $U \subset \mathcal{O}_L$ of the ring of integers which satisfies the following.

- (1) U is stable under the action of $\text{Gal}(L/K)$.
- (2) We have that the cohomology $H^i(\text{Gal}(L/K), U)$ vanishes for all $i > 0$.

Moreover, we may assume that, for all $x \in U$, the valuations $v_L(-) : L \rightarrow \mathbb{Z}$ of all elements in U are larger than m , for any $m \in \mathbb{Z}$.

Proof. By the normal basis theorem, we may find $\alpha \in L$ such that the $\text{Gal}(L/K)$ -translates of α generated L as a K -vector space. We may rescale α to assume that α is in \mathcal{O}_L^* . We then consider the subgroup U of \mathcal{O}_L generated by the translates of α under $\text{Gal}(L/K)$ under the scaling action of \mathcal{O}_K . We note that, as a $\text{Gal}(L/K)$ -module, we have that $U \simeq \text{Ind}_1^{\text{Gal}(L/K)}(\mathcal{O}_K)$. In particular, by Schapiro's Lemma, it satisfies the desired property (cf. Exercise 2.51). To guarantee the condition on the p -adic valuations, we note that it simply suffices to show the desired condition for α since the valuation is Galois equivariant, which may be rearranged after further rescaling. \square

We now deduce the analogous result in the multiplicative case.

Lemma 3.22. *Let L/K be a Galois extension of local fields then there is an open finite index subgroup $V \subset \mathcal{O}_L^*$ of the ring of integers which satisfies the following.*

- (1) V is stable under the action of $\text{Gal}(L/K)$.
- (2) We have that the cohomology $H^i(\text{Gal}(L/K), V)$ vanishes for all $i > 0$.

Proof. We consider the formal power series

$$\exp(x) := \sum_{n=0}^{\infty} \frac{x^n}{n!}.$$

By choosing the subgroup $U \subset \mathcal{O}_L$ of Lemma 3.21 to have sufficiently large valuations, we may arrange that this power series converges p -adically (Use that $v_p(n!) = \sum_{k=0}^{\infty} \lfloor \frac{n}{p^k} \rfloor$), and it will define a topological isomorphism of U onto a subgroup of $V \subset \mathcal{O}_L^*$ (as it has an inverse given by the logarithm map), which will be equivariant for $\text{Gal}(L/K)$. In particular, we have isomorphisms

$$H^i(\text{Gal}(L/K), U) \simeq H^i(\text{Gal}(L/K), V),$$

from which the claim follows. \square

Using similar logic to the prove of Lemma 3.22, we can deduce the following which will be useful for the proof of the local existence Theorem (Theorem 3.2).

Exercise 3.23. *Suppose K/\mathbb{Q}_p is a finite extension. Show that the intersection $\cap_{n \geq 1} (K^*)^n$ is trivial (Hint: reduce to checking it for a open finite index subgroup $V \subset \mathcal{O}_L^*$ and then argue as in the proof of Lemma 3.22).*

We now deduce the following partial realization of Goal 3.8, using the theory of the Herbrand quotient introduced in Definition 2.110.

Theorem 3.24. *For L/K a cyclic extension of p -adic fields, we have that*

$$|H_T^0(\text{Gal}(L/K), L^*)| = |H^2(\text{Gal}(L/K), L^*)|$$

is of cardinality $[L : K]$.

Proof. We note, by Example 2.111 and 2.112 (1) applied to the short exact sequence (2.42) we have an equality

$$h(L^*) = h(\mathbb{Z})h(\mathcal{O}_L^*).$$

However, we note that $V \subset \mathcal{O}_L^*$ is open so it has finite index. In particular, by Proposition 2.112 (1)-(2), we have an equality

$$h(V) = h(\mathcal{O}_L^*),$$

where we note, by Tate-Periodicity and Lemma 3.22 (2), we have that $h(V) = 1$. In summary, we have deduced that

$$h(L^*) = h(\mathbb{Z}) = [L : K],$$

where the last equality follows from Example 2.111. However, by Hilbert 90 (Theorem 2.49) and Tate-periodicity again, this now implies that we have

$$|H_T^0(\text{Gal}(L/K), L^*)| = [L : K],$$

as desired. \square

In order to push this claim forward, we will need to exploit a particular property of the Galois groups of a finite extension of p -adic fields; namely, that they are always solvable, as explained in Proposition 3.10.

3.2.4. General Extensions. We now have the following extension/weakening of Theorem 3.24 to general extensions.

Theorem 3.25. *For any finite Galois extension L/K , we have an inequality*

$$|H^2(\text{Gal}(L/K), L^*)| \leq [L : K].$$

Proof. The case of L/K cyclic was checked in Theorem 3.24. To reduce to the case, we induct on the number of normal subgroups of $\text{Gal}(L/K)$. In particular, by Corollary 2.107, either $\text{Gal}(L/K)$ is cyclic and we are done, or we may choose a non-trivial finite cyclic subextension L/M . To proceed further, we then apply the inflation and restriction exact sequence Proposition 2.117 to the subgroup $\text{Gal}(L/M) \subset \text{Gal}(L/K)$. In particular, by combining with Hilbert 90 (Theorem 2.49), this tells us that we have a left exact sequence

$$0 \rightarrow H^2(\text{Gal}(M/K), M^*) \rightarrow H^2(\text{Gal}(L/K), L^*) \rightarrow H^2(\text{Gal}(L/M), L^*)$$

However, this gives us an inequality

$$|H^2(\text{Gal}(L/K), L^*)| \leq |H^2(\text{Gal}(M/K), M^*)| |H^2(\text{Gal}(L/M), L^*)| = [M : K][L : M] = [L : K],$$

where we have used our inductive hypothesis to conclude the equality. \square

Now, in light of Theorem 3.24, all that remains to do is exhibit a cyclic subgroup of $H^2(\text{Gal}(L/K), L^*)$ of order $[L : K]$ to achieve Goal 3.8. We will do this by comparing to the case of unramified extensions, where we saw this already in Theorem 3.15 and Exercise 2.108.

