

Notes on Local Fields

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1 Review: Galois theory

1.1 Field Extensions

Let L/K be an algebraic extension. It is called:

- ◇ **normal**, if every polynomial $f \in K[T]$ with a root in L splits in L , $\iff L$ is the splitting field of a bunch of polynomials over K ;
- ◇ **separable**, if for every element in L , its minimal polynomial over K has no multiple roots in its splitting field, $\iff \gcd(f, f') = 1$;
- ◇ **Galois**, if it is normal and separable, i.e., L is the splitting field of a bunch of *separable* polynomials over K . We put $\text{Gal}(L/K) := \text{Aut}_K(L)$.

Remark. 1. For a finite *normal* extension L/K , $|\text{Aut}_K(L)| \leq [L : K]$, where the equality holds $\iff L/K$ is separable, i.e. Galois. This is because a K -automorphism of $L = K[T]/(f)$ just permutes the roots of f .

2. Normality is NOT transitive. As an example, take $\mathbb{Q} \subset \mathbb{Q}(\sqrt{2}) \subset \mathbb{Q}(\sqrt[4]{2})$.

1.2 Galois theory

Now let L/K be a Galois extension. Equip $\text{Gal}(L/K)$ with the following **Krull topology**: $\forall \sigma \in \text{Gal}(L/K)$, a basis of nbhd around σ is given by

$$\sigma \text{Gal}(L/F), \quad \text{where } L/F/K, \ F/K < \infty \text{ \& Galois.}$$

- Two elements $\sigma, \tau \in \text{Gal}(L/K)$ are “close” to each other, if $\sigma|_F = \tau|_F$ for sufficiently large finite Galois subextensions F/K .
- Both multiplication and inverse on $\text{Gal}(L/K)$ are continuous for Krull topology.
- The Krull topology is profinite for L/K infinite, whence

$$\text{Gal}(L/K) \simeq \varprojlim_{F/K < \infty \text{ \& Galois}} \text{Gal}(F/K).$$

When $L/K < \infty$, this is the discrete topology.

- If there is a tower

$$K \subset L_1 \subset L_2 \subset \cdots \subset L,$$

where all L_n/K 's are Galois, and

$$L = \bigcup_n L_n,$$

then

$$\text{Gal}(L/K) = \varprojlim_n \text{Gal}(L_n/K).$$

Galois theory says that the intermediate fields of L/K corresponds to the closed subgroups of $\text{Gal}(L/K)$ bijectively and $\text{Gal}(L/K)$ -equivariantly.

→: For an intermediate field F , it gives $\text{Gal}(L/F) \subset \text{Gal}(L/K)$. Note that L/F is Galois, but F/K is NOT always Galois. The Galois group acts on $\{\text{intermediate field of } L/K\}$ via $(\sigma, F) \mapsto \sigma F = \sigma(F)$.

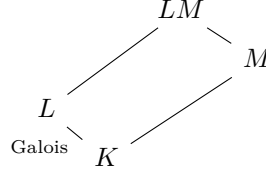
←: For a closed subgroup $H < G$, it fixes a subfield $L^H \subset L$. The Galois group acts on $\{H : H < \text{Gal}(L/K)\}$ by conjugation, i.e., $(\sigma, H) \mapsto \sigma H \sigma^{-1}$.

In particular,

- ◇ *Galois* extensions correspond to *normal closed* subgroups, and
- ◇ *finite* extensions correspond to *open* subgroups.

Base change

Proposition 1.1.



Let L/K be Galois. If M/K is any extension, and both L and M are subextensions of Ω/K , then LM/M is Galois, and

$$\begin{aligned} \text{Gal}(LM/M) &\xrightarrow{\sim} \text{Gal}(L/L \cap M) \\ \sigma &\mapsto \sigma|_L. \end{aligned}$$

As a corollary, if L, L' are Galois subextensions of Ω/K , then LL'/K is also Galois, and

$$\begin{aligned} \text{Gal}(LL'/K) &\hookrightarrow \text{Gal}(L/K) \times \text{Gal}(L'/K) \\ \sigma &\mapsto (\sigma|_L, \sigma|_{L'}). \end{aligned}$$

This embedding is an isomorphism if $L \cap L' = K$.

2 Extensions of Local Fields

2.1 Simple Extensions of DVRs

Let A be a local ring with (\mathfrak{m}, k) , $f \in A[X]$ a monic polynomial of $\deg n$. We consider the extension

$$A \rightarrow B_f := A[X]/f.$$

Let \bar{f} be the image of f in $k[X] \simeq A[X]/\mathfrak{m}$ with decomposition

$$\bar{f} = \prod_i \bar{g}_i^{e_i}, \quad g_i \in A[X], \quad \bar{g}_i \in k[X] \text{ irreducible.}$$

and

$$\bar{B}_f := B_f/\mathfrak{m}B_f \simeq A[X]/(\mathfrak{m}, f) \simeq k[X]/(\bar{f}).$$

Lemma 2.1. $\mathfrak{m}_i := (\mathfrak{m}, g_i \bmod f) \subset B_f$ are all the distinct maximal ideals of B_f .

Proof. Denote $\pi : B_f \rightarrow \bar{B}_f$. We have $B_f/\mathfrak{m}_i \simeq \bar{B}_f/(\bar{g}_i)$, so \mathfrak{m}_i 's are maximal. Note that $\mathfrak{m}_i = \pi^{-1}(\bar{g}_i)$.

Take $\mathfrak{n} \in \text{MaxSpec } B_f$. If $\mathfrak{n} \supset \mathfrak{m}$, then $\mathfrak{n} = \pi^{-1}\pi\mathfrak{n}$, and goes to a maximal ideal in \bar{B}_f (because $\bar{B}_f/\pi\mathfrak{n} \simeq B_f/\mathfrak{n}$), so $\mathfrak{n} = \pi^{-1}(\bar{g}_i) = \mathfrak{m}_i$.

So assume that $\mathfrak{m} \not\subset \mathfrak{n}$, then $\mathfrak{n} + \mathfrak{m}B_f = B_f$.¹ Therefore

$$\frac{B_f}{\mathfrak{n}} = \frac{\mathfrak{n} + \mathfrak{m}B_f}{\mathfrak{n}} \simeq \frac{\mathfrak{m}B_f}{\mathfrak{n}}.$$

Since A is local and B_f is a f.g. A -mod, by Nakayama's lemma, we see $\mathfrak{n} = B_f$. Contradiction. □

Now take A to be a DVR with $\mathfrak{m} = (\varpi)$ and $K = \text{Frac } A$. Put $L := K[X]/(f)$. We give two cases where B_f is a DVR.

Unramified case

Let $\bar{f} \in k[X]$ be irreducible. Then B_f is a DVR with maximal ideal $\mathfrak{m}B_f$.

Corollary 2.1. $f \in A[X]$ is also irreducible, so L is a field. Moreover, B_f is the integral closure of A in L , and L/K is unramified if \bar{f} is separable.

Proof. $L = K[X]/f \simeq (A[X]/f) \otimes_A K = B_f \otimes_A K$. As B_f is a domain, L is a field and $L = \text{Frac } B_f$. Since A is integrally closed, B_f is also integrally closed, so B_f is the integral closure of A in L . □

Totally ramified case

Let $f \in A[X]$ be an **Eisenstein polynomial**, i.e.,

$$f = X^n + a_{n-1}X^{n-1} + \cdots + a_0, \quad a_i \in \mathfrak{m}, \quad a_0 \notin \mathfrak{m}^2.$$

Proposition 2.1. B_f is a DVR, with maximal ideal generated by the image of X and residue field k .

Proof. Let x be the image of X in B_f . We have $\bar{f} = X^n$, so B_f is a local ring with maximal ideal (\mathfrak{m}, x) . Because $a_0 \in \mathfrak{m} \setminus \mathfrak{m}^2$, a_0 must uniformise $\mathfrak{m} \subset A$, and

$$-a_0 \bmod f = x^n + \cdots + (a_1 \bmod f)x,$$

Therefore $(\mathfrak{m}, x) = (x)$. □

Similar to Corollary 2.1, f is irreducible and L is a field with B_f the integral closure of A in L .

¹In this case $\mathfrak{n}/(\mathfrak{n} \cap \mathfrak{m}) \simeq \bar{B}_f$ as B_f -module, and thus $\pi^{-1}\pi\mathfrak{n} = B_f$.

2.2 Hensel's Lemma

Let K be a local field, or CDVF ².

There are many versions of Hensel's lemma. A relatively complicated one is: the decomposition of a polynomial modulo \mathfrak{m}_K into *coprime* factors can be lifted to K .

Theorem 1 (Hensel's lemma). Let $f \in \mathcal{O}_K[X]$, $\gamma, \eta \in k[X]$ s.t.

$$\begin{cases} \bar{f} = \gamma\eta, \\ (\gamma, \eta) = 1 \end{cases} \quad \text{in } k[X].$$

Then there exists $g, h \in \mathcal{O}_K[X]$ s.t.

$$\begin{cases} f = gh, & \text{in } \mathcal{O}_K[X], \\ \bar{g} = \gamma, \bar{h} = \eta & \text{in } k[X]. \end{cases}$$

Also the most famous ones about lifting roots in residue fields.

Theorem 2. Let $f \in \mathcal{O}_K[X]$, $\pi \in \mathfrak{m}_K$, $\alpha_0 \in \mathcal{O}_K$ s.t.

$$\begin{cases} P(\alpha_0) \in \pi\mathcal{O}_K, \\ P'(\alpha_0) \in \mathcal{O}_K^\times. \end{cases}$$

Then $\exists! \alpha \in \alpha_0 + \pi\mathcal{O}_K$ s.t.

$$P(\alpha) = 0.$$

Theorem 3. Let $f \in \mathcal{O}_K[X]$, $0 \leq \lambda < 1$, $\alpha_0 \in \mathcal{O}_K$ s.t.

$$|P(\alpha_0)| \leq \lambda |P'(\alpha)|^2.$$

Then $\exists! \alpha \in \mathcal{O}_K$ s.t.

$$\begin{cases} P(\alpha) = 0, \\ |\alpha - \alpha_0| \leq \lambda |P'(\alpha_0)|. \end{cases}$$

Note that in both cases, the lift is *unique*.

Proof of Hensel's lemma

We propose two kind of proofs for them. Full proof is only given to Theorem 1.

The first one is the traditional π -adic approximation.

Lemma 2.2. If k is a field, $P, Q \in k[X]$ are coprime and $R \in k[X]$, then

$$\exists A, B \in k[X], \quad R = AP + BQ \quad \text{s.t.} \quad \deg A \leq \deg Q - 1.$$

Proof. Let $R = A_0P + B_0Q$, then $R = (A_0 - uQ)P + (B_0 + uP)Q$ are all the possibilities. By Euclidean division, dividing A_0 by Q gives us $u \in k[X]$ with $\deg(A_0 - uQ) \leq \deg Q - 1$. \square

²We define a **local field** to be a complete discretely valued field, without the assumption of residue field being finite.

Proof of Theorem 1. Let π be a uniformiser. Take a lift g_1 of γ with $\deg g_1 = \deg \gamma$, and a lift h_1 of η with $\deg h_1 = \deg \eta$. We seek for : $\{g_n\}_n, \{h_n\}_n \subset \mathcal{O}_K[X]$ s.t.

$$f \equiv g_n h_n \pmod{\pi^n}, \quad g_{n+1} = g_n + \pi^n y_n, \quad h_{n+1} = h_n + \pi^n z_n.$$

In order $\lim_n g_n, \lim_n h_n \in \mathcal{O}_K[X]$, we require $\deg y_n \leq \deg \gamma$, $\deg z_n \leq \deg \eta$.

