

## Abstract

Let  $G$  be any group. For any natural number  $n \in \mathbb{N}$ , let  $a_n$  be the number of subgroups  $H \leq G$ , such that  $[G : H] = n$ . Assume  $G$  is finitely-generated, then  $a_n < \infty$ , and we can define a  $\zeta$ -function of the form  $\zeta_G(s) := \sum_{i=1}^{\infty} a_n n^{-s}$ , where  $s \in \mathbb{C}$ . Assume, in addition, that  $G$  is also nilpotent and torsion-free, then this function has properties of the Riemann  $\zeta$ -function, mainly the decomposition of  $\zeta$  to an Euler product of local factors indexed by primes. Using different variations of the  $\zeta$ -function and its factorization, we can obtain more information about  $G$  and specific subgroups of  $G$ . Specifically, we are interested in the number of pro-isomorphic subgroups of  $G$ , and in this research we shall display an approach to the problem of counting them.

# 1 Scientific Background

## 1.1 Introduction

**Proposition 1.1.1.** *Let  $G$  be any finitely generated group, and let  $n \in \mathbb{N}$  any natural number. Then there is a finite number of subgroups  $H \leq G$ , such that  $[G : H] = n$*

*Proof.* Let  $H \leq G$ , such that  $[G : H] = n$ , then  $G/H := \{g_1H, g_2H, \dots, g_nH\}$  is the set containing all left cosets of  $H$ . We shall define an operation  $*$  :  $G \times G/H \rightarrow G/H$ , in the following way.  $\forall g \in G$ , and  $\forall g_iH \in G/H$ , the operation is  $g * g_iH := (gg_i)H = g_jH$ , that is,  $g$  maps a left coset to another left coset. But that means that  $g$  maps every index  $i \in [n]$  to another index, which means that  $g$  operates as a permutation on  $[n]$ , so  $*$  defines a homomorphism  $f : G \rightarrow \mathcal{S}_n$ , from  $G$  to the symmetric group of order  $n$ .  $H$  is a subgroup, so  $\forall g \in G$ , it is clear that  $g \in H$  iff  $gH = H$ . Assume that  $i_0$  is the index of the left coset which identifies with  $H$ , i.e.  $g_{i_0}H = H$ , then  $g \in H$  iff  $g * g_{i_0}H = H$ , which means that the permutation  $f(g)$  stabilizes  $i_0$ , i.e.  $f(g)(i_0) = i_0$ . So, we can write  $H = \{g \in G : f(g)(i_0) = i_0\}$ . From this observation, it is clear that  $\#\{H \leq G : [G : H] = n\} \leq \#\{f : G \rightarrow \mathcal{S}_n\}$ . But all  $f$  are homomorphisms from a finitely generated group to a finite group, and since group homomorphisms are uniquely determined by the mapping of the generators, it is clear that  $\#\{f : G \rightarrow \mathcal{S}_n\} < \infty$ , which proves the proposition.  $\square$

**Definition 1.1.2.** Let  $G$  be a group, and let  $\mathcal{N} := \{N \trianglelefteq G\}$  the set of all normal subgroups of  $G$ . Let  $I \subset \mathbb{N}$  be a set of indices, for which we shall define the following partial order,  $\forall i, j \in I, i \leq j$  iff  $N_j \subseteq N_i$  iff  $G/N_i \subseteq G/N_j$ . So, for each  $i \leq j$ , there exists an epimorphism  $\pi_{ji} : G/N_j \rightarrow G/N_i$ , which projects  $G/N_j$  onto  $G/N_i$ . Then,  $\widehat{G} = \varprojlim \{G/N_k\}_{k \in I} := \{(h_k)_{k \in I} \in \prod_{k \in I} G/N_k : \pi_{ji}(h_j) = h_i, \forall i \leq j\}$  is an inverse limit of  $\{G/N_k\}_{k \in I}$ , and is called the **profinite closure** of  $G$ .

**Definition 1.1.3.** Let  $G$  be any group. a subgroup  $H \leq G$  is called **pro-isomorphic**, if  $\widehat{H} \cong \widehat{G}$ .

**Definition 1.1.4.** Let  $G$  be any group, and let  $\widehat{a}_n(G) := \#\{H \leq G : \widehat{H} \cong \widehat{G}, [G : H] = n\}$ , in words, the number of pro-isomorphic subgroups of  $G$ , of index  $n$ . The **pro-isomorphic  $\zeta$ -function** of  $G$  is defined by  $\widehat{\zeta}_G(s) := \sum_{n=1}^{\infty} \widehat{a}_n(G) n^{-s}$ , for some  $s \in \mathbb{C}$ . We assume, in this research, that  $\widehat{a}_n(G)$  is finite for all  $G$ . A sufficient condition for this would be that  $G$  is finitely-generated, by proposition 1.1.1.

**Example 1.1.5.**  $G = (\mathbb{Z}, +)$ .  $G$  is an abelian group, and every  $H \leq G$  is of the form  $H = n\mathbb{Z} = \langle n \rangle$ , for some  $n \in \mathbb{N}$ , which means that  $H \cong G$ , as both are infinite cyclic groups. From this, it is obvious that  $\widehat{H} \cong \widehat{G}$ , for every  $H \leq G$ . Any such  $H = n\mathbb{Z}$  is the only subgroup of  $G$ , which is of index  $n$ , therefore, the pro-isomorphic  $\zeta$ -function of  $G$  is  $\widehat{\zeta}_G(s) = \sum_{n=1}^{\infty} \widehat{a}_n(G) n^{-s}$ , where  $\widehat{a}_n(G) = 1$ , which comes to  $\widehat{\zeta}_G = \sum_{n=1}^{\infty} n^{-s} = \zeta(s)$ , the Riemann  $\zeta$ -function.

**Proposition 1.1.6.** The Riemann  $\zeta$ -function decomposes to an infinite product of  $\zeta_p$ -functions, that is,  $\zeta(s) = \prod_p \zeta_p(s) = \prod_p \sum_{k=0}^{\infty} \frac{1}{p^{ks}} = \prod_p \frac{1}{1-p^{-s}}$ , where  $p$  is prime, and the product runs over all the prime numbers.