Proposition 3.26. *Let L/K be a finite Galois extension of local fields and let M/K be an unramified extension of degree $[L : K]$. We write ML for the compositum of the two fields over K , which is also a finite Galois extension (since L/K and M/K are both finite Galois) with quotients $\text{Gal}(ML/K) \rightarrow \text{Gal}(L/K), \text{Gal}(M/K)$. We consider the inflation maps*

$$(3.16) \quad H^2(\text{Gal}(L/K), L^*) \rightarrow H^2(\text{Gal}(ML/K), (ML)^*)$$

and

$$(3.17) \quad H^2(\text{Gal}(M/K), M^*) \rightarrow H^2(\text{Gal}(ML/K), (ML)^*).$$

However, now the image of (3.16) contains the image of (3.17).

Proof. We consider the diagram
(3.18)

$$\begin{array}{ccccc}
 & & 0 & & \\
 & & \downarrow & & \\
 & & H^2(\mathrm{Gal}(M/K), M^*) & & \\
 & & \downarrow (3.17) & \searrow & \\
 0 & \longrightarrow & H^2(\mathrm{Gal}(L/K), L^*) & \xrightarrow{(3.16)} & H^2(\mathrm{Gal}(ML/K), (ML)^*) \longrightarrow H^2(\mathrm{Gal}(ML/L), (ML)^*),
 \end{array}$$

where the claimed exactness properties follow from combining (2.117) with Theorem (2.49). By these exactness properties, it suffices to show the diagonal arrow is the zero map, as this will imply the existence of an injective map $H^2(\mathrm{Gal}(M/K), M^*) \rightarrow H^2(\mathrm{Gal}(L/K), L^*)$. In order to do this, we let $K \subset U \subset L$ be the maximal unramified subextension of L/K , as in Remark 3.13. We note that we have an inclusion $U \subset M$ since $[U : K][M : K]$ by Theorem 3.14. Using the obvious functoriality of inflation maps, we may extend (3.18) to a commutative diagram

(3.19)

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & \\
 & & \downarrow & & \downarrow & & \\
 0 & \longrightarrow & H^2(\mathrm{Gal}(U/K), U^*) & \longrightarrow & H^2(\mathrm{Gal}(M/K), M^*) & \longrightarrow & H^2(\mathrm{Gal}(M/U), U^*) \\
 & & \downarrow & & \downarrow (3.17) & \searrow & \\
 0 & \longrightarrow & H^2(\mathrm{Gal}(L/K), L^*) & \xrightarrow{(3.16)} & H^2(\mathrm{Gal}(ML/K), (ML)^*) & \longrightarrow & H^2(\mathrm{Gal}(ML/L), (ML)^*), \\
 & & \downarrow & & \downarrow & & \\
 0 & \longrightarrow & H^2(\mathrm{Gal}(L/U), L^*) & \longrightarrow & H^2(\mathrm{Gal}(ML/M), (ML)^*) & \longrightarrow & H^2(\mathrm{Gal}(ML/L), L^*)
 \end{array}$$

where exactness of the maps again follows by Theorem 2.49 and Proposition 2.117. In particular, by passing to the quotient of $H^2(\mathrm{Gal}(M/K), M^*)$ (resp. $H^2(\mathrm{Gal}(L/K), L^*)$) by $H^2(\mathrm{Gal}(U/K), U^*)$ and using the exactness properties of the diagram, we see that it suffices to show that $H^2(\mathrm{Gal}(L/U), L^*) \rightarrow H^2(\mathrm{Gal}(ML/U), (ML)^*)$ admits an injection from $H^2(\mathrm{Gal}(M/K), M^*)/H^2(\mathrm{Gal}(U/K), U^*) \hookrightarrow H^2(\mathrm{Gal}(M/U), U^*)$. However, this reduces us to showing that the natural map $H^2(\mathrm{Gal}(M/U), U^*) \hookrightarrow H^2(\mathrm{Gal}(ML/M), (ML)^*)$ factors through $H^2(\mathrm{Gal}(L/U), L^*) \rightarrow H^2(\mathrm{Gal}(ML/U), (ML)^*)$. In other words, we may replace K by U , and assume without loss of generality that L/K is a totally ramified extension in the sense of Definition 3.11 (2). In particular, by Remark 3.13, this implies that we may assume that L/K and M/K are disjoint extensions. From here, we deduce that $L \cap M = K$ and that the restriction map

$$\mathrm{Gal}(ML/L) \xrightarrow{\cong} \mathrm{Gal}(M/M \cap L) = \mathrm{Gal}(M/K)$$