Assume we have found $g_n h_n \equiv f \pmod{\pi^n}$, then we need

$$\begin{aligned} f &\equiv (g_n + \pi^n y_n)(h_n + \pi^n z_n) \equiv g_n h_n + \pi^n (g_n z_n + h_n y_n) && \pmod{\pi^{n+1}} \\ \implies \mathcal{O}_K[X] \ni \frac{f - g_n h_n}{\pi^n} &\equiv g_n z_n + h_n y_n \equiv \gamma z_n + \eta y_n && \pmod{\pi}. \end{aligned}$$

Via Lemma 2.2, we find $z_n, y_n \in \mathcal{O}_K[X]$ with

$$\deg y_n \leq \deg \gamma - 1, \implies \deg z_n \leq \deg f - \deg \eta. \quad \square$$

Another proof uses the *fixed point theorem*.

Lemma 2.3 (Fixed point theorem). Let C be a complete metric space, $f : C \rightarrow C$ a **contracting map**, i.e.,

$$\exists \alpha, 0 \leq \alpha < 1 \text{ s.t. } |f(x) - f(y)|^3 < \alpha |x - y|, \quad \forall x, y \in C.$$

Then f has a *unique* fixed point in C .

Recall that the $K[X]$ is equipped with the **Gauss norm**: for $f = \sum_{i=0}^n a_i X^i$,

$$|f| := \max\{a_0, \dots, a_n\}.$$

$K[X]$ is not complete w.r.t. Gauss norm, but each subspace

$$K[X]_n := \{f \in K[X] \mid \deg f \leq n-1\}$$

is complete, since it is a sup-norm on a f.d. K -vector space; see Theorem 4. (T.B.C.)

2.3 Extending the norm

Let K be a complete normed field⁴. Consider an algebraic extension L/K , we wonder if the norm extend to L .

Recall: two norms $|\cdot|_1$ and $|\cdot|_2$ on a K -vector space V are **equivalent**

$:=$ they give the same topology

$$\iff (|x_n|_1 \rightarrow 0 \iff |x_n|_2 \rightarrow 0).$$

Proposition 2.2. If $|\cdot|_1$ and $|\cdot|_2$ are two equivalent norms on K , then

$$\exists \alpha > 0, \quad |\cdot|_1 = |\cdot|_2^\alpha$$

³Not a right notation, but anyway.

⁴By a **complete normed field** K , we always require an *ultrametric* / *nonarchimedean* norm $|\cdot|_K$. The norm corresponds to a valuation $\text{val} : K \rightarrow \mathbb{R} \cup \{\infty\}$ by $\text{val}(x) = -\log_a |x|$ for any chosen $a \in \mathbb{R}_{\geq 1}$, which is not necessarily discrete. Then

$$K \text{ is a local field} \iff \mathfrak{m}_K \text{ is a principal ideal} \iff \text{val}(K^\times) \text{ is a discrete subgroup of } \mathbb{R}.$$

Proof. (\Leftarrow) Assume $|\cdot|_1 \sim |\cdot|_2$.

- Let $y \in K$. $|y^n|_i \rightarrow 0 \iff |y|_i < 1$,

$$\implies (|y|_1 < 1 \iff |y|_2 < 1).$$

Fix $y \in K^\times$ with $|y|_1 \neq 1$. Then $|y|_2 \neq 1$.

- Let $x \in K$. By previous computation,

$$\begin{aligned} |x^m y^{-n}|_1 < 1 &\iff |x^m y^{-n}|_2 < 1, & \forall m, n \in \mathbb{Z}, \\ \implies |x|_1 < |y|_1^r &\iff |x|_2 < |y|_2^r, & \forall r \in \mathbb{Q}, \\ \implies |x|_1 < |y|_1^s &\iff |x|_2 < |y|_2^s, & \forall s \in \mathbb{R} \\ \implies |x|_2 &= |x|_1^\alpha. \end{aligned}$$

where $\alpha > 0$ is determined by $|y_2| = |y_1|^\alpha$. \square

Theorem 4 (Artin). Let K be complete normed field, V a f.d. K -vector space. Then all norms on V are equivalent, and V is complete for them.

Note that we don't require K to be locally compact; as a price, the norm on V need to be ultrametric too (which is our convention).

Proof. Let e_1, \dots, e_d be a K -basis of V , $\|\cdot\|_\infty$ the corresponding sup-norm. The sup-norm is complete. Then we do induction on d to show $\|\cdot\| \sim \|\cdot\|_\infty$ for any norm $\|\cdot\|$. Omitted. \square

Corollary 2.2. Let K be a complete normed field, $L/K < \infty$. If the norm on K extends to a norm on L , then there is at most one way to do so, and L will be complete.

Proof. All such norm will be $|\cdot|^\alpha$ for a fixed norm $|\cdot|$. These norms coincide on K , so $\alpha = 1$. \square

In case of complete *discretely valued* fields, there is indeed such an extension.

Theorem 5. Let K be a local field, $L/K < \infty$. Then the norm on K extends uniquely to L , making L also a local field. The norm is given by

$$|x|_L = |N_{L/K}(x)|_K^{1/[L:K]},$$

and \mathcal{O}_L = integral closure of \mathcal{O}_K in L .

We give two proofs.

Proof (algebraic). Recall that:

Lemma 2.4. If A is a Dedekind, $L/\text{Frac}(A) < \infty$, B is the integral closure of A in L , then: B is a Dedekind domain.

Apply this to $A = \mathcal{O}_K$, we see that $B :=$ integral closure of \mathcal{O}_K in L is a Dedekind domain. Let

$$\mathfrak{m}_K B = \mathfrak{P}_1^{e_1} \dots \mathfrak{P}_r^{e_r}$$

be the decomposition of \mathfrak{m}_K in B . Define $v_i(x) :=$ exponent of \mathfrak{P}_i in xB . One verifies that $v(\cdot)/e_i$ extends the valuation v_K on K with value group \mathbb{Z} . The uniqueness forces $r = 1$, and $\mathcal{O}_L = \{x \in L \mid v_i(x) > 0\} = B$. \square

Another proof gives the explicit formula for the norm. We need a result on integrality.

Proposition 2.3. Let K be a local field, $P(X) = a_d X^d + a_{d-1} X^{d-1} + \cdots + a_0 \in K[X]$ an irreducible polynomial with $a_0 a_d \neq 0$. Then the Gauss norm of f is

$$|f| = \max\{|a_0|, |a_d|\}.$$

In particular, if f is monic and its constant term $a_0 \in \mathcal{O}_K$, then $P(X) \in \mathcal{O}_K[X]$.

Proof. Let $n \in \mathbb{Z}$ s.t. $\pi^n P \in \mathcal{O}_K[X]$ and $\overline{\pi^n P} \neq 0 \in k[X]$. Let r be the Weierstrass degree of $\pi^n P$, so that

$$\pi^n P(X) \bmod \pi = \pi^n X^r (a_r + a_{r+1} X + \cdots + a_d X^{d-r}).$$

If $0 < r < d$, then the decomposition lift to a nontrivial decomposition of $\pi^n P$ in $K[X]$ via Theorem 1. Therefore $r = 0$ or $r = d$. Now note that $|f| = |a_r|$. \square

Proof of Theorem 5 (analytic). Let $d := [L : K]$. We show that $|\cdot|_L := |N_{L/K}(\cdot)|_K^{1/d}$ is indeed a norm on L (it obviously extends $|\cdot|_K$). The only nontrivial step is to check the strong triangle inequality, which is equivalent to

$$|z|_L < 1 \implies |1 + z|_L < 1.$$

Let $P(X)$ be the minimal polynomial of z over K . Since $N_{L/K}(z) = (-1)^d P(0)^{[L:K(z)]^5}$, so by Section 2.3,

$$|z| \leq 1 \iff P(0) \in \mathcal{O}_K[X] \implies \text{minimal polynomial of } z + 1 \in \mathcal{O}_K[X] \implies |1 + z| \leq 1. \quad \square$$

Corollary 2.3. Let K be a local field.

- (1) The norm on K extends uniquely to its algebraic closure K^{alg} ⁶.
- (2) If L and L' are two algebraic extension of K , then any K -embedding $\sigma \in \text{Hom}_K(L, L')$ preserves the norm; i.e., $|\sigma(x)|_{L'} = |x|_L$.

2.4 Unramified Extensions of Local Fields

Let K be a local field (i.e., CDVF). We assume further that both K and its residue field $k = \mathcal{O}_K/\mathfrak{m}$ are perfect.

The slogan is that unramified extensions are just extensions of residue fields. Using Hensel's lemma, an extension $k(a)/k$ can be lifted to a unique extension $K(a)/K$ over K with

$$\text{Gal}(K(a)/K) \simeq \text{Gal}(k(a)/k).$$

Moreover, given an extension L/K , there is a maximal unramified subextension K_0 in L containing every unramified extensions.

Now we assume k to be finite. Then adjoining roots of unities with order coprime to $p = \text{char } k$ gives all finite unramified extensions of K .

Example 1. Let $K/\mathbb{Q}_p < \infty$ and $k = \mathbb{F}_q$. Then the unique extension of k of degree n is the splitting field of $X^{q^n} - X$ over k , which equals $k(\mu_{q^n-1})$ once we fix an algebraic closure of k . So the unramified extension K_n/K of degree n is the splitting field of $X^{q^n} - X$ over K , i.e.,

$$K_n = K(\mu_{q^n-1}).$$

⁵Simple fact, see Lemma 4.5.

⁶Note that K^{alg} is not a local field and not complete. We'll see this later.

The Galois group $\text{Gal}(K_n/K)$ is generated by Frob_K , which is determined by

$$\text{Frob}_K \beta \equiv \beta^q \pmod{\varpi}, \quad \forall \beta \in \mathcal{O}_{K_n}$$

for any uniformiser ϖ (simultaneously of K and K_n).

What if we adjoin ζ_m to K where m is an arbitrary integer prime to p ? The answer is that $K(\mu_m)$ is unramified of degree the smallest positive integer f s.t. $m \mid p^f - 1$, by the following Lemma 2.5 on finite fields.

Lemma 2.5. Let ζ_n be a primitive n -th root of unity over \mathbb{F}_q with q, n coprime. Then $[\mathbb{F}_q(\zeta_n) : \mathbb{F}_q]$ is the smallest integer $f > 0$ s.t. $n \mid q^f - 1$.

Proof. Because $\text{char } \mathbb{F}_q \nmid n$, the primitive root ζ_n exists and $\mathbb{F}_q(\zeta_n)$ is the splitting field of $X^n - 1$ over \mathbb{F}_q . The degree $f = [\mathbb{F}_q(\zeta_n) : \mathbb{F}_q]$ is the order of Frob_q on $\mathbb{F}_q(\zeta_n)$, i.e., f is the smallest integer s.t.

$$\text{Frob}_q^f(\zeta_n) = \zeta_n^{q^f} = \zeta_n.$$

The definition of primitive root of unity says that

$$\zeta_n^{q^f - 1} = 1 \iff n \mid q^f - 1. \quad \square$$

2.5 Newton Polygon

Let K be a local field with valuation val extended to K^{alg} .

For $P = a_0 + a_1X + \dots + a_dX^d \in K[X]$, the **Newton polygon** of $P := \text{NP}(P) :=$ convex hull of points

$$(0, \text{val}(a_0)), (1, \text{val}(a_1)), \dots, (d, \text{val}(a_d)).$$

- $\text{NP}(P)$ is a union of linked segments with increasing slopes.
- **length of a segment** $:=$ its length along x -axis.

Theorem 6. The number of roots of P in K^{alg} with valuation $\lambda =$ the length of $\text{NP}(P)$ with slope $-\lambda$.

2.6 Ramification Groups

Let K be a local field with residue field k , $L/K < \infty$ Galois. We will study the Galois group

$$G := \text{Gal}(L/K)$$

by giving filtrations on it.