**Proposition 1.1.7.** Let  $G$  be any finitely-generated, nilpotent and torsion-free group, then we have the same decomposition as above, for the pro-isomorphic  $\zeta$ -function,  $\widehat{\zeta}_G(s) = \prod_p \widehat{\zeta}_{G,p}(s)$ , where  $\widehat{\zeta}_{G,p}(s) := \sum_{k=0}^{\infty} a_{p^{ks}}(G) \frac{1}{p^{ks}}$

**Definition 1.1.8.** Let  $G$  be any group, then the **lower central series** of  $G$  is series of subgroups of  $G$ , defined by the recursive rule,  $G_n := [G, G_{n-1}]$ , for every  $n \in \mathbb{N}$ , where  $G_0 := G$ . We recall that  $[G, G_n] \leq G$  is the subgroup of commutators,  $\{gg_n g^{-1} g_n^{-1} : g \in G, g_n \in G_n\}$

**Definition 1.1.9.** Let  $G$  be any group. the **nilpotency class** of  $G$  is  $\min\{n \in \mathbb{N} : G_n = [G, G_{n-1}] = \{e\}\}$ , in words, the smallest natural number, such that the subgroup of commutators of the form  $[G, G_n]$  is the trivial group. We can extend this definition, and say that the trivial group nilpotency class is 0.

## 1.2 Linearization

For finitely-generated torsion-free nilpotent groups we associate nilpotent Lie algebras over  $\mathbb{Z}_p$ , the ring of  $p$ -adic integers. We show here the basic properties of  $\mathbb{Z}_p$ -algebras, as subalgebras of  $\mathbb{Q}_p$ -algebras, where  $\mathbb{Q}_p$  is the fraction field of  $\mathbb{Z}_p$ .

**Proposition 1.2.1.** Let  $\mathcal{L}_p$  be any  $\mathbb{Q}_p$ -algebra, with  $n = \dim \mathcal{L}_p$ . Then  $G(\mathbb{Q}_p) \leq GL_n(\mathbb{Q}_p)$ . This is true for any field  $\mathbb{F}$  and  $\mathbb{F}$ -algebra  $\mathcal{L}_{\mathbb{F}}$ .

*Proof.* Choose a basis  $B = \{b_1, \dots, b_n\}$  of  $\mathcal{L}_p$ . Let  $\varphi \in G(\mathcal{L}_p)$ , and  $v \in \mathcal{L}_p$ .  $B$  is a basis, so there are  $\lambda_1, \dots, \lambda_n \in \mathbb{Q}_p$ , such that  $v = \lambda_1 b_1, \dots, \lambda_n b_n$ . Then,  $\varphi(v) = \varphi(\sum_{i=1}^n \lambda_i b_i) = \sum_{i=1}^n \varphi(\lambda_i b_i) = \sum_{i=1}^n \lambda_i \varphi(b_i)$ . Mark  $B_\varphi = \{\varphi(b_1), \dots, \varphi(b_n)\}$ .  $B_\varphi$  must span  $\mathcal{L}_p$ , otherwise, there exists a vector  $u \in \mathcal{L}_p$ , such that  $\sum_{i=1}^n \rho_i \varphi(b_i) \neq u$ , for any  $\rho_1, \dots, \rho_n \in \mathbb{Q}_p$ . But  $u = \sum_{i=1}^n \tau_i b_i$ ,  $\varphi$  is an automorphism, so  $u = \varphi \varphi^{-1}(u) = \varphi(\varphi^{-1}(\sum_{i=1}^n \tau_i b_i)) = \varphi(\sum_{i=1}^n \varphi^{-1}(\tau_i b_i)) = \varphi(\sum_{i=1}^n \tau_i \varphi^{-1}(b_i)) = \sum_{i=1}^n \varphi(\tau_i \varphi^{-1}(b_i)) = \sum_{i=1}^n \tau_i \varphi(\varphi^{-1}(b_i)) = \sum_{i=1}^n \tau_i b_i$ , in contradiction to the assumed.  $B_\varphi$  is also linearly-independent, because, supposed that  $\sum_{i=1}^n \rho_i \varphi(b_i) = 0$ , then, since  $\varphi$  is an automorphism, must be that  $\varphi^{-1}(\sum_{i=1}^n \rho_i \varphi(b_i)) = 0$ , which means that  $\sum_{i=1}^n \varphi^{-1}(\rho_i \varphi(b_i)) = \sum_{i=1}^n \rho_i \varphi^{-1}(\varphi(b_i)) = \sum_{i=1}^n \rho_i b_i = 0$ , which contradicts the fact that  $B$  is a basis. So,  $B_\varphi$  is also a basis of  $\mathcal{L}_p$ . It is immediate to conclude that the matrix representing  $\varphi$  is an inverse  $n \times n$  matrix, which means that  $\varphi \in GL_n(\mathbb{Q}_p)$ , and that  $\forall \varphi, \psi \in G(\mathbb{Q}_p)$ , their compositions  $\varphi\psi$ , and  $\psi\varphi$  are also in  $G(\mathbb{Q}_p)$ , which means that  $G(\mathbb{Q}_p) \leq GL_n(\mathbb{Q}_p)$ .  $\square$

**Proposition 1.2.2.** Let  $p$  be any prime number, then  $L_p < \mathcal{L}_p$

*Proof.* Let  $B = \{b_1, \dots, b_n\}$  a basis of  $\mathcal{L}_p$ , so, for any  $v \in \mathcal{L}_p$ , we have that  $v = \lambda_1 b_1 + \dots + \lambda_n b_n$ , where  $\lambda_1, \dots, \lambda_n \in \mathbb{Q}_p$ . Obviously, for any prime number  $p$ , we have that  $\mathbb{Z}_p \subset \mathbb{Q}_p$ , in other words,  $\iota : \mathbb{Z}_p \rightarrow \mathbb{Q}_p$  is a monomorphism of rings. This means that the ring  $\mathbb{Z}_p$  acts on the left  $\mathbb{Q}_p$ -module  $\mathcal{L}_p$  by restriction of scalars, that is, for every  $r \in \mathbb{Z}_p$ , and  $s \in \mathcal{L}_p$ , we have that