is an isomorphism, where $\mathrm{Gal}(M/K)$ and in turn $\mathrm{Gal}(ML/L)$ is cyclic, by Theorem 3.15. Moreover, ML/L will be unramified as it the compositum of an unramified extension M/K with L . In particular, the natural map $M^* \rightarrow (ML)^*$ is an map of Galois modules with respect to this isomorphism, and thus we obtain a natural map

$$(3.20) \quad H^2(\mathrm{Gal}(M/K), M^*) \rightarrow H^2(\mathrm{Gal}(ML/L), (ML)^*)$$

which is the one we want to show is zero. However, the groups appearing here are both cyclic so we may apply Tate periodicity (Theorem 2.105) to replace (3.20) with the map

$$K^*/\mathrm{Nm}_{M/K}(M^*) \rightarrow L^*/\mathrm{Nm}_{ML/L}((ML)^*).$$

However, the target of this map is a cyclic group of order $[L : K]$ generated by π_K (Remark 3.18) and the source is again a cyclic group of order $[L : K]$ by the above discussion. Therefore, it suffices to show the image of π_K is zero. However, since L/K is totally ramified $\pi_K = \pi_L^{[L:K]}$ up to a unit of \mathcal{O}_L as in (3.6) and therefore it is indeed zero, as desired. \square

This indeed implies the claim we want, allowing us to finally accomplish Goal 3.8.

Corollary 3.27. *For L/K a finite Galois extension of p -adic fields, we have an isomorphism*

$$\mathbb{Z}/[L : K]\mathbb{Z} \simeq H^2(\mathrm{Gal}(L/K), L^*).$$

Proof. As explained above, by Theorem 3.25, it suffices to exhibit a cyclic subgroup of order $[L : K]$ in $H^2(\mathrm{Gal}(L/K), L^*)$. We consider the situation of Proposition 3.26. By combining Proposition 2.117 with Hilbert Theorem 90 (Theorem 2.49), we deduce the inflation maps

$$H^2(\mathrm{Gal}(L/K), L^*) \xrightarrow{(3.16)} H^2(\mathrm{Gal}(ML/K), (ML)^*)$$

and

$$H^2(\mathrm{Gal}(M/K), M^*) \xrightarrow{(3.17)} H^2(\mathrm{Gal}(ML/K), (ML)^*).$$

are injective, as in (3.18). However, now the desired claim easily follows by applying Theorem 3.15 to deduce that $H^2(\mathrm{Gal}(M/K), M^*) \simeq \mathbb{Z}/[L : K]\mathbb{Z}$ together with Proposition 3.26. \square

In particular, by Theorem 3.9, this allows us to (finally) proudly proclaim the following result.

Theorem 3.28. *Assume L/K is a finite Galois extension of p -adic fields, then we have an isomorphism*

$$\mathrm{Gal}(L^{\mathrm{ab}}/K) = \mathrm{Gal}(L/K)^{\mathrm{ab}} \simeq H_T^{-2}(\mathrm{Gal}(L/K), \mathbb{Z}) \xrightarrow{\simeq} H_T^0(\mathrm{Gal}(L/K), L^*) \simeq K^*/\mathrm{Nm}_{L/K}(L^*),$$

induced by cupping with a generator $\langle u_{L/K} \rangle \simeq \mathbb{Z}/[L : K]\mathbb{Z} \simeq H^2(\mathrm{Gal}(L/K), L^)$ given by Corollary 3.27.*

Remark 3.29. We let $K \subset K^{\mathrm{un}} \subset \overline{K}$ be the maximal unramified extension. We view \overline{K}^* as an object in $\mathrm{Mod}_{\mathrm{Gal}(\overline{K}/K), \mathrm{cont}}$ and view $K^{\mathrm{un},*}$ as an object in $\mathrm{Mod}_{\mathrm{Gal}(\overline{K}/K), \mathrm{cont}}$ via the restriction map $\mathrm{Gal}(\overline{K}/K) \rightarrow \mathrm{Gal}(K^{\mathrm{un}}/K)$. The natural inclusion $K^{\mathrm{un},*} \hookrightarrow \overline{K}^*$ induces a natural map

$$(3.21) \quad H^2(\mathrm{Gal}(\overline{K}/K), K^{\mathrm{un},*}) \rightarrow H^2(\mathrm{Gal}(\overline{K}/K), \overline{K}^*),$$

by the construction described in 2.3.2. By 3.15, the former also identifies with \mathbb{Q}/\mathbb{Z} by virtue of the invariant map $\mathrm{inv}_{L/K} : H^2(\mathrm{Gal}(L/K), L^*) \rightarrow \mathbb{Q}/\mathbb{Z}$ introduced for an unramified extension in (3.13). Using Theorem 3.28, we may construct a map

$$(3.22) \quad \mathrm{inv}_{L/K} : H^2(\mathrm{Gal}(L/K), L^*) \rightarrow \mathbb{Q}/\mathbb{Z}$$

after fixing a generator $u_{L/K} \in H^2(\mathrm{Gal}(L/K), L^*)$, by the exact same reasoning. It will also satisfy the obvious functorialities with respect to inflation, as in (3.14). By applying 2.79, we get a map

$$(3.23) \quad \mathrm{inv} : H^2(\mathrm{Gal}(\overline{K}/K), \overline{K}^*) \rightarrow \mathbb{Q}/\mathbb{Z}$$

and we claim that it is an isomorphism. However, one easily sees that the composition

$$H^2(\mathrm{Gal}(\overline{K}/K), K^{\mathrm{un},*}) \rightarrow H^2(\mathrm{Gal}(\overline{K}/K), \overline{K}^*) \xrightarrow{\mathrm{inv}} \mathbb{Q}/\mathbb{Z},$$

is the isomorphism (3.15) and that the first map is injective by the proof of Proposition 3.26, which implies that the map (3.22) is an isomorphism. In particular, by combining with (2.29) we deduce the following.