Let val_L be the valuation on L normalized by $\text{val}_L(L^\times) = \mathbb{Z}$. Assume $\text{char } k_K = \text{char } k_L = p > 0$ and k_L/k_K separable. The Galois group G acts on L/K , and its decomposition subgroup, by definition, acts on the integers $\mathcal{O}_L/\mathcal{O}_K$, and descends modulo π_L to k_L/k_K . We know that G acts by isometries, so the decomposition subgroup $= G$, giving a surjection $\text{Gal}(L/K) \rightarrow \text{Gal}(k_L/k_K)$, and the **inertia subgroup**

$$I(L/K) = \ker(\text{Gal}(L/K) \rightarrow \text{Gal}(k_L/k_K)) = \{g \in G \mid \text{val}_L(ga - a) \geq 1, \forall a \in \mathcal{O}_L\}.$$

We develop this idea, giving a filtration of G by how “small” the effect of $g \in G$ is.

2.6.1 Lower Ramification Filtration

For $g \in \text{Gal}(L/K)$, define

$$i_{L/K}(g) := \inf_{a \in \mathcal{O}_L} \text{val}_L(ga - a).$$

- If $\mathcal{O}_L = \mathcal{O}_K[x]$, then $i_L(g) = \text{val}_L(gx - x)$.

Proposition 2.4. Let $g, h \in G = \text{Gal}(L/K)$.

- (1) i_L is a class function: $i_L(ghg^{-1}) = i_L(h)$.
- (2) i_L verifies the strong triangle inequality: $i_L(gh) \geq \min\{i_L(g), i_L(h)\}$, with “=” $\iff i_L(g) \neq i_L(h)$.
- (3) $i_L(g^{-1}) = i_L(g)$.

Proof. Since k_L/k_K is separable, we can write $\mathcal{O}_L = \mathcal{O}_K[x]$. Note that

$$\mathcal{O}_L = \mathcal{O}_K[x] \implies \mathcal{O}_L = \mathcal{O}_K[gx], \forall g \in G.$$

So:

$$\begin{aligned} i_L(ghg^{-1}) &= \text{val}(ghg^{-1}x - x) \underset{G \text{ preserves val}}{=} \text{val}(hg^{-1}x - g^{-1}x) = i_L(h), \\ i_L(gh) &= \text{val}((ghx - hx) + (hx - x)) \geq \min i_L(g), i_L(h). \end{aligned}$$

The last assertion is as trivial. □

Now for $G = \text{Gal}(L/K)$, a real number $u \in \mathbb{R}_{\geq -1}$, we define⁷ the lower ramification group

$$\begin{aligned} G_u &:= \{g \in G \mid i_L(g) \geq u + 1\} \\ &= \{g \in G \mid ga \equiv a \pmod{\pi_L^{\lfloor u+1 \rfloor}}, \forall a \in \mathcal{O}_L\}. \end{aligned}$$

- $G_u \triangleleft G$ by Proposition 2.4.
- $G_u = G_{\lfloor u \rfloor}$.
- $G_{-1} = G$, $G_0 = I(L/K)$.
- If $u \geq \max_{g \neq 1} i_L(g)$, then $G_u = 1$.

Let $L_0 := L^{G_0} = L^{I(L/K)}$. This is the maximal unramified subextension of L/K , hence $\mathcal{O}_L = \mathcal{O}_{L_0}[\pi_L]$. Therefore,

- if $g \in G_0$, then

$$i_L(g) = \text{val}_L \left(\frac{g\pi_L}{\pi_L} - 1 \right) + 1,$$

- if $u \geq 0$, then

$$\begin{aligned} G_u &= \left\{ g \in G_0 \mid \text{val} \left(\frac{g\pi_L}{\pi_L} - 1 \right) \geq u \right\} \\ &= \left\{ g \in G_0 \mid \frac{g\pi_L}{\pi_L} \equiv 1 \pmod{\pi_L^{\lfloor u \rfloor}} \right\}. \end{aligned}$$

Lemma 2.6. If $n \in \mathbb{Z}_{\geq 1}$, then $G_n^p \subset G_{n+1}$.

⁷It is ok to put $G_u := G$ for $u < -1$.

Proof. Take $g \in G_n$ and write

$$\frac{g\pi_L}{\pi_L} = 1 + \alpha, \alpha \in \mathfrak{m}_L^n.$$

Then⁸

$$\frac{g^p\pi_L}{\pi_L} = \frac{g\pi_L}{\pi_L} \frac{g^2\pi_L}{g\pi_L} \dots \frac{g^p\pi_L}{g^{p-1}\pi_L} = (1 + \alpha)(1 + g\alpha) \dots (1 + g^{p-1}\alpha).$$

Note that $g\alpha \equiv \alpha \pmod{\pi_L^{n+1}}$, so the product

$$\equiv (1 + \alpha)^p \equiv 1 \pmod{\pi_L^{n+1}}. \quad \square$$

Proposition 2.5. G_1 is the unique Sylow p -group of G_0 .

Proof. By the last lemma, $G_1^{p^n} \subset G_{1+n}$ for all n , $\implies G_1^{p^n} = 1$ for $n \gg 0$, $\implies G$ is a p -group.

We show that: if $g \in G_0$ and $g^p \in G_1$, then $g \in G_1$. This would imply that all elements of p -power order fall in G_1 .

Take $g \in G_0$ and write $\frac{g\pi_L}{\pi_L} = \alpha \in \mathcal{O}_K^\times$.

- $g \in G_0 \implies g\alpha \equiv \alpha \pmod{\pi_L} \implies \frac{g^p\pi_L}{\pi_L} \equiv \alpha^p \pmod{\pi_L}.$
- $g^p \in G_1 \implies \frac{g^p\pi_L}{\pi_L} \equiv 1 \pmod{\pi_L}.$

$$\implies \alpha \equiv \alpha^p \equiv 1 \pmod{\pi_L} \iff g \in G_1. \quad \square$$

Write $[L : L_0] = p^k t$, $p \nmid t$. By Proposition 2.5, $L_1 := L^{G_1}$ has degree t over L_0 , and L_1/K is the unique maximal tamely ramified subextension.

The next goal is to investigate the subquotients G_n/G_{n+1} of the filtration $G \subset G_0 \subset G_1 \subset \dots$.

Proposition 2.6. Let $n \in \mathbb{Z}_{\geq 0}$.

- $G/G_0 \simeq \text{Gal}(k_L/k_K).$
- $G_0/G_1 \hookrightarrow \mathcal{O}_L^\times / (1 + \mathfrak{m}_L^\times) \simeq k_L^\times$ via $g \mapsto \frac{g\pi_L}{\pi_L}.$
- $G_n/G_{n+1} \hookrightarrow (1 + \mathfrak{m}_L^n) / (1 + \mathfrak{m}_L^{n+1}) \simeq \mathfrak{m}_L^n / \mathfrak{m}_L^{n+1} \simeq k_L$ via $g \mapsto \frac{g\pi_L}{\pi_L} \mapsto \frac{g\pi_L - \pi_L}{\pi_L^{n+1}}.$

In particular, all the quotients G_n/G_{n+1} ($n \geq 0$) are finite abelian, and hence G_0 is solvable.

Proof. G/G_0 is known and G_0/G_1 is a special case of G_n/G_{n+1} .

Injectivity is clear once we prove the multipliciy. For $g \in G_n$, let

$$\frac{g\pi_L}{\pi_L} = 1 + \alpha_g, \alpha_g \in \mathfrak{m}_L^n.$$

Then $g\alpha_h \equiv \alpha_h \pmod{\pi_L^n}$. So⁹

$$\frac{gh\pi_L}{\pi_L} \equiv (1 + g\alpha_h)(1 + \alpha_g) \equiv (1 + \alpha_h)(1 + \alpha_g) \pmod{\mathfrak{m}_L^{n+1}}. \quad \square$$

⁸ Note that

$$\frac{g\pi_L}{\pi_L} = 1 + \alpha \implies \frac{hg\pi_L}{g\pi_L} = 1 + h\alpha.$$

⁹ See 8.

2.6.2 Upper Ramification Filtration and Ramification Groups of Infinite Extensions

The lower ramification filtration is compatible with *subgroups*:

Proposition 2.7. If $H < G$, then

$$H_u = G_u \cap H.$$

Namely, if $L \mid F \mid K$ is a tower of finite extensions, then

$$\text{Gal}(L/F)_u = \text{Gal}(L/K)_u \cap \text{Gal}(L/F).$$

But in practice, we usually fix the bottom K rather than the top L ; we want a filtration compatible with quotients. This is given by Herbrand's theorem.

Define **Herbrand's** ϕ function

$$\phi_{L/K} : \mathbb{R}_{\geq -1} \rightarrow \mathbb{R}_{\geq -1}, \quad \phi_{L/K}(u) := \int_0^u \frac{1}{[G_0 : G_t]} dt.$$

- $\phi_{L/K}(0) = 0, \phi_{L/K}(-1) = -1$.
- $\phi_{L/K}$ is piece-wise affine, continuous, strictly increasing, concave, and a homeomorphism.

This gives

$$\psi_{L/K} : \mathbb{R}_{\geq -1} \rightarrow \mathbb{R}_{\geq -1} := \phi_{L/K}^{-1},$$

and we define

$$G^u := G_{\psi_{L/K}(u)}.$$

This upper ramification filtration is compatible with *quotients*.

Theorem 7. If $H \triangleleft G$, then

$$(G/H)^v = G^v H/H = \text{image of } G^v \text{ in } G/H.$$

Namely, if $L \mid F \mid K$ is a tower of extensions, then

$$\text{Gal}(F/K)^v = \text{im}(\text{Gal}(L/K)^v \hookrightarrow \text{Gal}(L/K) \twoheadrightarrow \text{Gal}(F/K)).$$

Since the upper ramification filtration is compatible with quotients, it extends to any infinite Galois extension L/K by

$$\text{Gal}(L/K)^v := \varprojlim_F (\text{Gal}(F/K)^v).$$

2.7 Krasner's lemma and the noncompleteness of $\bar{\mathbb{Q}}_p$

Fix an algebraic closure $\bar{\mathbb{Q}}_p = \mathbb{Q}_p^{\text{alg}}$ of \mathbb{Q}_p . Krasner's lemma states that if $\beta \in \bar{\mathbb{Q}}_p$ is closer to $\alpha \in \bar{\mathbb{Q}}_p$ than any other conjugate of α over F , then $\alpha \in F(\beta)$. Therefore, if two polynomials are “close enough”, they will give the same extension.

Theorem 8 (Krasner's lemma). Let $F/\mathbb{Q}_p < \infty$, $\alpha, \beta \in \bar{\mathbb{Q}}_p$. If

$$|\alpha - \beta| < |\alpha - \alpha_i|, \quad i = 2, \dots, n,$$

where $\alpha_1 = \alpha, \alpha_2, \dots, \alpha_n$ are all the conjugates of α over F , then

$$F(\alpha) \subset F(\beta).$$

Proof. Let K/F be finite Galois with $\alpha, \beta \in K$. Then $g\alpha, g \in \text{Gal}(K/F)$ are all the conjugates of α over F . Now if $g \in \text{Gal}(K/F(\beta))$, then

$$\begin{aligned} |g\alpha - \alpha| &= |(g\alpha - g\beta) + (\beta - \alpha)| \\ &\leq \min\{|g\alpha - g\beta|, |\alpha - \beta|\} = {}^{10}|\alpha - \beta| \end{aligned}$$

So by the assumption, we have $\alpha = g\alpha$, i.e., $\alpha \in K^{\text{Gal}(K/F(\beta))} = F(\beta)$. \square

Theorem 9. For every $d \geq 1$, \mathbb{Q}_p has only finitely many extensions of degree d .

Proof. Every finite extension has a unique maximal unramified extension, so it suffices to show that: there is only finitely many unramified extensions of each $F/\mathbb{Q}_p < \infty$ of given degree e .