$rs := \iota(r)s$ , which is well defined, because  $\iota(r) \in \mathbb{Q}_p$ . This means that  $\mathcal{L}_p$  inherits the structure of a left  $\mathbb{Z}_p$ -module. We mark  $L_p := \{r_1 b_1, \dots, r_n b_n\}$ , where  $r_1, \dots, r_n \in \mathbb{Z}_p$ .  $B$  is generating  $L_p$ , by the construction, and it is clear that  $B$  is  $\mathbb{Z}_p$ -linearly-independent, since  $B$  is  $\mathbb{Q}_p$ -linearly-independent, and  $\mathbb{Z}_p \subset \mathbb{Q}_p$ . So,  $B$  is a basis also for  $L_p$ , and it is clear that any  $\mathbb{Z}_p$ -linear combination of vectors of  $B$  is a  $\mathbb{Q}_p$ -linear combination of vectors of  $B$ , hence  $L_p \leq \mathcal{L}_p$ .  $\square$

**Proposition 1.2.3.** *Let  $p$  be a prime number, and let  $L_n(\mathbb{Z}_p)$  be a  $\mathbb{Z}_p$ -algebra, for any  $n \in \mathbb{N}$ , then there exists a  $\mathbb{Q}_p$ -algebra, denoted by  $\mathcal{L}_n(\mathbb{Q}_p)$ , such that 1.2.2 holds.*

*Proof.* We construct  $\mathcal{L}_n(\mathbb{Q}_p)$  from  $L_n(\mathbb{Z}_p)$  by extension of scalars.  $\mathbb{Q}_p$  is a  $\mathbb{Z}_p$ -module, as a trivial fact, so, taking the tensor product  $L_n \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$ , we have, for all  $a \in L_n(\mathbb{Z}_p)$ , and for all  $r, r' \in \mathbb{Q}_p$ , that  $r'(a \otimes r) = a \otimes rr' = rr'(a \otimes 1)$ , which is well-defined, because of the multiplication in  $\mathbb{Q}_p$ , and so, given  $B = \{b_1, b_2, \dots, b_n\}$ , a basis for  $L_n(\mathbb{Z}_p)$ , we have a natural bijection between  $b_i$  and  $b_i \otimes 1$ , for  $1 \leq i \leq n$ , which means that  $\{b_1 \otimes 1, b_2 \otimes 1, \dots, b_n \otimes 1\}$  is a basis for  $L_n \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$ , we denote  $\mathcal{L}_n(\mathbb{Q}_p) := L_n \otimes_{\mathbb{Z}_p} \mathbb{Q}_p$ , and we got that  $\mathcal{L}_n(\mathbb{Q}_p)$  is a  $\mathbb{Q}_p$ -algebra, with the same basis,  $B$ , but with scalars from  $\mathbb{Q}_p$ , which proves that  $L_n < \mathcal{L}_n$ .  $\square$

**Proposition 1.2.4.** *Let  $B = \{b_1, \dots, b_n\}$  be any basis of  $\mathcal{L}_p$ , and  $\varphi \in G(\mathbb{Q}_p)$  any  $\mathbb{Q}_p$ -automorphism. Then  $\varphi(L_p) \subseteq L_p$  iff  $\varphi(b_1), \dots, \varphi(b_n) \in L_p$*

*Proof.* Clearly, if  $\varphi(v) \in L_p$ , for every  $v \in L_p$ , then also  $\varphi(b_1), \dots, \varphi(b_n) \in L_p$ . We prove the opposite by taking  $v = r_1 b_1 + \dots + r_n b_n$ , then  $\varphi(v) = \varphi(\sum_{i=1}^n r_i b_i) = \sum_{i=1}^n \varphi(r_i b_i) = \sum_{i=1}^n r_i \varphi(b_i)$ , but  $\varphi(b_1), \dots, \varphi(b_n) \in L_p$ , so  $\sum_{i=1}^n r_i \varphi(b_i)$  is a  $\mathbb{Z}_p$ -linear combination, hence  $\varphi(v) \in L_p$ .  $\square$

**Proposition 1.2.5.** *Let  $G^+(\mathbb{Q}_p) := G(\mathbb{Q}_p) \cap \mathcal{M}_n(\mathbb{Z}_p) = \{\varphi \in \text{Aut}_{\mathbb{Q}_p}(\mathcal{L}_p) : \varphi \in \mathcal{M}_n(\mathbb{Z}_p)\}$ , in words, all the  $\mathcal{L}_p$ -automorphisms, which are matrices over  $\mathbb{Z}_p$ . Then,  $G^+(\mathbb{Q}_p)$  is a monoid.*

*Proof.*  $G(\mathbb{Q}_p)$  is a group, thus a monoid, and  $\mathcal{M}_n(\mathbb{Z}_p)$  is a monoid, so, their intersection is a monoid.  $\square$

**Proposition 1.2.6.** *Let  $g \in G^+(\mathbb{Q}_p)$ , then, the right coset  $G(\mathbb{Z}_p)g \subseteq G^+(\mathbb{Q}_p)$*

*Proof.* Let  $h \in G(\mathbb{Z}_p)$ . We proved in 1.2.2 that  $L_p \leq \mathcal{L}_p$ , so  $h \in G(\mathbb{Q}_p)$ . But,  $h(L_p) \subseteq L_p$ , and from 1.2.4, we know that  $h$  is a  $\mathbb{Z}_p$ -linear combination

of vectors in  $L_p$ , which means that  $h$  is a matrix with coefficients in  $\mathbb{Z}_p$ , that means,  $h \in \mathcal{M}_n(\mathbb{Z}_p)$ , so  $h \in G(\mathbb{Q}_p) \cap \mathcal{M}_n(\mathbb{Z}_p)$ , which means that  $hg \in G(\mathbb{Q}_p) \cap \mathcal{M}_n(\mathbb{Z}_p)$ .  $\square$