Corollary 3.30. *Let K/\mathbb{Q}_p be a p -adic field. Then we have an isomorphism*

$$\mathrm{Br}(K) \simeq \mathbb{Q}/\mathbb{Z},$$

where $\mathrm{Br}(K)$ denotes the local Brauer group.

In particular, we are now ready to deduce all the main Theorems of local class field theory from this result.

3.3. Clean Up. We begin with the proof of the Norm limitation Theorem.

Proof. (Theorem 3.6) We first consider a Galois extension L/K and let $K \subset M \subset L$ be the maximal abelian subextension. However, by applying Theorem 3.28, we deduce that we have an isomorphism

$$\mathrm{Gal}(L/K)^{\mathrm{ab}} \simeq \mathrm{Gal}(M/K) \xrightarrow{\cong} K^*/\mathrm{Nm}_{L/K}(L^*)$$

and an isomorphism

$$\mathrm{Gal}(M/K) \xrightarrow{\cong} K^*/\mathrm{Nm}_{M/K}(M^*).$$

However, this forces the obvious containment $\mathrm{Nm}_{L/K}(L^*) \subset \mathrm{Nm}_{M/K}(M^*)$, as described in Remark 3.7 to be an equality, since they are both subgroups of the same index in K^* .

We now consider the case of a general extension L/K , we again have an obvious inclusion $\mathrm{Nm}_{L/K}(L^*) \subset \mathrm{Nm}_{M/K}(M^*)$. To check the reverse inclusion, we replace L by its Galois closure $K \subset M \subset L \subset L^{\mathrm{Gal}}$ and then use the obvious containment

$$\mathrm{Nm}_{L^{\mathrm{Gal}}/K}((L^{\mathrm{Gal}})^*) \subset \mathrm{Nm}_{L/K}(L^*)$$

to reduce to the previous case. □

We now want to turn to the proof of Theorem 3.1.

Proof. (Theorem 3.1) We see that at least that part (2) is essentially covered by our key Theorem 3.28. In particular, we have produced an isomorphism

$$\phi_{L/K} : K^*/\mathrm{Nm}_{L/K}(L^*) \xrightarrow{\cong} \mathrm{Gal}(L/K).$$

for all finite abelian extensions L/K , and it is fairly easy to check that this will carry the uniformizing element to Frobenius. However, in order to get the map $\phi_K : K^* \rightarrow \mathrm{Gal}(K^{\mathrm{ab}}/K)$ with the desired properties. We need to show that these maps "patch together" in an appropriate way as we vary the extension. We will do this using the following Lemma.

Lemma 3.31. *For G a finite abelian, the cup product of 2.115*

$$H_T^{-2}(G, \mathbb{Z}) \times H_T^2(G, \mathbb{Z}) \rightarrow H_T^0(G, \mathbb{Z})$$

induces a perfect pairing (In the sense that something on either side which pairs to give 0 with the other side is already 0).

Proof. We note that we have identifications

$$H_T^{-2}(G, \mathbb{Z}) \simeq G$$

by Exercise 2.100 (4) and

$$H_T^0(G, \mathbb{Z}) \simeq \mathbb{Z}/|G|\mathbb{Z}$$

as in Example 2.111. Moreover, we claim that we have an identification

$$H_T^2(G, \mathbb{Z}) \simeq \mathrm{Hom}(G, \mathbb{Q}/\mathbb{Z}).$$

To see this, we use the exact sequence

$$0 \rightarrow \mathbb{Z} \rightarrow \mathbb{Q} \rightarrow \mathbb{Q}/\mathbb{Z} \rightarrow 0$$

of G -modules equipped with the trivial G -action. However, \mathbb{Q} is acyclic by Lemma 2.73. This implies that the boundary map in the long exact cohomology sequence of Tate-cohomology then induces the desired identification.

Now, using the above identifications, one can check that the cup product on Tate-cohomology identifies with the obvious pairing

$$G \times \mathbb{Z}/|G|\mathbb{Z} \rightarrow \mathrm{Hom}(G, \mathbb{Z}/|G|\mathbb{Z}) \rightarrow \mathrm{Hom}(G, \mathbb{Q}/\mathbb{Z}),$$

given by evaluating a map $\text{Hom}(G, \mathbb{Z}/|G|\mathbb{Z})$ on elements of G . This is easily checked to be perfect. \square

In particular, we may now combine 3.31 together with the isomorphism

$$H_T^{-2}(\text{Gal}(L/K), \mathbb{Z}) \rightarrow H_T^0(\text{Gal}(L/K), L^*)$$

of Theorem 3.28, which we recall is also induced by cup product, to deduce that the cup product map

$$(3.24) \quad H_T^0(\text{Gal}(L/K), L^*) \times H_T^2(\text{Gal}(L/K), \mathbb{Z}) \rightarrow H^2(\text{Gal}(L/K), L^*)$$

is a perfect pairing. We now massage this even further. In particular, after fixing generators $u_{L/K}$ of $H^2(\text{Gal}(L/K), L^*)$, we may define invariant maps (3.22) $H^2(\text{Gal}(L/K), L^*) \rightarrow \mathbb{Q}/\mathbb{Z}$, which then gives us a perfect pairing

$$H_T^0(\text{Gal}(L/K), L^*) \times H_T^2(\text{Gal}(L/K), \mathbb{Z}) \rightarrow \mathbb{Q}/\mathbb{Z}.$$

