

Informal Talk Notes for the P-Adic People Seminar

Stephanie A.

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1 2/2/26: The Algebra and Arithmetic of \mathbb{Q}_p and \mathbb{Z}_p

Goal(s):

1. Review canonical forms of p -adics and prove periodicity of the canonical form of a rational number
2. Introduce arithmetic with p -adics using their canonical forms
3. Describe and prove some algebraic properties of the ring of p -adic integers \mathbb{Z}_p , including existence of the **Teichmüller character** ω

Given a level of comfort with canonical p -adic expansions is required in order to perform p -adic arithmetic, we begin with relevant review.

1. Recall that a p -adic number x can be defined by a **formal Laurent series** $a = \sum_{i=k}^{\infty} a_i p^i$.
2. We follow an algorithm dependent on modular arithmetic in order to determine the coefficients of our series and write out the base p expansion of a .
3. We can now write a in its **canonical form**.

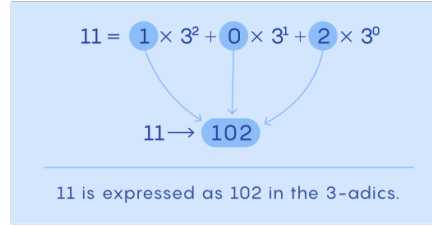


Figure 1: Recall in comparison the **base p expansion** of a number.

Definition 1. Canonical form of a p -integer

Let $a \in \mathbb{Z}_p$ be an equivalence class of **Cauchy sequences** in \mathbb{Q} w.r.t. to the extension of the **p -adic norm**. We can write

$$a = \dots d_n \dots d_2 d_1 d_0,$$

with d_i extending infinitely to the left.

Example 1. 5-adic Integers

- $15 = 3 \times 5^1 + 0 \times 5^0$, so $15 = \dots 0030_5$. Note the 5-adic base expansion of a positive integer is identical to its base 5 expansion.
- $-1 = \overline{.4_5}$, verifiable by the geo series formula $\sum_{i=0}^{\infty} \frac{a}{1-r} = \frac{4}{1-5} = -1$.
- $-3 = \overline{.42}$

Not all rational numbers can be written as p -integers, so we have the p -numbers of form $\frac{x}{p^k}$.

Example 2. $\frac{1}{p} = .1_p$, similar to how $\frac{1}{10} = .1_{10}$.

Recall the p -adic valuation of a number, denoted $|x|_p$, measures its “size” in the p -adic world. For a prime p , $|p|_p = 1/p$, and $|1/p|_p = p$. The p -adic integers \mathbb{Z}_p have a p -adic valuation of 1 or less by definition. Since $|1/p|_p = p > 1$, $1/p$ cannot be a p -adic integer, but it is a p -adic number.

Definition 2. Canonical form of a p -number

Let $a \in \mathbb{Q}_p$ be an equivalence class of **Cauchy sequences** in \mathbb{Q} w.r.t. to the extension of the **p -adic norm**. We can write

$$a = \dots d_n \dots d_2 d_1 d_0 d_{-1} \dots d_{-m},$$

with infinitely many p -adic digits d before a radix point and finitely many digits after a radix point.

Remark. If two p -adic expansions converge to the same p -adic number, *all their p -adic digits are identical*. We emphasize the uniqueness of such representations.

Theorem 1.1. [Kat07] The **canonical p -adic expansion** represents a rational number if and only if it is eventually periodic to the left.

(WTS: Rationality \implies Periodicity and Periodicity \implies Rationality)

Proof: ¹

\Rightarrow

1. Assume the canonical p -adic expansion of x is eventually periodic. **A useful tool in p -adic analysis is to reduce the scope of analysis to the ring \mathbb{Z}_p** , which we can achieve by multiplying x by a suitable power of p (if necessary). Now let us subtract a rational to give $x \in \mathbb{Z}_p$ a periodic expansion of form

$$x = x_0 + x_1p^1 + x_2p^2 + \dots + x_{k-1}^p k - 1 + x_0p^k + x_1p^{k+1}.$$

2. The number $a = x_0 + x_1p^1 + x_2p^2 + \dots + x_{k-1}^p k - 1$ is a rational by existence of negative powers and we can express x in form

$$x = a(1 + p^k + p^{2k} + \dots) = a \frac{1}{1 - p^k},$$

which is a rational number.