For $e \geq 1$, the set of Eisenstein polynomials over F is in bijection with

$$\Pi := (\mathfrak{m}_F \setminus \mathfrak{m}_F^2) \times \underbrace{\mathfrak{m}_F \times \cdots \times \mathfrak{m}_F}_{e-1},$$

which is compact. So we just need to show that for each Eisenstein polynomial P , its corresponding point in Π has a neighbourhood, in which all polynomials give the same extension.

(T.B.C.) \square

Corollary 2.4. $\bar{\mathbb{Q}}_p$ is not complete.

Proof. Now we know $\bar{\mathbb{Q}}_p$ is a countable union of finite dimensional \mathbb{Q}_p -vector spaces. Recall what Baire's theorem says:

Theorem 10 (Baire category theorem). A complete metric space is a Baire space; i.e, a countable intersection of open dense sets is dense.

As a corollary, a complete metric space is not a countable union of nowhere dense¹¹ sets.

A finite dimensional \mathbb{Q}_p -vector space is closed and nowhere dense, so the union is not complete. \square

Let $\mathbb{C}_p := \widehat{\bar{\mathbb{Q}}_p}$ be the completion of $\bar{\mathbb{Q}}_p$. Note that neither reidue field nor value group are not extended from $\bar{\mathbb{Q}}_p$ to \mathbb{C}_p :

- $v_p(\mathbb{C}_p) = v_p(\bar{\mathbb{Q}}_p) = \mathbb{Q}$ ¹².
- $k_{\mathbb{C}_p} = \mathcal{O}_{\mathbb{C}_p}/\mathfrak{m}_{\mathbb{C}_p} \simeq \mathcal{O}_{\bar{\mathbb{Q}}_p}/\mathfrak{m}_{\bar{\mathbb{Q}}_p} \simeq \mathbb{F}_p^{\text{alg}}$.¹³

Theorem 11. \mathbb{C}_p is algebraically closed.

Proof. The idea is simple: root of lim of polynomial = lim of root of polynomial. Let's make this clear.

Let $P \in \mathbb{C}_p[X]$ be monic of degree d . Replacing $P(X)$ by $p^{kd}P(p^{-k}X)$ for $k \gg 0$, we may assume $P \in \mathcal{O}_{\mathbb{C}_p}[X]$.

(T.B.C.) \square

¹⁰Because embeddings of finite extensions of \mathbb{Q}_p are isometries (the uniqueness of norm extension).

¹¹Being **nowhere dense** means its closure has empty interior.

¹²Consider a Cauchy sequence $\{a_n\}_n$ in $\bar{\mathbb{Q}}_p$. The difference $a_m - a_{m+d}$ will eventually have valuation $> v_p(a_m)$, making $v_p(\lim_n a_n) = v_p(a_m)$.

¹³In a sum $\sum_n a_n \in \mathbb{C}_p$, a.e. $a_n \in \mathfrak{m}_{\mathbb{C}_p}$.

2.8 Ax-Sin-Tate theorem and closed subfields of \mathbb{C}_p

Let $\mathbb{Q}_p \subset K \subset \bar{\mathbb{Q}}_p$, $G_K := \text{Gal}(\bar{\mathbb{Q}}_p/K)$ the absolute Galois group of K . Galois theory establishes a bijection

$$\{\text{subextension of } \bar{\mathbb{Q}}_p/\mathbb{Q}_p\} \longleftrightarrow \{\text{closed subgroup of } \text{Gal}(\bar{\mathbb{Q}}_p/\mathbb{Q}_p)\}$$

via $K = \bar{\mathbb{Q}}_p^{G_K}$. We are going to expand this relation to (certain) subextensions of $\mathbb{C}_p/\mathbb{Q}_p$.

Any $g \in \text{Gal}(\bar{\mathbb{Q}}_p/\mathbb{Q}_p)$ is an isometry, thus extends to an isometry and (continuous) field automorphism of \mathbb{C}_p , denoted still by g . So what is $\mathbb{C}_p^{G_K}$?

Theorem 12 (Ax-Sin-Tate). $\mathbb{C}_p^{G_K} = \hat{K}$.

Lemma 2.7. Let $P(X) \in \bar{\mathbb{Q}}_p[X]$ be monic of degree n , s.t. all the roots α of P have bounded valuation bounded from below; i.e., $v_p(\alpha) > c$ for some $c \in \mathbb{R}$. Let $n = p^k d$ with $p \nmid d$ or $p = d$. Then $P^{(p^k)}$ has a root β with

$$\begin{cases} v_p(\beta) \geq c, & n = p^k d, \ p \nmid d, \\ v_p(\beta) \geq c - \frac{1}{p^k(p-1)}, & n = p^{k+1}. \end{cases}$$

Proof. Write $P(X) = X^n + a_{n-1}X^{n-1} + \dots + a_0$, and $q := p^k$.

- $v_p(a_i) \geq (n-i)c$, because $a_i = \pm$ sum of product of $n-i$ roots; multiplicity counted.
- $\frac{1}{q!}P^{(q)}(X) = \sum_{i=0}^{n-q} \binom{n-i}{q} a_{n-i} X^{n-i-q}$, so the product of roots of $P^{(q)} = \pm \frac{a_q}{\binom{n}{q}}$.

Hence, \exists root β of $P^{(q)}$, s.y.

$$v_p(\beta) \geq \frac{1}{\deg P^{(q)}} v_p \left(\frac{a_q}{\binom{n}{q}} \right) \geq c - \frac{1}{n-q} v_p \left(\binom{n}{q} \right).$$

By looking at carries¹⁴, one verifies that

$$v_p \left(\binom{n}{q} \right) = \begin{cases} 0, & n = qd = p^k d, \ p \nmid d, \\ 1, & n = qp = p^{k+1}. \end{cases}$$

□

For $\alpha \in \bar{\mathbb{Q}}_p$, we define

$$\Delta_K(\alpha) := \inf_{g \in G_K} v_p(g\alpha - \alpha).$$

Theorem 13 (Ax). $\forall \alpha \in \bar{\mathbb{Q}}_p, \exists \delta \in K$, s.t.

$$v_p(\alpha - \delta) \geq \Delta_K(\alpha) - \frac{p}{(p-1)^2}.$$

Proof. We do induction on $n := [K(\alpha) : K]$ to show a stronger estimate: $\exists \delta \in K$ s.t.

$$v_p(\alpha - \delta) \geq \Delta_K(\alpha) - \sum_{k=1}^m \frac{1}{p^k(p-1)},$$

where $m \in \mathbb{Z}$ such that p^{m+1} is the largest p -power $\leq n$.

Let $Q(X) \in K[X]$ be the minimal polynomial of α over K , and set $P(X) := Q(X + \alpha) \in \bar{\mathbb{Q}}_p[X]$. The roots of P are $g\alpha - \alpha$, where $g \in G_K$.

¹⁴ $v_p \left(\binom{a+b}{b} \right) = \#$ of carries when compute $a+b$ in base p .

Apply Lemma 2.7 to $v_p(g\alpha - \alpha) \geq \Delta_K(\alpha)$, we obtain a root $\beta \in \bar{\mathbb{Q}}_p$ of $P^{(q)}(X)$, where $q = p^k$, s.t.

$$\begin{cases} v_p(\beta) \geq \Delta_K(\alpha), & n \text{ is not a power of } p, q \parallel n \\ v_p(\beta) \geq \Delta_K(\alpha) - \frac{1}{p^m(p-1)}, & n = p^{m+1} = qp, k = m. \end{cases}$$

Consider $\alpha' := \alpha + \beta$, a root of $Q^{(q)}(X) \in K[X]$. We have

$$[K(\alpha') : K] \leq \deg Q^{(q)} < \deg Q = [K(\alpha) : K]$$

as $q > 0$, so by induction hypothesis, $\exists \delta \in K$ s.t.

$$v_p(\alpha - \delta) \geq \Delta_K(\alpha') - \sum_{i=1}^r \frac{1}{p^i(p-1)},$$

where p^{r+1} is the largest p -power $\leq n - q = \deg Q^{(q)}$. Now we estimate $\Delta_K(\alpha')$. Note that

$$g\alpha' - \alpha' = \underbrace{g\alpha' - g\alpha}_{=g\beta} + \underbrace{g\alpha - \alpha}_{v_p \geq \Delta_K(\alpha)} + \underbrace{\alpha - \alpha'}_{=-\beta}.$$

- If $n = qd$ with $p \nmid d$, then $\Delta_K(\alpha') \geq \Delta_K(\alpha)$, and the estimation holds for α .
- If $n = p^{m+1}$, then $\Delta_K(\alpha') \geq \Delta_K(\alpha) - \frac{1}{p^m(p-1)}$. Since $r < m$, the estimation of α still holds. \square

Ax-Sin-Tate theorem is a direct corollary of Ax's theorem.

Proof of Ax-Sin-Tate. The inclusion $\widehat{K} \subset \mathbb{C}_p^{G_K}$ come from the fact that G_K acts on \mathbb{C}_p continuously.

For the other inclusion, take $\alpha \in \mathbb{C}_p^{G_K}$ and write $\alpha = \lim_n \alpha_n$ with $\alpha_n \in \bar{\mathbb{Q}}_p$. Note that

$$\alpha \in \mathbb{C}_p^{G_K} \iff \Delta_K(\alpha_n) \rightarrow \Delta_K(\alpha) = +\infty.$$

So by Ax's theorem, there exists $\delta_n \in K$ with

$$v_p(\delta_n - \alpha_n) \geq \Delta_K(\alpha_n) - \frac{p}{(p-1)^2} \rightarrow +\infty,$$

and thus $\alpha = \lim_n \delta_n \in \widehat{K}$. \square

Theorem 14. There is a bijection

$$\begin{aligned} \{\text{subfield of } \bar{\mathbb{Q}}_p\} &\longleftrightarrow \{\text{closed subfield of } \mathbb{C}_p\} \\ K &\longmapsto \widehat{K} \\ L \cap \bar{\mathbb{Q}}_p &\longleftarrow L. \end{aligned}$$

Proof. • Show $K < \bar{\mathbb{Q}}_p \implies \widehat{K} \cap \bar{\mathbb{Q}}_p = K$.

- Show $L \overset{\text{closed}}{<} \mathbb{C}_p \implies \widehat{L \cap \bar{\mathbb{Q}}_p} = L$, i.e., $L \cap \bar{\mathbb{Q}}_p$ is dense in L . \square

3 A Bit of p -adic Analysis

In this section, we consider some basic properties concerning powerseries over a closed subfield K of \mathbb{C}_p as functions.

Let $f(X) = \sum_{i \geq 0} a_i X^i \in K[[X]]$. We can evaluate f at $z \in \mathbb{C}_p$ iff $a_i z^i \rightarrow \infty$, so the **radius of convergence** is

$$\rho(f) := \sup\{\rho \in \mathbb{R} \mid a_i \rho^i \rightarrow \infty (i \rightarrow \infty)\}.$$

- If $|z| < \rho(f)$, then $f(z)$ converges in \mathbb{C}_p .
- If $|z| > \rho(f)$, then f diverges.
- $\rho(f(\alpha X)) = \rho(f) \cdot |\alpha|^{-1}$.

We are mainly interested in the power series converging on the unit disk, i.e.,

$$\begin{aligned} H_K &:= \{f \in K[[X]] \mid \rho(f) > 1\} \\ &= \{f \in K[[X]] \mid a_i \rho^i \rightarrow 0, \forall \rho < 1\} \\ &= \{f \in K[[X]] \mid f \text{ converges on the open unit disk } \mathfrak{m}_{\mathbb{C}_p} = B(0, 1)\}. \end{aligned}$$

Example 2. $K \otimes_{\mathcal{O}_K} \mathcal{O}_K[[X]] =$ power series over K with bounded coefficients $\subsetneq H_K$.

Example 3. $\log(1 + X) = \log_{\mathbb{G}_m}(X) = X - \frac{X^2}{2} + \frac{X^3}{3} - \dots \in H_K \setminus K \otimes_{\mathcal{O}_K} \mathcal{O}_K[[X]]$.