Moreover, we see that the fact that this pairing is perfect completely encodes the reciprocity map indeed the inverse of the cup map with a class in $H_T^2(\text{Gal}(L/K), \mathbb{Z})$ induces the desired isomorphism

$$\phi_{L/K} : K^*/\text{Nm}_{L/K}(L^*) \simeq H_T^0(\text{Gal}(L/K), L^*) \rightarrow H_T^{-2}(\text{Gal}(L/K), \mathbb{Z}) \simeq \text{Gal}(L/K).$$

However, as we now want to take limits over L/K it is better that we pass to a statement that just involves cohomology and not homology/Tate cohomology (cf. Remark 2.77). In particular, precomposing with the natural map $H^0(\text{Gal}(L/K), L^*) \rightarrow H_T^0(\text{Gal}(L/K), L^*)$, we obtain a natural map

$$(3.25) \quad H^0(\text{Gal}(L/K), L^*) \times H^2(\text{Gal}(L/K), \mathbb{Z}) \rightarrow \mathbb{Q}/\mathbb{Z},$$

which only involves cohomology. In particular, to construct the map

$$\phi_K : K^* \rightarrow \text{Gal}(K^{\text{ab}}/K)$$

of Theorem 3.1 (1), we just need to see that this pairing is compatible with varying the extension. We recall that the cup product is compatible with the restriction map induced by $\text{Gal}(L/K) \rightarrow \text{Gal}(M/K)$, by Proposition 2.116 (2), and we know that the same is true for the invariant map, as explained in Remark 3.29. This gives us the claim. \square

All that is left to do now is show the local Existence Theorem. We start with the following.

Proposition 3.32. *Let K/\mathbb{Q}_p be a p -adic field. Then the intersection of all of the norm groups $\text{Nm}_{L/K}(L^*)$ for all finite extensions L/K is trivial.*

Proof. We let D_K denote the intersection of all the norm groups. We note that this is contained in $D_K \subset \mathcal{O}_K^*$. Indeed, for K_n/K the unique unramified extension of K/\mathbb{Q}_p of degree n guaranteed by Theorem 3.14, we note that $\text{Nm}_{K_n/K}(K^*) \simeq n\mathbb{Z} \times \mathcal{O}_{K^*} \subset \mathbb{Z} \times \mathcal{O}_K^* \simeq K^*$, as in Remark 3.18. In particular, the intersection of all of these subgroups is \mathcal{O}_K^* . In particular, we deduce that D_K is a compact as a topological group. By Kummer theory, in particular 3.4 (7), we also note that every element of D_K is an ℓ th power of an element in K^* for every prime ℓ . We claim that it is actually an ℓ th power for an element in D_K , which will in turn allow us to conclude that every element is an n th power of an element in D_K (by looking at the prime factorization of n and iteratively applying the claim on the primes ℓ appearing). In particular, we deduce that $D_K \subset \bigcap_{n \geq 1} (K^*)^n$, which is trivial by Exercise 3.23.

We first show that for every finite extension, we have that

$$(3.26) \quad \text{Nm}_{L/K} D_L = D_K$$

It is clear that we have an inclusion $\text{Nm}_{L/K} D_L \subset D_K$. For the opposite inclusion, suppose we have $x \in D_K$ then, for any finite extension $K \subset L \subset M$, we can write $x = \text{Nm}_{M/K}(z)$ for some $z \in M^*$. It now suffices to show that that we can choose z such that $y = \text{Nm}_{M/L}(z)$ is equal for

all M . For any fixed M , the set of such y occurring for varying z satisfying $x = \text{Nm}_{M/K}(z)$ is a non-empty compact subset of \mathcal{O}_L^* (as the valuations of the possible y are fixed by the condition $\text{Nm}_{L/K}(y) = x$). In particular, the intersection of all these compact subsets since their pairwise intersection is non-empty, which gives us the desired claim.

Now we need to show that every $x \in D_K$ has an ℓ th root. For each finite extension L/K containing a primitive ℓ th root of unity let $E(L)$ be the set of ℓ th roots of $x \in K$ which belong to $\text{Nm}_{L/K}L^*$. This is non-empty. In particular, by (3.26) paragraph $x = \text{Nm}_{L/K}(y)$ for some $y \in D_L$ by the above logic, and y has an ℓ th root $z \in L^*$ by the Kummer theory argument above. Now if we have a finite extension $L \subset M$ we have an inclusion $E(M) \subset E(L)$ again by 3.26. This guarantees that if we look at the set of $E(L)$ for varying L/K it has the property that its pairwise intersection is non-empty, since if we have $E(L)$ and $E(L')$ we have an inclusion $E(LL') \subset E(L) \cap E(L')$. As before, this implies that the intersection of the $E(L)$ over all L/K is non-empty by Lemma 2.13, which implies the desired claim. \square

We now have the following weaker version of the norm limitation theorem.