**Corollary 1.2.7.**  $G^+(\mathbb{Q}_p) = \bigsqcup_{i=1}^n G(\mathbb{Z}_p)g_i$ , where  $[G(\mathbb{Q}_p) : G(\mathbb{Z}_p)] = n$

**Proposition 1.2.8.** *There is a bijection between  $G(\mathbb{Z}_p) \backslash G^+(\mathbb{Q}_p)$  and  $\{M \leq L_p : M \cong L_p\}$*

*Proof.* Let  $\varphi \in G(\mathbb{Z}_p)g \in G(\mathbb{Z}_p) \backslash G^+(\mathbb{Q}_p)$ , and let  $M = \varphi(L_p)$ . But, from 1.2.6, we have that  $\varphi \in G^+(\mathbb{Q}_p)$ , so  $M = \varphi(L_p) \subseteq L_p$ . Choose a different representative  $\psi \in G(\mathbb{Z}_p)g$ , we have that  $\tau = \psi\varphi^{-1} \in G(\mathbb{Z}_p)$ , which means that  $\tau(L_p) = L_p$ . But  $\tau\varphi = \psi\varphi^{-1}\varphi = \psi$ , which means that  $\psi(L_p) = \tau\varphi(L_p) = \varphi(\tau(L_p)) = \varphi(L_p) = M$ , so we have that  $M$  is the image of any representative of  $G(\mathbb{Z}_p)g$ . Let  $\varphi|_{L_p} : L_p \rightarrow M$  be the restriction of  $\varphi$  to  $L_p$ . Obviously,  $\varphi|_{L_p}$  is onto  $M$ , and is one-to-one, as a restriction of an automorphism. So we have that  $\varphi|_{L_p}$  is an isomorphism, which means that  $L_p \cong M$ . So, we conclude that every right coset of the form  $G(\mathbb{Z}_p)g$  defines an isomorphism of the form  $L_p \cong M$ . For the opposite direction, we show that for every isomorphism  $L_p \cong M$ , we can find some  $\varphi \in G^+(\mathbb{Q}_p)$ , for which  $\varphi(L_p) = M$ . Choose another automorphism,  $\psi \in G^+(\mathbb{Q}_p)$ , such that  $\psi(L_p) = M$ , and let  $\tau = \varphi\psi^{-1}$ . But  $\tau(L_p) = \varphi\psi^{-1}(L_p) = \psi^{-1}(\varphi(L_p)) = \psi^{-1}(M) = L_p$ , which means that  $\tau \in G(\mathbb{Z}_p)$ . But  $\tau\psi = \varphi\psi^{-1}\psi = \varphi \in G(\mathbb{Z}_p)\psi$ , and, obviously,  $\tau^{-1}\varphi = \tau^{-1}\tau\psi = \psi$  means that also  $\psi \in G(\mathbb{Z}_p)\varphi$ , so  $\varphi$  and  $\psi$  are in the same right coset of  $\mathbb{Z}_p$ , so we have that every isomorphism  $L_p \cong M$  is common to all representatives of the same right coset of  $G(\mathbb{Z}_p)$ , proving the bijection.  $\square$

**Proposition 1.2.9.** *Let  $G(\mathbb{Z}_p)g \in G(\mathbb{Z}_p) \backslash G^+(\mathbb{Q}_p)$  be a right coset, and  $M \leq L_p$  the image of this coset, as constructed in 1.2.8, then  $[L_p : M] = |\det g|_p^{-1}$ .*

### 1.3 $p$ -adic Integration

**Proposition 1.3.1.** *Let  $\Gamma$  be a topological group, and let  $U \subseteq \Gamma$ , be an open subset in  $\Gamma$ . Then  $\gamma U := \{\gamma u : \gamma \in \Gamma, u \in U\}$  is also an open subset of  $\Gamma$ .*

*Proof.* We define a map  $f = f_{\gamma^{-1}} : \Gamma \rightarrow \Gamma$ , by  $f(g) := \gamma^{-1}g$ , for any  $g \in \Gamma$ . Clearly,  $f$  is continuous, as a composition of continuous maps, that is, the inverse map  $\gamma \mapsto \gamma^{-1}$ , and the multiplication map  $(\gamma^{-1}, g) \mapsto \gamma^{-1}g$ , so any inverse image  $f^{-1}$  of an open subset is an open subset. But  $f^{-1}(U) = \{g \in G : f(g) = \gamma^{-1}g \in U\} = \{\gamma h : f(\gamma h) = \gamma^{-1}\gamma h = h \in U\} = \{\gamma h : h \in U\} = \gamma U$ , which proves that  $\gamma U$  is an open subset in  $\Gamma$ .  $\square$

**Proposition 1.3.2.** *Let  $\Gamma$  be a locally compact topological group, i.e.,  $\forall \gamma \in \Gamma$ , there is an open environment  $U_\gamma$  of  $\gamma$ , and a compact subset  $K_\gamma$ , such that  $\gamma \in U_\gamma \subset K_\gamma$ . Then there is a measure  $\mu$ , with the following property: for any measurable subset,  $U \subseteq \Gamma$ , and any  $\gamma \in \Gamma$ ,  $\mu(U\gamma) = \mu(U)$ , where  $U\gamma := \{u\gamma : u \in U\}$ , and  $\mu$  is unique up to multiplication in constant.  $\mu$  is called a **Right Haar Measure***

**Proposition 1.3.3.** *Let  $p$  be a prime number, then  $G(\mathbb{Q}_p)$  is a locally compact topological group.*

**Proposition 1.3.4.** *Let  $p$  be a prime number, then  $G(\mathbb{Q}_p)$  has a unique right Haar measure  $\mu$ , with the following property:  $\mu(G(\mathbb{Z}_p)) = 1$ .*

**Corollary 1.3.5.** *For every  $g \in G(\mathbb{Q}_p)$ , we have that  $\mu(G(\mathbb{Z}_p)g) = \mu(G(\mathbb{Z}_p)) = 1$*