3.1 The Gauss Norm

Theorem 15. Let $f(X) = \sum_{i \geq 0} a_i X^i \in K[[X]]$ with $\rho(f) > 0$, a real number $\rho < \rho(f)$ s.t. $\rho \in |\mathbb{C}_p^\times|$. Then $\sup_{i \geq 1} |a_i| \rho^i$ is a maximum (i.e., $\sup_{i \geq 1} |a_i| \rho^i = |a_j| \rho^j$ for some j), and

$$\sup_{i \geq 1} |a_i| \rho^i = \sup_{|z|=\rho} |f(z)| =: |f|_\rho.$$

Proof. • $\rho < \rho(f) \implies |a_i| \rho^i \rightarrow 0 \implies \sup_{i \geq 0} |a_i| \rho^i$ is a maximum.

- $|f(z)| = \left| \sum_{i \geq 0} a_i z^i \right| \leq \sup_{i \geq 1} |a_i| |z|^i$, so $|f|_\rho \leq \sup_{i \geq 1} |a_i| \rho^i$.
- Take $\alpha \in \mathbb{C}_p$ with $|\alpha| = \rho$, and $j \in \mathbb{Z}_{\geq 0}$ s.t. $\sup_{i \geq 1} |a_i| \rho^i = |a_j| \rho^j$. Let $\beta := a_j \alpha^j$. We aim to find $|z| = \rho$ s.t. $|f(z)| = |\beta|$. Consider

$$g(X) = \sum_{i \geq 0} g_i X^i := \frac{f(\alpha X)}{\beta} \in \mathcal{O}_{\mathbb{C}_p}[[X]].$$

Moreover, the coefficients $g_i = \frac{a_i \alpha^i}{\beta} \rightarrow 0$ as $i \rightarrow \infty$, because $|g_i| = \beta^{-1} |a_i| \rho^i$. So $\bar{g}(X) \in k_{\mathbb{C}_p}[[X]]$ is actually a polynomial, and it is nonzero since $|g_j| = 1$. Take $\bar{w} \in \bar{k}^\times$ s.t. $\bar{g}(\bar{w}) \neq 0$. Then a lift $w \in \mathcal{O}_{\mathbb{C}_p}^\times$ verifies $|g(w)| = 1$. Hence $|f(\alpha w)| = |\beta|$ and $|\alpha w| = |\alpha| = \rho$. \square

Thus, the expression $|f|_\rho \in \mathbb{R} \cup \{+\infty\}$ is defined on $\rho \in \mathbb{R}$. In addition,

- $\rho \rightarrow |f|_\rho$ is continuous,
- $|f|_\sigma \leq |f|_\rho$ if $\sigma \leq \rho < \rho(f)$.

\implies the **maximum modulus principle** holds: $|f|_\rho = \sup_{|z| \leq \rho} |f(z)| = \max_{|z| \leq \rho} |f(z)|$ for $\rho < \rho(f)$.

- $|\cdot|_\rho$ is multiplicative: $|fg|_\rho = |f|_\rho |g|_\rho$.

Example 4. If $f \in H_K$, then *as a function*:

- f is bounded on $\mathfrak{m}_{C_p} \iff f \in K \otimes_{\mathcal{O}_K} \mathcal{O}_K[[X]]$,
- f is bounded by 1 on $\mathfrak{m}_{C_p} \iff f \in \mathcal{O}_K[[X]]$.

3.2 Weierstrass Preparation Theorem

For $f(X) = \sum_{i \geq 0} a_i X^i \in \mathcal{O}_K[[X]]$, we define its **Weierstrass degree** $:= \text{wideg}(f) :=$ smallest $i \in \mathbb{Z}_{\geq 0}$ s.t. $a_i \in \mathcal{O}_K^\times$.

- wideg is multiplicative.
- $\text{wideg}(f) = \infty \iff f \in \mathfrak{m}_K[[X]]$.
- $\text{wideg}(f) = 0 \iff a_0 \in \mathcal{O}_K^\times \iff f \in (\mathcal{O}_K[[X]])^\times$.
- If $K/\mathbb{Q}_p < \infty$, then for $f \in K \otimes_{\mathcal{O}_K} \mathcal{O}_K[[X]]$, $\exists! n \in \mathbb{Z}$ s.t. $\pi^n f$ has finite Weierstrass degree, which is the smallest degree of the term in f with minimum valuation (maximum norm).

Remark. The last statement fails if K is not finite over \mathbb{Q}_p , i.e., if there is no uniformiser. For example, $f(X) = \sum_{i \geq 1} \frac{1}{p^i} X^i$.

From now on, assume $K/\mathbb{Q}_p < \infty$ with uniformiser π .

Proposition 3.1 (Euclidean Division). Let $f \in \mathcal{O}_K[[X]]$ with $\text{wideg}(f) < \infty$. Then: $\forall g \in \mathcal{O}_K[[X]]$, $\exists! q \in \mathcal{O}_K[[X]]$ & $r \in \mathcal{O}_K[X]$ ¹⁵ s.t.

$$g = q \cdot f + r, \quad \deg(r) \leq \text{wideg}(f) - 1.$$

Proof. Idea is, again, π -adic approximation.

First we do “Euclidean division” in $k[[X]]$. Write $\bar{f}(X) = X^n f_0(X)$ with $f_0(X) \in k[[X]]^\times$. For $h = \sum_{i \geq 0} h_i X^i \in k[[X]]$, it decomposes as

$$h = X^n s + r, \quad \text{with } r = h_0 + \cdots + h_{n-1} X^{n-1}$$

$$\implies h = q \cdot f + r, \quad \text{where } q = s \cdot f_0^{-1}.$$

Therefore,

$$\begin{aligned} g &= q_0 f + r_0 + \pi g_1 && \text{with } \deg r_0 \leq n-1, \\ &= (q_0 + \pi q_1) f + (r_0 + \pi r_1) + \pi^2 g_2 && \text{with } \deg r_1 \leq n-1 \\ &= \dots \\ \implies g &= q f + r, && \text{with } q = \sum_{i \geq 0} \pi^i q_i, r = \sum_{i \geq 1} \pi^i r_i. \end{aligned}$$

Unicity. If $qf + r = 0$, then $\underbrace{\bar{q}\bar{f}}_{\text{divided by } X^n} + \underbrace{\bar{r}}_{\deg \leq n-1} = 0$, so $\bar{q}\bar{f} = \bar{r} = 0$. Deduce inductively mod π^n . \square

¹⁵The residue $r(X)$ is a polynomial!

Remark. Jiang Jiedong provided a proof for this theorem when K is not finite over \mathbb{Q}_p .

For a polynomial $P(X) \in \mathcal{O}_K[X]$, we say $P(X)$ is **distinguished**, if it is monic with other coefficients in \mathfrak{m}_K , i.e.,

$$P(X) = X^n + a_{n-1}X^{n-1} + \cdots + a_0, \quad a_{n-1}, \dots, a_0 \in \mathfrak{m}_K.$$

- The Newton polygon of a distinguished polynomial P will be above x -axis with only the end point on x -axis, and all slopes are < 0 . So every root of P lies in $\mathfrak{m}_{\mathbb{Q}_p^{\text{alg}}}$.

Theorem 16 (Weierstrass Preparation Theorem). Let $f \in \mathcal{O}_K[[X]]$ with $\text{wdeg } f < \infty$.

Then $\exists!$ distinguished polynomial $P \in \mathcal{O}_K[[X]]$ with $\deg P = \text{wdeg } f$, s.t.

$$f(X) = P(X) \cdot u(X), \quad u \in (\mathcal{O}_K[[X]])^\times.$$

So, power series over K with bounded coefficients would have finitely many zeros in the unit disk.

Corollary 3.1. Let $f(X) \in K \otimes_{\mathcal{O}_K} \mathcal{O}_K[[X]]$.

1. $f(X) = \pi^\mu P(X)u(X)$ uniquely, where $\mu \in \mathbb{Z}$, P a distinguished polynomial, $u \in (\mathcal{O}_K[[X]])^\times$.
2. f has finitely many zeros in $\mathfrak{m}_{\mathbb{C}_p}$, and they are actually in $\mathfrak{m}_{\mathbb{Q}_p^{\text{alg}}}$. The number of zeros is $\text{wdeg}(\pi^{-\mu} f) = \deg P$ ¹⁶. □

Corollary 3.2. $K \otimes_{\mathcal{O}_K} \mathcal{O}_K[[X]]$ is a PID.

Proof. For $I = (\{f_i\}_i)$, write $f_i = \pi^{\mu_i} P_i u_i$, then $I = (\gcd_i(P_i))$. □

Theorem 17. Let $f \in H_K$, $\rho < 1$. Then f has finitely many zeros in $B(0, \rho)$, all of which are in $\mathfrak{m}_{\mathbb{Q}_p^{\text{alg}}}$.

Remark. $f \in H_K$ could have infinitely many zeros in $\mathfrak{m}_{\mathbb{C}_p} = B(0, 1)$. For example, we saw in the homework that the zeros of \log_F in $\mathfrak{m}_{\mathbb{C}_p}$ are $F[p^\infty]$, which is infinite in many cases, such as $F = \mathbb{G}_m$.

Proof. We may assume $\rho \in |\mathbb{C}_p|$.

Take $L/\mathbb{Q}_p < \infty$ and $\alpha \in \mathfrak{m}_L$ with $|\alpha| = \rho$. Then $f(\alpha X) \in L \otimes_{\mathcal{O}_L} \mathcal{O}_L[[X]]$, because $|a_i| \rho^i \rightarrow 0$ for $f = \sum a_i X^i \in H_K$. Hence $f(\alpha X)$ has finitely many zeros in $\mathfrak{m}_{\mathbb{C}_p} = B(0, 1)$ and they are algebraic over \mathbb{Q}_p . These zeros are in bijection with zeros of $f(X)$ in $B(0, \rho)$. □

Now we can prove the converse of Corollary 3.1.

Theorem 18. If $f \in H_K$, then

$$f \in K \otimes_{\mathcal{O}_K} \mathcal{O}_K[[X]] \iff f \text{ has finitely many zeros in } \mathfrak{m}_{\mathbb{C}_p}.$$

Proof. (\Leftarrow) Assume that $f = \sum_{i \geq 0} f_i X^i$ has n zeros in $\mathfrak{m}_{\mathbb{C}_p}$.

Take $\rho \in \mathfrak{m}_{\mathbb{C}_p}$ and $\alpha \in \mathfrak{m}_{\mathbb{Q}_p}$ with $|\alpha| = \rho$. By previous results,

$$\begin{aligned} \#\{\text{zero of } f \text{ in } B(0, \rho)\} &= \text{“Weierstrass degree” of } f(\alpha X) \\ &= \min \left\{ j \in \mathbb{Z}_{\geq 0} \mid \rho^j |f_j| = \max_{i \in \mathbb{Z}_{\geq 0}} \rho^i |f_i| \right\}. \end{aligned}$$

Hence

$$\begin{aligned} \min \left\{ j \in \mathbb{Z}_{\geq 0} \mid \rho^j |f_j| = \max_{i \in \mathbb{Z}_{\geq 0}} \rho^i |f_i| \right\} &\leq n, \\ \iff \rho^i |f_i| &\leq \max \{|f_0|, \rho |f_1|, \dots, \rho^n |f_n|\}, \quad \forall i \geq 0. \end{aligned}$$

Letting $i \rightarrow \infty$ tells us that the coefficients of f are bounded. □

¹⁶I want to call this “the Weierstrass degree of f ”.

3.3 p -adic Banach Spaces

Let $K/\mathbb{Q}_p < \infty$ with uniformiser π , $k := \mathcal{O}_K/\pi$.

4 Lubin-Tate Theory

4.1 Formal Groups

Let A be a commutative ring.