Lemma 3.33. *For every open finite index subgroup $U \subset K^*$, there exists a finite abelian extension L/K such that $\text{Nm}_{L/K}(L^*) \subset U \subset K^*$.*

Proof. By the already established norm limitation theorem 3.6, it suffices to produce a finite extension L/K which is not necessarily abelian such that $\text{Nm}_{L/K}L^* \subset U^*$. In particular, we have some additional flexibility. We let $n\mathbb{Z} \subset \mathbb{Z}$ be the image of U in the subgroup $K^*/\mathcal{O}_K^* \simeq \mathbb{Z}$ as in (3.11). In particular, if we assume that $K_n \subset L$ contains the maximal unramified extension of degree n we may assume that $\text{Nm}_{L/K}L^*$ is also contained in $n\mathbb{Z}$ by Remark 3.18. By the exactness of (3.11), we therefore reduce to choosing L such that

$$(3.27) \quad \text{Nm}_{L/K}L^* \cap \mathcal{O}_K^* \subset U \cap \mathcal{O}_K^*.$$

Since \mathcal{O}_K^* is compact we have that subgroup $\text{Nm}_{L/K}L^* \cap \mathcal{O}_K^*$ is open and hence also closed (since \mathcal{O}_{K^*} is profinite, by Lemma 2.8) and therefore is compact. By Proposition 3.32, we have that the intersection of these compact open subgroups

$$\text{Nm}_{L/K}L^* \cap \mathcal{O}_K^*$$

for varying L/K is also trivial. This in particular implies that the intersection with $\mathcal{O}_K^* \setminus U \cap \mathcal{O}_K^*$ is also trivial. Therefore, by taking L/K sufficiently large, we may arrange that we have the containment (3.27), as desired. \square

We may now finally prove the local existence theorem.

Proof. (Theorem 3.2) By Lemma 3.33, we have that we can find a finite abelian extension M/K such that $\text{Nm}_{M/K}M^* \subset U$. However, by the reciprocity isomorphism Theorem 3.1, we have that $\text{Gal}(M/K) \simeq K^*/\text{Nm}_{M/K}M^*$. In particular, if we take L/K to be the fixed field defined by the finite index subgroup $U/\text{Nm}_{M/K}M^*$ this gives us the desired claim. \square

We have now finished our discussion of local class field theory. Armed with the knowledge gained here, we now embark on the more treacherous path towards global class field theory.

4. GLOBAL CLASS FIELD THEORY, REFERENCE: [KED; NSW08; CF10]

As we saw in the proof of local class field theory, a key was using the Theorem of Tate-Nakayama (Theorem 2.120) to reduce the proof of the reciprocity map to showing that the $H^2(\text{Gal}(L/K), L^*)$ for a finite Galois extension L/K was always given by a cyclic group. This is a shadow of a more general formalism of Artin-Tate that was designed to axiomatize the proofs of global and local class field theory. We start by explaining this axiomatic framework now and then we will apply this to

certain groups attached to number fields known as the ideles. Throughout, we will assume all our fields of characteristic 0 (for simplicity).

4.1. Class Formations and Abstract Class Field Theory. We first introduce the analogue of the groups L^* for L/K a finite extension, which will allow us to formulate the analogue of Goal 3.8 in the case of local class field theory.

Definition 4.1. Let k be a field with algebraic closure \bar{k} . We let $G := \text{Gal}(\bar{k}/k)$ be the profinite group of Example 2.5 (1). For K/k a subextension, we set $G_K := \text{Gal}(\bar{k}/K)$ to be the closed subgroup of G corresponding to it via Theorem 2.16. We let $A \in \text{Mod}_{\text{Gal}(\bar{k}/k), \text{cont}}$ be an abelian group with continuous $\text{Gal}(\bar{k}/k)$ action, where we equip A with the multiplicative notation. We set $A_K := A^{G_K}$, it is equipped with a natural action of the subgroup $\text{Gal}(K/k)$ if K/k is Galois again via Theorem 2.16.

For L/K all finite subextensions of \bar{k}/k , we also have the norm map

$$(4.1) \quad \begin{aligned} \text{Nm}_{L/K} : A_L &\rightarrow A_K \\ a &\mapsto \prod_g g.a, \end{aligned}$$

where g runs over the coset representatives of $\text{Gal}(L/k)/\text{Gal}(L/K) \simeq \text{Gal}(K/k)$ (as in Theorem 2.16) inside G_K . This is precisely the norm map applied to the A_L equipped with its natural $\text{Gal}(L/K) \subset \text{Gal}(L/k)$ -module structure.

We now have the following analogue of Goal 3.8 in light of Hilbert Theorem 90.

Definition 4.2. We say that $A \in \text{Mod}_{\text{Gal}(\bar{K}/K), \text{cont}}$ satisfies the class field axiom if for every cyclic extension L/K of finite subextensions of \bar{k}/k , we have that

$$|H_T^0(\text{Gal}(L/K), A_L)| = [L : K]$$

and

$$H_T^0(\text{Gal}(L/K), A_L) = 1$$

The goal is now to combine this axiom with other conditions to construct for each finite Galois extension L/K a canonical isomorphism

$$r_{L/K} : \text{Gal}(L/K)^{\text{ab}} \rightarrow A_K / \text{Nm}_{L/K} A_L.$$

In order to describe this, we will need to encode some ramification theory into our abstract setup. We already saw the required local theory pop up in §3.2.1. In particular, we note that we have a natural map

$$\text{Gal}(\bar{K}/K) \rightarrow \text{Gal}(K^{\text{un}}/K) \simeq \hat{\mathbb{Z}},$$

for K/\mathbb{Q}_p a p -adic field, which is the inverse limit of the map appearing in (3.3). Here K^{un}/K is the compositum of all unramified extensions and the isomorphism is given by Theorem 3.14 and Example 2.15. We recall that the Prüfer ring $\hat{\mathbb{Z}}$ is the profinite completion of \mathbb{Z} defined in Example 2.5 (3).