**Proposition 1.3.6.** *Let  $p$  be a prime number,  $s \in \mathbb{C}$ , and let  $g \in G^+(\mathbb{Q}_p)$ , then  $|det(g)|_p^s = \int_{h \in G^+(\mathbb{Q}_p)} |det(h)|_p^s d\mu$ .*

*Proof.* We saw in 1.2.9 that for every  $g \in G(\mathbb{Z}_p)h$ , we have that  $|det(g)|_p^{-1}$  does not depend on the choice of representative, which means that  $|det(g)|_p$  is constant on the entire coset, which means that  $|det(g)|_p = |det(h)|_p$ . so,  
 $|det(g)|_p^s = \int_{h \in G^+(\mathbb{Q}_p)} |det(h)|_p^s d\mu = \int_{h \in G^+(\mathbb{Q}_p)} |det(g)|_p^s d\mu = |det(g)|_p^s \int_{h \in G^+(\mathbb{Q}_p)} d\mu$ .  
But,  $\mu = \mu(G(\mathbb{Z}_p)h)$ , and we saw in 1.3.5 that  $\mu(G(\mathbb{Z}_p)h) = \mu(G(\mathbb{Z}_p)) = 1$ ,  
so  $\int_{h \in G^+(\mathbb{Q}_p)} |det(h)|_p^s d\mu = |det(g)|_p^s \int_{h \in G^+(\mathbb{Q}_p)} d\mu = |det(g)|_p^s \cdot 1 = |det(g)|_p^s \quad \square$

**Corollary 1.3.7.** *Let  $p$  be a prime number,  $s \in \mathbb{C}$ , then  $\widehat{\zeta_{L,p}}(s) = \sum_{G(\mathbb{Z})g \in G(\mathbb{Z}_p) \setminus G^+(\mathbb{Q}_p)} |det(g)|_p^s = \sum_{G(\mathbb{Z})g \in G(\mathbb{Z}_p) \setminus G^+(\mathbb{Q}_p)} \int_{h \in G(\mathbb{Z}_p)g} |det(h)|_p^s d\mu = \int_{h \in G^+(\mathbb{Q}_p)} |det(h)|_p^s d\mu$*

**Theorem 1.3.8.** *Let  $p$  be a prime number,  $s \in \mathbb{C}$ , then there exists a rational function,  $w_p(s) := \frac{f(x)}{g(x)}$ , where  $f, g \in \mathbb{Z}_p[x]$ , which satisfies  $\widehat{\zeta_{L,p}}(s) = w_p(p^{-s})$ .*

## 2 Research

### 2.1 The group $U_n$

**Proposition 2.1.1.** *Let  $A \in \mathcal{M}_n(\mathbb{Z}_p)$ , then  $A \in GL_n(\mathbb{Z}_p)$  iff  $\det(A) = \pm 1$*

*Proof.* We shall prove only one direction. Assume  $\det(A) = \pm 1$ . For  $A$ , we calculate the adjoint matrix,  $Adj(A)$ , by calculating minors for all the elements of  $A$ , and create the cofactor matrix of  $A$ , then take the transpose of the cofactor matrix. With this calculation,  $A^{-1} = \frac{Adj(A)}{\det(A)}$ , and, since calculating minors requires multiplication and subtraction between elements of the  $A$ . But  $\mathbb{Z}_p$  is a ring, so closed under multiplication and subtraction, hence all the minors are also in the ring, which means that  $Adj(A) \in \mathcal{M}_n(\mathbb{Z}_p)$ . But  $\det(A) = \pm 1$ , so  $A^{-1} = \frac{Adj(A)}{\det(A)} = \pm 1 \cdot Adj(A) \in \mathcal{M}_n(\mathbb{Z}_p)$ , which means that  $A, A^{-1} \in GL_n(\mathbb{Z}_p)$ .  $\square$

**Corollary 2.1.2.** *Let  $A$  be a  $n \times n$  matrix, with 1 on the main diagonal, and  $a_{ij} \in \mathbb{Z}_p$ , where  $i < j$ , and all the other elements, namely, the elements below the main diagonal, are 0. Then every matrix  $A$  of this form has an inverse matrix,  $A^{-1}$ , of the same form.*

*Proof.* One checks that all the minors of the elements on the main diagonal are 1, all the minors of the elements above the main diagonal are 0, and all the minors of the elements below the main diagonal can be any  $p$ -adic integers. constructing the cofactor matrix and transposing it, gives a matrix of the form described above, which is the inverse matrix of  $A$ , as we prove in 2.1.1.  $\square$

**Corollary 2.1.3.** *Let  $U_n$  be the set of all matrices of the form described in 2.1.2, then  $(U_n, \cdot)$  is a group, where  $\cdot$  is the standard matrix multiplication.*

*Proof.* One checks that multiplying two matrices in  $U_n$  gives a product matrix of the same form. Associativity comes from the standard matrix multiplication, and clearly, the standard unit matrix,  $I_n$ , is also in  $U_n$ . By 2.1.2, we know that  $A$  has an inverse matrix,  $A^{-1}$ , which is of the same form, hence  $A^{-1} \in U_n$ , which completes the proof.  $\square$

**Proposition 2.1.4.** *Let  $E_{ij} \in U_n$ , where  $1 \leq i < j \leq n$ , be a  $n \times n$  matrix, with 1 on the main diagonal, and  $a_{ij} = 1$ , and 0 anywhere else. Then,  $E_{ij}^m$  is a matrix of the same form, except that  $a_{ij} = m$ .*

*Proof.* By induction on  $m$ . For  $m = 1$ ,  $E_{ij}^1 = E_{ij}$ , so, trivially,  $a_{ij} = 1 = m$ . For  $m + 1$ , we have that  $E_{ij}^{m+1} = E_{ij}^m E_{ij}$ . But  $E_{ij}^m$  has that  $a_{ij} = m$ , by the as-

sumption, and one checks that  $E_{ij}^m E_{ij} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & m & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} =$

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & m+1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix},$$

which proves the induction step, and the proposition.  $\square$

**Corollary 2.1.5.** *Let  $A = E_{ij}^m$ , and  $B = E_{ij}^r$ . Then,  $D = AB = E_{ij}^m E_{ij}^r$  is the matrix with 1 on the main diagonal,  $d_{ij} = m + r$ , and all the other elements are 0.*