- If $f \in A[[T]]$ and $g \in A[[X_1, \dots, X_n]]$, then

$$\begin{aligned} f \circ g &:= f(g(X_1, \dots, X_n)), \\ g \circ f &:= g(f(X_1), \dots, f(X_n)). \end{aligned}$$

- If $F \in A[[X_1, \dots, X_n]]$, we put $F_i :=$ the partial derivative of F w.r.t. the i -th variable X_i .

Lemma 4.1. Let $f = \sum_{i \geq 1} a_i T^i \in A[[T]]$. Then

$$\exists g \in A[[T]] \text{ s.t. } f \circ g = g \circ f = T \iff a_1 = f'(0) \in A^\times.$$

Such a power series is called **reversible**.

Proof. Use $A[[T]] = \varprojlim A[T]/T^n$. For details, see the proof of Lemma 4.2. □

In this section, a **formal group** means a (commutative) formal group law of dimension one.

A **homomorphism** $h : F \rightarrow G$ between formal groups F and G over A

$$:= h \in XA[[X]], \text{ s.t. } h \circ G = F \circ h,$$

that is $h(G(X, Y)) = F(h(X), h(Y))$.

- A homomorphism $h : F \rightarrow G$ is an isomorphism $\iff h'(0) \in A^\times$.
- Every integer $n \in \mathbb{Z}$ gives rise to an endomorphism $[n] = nX + O(X^2) \in \text{End}(F)$, yielding a ring homomorphism $\mathbb{Z} \rightarrow \text{End}(F)$.

A **differential form** on F

$$:= \omega(X) = p(X)dX \in A[[X]]dX, \text{ s.t.}$$

$$\omega(f(X)) = p(f(X))df(X) := p(f(X))f'(X)dX, \forall f(X).$$

We say $\omega(X)$ is **invariant**, if $\omega \circ F(-, Y) = \omega$; i.e.,

$$p(F(X, Y))F_1(X, Y) = p(X).$$

Set $X = 0$, we see that

$$p(Y) = p(0) \frac{1}{F_1(0, Y)}.$$

Hence any invariant differential takes the form

$$\omega(X) = \frac{a \cdot dX}{F_1(0, X)}.$$

Conversely, we define

$$\omega_F := \frac{dX}{F_1(0, X)}$$

and call it **normalized invariant differential**. This name is verified as below.

Proposition 4.1. ω_F is invariant for F .

Proof. Take $\frac{d}{dZ}\big|_{Z=0}$ for

$$F(Z, F(X, Y)) = F(F(Z, X), Y),$$

we get

$$F_1(0, F(X, Y)) = F_1(X, Y)F_1(0, X).$$

□

- If $h \in \text{Hom}(F, G)$, then

$$\omega_G \circ h = h'(0) \cdot \omega_F.$$

4.2 Formal Groups over local fields

Let K be an extension of \mathbb{Q}_p inside \mathbb{C}_p .

4.2.1 The Logarithm

Let F be a formal group over K and ω_F the normalized invariant differential. We define

$$\log_F(X) := \int \omega_F \in K[[X]], \quad \text{s.t. } \log_F(0) = 0.$$

- If $\omega(X) = (1 + p_1X + p_2X^2 + \cdots)dX$, then

$$\log_F(X) = X + \frac{p_1X^2}{2} + \frac{p_2X^3}{3} + \cdots \in XA[[X]].$$

- $\log_F(X) \in H_K$ if F is defined over \mathcal{O}_K .

Proposition 4.2. $\log_F(X + Y) = \log_F(X) + \log_F(Y)$, so $\log_F : F \rightarrow_K \mathbb{G}_a$ is an isomorphism over K .

Proof. Let $E(X) := \log_F(X + Y) - \log_F(X)$. Then $dE(X) = \omega_F \circ F - \omega_F = 0$, thus $E(X) = E(0) = \log_F(Y)$. □

Example 5. $\log_{\mathbb{G}_a}(X) = X$, $\log_{\mathbb{G}_m}(X) = \log(1 + X)$.

Example 6. \mathbb{G}_a and \mathbb{G}_m are *NOT* isomorphic over \mathcal{O}_K , because

$$(\mathfrak{m}_{\mathbb{C}_p}, +_{\mathbb{G}_a}) = (\mathfrak{m}_{\mathbb{C}_p}, +) \not\simeq (1 + \mathfrak{m}_{\mathbb{C}_p}, \cdot) \simeq (\mathfrak{m}_{\mathbb{C}_p}, +_{\mathbb{G}_m}),$$

as the former is torsion-free while the latter has many torsion.

Remark. Proposition 4.2 holds for any formal group over a \mathbb{Q} -algebra A . As the proof involves not the axiom of commutativity, it shows that any formal group (of dimension 1) over a \mathbb{Q} -algebra is necessarily commutative.

4.2.2 The Height

Let k be a ring of characteristic $p > 0$. If F, G are formal groups over k , and $f \in \text{Hom}(F, G)$, we define the **height** of f to be

$$\text{ht}(f) := \text{largest integer } h \in \mathbb{Z}, \text{ s.t. } f(X) = g(X^{p^h}) \text{ for some } g \in k[[X]].$$

Proposition 4.3. If $f \in \text{Hom}(F, G)$ and $f(X) = g(X^{p^h})$ with $h = \text{ht}(f)$, then $g'(0) \neq 0$.

Proof. Two steps.

- If $f \in \text{Hom}(F, G)$ with $f'(0) = 0$, then $f(X) = g(X^{p^h})$ for some g .

This is because

$$0 = f'(0)\omega_F = \omega_G \circ f = \frac{f'(X)dX}{G_1(0, X)},$$

So $f'(X) = 0$. As $\text{char } k = p$, this leads to the result.

- If $F \in \text{Hom}(F, G)$, $f(X) = g(X^{p^h})$, then $g \in \text{Hom}(F^{\text{Frob}_{p^h}}, G)$.

Write $F = \sum a_{ij} X^i Y^j$, so $F^{\text{Frob}_{p^h}}(X) = \sum a_{ij}^{p^h} X^i Y^j$. As $\text{char } k = p$, $F^{\text{Frob}_{p^h}}$ is also a formal group over k . What left is obvious. □

4.2.3 The Torsion of Formal Groups and the Tate Module

Let $K/\mathbb{Q}_p < \infty$, $k = \mathcal{O}_K/\pi$ the residue field, F a formal group over \mathcal{O}_K .

- Note that F can be regarded as a formal group over K , and $\bar{F} := F \bmod \pi \in k[[X]]$ is a formal group over k .

We define the **height** of F to be

$$\text{ht}(F) := \text{height of } [p] \in \text{End}_k(\bar{F}).$$

Example 7. For \mathbb{G}_a , $[p](X) = 0$ in $k[[X]]$, so $\text{ht}(\mathbb{G}_a/\mathcal{O}_K) = \infty$.

For \mathbb{G}_m , $[p](X) = (1 + X)^p - 1 = X^p$ in $k[[X]]$, so $\text{ht}(\mathbb{G}_m/\mathcal{O}_K) = 1$.

and consider the p^n -torsion points of F , namely

$$F[p^n] := \{z \in \mathfrak{m}_{\mathbb{C}_p} \mid [p^n]_F(x) = 0\}.$$

- $F[p^n]$ is a subgroup of $(\mathfrak{m}_{\mathbb{C}_p}, +_F)$ and a $\mathbb{Z}/p^n\mathbb{Z}$ -module.
- $[p] : F[p^{n+1}] \hookrightarrow F[p^n]$ is a surjective homomorphism of $\mathbb{Z}/p^{n+1}\mathbb{Z}$ -module

We look at the equation $[p](z) = y$ with $y \in \mathfrak{m}_{\mathbb{Q}_p}$ first.

- If $h = \text{ht}(F) < \infty$, then $[p](X) \in \mathcal{O}_K[[X]]$ has Weierstrass degree p^h .
 $\implies [p](z) = y$ has p^h solutions in $\mathfrak{m}_{\mathbb{Q}_p}$.
- From $\omega_F \circ [p] = [p]'(0)\omega_F$, one deduce that $[p]'(X) = p(1 + O(X))$.
 \implies all roots of $[p](z) = y$ are simple.

Therefore, if $\text{ht}(F) < \infty$, then

$$\#F[p^n] = p^{hn}.$$

Now define

$$T_p F := \varprojlim_n F[p^n].$$

- $T_p F$ is a \mathbb{Z}_p -module.

- If $z = (z_1, z_2, \dots) \in T_p F$, then $pz = (0, z_1, z_2, \dots)$.
 $\implies T_p F$ is torsion-free. In addition,

$$\bigcap_{n \geq 0} p^n T_p F = \{0\}.^{17}$$

- We have an isomorphism

$$\begin{aligned} T_p F / p^n T_p F &\simeq F[p^n] \\ (z_1, z_2, \dots) &\mapsto z_n. \end{aligned}$$

Proposition 4.4. $T_p F$ is a free \mathbb{Z}_p -module of rank $h = \text{ht } F$.

Proof. Let m_1, \dots, m_h be a lift of a \mathbb{F}_p -basis of the dimension h vector space $T_p F / p T_p F \simeq F[p]$. We claim that m_1, \dots, m_h is a \mathbb{Z}_p -basis for $T_p F$.

- (linear independence.) Suppose $\lambda_1 m_1 + \dots + \lambda_h m_h = 0$ with $\lambda_i \in \mathbb{Z}_p \setminus \{0\}$. $T_p F$ is torsion-free, so $\exists j$ s.t. $p \nmid \lambda_j$. Hecen it will give a nontrivial relation modulo p .
- (generate $T_p F$.) Use the standard method. Obtain

$$m = \sum_i \lambda_i^{(k)} m_i + p^k n^{(k)}$$

inductively for all $k \geq 1$ Take $\lambda_i := \lim_k \lambda_i^{(k)}$ by $\lambda_i^{(k+1)} \equiv \lambda_i^{(k)} \pmod{p^k}$. Then

$$m - \sum_i \lambda_i m_i \in \bigcap_{k \geq 1} p^k T_p F = 0. \quad \square$$

4.2.4 Galois representation attached to a formal group

The Galois group $G_K = \text{Gal}(\bar{\mathbb{Q}}_p / K)$ acts \mathbb{Z}/p^n -linearly on $F[p^n]$,

$\rightsquigarrow G_K$ acts \mathbb{Z}_p -linearly on $T_p F$.

\rightsquigarrow continuous group homomorphism

$$\rho_F : G_K \rightarrow \text{Aut}_{\mathbb{Z}_p}(T_p F) \xrightarrow[\text{choose basis}]{\simeq} \text{GL}(h, \mathbb{Z}_p).$$

Example 8. For $K = \mathbb{Q}_p$ and $F = \mathbb{G}_m$, $\rho_F =$ cyclotomic charater χ_{cycl} .

4.3 Lubin-Tate formal groups

From now on, we write $A := \mathcal{O}_K$.

Choose a uniformiser ϖ of K . Define

$$\mathcal{F}_\varpi := \left\{ f \in \mathcal{O}_K[[T]] \mid \begin{array}{ll} f(T) \equiv \varpi T & \pmod{T^2} \\ f(T) \equiv T^q & \pmod{\varpi} \end{array} \right\}.$$

For example, $f(T) = T^q + \varpi T \in \mathcal{F}_\varpi$. The following lemma is a fundamental property of \mathcal{F}_ϖ .

¹⁷We say $T_p F$ is seperated.

Lemma 4.2. Let $f, g \in \mathcal{F}_\varpi$, Φ_1 be a linear form¹⁸ over \mathcal{O}_K . Then there is a **unique** $\Phi \in \mathcal{O}_K[[X_1, \dots, X_n]]$, s.t.

$$\begin{cases} \Phi \equiv \Phi_1 \pmod{(X_1, \dots, X_n)^2}, \\ f(\Phi(X_1, \dots, X_n)) = \Phi(g(X_1), \dots, g(X_n)). \end{cases}$$

Proof. We use a standard method. Finding Φ is equivalent to finding $\Phi_r \in A[X_1, \dots, X_n]$ s.t.

$$\begin{cases} \Phi_{r+1} \equiv \Phi_r \pmod{\deg \geq r+1}, \\ f(\Phi_r) \equiv \Phi_r(g(X_1), \dots, g(X_n)) \pmod{\deg \geq r+1}. \end{cases}$$

The second condition is guaranteed because $X \mapsto h(X)$ is X -adically continuous for any power series h .