Definition 4.3. With notation as above, we let $d : G \rightarrow \hat{\mathbb{Z}}$ be a continuous surjective homomorphism of profinite groups. With respect to this map, we define the following.

- (1) We define the Weil group of k , denoted $W_k \subset G$ to be the preimage of $d^{-1}(\mathbb{Z})$. It has the structure of a locally compact group.
- (2) We define the inertia group I_k to be the kernel of d . We call the fixed field of I_k as in Theorem 2.16, denoted k^{un} , to be the maximal unramified extension. For any subextension K of \bar{k}/k put $I_K := G_K \cap I_k$ and let $K^{\text{un}} = k^{\text{un}}K$ be the fixed field of I_K .
- (3) We say a finite extension L/K is unramified if $L \subset K^{\text{unr}}$.

Remark 4.4. We note that we have a natural inclusion

$$G_K/I_K \subset G_k/I_k \xrightarrow{d, \simeq} \hat{\mathbb{Z}},$$

and if K/k is finite then this is the inclusion of an open subgroup of $\hat{\mathbb{Z}}$, which one may check is isomorphic to $f_{K/k}\hat{\mathbb{Z}}$ for some $f_{K/k} \in \mathbb{N}_{\geq 0}$. We may renormalize the valuation $d|_{G_K}$ with respect to the finite extension d_K by setting

$$d_K := \frac{1}{f_{K/k}} d|_{G_K}$$

and this gives a surjective continuous homomorphism $d_K : G_K \rightarrow \hat{\mathbb{Z}}$ with kernel I_K .

As the notation suggests, the indices $f_{K/k}$ appearing in 4.4 should capture ramification of K over k , as in Definition 3.11. In particular, we may define the following.

Definition 4.5. Given a finite extension L/K of subextensions of k , we note that $G_K \subset G_L$ has finite index since L/K is a finite extension. We define the following.

- (1) The inertia degree is $f_{L/K} := [d(G_K) : d(G_L)]$,
- (2) The ramification degree $e_{L/K} := [I_K : I_L]$.

These have the following basic properties.

Lemma 4.6. *The following is true. Let $K \subset L \subset M$ be finite subextensions \bar{k}/k .*

- (1) *We have that*

$$f_{M/K} = f_{M/L} f_{L/K}.$$

- (2) *We have that*

$$e_{M/K} = e_{M/L} e_{L/K}.$$

- (3) *If L/K Galois then we have a short exact sequence*

$$1 \rightarrow I_K/I_L \rightarrow \text{Gal}(L/K) \rightarrow d(G_K)/d(G_L) \rightarrow 0,$$

where $d(G_K)/d(G_L)$ is a finite cyclic group.

- (4) *If L/K is an unramified extension. Then we have an isomorphism*

$$\text{Gal}(L/K) \simeq d(G_K)/d(G_L).$$

- (5) *We have the "fundamental identity"*

$$e_{L/K} f_{L/K} = [L : K].$$

Proof. We note that items (1)-(4) follow from the definitions. For (5), we note that it follows from item (3) if L/K is Galois. In general, we may replace L by its Galois closure M , and then apply (1) and (2) with respect to the $L \subset K \subset M$ to deduce the claim in general. \square

In order to get interesting consequences, for A_k satisfying (1), we need to tie A_k with the structure of this valuation in an interesting way. This is accomplished by the following definition.

Definition 4.7. With notation as in 4.1 and 4.3, we say that a Henselian valuation v of A_k with respect to d is a homomorphism $v : A_k \rightarrow \hat{\mathbb{Z}}$ satisfying the following.

- (1) The group $Z = \text{Im}(v)$ contains \mathbb{Z} and satisfies $Z/nZ \simeq \mathbb{Z}/n\mathbb{Z}$ for all positive integers n .
- (2) For every finite extension K/k , we have that $v(\text{Nm}_{K/k} A_K) = f_{K/k} Z$.

Remark 4.8. Condition (1) looks a bit bizarre. In particular, one might expect that this is just saying that Z identifies with $\mathbb{Z} \hookrightarrow \hat{\mathbb{Z}}$ or $\hat{\mathbb{Z}}$ itself. However, recall that we have a decomposition $\hat{\mathbb{Z}} \simeq \prod_p \mathbb{Z}_p$ by the Chinese Remainder Theorem. In particular, we could take the subgroup \mathbb{Z} embedding diagonally, and the subgroup generated by \mathbb{Z}_p on the p th coordinate and 1 elsewhere. This would give an interesting example of a group satisfying (1) that is not one of these two examples.

Given such a Henselian valuation, we define the following.

Definition 4.9. We define the following.

- (1) For each finite subextension K/k of \bar{k}/k , we obtain a henselian valuation

$$v_K : A_K \rightarrow Z$$

by setting

$$v_K = \frac{1}{f_{K/k}} \text{Nm}_{K/k},$$

where we recall that the norm map is defined in 4.1.