*Proof.* One checks that the product matrix has also 1 on the main diagonal, and all the other elements are 0, except for  $d_{ij} = 1 \cdot r + m \cdot 1 = m + r$   $\square$

**Proposition 2.1.6.** *Let  $E_{ij} \in U_n$  be a matrix of the form described in 2.1.4. then  $E_{ij}^{-m}$  is a matrix of the same form, but with  $a_{ij} = -m$ .*

*Proof.* From 2.1.4, we have that  $E_{ij}^m = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & m & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$ . From 2.1.2, we

know that  $B = (E_{ij}^m)^{-1} \in U_n$ , that is,  $B = \begin{pmatrix} 1 & b_{12} & \dots & \dots & b_{1n} \\ 0 & 1 & b_{23} & \dots & b_{2n} \\ 0 & 0 & 1 & b_{ij} & b_{in} \\ 0 & 0 & 0 & 1 & b_{n-1n} \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$ , which

means that  $\begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & m & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & b_{12} & \dots & \dots & b_{1n} \\ 0 & 1 & b_{23} & \dots & b_{2n} \\ 0 & 0 & 1 & b_{ij} & b_{in} \\ 0 & 0 & 0 & 1 & b_{n-1n} \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$



Easy to check that all the elements  $b_{kl}$  must be 0, but for the element in row  $i$  and column  $j$ , we must have that  $1 \cdot b_{ij} + m \cdot 1 = 0$ , which means that  $b_{ij} = -m$ . One checks that the same calculation holds for  $(E_{ij}^{-1})^m$ , and so,  $E_{ij}^{-m} = (E_{ij}^m)^{-1} = (E_{ij}^{-1})^m$  is of the form described above.  $\square$

**Proposition 2.1.7.** *Let  $A = E_{ij}, B = E_{kl} \in U_n$  be two matrices of the form described in 2.1.2, i.e., 1 on the main diagonal, and all the other elements are 0, except for  $a_{ij}$  and  $b_{kl}$ , which are 1. Then the commutator,  $[E_{ij}, E_{kl}] =$*

$$\begin{cases} E_{il}, & j = k \\ E_{kj}^{-1}, & i = l \\ 0, & j \neq k \wedge i \neq l \end{cases}$$

*Proof.* There are two cases, The first, is where  $j = i + 1$ , or  $l = k + 1$ , and the second is where  $j > i + 1$ , and  $l > k + 1$ . One checks that the proposition is true in both cases.  $\square$

**Corollary 2.1.8.** *Let  $A = E_i = E_{ii+1} \in U_n$ , be a matrix of the form described in 2.1.4, where the only 1 which is outside the main diagonal is one of the elements  $a_{12}, a_{23}, \dots, a_{n-1n}$ , i.e., on the diagonal above the main diagonal. Then the set  $\mathcal{E}_n = \{E_1, E_2, \dots, E_{n-1}\}$  is a set of generators for the unipotent group  $U_n$ .*

*Proof.* By proposition 2.1.7, we can create any matrix  $E_{ij} \in U_n$  by composition of commutators of the form  $[E_i, [E_{i+1}, [\dots [E_{j-2}, E_{j-1}]]]]$ . From 2.1.4, we know that  $A = E_{ij}^m$  has that  $a_{ij} = m \in \mathbb{Z}_p$ , and by 2.1.5, we know that  $D = AB = E_{ij}^m E_{ij}^r$  is the matrix with 1 on the main diagonal, and all the other elements are 0, except for  $d_{ij} = m + r$ . Checking further gives that if  $A = E_{ij}^m$  and  $B = E_{jk}^r$ , then the commutator  $[E_{ij}^m, E_{kl}^r]$  is the matrix with 1 on the main diagonal, and all the other elements are 0, except for  $d_{ik} = mr$ . Easy to see how to apply the above calculations also for the inverse matrices. This means that we can generate any matrix in  $U_n$ , by multiplying matrices that come from commutators on the set  $\mathcal{E}_n = \{E_1, E_2, \dots, E_{n-1}\}$ , which means that  $\mathcal{E}_n$  generates the unipotent group  $U_n$ .  $\square$

**Proposition 2.1.9.** *The unipotent group  $U_n$  is nilpotent, of nilpotency class  $n$ .*

*Proof.* Easy to observe that for the set of generators,  $\mathcal{E}_n$ , the longest composition of commutators,  $[E_{i_1}, [E_{i_2}, [\dots [E_{i_k}]]]]$  has that  $i_1 = 1, i_2 = 2, \dots, i_k =$

$n - 1$ , or  $i_1 = n - 1, i_2 = n - 2, \dots, i_k = 1$ , which means that composing  $n - 1$  commutators of elements in  $\mathcal{E}_n$  leaves only  $E_{1n-1}$  and  $E_{1n-1}^{-1}$ , but  $[E_{1n-1}, E_{1n-1}^{-1}] = [E_{1n-1}^{-1}, E_{an-1}] = I_n$ . One can check that this holds for the unipotent group  $U_n$  itself, as generated by  $\mathcal{E}_n$ .  $\square$

**Proposition 2.1.10.** *The unipotent group  $U_n$  is torsion free.*

*Proof.* Again, we show the proposition for the set of generators,  $\mathcal{E}_n$ . Let  $A = E_i \in \mathcal{E}_n$ , and suppose it has a finite order, which means that there exists a  $m \in \mathbb{N}$ , such that  $E_i^m = I_n$ . But by 2.1.4, we know that  $E_i^m$  is the matrix with  $a_{ii+1} = m$ , which means that  $m = 0$ , which is a contradiction.  $\square$

## 2.2 The algebra $L_n$

**Proposition 2.2.1.** *Let  $E_{ij} \in \mathcal{E}_n$ . Let  $e_{ij} = E_{ij} - I_n$ , in words,  $e_{ij}$  is obtained by replacing all the 1 on the main diagonal with 0. Then  $e_{ij}e_{jk} = e_{ik}$ , and  $e_{jk}e_{ij} = 0_n$ , where  $0_n$  is the  $n \times n$  zero matrix.*