\Leftarrow

1. Suppose a, b rel. prime and b, p rel. prime for

$$\frac{a}{b} = \sum_{i \geq 0} x_i p^i \in \mathbb{Z}_p.$$

2. Since $\gcd(b, p^n) = 1$, there exists c_n, d_n st $1 = c_n b + d_n p^n$, which we **multiply by a** to obtain $a = ac_n b + ad_n p^n$.
3. Add $ac_n + p^n$ and set $A_n = ac_n + p^n \leq p^n - 1$ considering the above equation. Also set $r_n = ad_n$ so that we have

$$a = A_n b + r_n p^n$$

4. **Divide by b** to obtain

$$\frac{a}{b} = A_n + p^n \frac{r_n}{b}.$$

So

$$r_n = \frac{a - A_n b}{p^n},$$

which we will use to **form an inequality**:

$$\frac{a - (p^n - 1)b}{p^n} \leq r_n \leq \frac{a}{p^n}.$$

¹As a convention, we intend to keep most proofs terribly informal throughout, but refer one to the **bibliography** for appropriate constructions and details.

5. For sufficiently large n ,

$$-b \leq r_n \leq 0,$$

r_n only takes finite many values, bounding A_n . We can write

$$\frac{a}{b} = A_n + p^n \frac{r_n}{b} = A_{n+1} + p^{n+1} \frac{r_{n+1}}{b},$$

which implies

$$A_{n+1} - A_n = p^n \left(\frac{r_n}{b} - p \frac{r_{n+1}}{b} \right).$$

Since $A_{n+1} - A_n$ is an integer, $\frac{r_n - pr_{n+1}}{b}$ must also be an integer. Crucially, as $A_{n+1} \equiv A_n \pmod{p^n}$, so we have $A_{n+1} = A_n + x_n p^n$, where $\{A_n\}$ is the sequence of partial sums of the p -adic expansion of $\frac{a}{b}$.

6. Since r_n takes only finite many values, there exists an index and positive integer P st $r_m = r_{m+P}$, hence

$$x_m b + pr_{m+1} = x_{m+P} b + pr_{m+P+1},$$

so that

$$(x_m - x_{m+P})b = p(r_{m+P+1} - r_{m+1}).$$

7. Since $(b, p) = 1$, it follows $p \mid (x_m - x_{m+P})$ and given x_m, x_{m+P} are both digits in $\{0, 1, 2, \dots, p-1\}$, we must have $x_m = x_{m+1}$. Subbing back into

$$x_m b + pr_{m+1} = x_{m+P} b + pr_{m+P+1},$$

also gives $r_m = m + 1 = r_{m+P+1}$.

8. Repeating the above argument,

$$r_n = r_{n+P}, \quad x_n = x_{n+P}, \quad n \geq m,$$

which shows that the digits x_n and numerators r_n have period length P for $n \geq m$.

■

1.1 Arithmetic

The reduction to canonical form leads to an addition/subtraction system of carries similar to \mathbb{R} but starting from right to left.

We must recall the concept of a multiplicative inverse in order to retain some notion of division with p -adics.

Definition 3. Multiplicative Inverse

We say a^{-1} is the inverse of a if $aa^{-1} = e$, where e is the multiplicative identity. If the multiplicative inverse a^{-1} exists, it is *unique*.

Proposition 1.1. [Kat07] A p -adic integer $a = \dots a_1 a_0 \in \mathbb{Z}_p$ has a multiplicative inverse in \mathbb{Z}_p if and only if $a_0 \neq 0$.

$$\begin{array}{rcccccccc}
 & & & & 1 & 1 & & 1 \\
 & \cdots & 0 & 1 & 2 & 1 & 0 & 2_3 \\
 + & \cdots & 1 & 0 & 1 & 2 & 1 & 1_3 \\
 \hline
 & \cdots & 1 & 2 & 1 & 0 & 2 & 0_3
 \end{array}$$

Figure 2: $146 + 292 = 438$ in the 3-adics [Image Source: Wikipedia]

$$\begin{array}{r}
 \dots \quad \mathbf{6 \quad 6 \quad 6 \quad 7} \\
 + \quad \dots \quad \mathbf{9 \quad 9 \quad 9 \quad 9} \\
 \hline
 = \quad \dots \quad \mathbf{15|15|15|16} = \dots \quad \mathbf{6666}
 \end{array}$$

Figure 3: $\frac{1}{3} + (-1) = -\frac{6}{9}$ in the 10-adics. [Image Source: James Tanton]

$$\begin{array}{r}
 \dots \quad \mathbf{6 \quad 6 \quad 6 \quad 7} \\
 \times \quad \dots \quad \mathbf{9 \quad 9 \quad 9 \quad 9} \\
 \hline
 = \quad \dots \quad \mathbf{54|54|54|63} \\
 \dots \quad \mathbf{54|54|63|0} \\
 \dots \quad \mathbf{54|63|0|0} \\
 \dots \quad \mathbf{63|0|0|0} \\
 \vdots \\
 \hline
 = \quad \dots \quad \mathbf{225|171|117|63} = \dots \quad \mathbf{3|3|3|3}
 \end{array}$$