- (2) For each finite subextension K/k of \bar{k}/k , we define the unit subgroup $U_K := \nu_k^{-1}(\{0\})$. Similarly, for infinite extensions we define U_K as the union of these subgroups as we range over finite subextensions.
- (3) We say that $\pi \in A_K$ is a uniformizer if $v_K(\pi) = 1$, where we recall this makes sense by the assumption in Definition 4.7 (1) that Z contains \mathbb{Z} .

Remark 4.10. Since the Norm map is Galois invariant by definition. We note that we have $v_K(a) = v_{K^g}(g)$ for any $g \in G$. Moreover, for any finite subextension, we have

$$v_L(a) := \frac{1}{f_{L/K}} v_K(\text{Nm}_{L/K}(a))$$

for any $a \in A_L$ (cf. 3.2). In particular, we have that the group of units U_K are $\text{Gal}(K/k)$ sub-module and we have a $\text{Gal}(K/k)$ -equivariant short exact sequence

$$(4.2) \quad 0 \rightarrow U_K \rightarrow A_K \rightarrow A_K/U_K \rightarrow 0,$$

where $A_K/U_K \hookrightarrow Z \hookrightarrow \hat{Z}$ has the trivial action. In particular, this will play the role of (3.11) in this more abstract setting.

We have already encountered a plethora of examples of this structure.

Exercise 4.11. Using results already shown in class, explain why the following tuples (k, A, v, d) as in Definition 4.7 and 4.1, satisfy the conditions on the Henselian valuation and the Class Field axiom.

- (1) The tuple:
- k/\mathbb{Q}_p is a p -adic field.
 - $A = \bar{k}^*$
 - $d : \text{Gal}(\bar{k}/k) \rightarrow \hat{Z}$ is the map given by $\text{Gal}(\bar{k}/k) \rightarrow \text{Gal}(k^{\text{un}}/k) \simeq \hat{Z}$ where k^{un}/k is the maximal unramified extension.
 - $v : A_k = k^* \rightarrow \hat{Z}$ is the map given by the p -adic valuation v_K .
- (2) The tuple:
- k is a finite field.
 - $d : \text{Gal}(\bar{k}/k) \rightarrow \hat{Z}$ is the isomorphism of Example 2.15.
 - A is the group \mathbb{Z} with its trivial action.
 - $v : A_k = \mathbb{Z} \rightarrow \hat{Z}$ is the inclusion of \mathbb{Z} into its profinite completion.

We now fix a tuple (k, A, d, v) satisfying the class field theory axiom. We now have the following analogue of Theorem 3.15 and Corollary 3.17 in this abstract setup.

Theorem 4.12. Let L/K be an unramified extension of finite subextensions of \bar{k}/k . The following is true.

- (1) The groups $H_T^i(\text{Gal}(L/K), U_L) = 0$ for all $i \in \mathbb{Z}$.
- (2) The group $H_T^0(\text{Gal}(L/K), A_L)$ is cyclic of order $[L : K]$ and generated by any uniformizer π_L of L .

Proof. We consider the long exact sequence of Tate cohomology groups attached to (2.42) attached to the subgroup $\text{Gal}(L/K) \subset \text{Gal}(L/k)$. We note that $A_L/U_L \hookrightarrow Z$ has the trivial $\text{Gal}(L/K)$ -action, so we have that

$$H_T^0(\text{Gal}(L/K), A_L/U_L) \simeq \mathbb{Z}/[L : K]\mathbb{Z}$$

by property 4.7 (2) and the fact that $Z/[L : K]\mathbb{Z} \simeq \mathbb{Z}/[L : K]\mathbb{Z}$ together with the assumption that the extension is unramified so that $f_{L/K} = [L : K]$. Similarly, we have that $H_T^{-1}(\text{Gal}(L/K), A_L/U_L) = 0$ by the assumption that $Z \hookrightarrow \hat{Z}$ and therefore A_L/U_L must be torsion free. In particular, by combining with Tate periodicity (Theorem 2.105) which applies by lemma 4.6 (4) and the unramified assumption, the long exact sequence becomes the following

$$\begin{aligned} 1 = H_T^{-1}(\text{Gal}(L/K), A_L/U_L) &\rightarrow H_T^0(\text{Gal}(L/K), U_L) \rightarrow H_T^0(\text{Gal}(L/K), A_L) \\ &\rightarrow H_T^0(\text{Gal}(L/K), A_L/U_L) \rightarrow H_T^1(\text{Gal}(L/K), U_L) \rightarrow H_T^1(\text{Gal}(L/K), A_L) = 1 \end{aligned}$$

By the class field axiom, we have that $H_T^0(\text{Gal}(L/K), A_L) \rightarrow H_T^0(\text{Gal}(L/K), A_L/U_L)$ is a map between abelian groups of the same order, and since the target is cyclic it suffices to show that $H_T^1(\text{Gal}(L/K), U_L) = H^1(\text{Gal}(L/K), U_L) = 0$ to prove all the desired claims, again using Tate-periodicity. To do this, we use the assumption that L/K is unramified. In particular, this tells us that the map $A_L \rightarrow A_L/U_L$ is split as $\text{Gal}(L/K)$ -modules, since a uniformizer of K is also a uniformizer of L . In particular, $H^1(\text{Gal}(L/K), A_L/U_L)$ is a direct summand of $H^1(\text{Gal}(L/K), A_L)$ by the class field axiom (Definition 4.2). \square

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