*Proof.* Clearly, since  $A = e_{ij}$  has a single non-zero element,  $a_{ij} = 1$ , and  $B = e_{jk}$  has that  $b_{jk} = 1$ , then the product matrix  $D = AB = e_{ij}e_{jk}$  has a single element,  $d_{ik} = a_{ij}b_{jk} = 1 \cdot 1 = 1$ , but in the product  $BA = e_{jk}e_{ij}$ , we observe that  $b_{jk}$  is multiplied by all the elements of the  $k$ th row of  $A$ , which is all zeros, and  $a_{ij}$  is being multiplied by the  $i$ th column of  $B$ , which is all zeros, thus the product matrix,  $BA$ , is all zeros.  $\square$

**Corollary 2.2.2.** *Let  $\mathcal{B}_n$  be the set  $\{e_{ij} : i < j\}$ , of all the matrices of the form described in 2.2.1. Then  $\mathcal{B}_n$ , with the standard matrix addition, and a multiplication operation  $*$ , defined by  $e_{ij} * e_{jk} = e_{ij}e_{jk} - e_{jk}e_{ij}$ , is a basis for a Lie algebra over  $\mathbb{Z}_p$ , which shall be denoted by  $L_n(\mathbb{Z}_p)$ , or  $L_n$ , for abbreviation, which is the  $\mathbb{Z}_p$ -algebra of all the matrices  $A \in \mathcal{M}_n(\mathbb{Z}_p)$ , with 0 on the main diagonal. The multiplication operation  $*$  shall be denoted by Lie Brackets, that is,  $e_{ij} * e_{jk} = [e_{ij}, e_{jk}]$ .*

*Proof.* Since we have defined the multiplication operation as the standard Lie brackets, for matrix Lie algebras, i.e.,  $[A, B] = AB - BA$ , for all the matrices  $A, B$  in the algebra, one easily checks that all the axioms of a Lie algebra hold for this definition. Obviously,  $L_n$  is a  $\mathbb{Z}_p$ -span of  $\mathcal{B}_n$ , since every

matrix of the form  $A = \begin{pmatrix} 0 & a_{12} & a_{13} & \dots & a_{1n} \\ 0 & 0 & a_{23} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & a_{n-1n} \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$  is a linear combination

of matrices of  $\mathcal{B}_n$ , i.e.,  $A = \sum_{i=1}^{n-1} \sum_{j=i+1}^n a_{ij} e_{ij}$ . We can observe that if  $B = \sum_{i=1}^{n-1} \sum_{j=i+1}^n b_{ij} e_{ij} = 0_n$ , then clearly all the  $b_{ij}$  are 0. We conclude that  $\mathcal{B}_n$  is a basis for  $L_n$ .  $\square$

**Proposition 2.2.3.** *Let  $p$  be a prime number, and let  $n \in \mathbb{N}$  be any natural number, then  $\dim L_n(\mathbb{Z}_p) = \binom{n}{2}$*

*Proof.* From 2.2.2, we have that a basis for  $L_n(\mathbb{Z}_p)$  is the set of all  $e_{ij}$ , where  $i < j$ . For each row  $1 \leq i \leq n-1$ , we have  $n-i$  elements of the form  $e_{ij}$ , which gives, in total,  $\frac{n(n-1)}{2} = \frac{n!}{2!(n-2)!} = \binom{n}{2}$  elements of the the basis.  $\square$

**Proposition 2.2.4.** *Let  $p$  be a prime number, and let  $n \in \mathbb{N}$  be any natural number, then  $L_n(\mathbb{Z}_p)$  is a nilpotent Lie algebra.*

*Proof.* It is followed directly from 2.2.1, and from 2.1.9, since  $[e_{ij}, e_{jk}] = [E_{ij}, E_{jk}] - I_n = E_{ik} - I_n = e_{ik}$ , where the first brackets are Lie Brackets of  $L_n(\mathbb{Z}_p)$ , and the second brackets are a group commutator of  $U_n(\mathbb{Z}_p)$ .  $\square$

By considering the behavior of  $\mathcal{L}_n(\mathbb{Q}_p)$  under the Lie brackets, we can learn about the structure of  $\text{Aut}_{\mathbb{Q}_p}(\mathcal{L}_n)$ . As a basic fact, every  $\mathcal{L}_n(\mathbb{Q}_p)$ -automorphism  $\varphi$  must obey the  $\mathcal{L}_n$  Lie brackets, meaning that for all  $x, y \in \mathcal{L}_n$ , we must have that  $\varphi([x, y]) = [\varphi(x), \varphi(y)]$ . Let  $B = \{b_1, b_2, \dots, b_m\}$  be a basis for  $\mathcal{L}_n$ , we have that  $x = \sum_{i=1}^m \lambda_i b_i$ , and  $y = \sum_{i=1}^m \rho_i b_i$ , so  $\varphi([x, y]) = [\varphi(\sum_{i=1}^m \lambda_i b_i), \varphi(\sum_{i=1}^m \rho_i b_i)] = [\sum_{i=1}^m \varphi(\lambda_i b_i), \sum_{i=1}^m \varphi(\rho_i b_i)] = [\sum_{i=1}^m \lambda_i \varphi(b_i), \sum_{i=1}^m \rho_i \varphi(b_i)] = \sum_{i=1}^m \sum_{j=1}^m [\lambda_i \varphi(b_i), \rho_j \varphi(b_j)] = \sum_{i=1}^m \sum_{j=1}^m \lambda_i \rho_j [\varphi(b_i), \varphi(b_j)]$ . This technique can be demonstrated in the most simple case, which is the Heisenberg group.

## 2.3 The Heisenberg group

**Definition 2.3.1.** *The **Heisenberg group** is the unipotent group of  $3 \times 3$  matrices, over  $\mathbb{Q}_p$ , namely  $U_3(\mathbb{Q}_p)$ . Every matrix  $A \in U_3$  is of the form*

$$\begin{pmatrix} 1 & a_{12} & a_{13} \\ 0 & 1 & a_{23} \\ 0 & 0 & 1 \end{pmatrix}$$

where  $a_1, a_2, a_3 \in \mathbb{Q}_p$ .