Suppose we have found Φ_r . We look for Φ_{r+1} of the form $\Phi_{r+1} = \Phi_r + Q$, where Q is homogeneous of degree $r+1$, s.t.

$$f(\Phi_{r+1}) \equiv \Phi_{r+1}(g(X_1), \dots, g(X_n)) \pmod{\deg \geq r+2}.$$

The LHS is

$$f(\Phi_r) + f(Q) \equiv f(\Phi_r) + \varpi Q \pmod{\deg \geq r+2},$$

while the RHS is

$$\Phi_r \circ g + Q(\varpi X_1, \dots, \varpi X_n) \equiv \Phi_r \circ g + \varpi^{r+1} Q,$$

so if such a $Q \in A[X_1, \dots]$ exists, it must satisfy

$$\varpi(\varpi^r - 1)Q \equiv f \circ \Phi_r - \Phi_r \circ g \pmod{\deg \geq r+2}$$

and thus being unique. This procedure also shows that all Φ_r 's are unique if we require $\Phi_{r+1} - \Phi_r$ to be homogeneous.

Because $\varpi^r - 1 \in A^\times$, it suffices to show

$$f(\Phi_r) \equiv \Phi_r \circ g \pmod{\varpi},$$

which is clear. □

By Lemma 4.2, one may define the **Lubin-Tate formal groups**. They are exactly the formal group laws admitting an endomorphism

- that has derivative at the origin equal to a uniformiser of K , and
- reduces mod \mathfrak{m} to the Frobenius map $T \mapsto T_q$.

Moreover, these formal groups admit \mathcal{O}_K -actions and are isomorphic as formal \mathcal{O}_K -modules.

Proposition 4.5. For each $f \in \mathcal{F}_\varpi$, there is a unique formal group F_f over \mathcal{O}_K admitting f as an endomorphism.

Proof. Lemma 4.2 gives $F_f \in A[[X, Y]]$ s.t.

$$\begin{cases} F_f = X + Y + \deg \geq 2, \\ f(F_f(X + Y)) = F_f(f(X), f(Y)). \end{cases}$$

¹⁸A **linear form** is a homogeneous polynomial of degree 1.

The associativity is proved by showing that both $G_1 = F_f(X, F_f(Y, Z))$ and $G_2 = F_f(F_f(X, Y), Z)$ satisfies

$$\begin{cases} G = X + Y + Z + \deg \geq 2, \\ f(G) = G(f(X), f(Y), f(Z)). \end{cases}$$

This is a direct application of Lemma 4.2 and will be used many times. \square

So Lubin-Tate formal groups exist. Now we investigate their homomorphisms.

Proposition 4.6. For each $f, g \in \mathcal{F}_\varpi$ and $a \in \mathcal{O}_K$, there is a unique $[a]_{g,f} \in \mathcal{O}_K[[T]]$ s.t.

$$\begin{cases} [a]_{g,f} = aT + \dots, \\ g \circ [a]_{g,f} = [a]_{g,f} \circ f, \end{cases}$$

and $[a]_{g,f} \in \text{Hom}(F_f, F_g)$, i.e.

$$F_g \circ [a]_{g,f} = [a]_{g,f} \circ F_f.$$

As a corollary of Lemma 4.1, each $u \in A^\times$ gives an isomorphism $[u]_{g,f} : F_f \xrightarrow{\sim} F_g$, and there is a unique isomorphism $F_f \simeq F_g$ of the form $T + \dots$. \square

We write $[a]_f := [a]_{f,f} \in \text{End } F_f$. Note that

$$[\varpi]_f = f.$$

Proposition 4.7. For any $a, b \in \mathcal{O}_K$,

$$[a + b]_{g,f} = [a]_{g,f} + [b]_{g,f},$$

and

$$[ab]_{h,f} = [a]_{h,g} \circ [b]_{g,f}.$$

In particular, $\mathcal{O}_K \hookrightarrow \text{End } F_f$ as a ring by $a \mapsto [a]_f$, making F_f a formal \mathcal{O}_K -module. The canonical isomorphism $[1]_{g,f}$ is an isomorphism of \mathcal{O}_K -modules. \square

4.4 Construction of K_ϖ

Fix an algebraic closure K^{alg} of K . Each $f \in \mathcal{F}_\varpi$ associates to $\mathfrak{m}_{K^{\text{alg}}}$ an \mathcal{O}_K -module structure via

$$\alpha +_{F_f} \beta := F_f(\alpha, \beta)$$

and

$$a \cdot \alpha := [a]_f(\alpha)^{19}.$$

for $|\alpha| < 1, |\beta| < 1$ and $a \in \mathcal{O}_K$. We denote this \mathcal{O}_K -module by Λ_f . If $g \in \mathcal{F}_\pi$, then the canonical isomorphism $[1] : F_f \rightarrow F_g$ yields an isomorphism of \mathcal{O}_K -modules $\Lambda_f \xrightarrow{\sim} \Lambda_g$.

The ϖ^n -torsion part of Λ_f is denoted by $\Lambda_{f,n}$ or $F_f[n]$, i.e.,

$$\Lambda_{f,n} = F_f[n] := \Lambda_f[[\varpi]_f^n].$$

Because $[\varpi]_f = f$, $\Lambda_{f,n}$ is the \mathcal{O}_K -module consisting of the roots of $f^{(n)} := f \circ \dots \circ f$. If one takes f to be an Eisenstein polynomial, then all the roots of $f^{(n)}$ lie in $\mathfrak{m}_{K^{\text{alg}}}$, so $\Lambda_{f,n}$ is precisely the set of roots of $f^{(n)}$ equipped with the \mathcal{O}_K -module structure from F_f .

¹⁹These power serieses converges because they actually falls in a finite extension of K .

Lemma 4.3. Let M an \mathcal{O}_K -module, $M_n = M[\varpi^n]$. If

- M_1 has $q = [\mathcal{O}_K : \varpi]$ elements, and
- $\varpi : M \rightarrow M$ is surjective,

then $M_n \simeq \mathcal{O}_K / \varpi^n$.

Proof. Do induction on n . The structure theorem of f.g. modules over a PID shows that M_1 having q elements implies that $M_1 \simeq \mathcal{O}_K / \varpi$. Now assume it true for $n - 1$. Look at the sequence

$$0 \rightarrow M_1 \rightarrow M_n \xrightarrow{\varpi} M_{n-1} \rightarrow 0.$$

Surjectivity of ϖ implies the exactness of this sequence, and thus M_n has q^n elements. In addition, M_n must be cyclic, otherwise $M_1 = M_n[\varpi^n]$ is not cyclic. \square

Proposition 4.8. The \mathcal{O}_K -module $\Lambda_{f,n}$ is isomorphic to \mathcal{O}_K / ϖ^n , and hence $\text{End}(\Lambda_{f,n}) \simeq \mathcal{O}_K / \varpi^n$.

Proof. It suffices to show for a chosen f , so let's take $f = \varpi T + \dots + T^q$, an Eisenstein polynomial. We use the above Lemma 4.3 by the following observations.

- All roots of an Eisenstein polynomial have valuation > 0 .
- If $|\alpha| < 1$, then the Newton polygon of $f(T) - \alpha$ shows that its roots have valuation > 0 , and thus $[\varpi] = f(T)$ is surjective on Λ_f . \square

Lemma 4.4. Let L be a finite Galois extension of K . Then for every $F \in \mathcal{O}_K[[X_1, \dots, X_n]]$, $\alpha_1, \dots, \alpha_n \in \mathfrak{m}_L$ and $\tau \in \text{Gal}(L/K)$,

$$\tau F(\alpha_1, \dots, \alpha_n) = F(\tau\alpha_1, \dots, \tau\alpha_n).$$

Proof. Note that τ acts continuously on L , because the extension of valuation for local fields is unique. Therefore writing $F = \lim_{m \rightarrow \infty} F_m$ gives the desired result. \square

Theorem 19. Let $K_{\varpi,n} := K(\Lambda_{f,n}) \subset K^{\text{alg}}$. These fields are independent to the choice of f .

- $K_{\varpi,n}/K$ is totally ramified of degree $q^{n-1}(q-1)$.
- The action of \mathcal{O}_K on $\Lambda_{f,n}$ defines an isomorphism

$$(\mathcal{O}_K / \mathfrak{m}_K^n)^\times \simeq \text{Gal}(K_{\varpi,n}/K). \quad (1)$$

- For all n , ϖ is a norm from $K_{\varpi,n}$, i.e., $\exists \alpha_n \in K_{\varpi,n}$ with $N_{K_{\varpi,n}/K}(\alpha_n) = \varpi$.

Proof. Since $F_f[n] \simeq_{\mathcal{O}_K} F_g[n]$, the extensions over K given by them equal. Let f be a polynomial $T^q + \dots + \varpi T$.

Choose a nonzero root ϖ_1 of $f(T)$ and, inductively, a root ϖ_n of $f(T) - \varpi_{n-1}$. So $\varpi_n \in \Lambda_{f,n}$, and we obtain a tower of extensions

$$K_{\varpi,n} \supset K(\varpi_n) \xrightarrow{q} K(\varpi_{n-1}) \xrightarrow{q} \dots \xrightarrow{q} K(\varpi_1) \xrightarrow{q-1} K.$$

All the extensions with indicated degrees are given by Eisenstein polynomials, and thus Galois and totally ramified.

The field $K_{\varpi,n} = K(\Lambda_{f,n})$ is the splitting field of $f^{(n)}$ over K , hence $\text{Gal}(K_{\varpi,n}/K)$ embeds into the permutation group of the set $\Lambda_{f,n}$. By Lemma 4.4, the action of $\text{Gal}(K_{\varpi,n}/K)$ on Λ_n preserves its \mathcal{O}_K -action, so

$$\text{Gal}(K_{\varpi,n}/K) \hookrightarrow \text{Aut}(\Lambda_{f,n}) \simeq (\mathcal{O}_K/\varpi^n)^\times.$$

So $[K_{\varpi,n} : K] \leq (q-1)q^{n-1}$. Comparing the degree gives $K_{\varpi,n} = K(\varpi_n)$.