The  $\mathbb{Q}_p$ -algebra associated with  $U_3$  consists of matrices of the form

$$A - I_3 = \begin{pmatrix} 0 & a_{12} & a_{13} \\ 0 & 0 & a_{23} \\ 0 & 0 & 0 \end{pmatrix} = a_{12}e_{12} + a_{13}e_{13} + a_{23}e_{23}$$

. Let  $\varphi \in \text{Aut}_{\mathbb{Q}_p}(\mathcal{L}_p)$  be an  $\mathcal{L}_{p,n}$ -automorphism. The image of every  $A \in \mathcal{L}_{p,n}$ , as a linear combination of elements of the basis, is a linear combination of the images of these elements. So, let  $v = (e_{12}, e_{23}, e_{13})$ , we have that

$$\varphi(v) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} e_{12} \\ e_{23} \\ e_{13} \end{pmatrix}, \text{ which means that}$$

$$\varphi(e_{12}) = a_{11}e_{12} + a_{12}e_{23} + a_{13}e_{13}$$

$$\varphi(e_{23}) = a_{21}e_{12} + a_{22}e_{23} + a_{23}e_{13}$$

$$\varphi(e_{13}) = a_{31}e_{12} + a_{32}e_{23} + a_{33}e_{13}$$

. We want to find relations between the elements of  $\varphi$ . Considering the fact that  $[\varphi(x), \varphi(y)] = \varphi([x, y]) = 0$ , we observe that the Lie brackets on images of any two commuting elements of the basis give 0, as they are images of 0, i.e., for every  $x, y \in \mathcal{L}_n$ , such that  $[x, y] = 0$ , we have that  $[\varphi(x), \varphi(y)] = \varphi([x, y]) = \varphi(0) = 0$ . Hence, the only images that do not vanish under Lie brackets are  $[\varphi(e_{12}), \varphi(e_{23})] = [a_{11}e_{12} + a_{12}e_{23} + a_{13}e_{13}, a_{21}e_{12} + a_{22}e_{23} + a_{23}e_{13}] = a_{11}a_{21}[e_{12}, e_{12}] + a_{11}a_{22}[e_{12}, e_{23}] + \dots + a_{13}a_{23}[e_{13}, e_{13}] = \varphi([e_{12}, e_{23}]) = \varphi(e_{13}) = a_{31}e_{12} + a_{32}e_{23} + a_{33}e_{13}$ . Considering again only the non-vanishing Lie brackets, we have that  $[\varphi(e_{12}), \varphi(e_{23})] = a_{11}a_{22}[e_{12}, e_{23}] + a_{12}a_{21}[e_{23}, e_{12}] = a_{11}a_{22}e_{13} - a_{12}a_{21}e_{13} = (a_{11}a_{22} - a_{12}a_{21})e_{13} = a_{31}e_{12} + a_{32}e_{23} + a_{33}e_{13} = \varphi(e_{13})$ . Comparing the scalars, for the three elements of the basis, gives the following relations,

$$a_{31} = 0$$

$$a_{32} = 0$$

$$a_{33} = (a_{11}a_{22} - a_{12}a_{21}) \neq 0$$

which gives the following matrix,

$$\varphi(v) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & \det(A) \end{pmatrix}$$

where  $A$  is the minor

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$$

By 1.2.4, we have that any  $L_p(\mathbb{Z}_p)$ -automorphism must be in  $G_n(\mathbb{Z}_p)$ , in words, any  $\varphi \in G(\mathbb{Z}_p)$  is an invertible matrix with elements in  $\mathbb{Z}_p$ . Our goal is to find a way to compute  $G(\mathbb{Z}_p)$ , the automorphism group of  $L_n(\mathbb{Z}_p)$ , for any  $n \in \mathbb{N}$ . After finding a general formula for this calculation, we shall be able to show a way to compute the  $n$ -multiple  $p$ -adic integral of the form  $\int \int \cdots \int \int_{D_1 \times D_2 \cdots \times D_{n-1} \times D_n} f(h_1, h_2, \dots, h_{n-1}, h_n) d(\mu_1, \mu_2, \dots, \mu_{n-1}, \mu_n)$ , where  $D_i$  is the set of  $G(\mathbb{Z}_p)$ -cosets, for  $G(\mathbb{Z}_p)$ , the group of  $\mathbb{Z}_p$ -automorphisms on the algebra  $L_i(\mathbb{Z}_p)$ , and  $h_i$  is any element of this group, and  $\mu_i$  is the Haar measure on this group. By Fubini, this multiple integral can be calculated as the iterated integral

$$\int_{D_n} \left( \int_{D_{n-1}} \cdots \left( \int_{D_2} \left( \int_{D_1} f(h_1, h_2, \dots, h_{n-1}, h_n) d\mu_1 \right) d\mu_2 \right) \cdots d\mu_{n-1} \right) d\mu_n$$

. Alternatively, if we do not find an explicit formula for this calculation, we will show the general approach for this calculation, and prove the necessary conditions for its validity.

### 3 Notations

- $\mathbb{Z}_p$ , the ring of  $p$ -adic integers.
- $\mathbb{Q}_p$ , the fraction field of  $\mathbb{Z}_p$ .
- $L_p$ , a  $\mathbb{Z}_p$ -algebra over the ring of  $p$ -adic integers.
- $\mathcal{L}_p$ , a  $\mathbb{Q}_p$ -algebra, over the fraction field of  $\mathbb{Z}_p$ .
- $G(L_p) := \text{Aut}_{\mathbb{Z}_p}(L_p)$ , the group of  $\mathbb{Z}_p$ -automorphisms of  $L_p$ .
- $G(\mathcal{L}_p) := \text{Aut}_{\mathbb{Q}_p}(\mathcal{L}_p)$ , the group of  $\mathbb{Q}_p$ -automorphisms of  $\mathcal{L}_p$ .