Now we prove (c). Let $f^{[n]} := (f/T) \circ f \circ \cdots \circ f$. Then $f^{[n]}$ is monic with degree $q^{n-1}(q-1)$ and $f^{[n]}(\varpi_n) = 0$, and thus $f^{[n]}$ is the minimal polynomial of ϖ_n over K . So we have

$$N_{K_{\varpi,n}/K}(\varpi_n) = (-1)^{q^{n-1}(q-1)}$$

by the following Lemma 4.5. □

Lemma 4.5. Let L/K be a finite extension in an algebraic closure K^{alg} , and $\alpha \in L$ has minimal polynomial f over K of degree d . Suppose

$$f(X) = (X - \alpha_1) \cdots (X - \alpha_d) \in K^{\text{alg}}[X],$$

and let $e = [L : K(\alpha)]$ then

$$N_{L/K}(\alpha) = \left(\prod_{i=1}^d \alpha_i \right)^e, \quad \text{Tr}_{L/K}(\alpha) = e \sum_{i=1}^d \alpha_i.$$

Moreover, if

$$f(X) = a_d X^d + a_{d-1} X^{d-1} + \cdots + a_0,$$

then

$$N_{L/K}(\alpha) = (-1)^{de} a_0^e, \quad \text{Tr}_{L/K}(\alpha) = -e a_{d-1}.$$

Proof. This follows directly from $N_{L/K} = N_{K(\alpha)/K} \circ N_{L/K(\alpha)}$ and $\text{Tr}_{L/K} = \text{Tr}_{L/K(\alpha)} \circ \text{Tr}_{K(\alpha)/K}$. For example,

$$\begin{aligned} N_{L/K}(\alpha) &= N_{L/K(\alpha)}(N_{K(\alpha)/K} \alpha) \\ &= \left(\prod_{\sigma \in \text{Hom}_K(K(\alpha), \bar{K})} \sigma \alpha \right)^{[L:K(\alpha)]} = \left(\prod_{i=1}^d \alpha_i \right)^{[L:K(\alpha)]}. \end{aligned} \quad \square$$

Define

$$K_\varpi := \bigcup_n K_{\varpi,n}.$$

Then K_ϖ/K is totally ramified, Galois, and abelian. The isomorphisms in Theorem 19 (b) are

$$(\mathcal{O}_K/\varpi^n)^\times \rightarrow \text{Gal}(K_{\varpi,n}/K) \quad \bar{u} \mapsto (\Lambda_{f,n} \ni \alpha \mapsto [u]_f(\alpha)),$$

and clearly lift to an continuous isomorphism

$$\mathcal{O}_K^\times \simeq \text{Gal}(K_\varpi/K).$$

We call

$$\chi_\varpi : G_K \rightarrow \text{Gal}(K_\varpi/K) \xrightarrow{\sim} \mathcal{O}_K^\times, \quad g\alpha = [\chi_\varpi(g)]_f(\alpha), \forall \alpha \in \Lambda_f = F_f[\pi^\infty]$$

the **Lubin-Tate charater** attached to ϖ .

4.5 Local Class Field Theory: Statement

Let $K_\pi = K(F[\pi^\infty])$ be the Lubin-Tate extension. We have $\text{Gal}(K_\pi/K) \simeq \mathcal{O}_K^\times$.

Recall that the maximal unramified extension K^{nr}/K has Galois group

$$\text{Gal}(K^{\text{nr}}/K) \simeq \text{Gal}(\bar{k}/k) \simeq \hat{\mathbb{Z}}.$$

If $q \neq k$, then $\text{Frob}_q : x \mapsto x^q$ generates a dense subgroup of $\text{Gal}(\bar{k}/k)$.

We define the **local Artin map** to be the group homomorphism

$$\text{Art}_K : K^\times \simeq \pi^{\mathbb{Z}} \times \mathcal{O}_K^\times \rightarrow \text{Gal}(K_\pi/K) \times \text{Gal}(K^{\text{nr}}/K) \simeq {}^{20}\text{Gal}(K_\pi K^{\text{nr}}/K)$$

s.t.

- $\pi \mapsto \text{Frob}_q$,
- $\mathcal{O}_K^\times \ni u \mapsto g \in \text{Gal}(K_\pi/K)$ s.t. $\chi_\pi(g) = \chi_\pi(\text{Art}_K(u)) = u^{-1}$.

Theorem 20 (Local Class Field Theory). (1) $K^{\text{ab}} := K_\pi K^{\text{nr}}$ is the maximal abelian extension of K .

(2) $\text{Art}_K : K^\times \rightarrow K^{\text{ab}}$ is independent of all choices.

(3) If $L/K < \infty$, then the Artin map induces

$$K^\times / N_{L/K}(L^\times) \simeq \text{Gal}(L/K),$$

which gives a bijection²¹

$$\{\text{open subgroup of } K^\times\} = \{\text{finite extension of } K\}.$$

(4) If $L/K < \infty$, then

$$\begin{array}{ccc} L^\times & \xrightarrow{\text{Art}_K} & \text{Gal}(L^{\text{ab}}/L) \\ N_{L/K} \downarrow & & \downarrow \text{res}^{22} \\ K^\times & \xrightarrow{\text{Art}_L} & \text{Gal}(K^{\text{ab}}/K) \end{array}$$

commutes.

Corollary 4.1. \exists unramified charater $\eta : G_K = \text{Gal}(\bar{\mathbb{Q}}_p/K) \rightarrow \mathbb{Z}_p^\times$, s.t.

$$\forall g \in G_K, N_{K/\mathbb{Q}_p}(\chi_\pi(g)) = \chi_{\text{cycl}}(g)\eta(g).$$

We say a charater η on G_K is **unramified**, if it restricts to the trivial charater on the inertia subgroup $I_K = I(\bar{\mathbb{Q}}_p/K)$. That is, η is lifted from a charater on $\text{Gal}(K^{\text{nr}}/K) \simeq \text{Gal}(\bar{k}/k) \simeq G_K/I_K$.

Proof. We construct this charater η on the dense subgroup

$$\text{im}(\text{Art}_K) = \langle \text{Frob}_q \rangle \times \text{Gal}(K_\pi/K)$$

²⁰ K_π and K^{nr} are disjoint.

²¹In particular, all open subgroups of K^\times are norm of some L^\times .

²²Here

$$\text{res} : \text{Gal}(L^{\text{ab}}/L) \hookrightarrow \text{Gal}(L^{\text{ab}}/K) \twoheadrightarrow \text{Gal}(K^{\text{ab}}/K).$$

first. Let $g \in \text{Gal}(\bar{\mathbb{Q}}_p/K)$ with

$$g|_{K^{\text{nr}}} = \text{Frob}_q^n$$

for $n(g) \in \mathbb{Z}$ so that $g \in \text{im}(\text{Art}_K)$. Write $q = p^f$, and note that

$$\text{Frob}_q|_{\mathbb{Q}_p^{\text{nr}}} = \text{Frob}_p^f,$$

Then we have the commutative diagram

$$\begin{array}{ccc} \pi^{n(g)} \chi_\pi(g)^{-1} & \xleftarrow{\hspace{1.5cm}} & g = \left(\text{Frob}_q^{n(g)}, g \right) \\ \downarrow & & \downarrow \\ (N_{K/\mathbb{Q}_p} \pi)^{n(g)} N_{K/\mathbb{Q}_p} (\chi_\pi(g)^{-1}) = p^{fn(g)} \chi_{\text{cycl}}(g)^{-1} & \xleftarrow{\hspace{1.5cm}} & g|_{\mathbb{Q}_p^{\text{ab}}} = \left(\text{Frob}_p^{fn(g)}, g \right) \end{array}$$

and we thereby find

$$N_{K/\mathbb{Q}_p}(\chi_\pi(g)) = \left(\frac{N_{K/\mathbb{Q}_p} \pi}{p^f} \right)^{n(g)} \chi_{\text{cycl}}(g)$$

and $\eta(g) := N_{K/\mathbb{Q}_p}(\chi_\pi(g))/\chi_{\text{cycl}}(g)$ indeed defines an unramified character on $\text{im}(\text{Art}_K)$. Hence it is unramified also on G_K . \square

4.6 The Case of \mathbb{Q}_p

Let $K = \mathbb{Q}_p$ and $\varpi = p$. Then $f(T) := (1+T)^p - 1 \in \mathcal{F}_p$. Note that f is an endomorphism of

$$\mathbb{G}_m(X, Y) = X + Y + XY,$$

so $F_f = \mathbb{G}_m/\mathbb{Z}_p$. Under the isomorphism

$$(\mathfrak{m}, +_{\mathbb{G}_m}) \simeq (1 + \mathfrak{m}, \cdot),$$

the endomorphism $f : a \mapsto (1+a)^p - 1$ is converted to the Frobenius map $a \mapsto a^p$.

The field $(\mathbb{Q}_p)_p = \mathbb{Q}_p(\mu_{p^\infty})$

For each $r \geq 1$, the p^r -torsion part of Λ_f is

$$\Lambda_{f,r} = \left\{ \alpha \in \mathbb{Q}_p^{\text{alg}} \mid (1+\alpha)^{p^r} = 1 \right\} \simeq \left\{ \zeta \in (\mathbb{Q}_p^{\text{alg}})^\times \mid \zeta^{p^r} = 1 \right\} = \mu_{p^r}.$$

The isomorphism is for \mathcal{O}_K -modules. So choose primitive p^r -th roots of unity ζ_{p^r} s.t. $\zeta_{p^r}^p = \zeta_{p^{r-1}}$, then $\varpi_r := \zeta_{p^r} - 1$ forms a sequence of compatible generators of $\Lambda_{f,r}$. Therefore

$$(\mathbb{Q}_p)_{p,r} = \mathbb{Q}_p(\varpi_r) = \mathbb{Q}_p(\mu_{p^r}),$$

and the Lubin-Tate extension of \mathbb{Q}_p given by uniformiser p is $(\mathbb{Q}_p)_p = \mathbb{Q}_p(\mu_{p^\infty})$, the cyclotomic extension.

The local Artin map $\phi_p : \mathbb{Q}_p^\times \rightarrow \text{Gal}(\mathbb{Q}_p^{\text{ab}}/\mathbb{Q}_p)$

It suffices to look at every

$$\phi_p : \mathbb{Q}_p^\times \rightarrow \text{Gal}(\mathbb{Q}_p(\mu_n)/\mathbb{Q}_p).$$

- If n is prime to p , then $\mathbb{Q}_p(\mu_n)/\mathbb{Q}_p$ is unramified of degree f , where f is the minimum natural number s.t. $m \mid p^f - 1$. The map ϕ_p sends up^t to the t -th power of Frobenius- p^f on $\mathbb{Q}_p(\mu_n) = \mathbb{Q}_p(\mu_{p^f-1})$, and $\ker \phi_p = (p^f)^\mathbb{Z} \times \mathbb{Z}_p^\times$.

- If $n = p^r$, then $\mathbb{Q}_p(\mu_{p^r})/\mathbb{Q}_p$ is totally ramified. The map ϕ_p sends up^t to the element sending a root of unity ζ to $\zeta^{\bar{u}^{-1}}$, where $\bar{u} \in \mathbb{Z}$ has the same residue modulo p^r as u . The kernel is $p^{\mathbb{Z}} \times (1 + p^r \mathbb{Z}_p)$.
- In general, let $n = p^r \cdot m$ with $p \nmid m$. Then $\mathbb{Q}_p(\mu_n) = \mathbb{Q}_p(\mu_{p^r})\mathbb{Q}_p(\mu_m)$, and $\mathbb{Q}_p(\mu_{p^r}) \cap \mathbb{Q}_p(\mu_m) = \mathbb{Q}_p$.

5 Periods

5.1 Periods of Characters

Let K be an algebraic extension of \mathbb{Q}_p , $G_K = \text{Gal}(\bar{\mathbb{Q}}_p/K)$. If $\eta : G_K \rightarrow \mathbb{Z}_p^\times$ is a character of G_K , then a **period in \mathbb{C}_p for η**

$$:= \alpha \in \mathbb{C}_p \text{ s.t. } \eta(g) = \frac{g\alpha}{\alpha}, \forall g \in G_K.$$

Remark. • Look at this “example”: if we consider “ $\chi_{\text{cycl}} : G_K \rightarrow \mathbb{C}^\times$ ”, then “ $g(e^{2\pi i/n}) = e^{2\pi i/n} \chi_{\text{cycl}}(g)$ ”, so “ $2\pi i$ ” is a “character for χ_{cycl} in \mathbb{C} ”. We are looking for this kind of “ $2\pi i$ ” under p -adic setting.

- In general, for $\alpha \in \mathbb{C}_p$, $g \mapsto \frac{g\alpha}{\alpha}$ is a cocycle, but not a character.

Theorem 21. If $\eta : G_K \rightarrow \mathbb{Z}_p^\times$ is unramified, then $\exists y \in \mathcal{O}_{\widehat{K^{\text{nr}}}}^\times$, s.t. $\eta(g) = \frac{gy}{y}$.

Proof. □

5.2 Periods of Lubin-Tate Characters - Not Exist

5.2.1 Periods of Twisted Lubin-Tate Characters

5.2.2 Tate’s Normalized Trace

5.3 Rings of Periods and Admissible Representations