Figure 4: $\frac{1}{3} \times (-1) = -\frac{1}{3}$ in the 10-adics. [Image Source: James Tanton]

$$\begin{array}{r}
 \dots \quad \mathbf{3 \quad 1 \quad 2 \quad 5} \\
 \times \quad \dots \quad \mathbf{8 \quad 3 \quad 2} \\
 \hline
 = \quad \dots \quad \mathbf{6|2|4|10} \\
 \dots \quad \mathbf{9|3|6|15|0} \\
 \dots \quad \mathbf{24|8|16|40|0|0} \\
 \dots \quad \mathbf{|0|0|0|0} \\
 \vdots \\
 \hline
 \dots \quad \mathbf{|48|19|10} = \dots \quad \mathbf{0|0|0}
 \end{array}$$

Figure 5: [Image Source: James Tanton]

Proof: We will leave the details of this proof as a straightforward exercise, but **one should show:** Existence of unit $u \in \mathbb{Z}_p^\times \implies a_0 \neq 0$ and $a_0 \neq 0 \implies$ Existence of unit $u \in \mathbb{Z}_p^\times$. ■

Example 3. Inverses² in \mathbb{Z}_5 and their 5-adic expansions

- The inverse of 2 is 3 in \mathbb{Z}_5 , with 5-adic expansion . . . 0003₅.
- The inverse of 3 is 2 in \mathbb{Z}_5 , with 5-adic expansion . . . 0002₅.
- The inverse of 4 is 4 in \mathbb{Z}_5 , with 5-adic expansion. . . 0004₅

Proposition 1.2. [Kat07] Let x be a p -adic number of norm p^{-n} . Then p can be written as the product $p^n u$, where $u \in \mathbb{Z}_p^\times$.

Recall the below basic definitions:

Definition 4. p -adic valuation

The valuation $v_p(x)$ is an integer representing the exponent of p in the prime factorization of x (in the field of p -adic numbers \mathbb{Q}_p).

Definition 5. p -adic norm

The p -adic norm of a non-zero p -adic number x , denoted by $|x|_p$, is defined as $p^{-v_p(x)}$, where $v_p(x)$ is the p -adic valuation of x .

Proof: We will also leave this proof as an exercise. ■

1.2 Algebra

1.2.1 Review of Ring Theory

Given we perform addition and multiplication in \mathbb{Z}_p , it forms a **ring**. Let us review some basic definitions from ring theory.

Definition 6. Commutative Ring

A ring R is a set equipped with two binary operations $(+, \times)$ in which multiplication is commutative. As a ring, R must also satisfy the following ring axioms:

1. R is abelian under addition
2. R is a monoid under multiplication (i.e. we require a **unity** element)
3. Multiplication is distributive w.r.t. addition

Example 4. $\mathbb{Z}/4\mathbb{Z}$

Consider cosets

- $0 + 4\mathbb{Z}$
- $1 + 4\mathbb{Z}$

²We omit the invertible element 1 in this example

- $2 + 4\mathbb{Z}$
- $3 + 4\mathbb{Z}$

with additive identity $0 + 4\mathbb{Z}$ and unity $1 + 4\mathbb{Z}$.

Non-Example 5. (Not a ring)

The even integers $2\mathbb{Z}$ is not a ring because it lacks a multiplicative identity.

Non-Example 6. (Non-commutative Ring)

The set of 2×2 real matrices $M_2(\mathbb{R})$ form a **non-commutative ring**.

Definition 7. **Integral Domain**

A commutative ring that has no zero divisors; that is, the product of any two nonzero elements is nonzero.

Example 7. The integers \mathbb{Z} under multiplication and addition form an integral domain.

Example 8. Every field is an integral domain, following from existence of an inverse for every element of the field.

Non-Example 9. $\mathbb{Z}/4\mathbb{Z} : 2 \times 2 \equiv 0$ modulo 4, but $2 \neq 0$, so $\mathbb{Z}/4\mathbb{Z}$ is not an integral domain, nor a field.

The fields \mathbb{Q}_p and \mathbb{R} are both what are known as **local fields**, yet they are not isomorphic. It is a major result of **Local Class Field Theory** that every local field is isomorphic to one of the below possibilities:

1. \mathbb{R} (Archimedean, char = 0)
2. \mathbb{C} (Archimedean, char = 0)
3. \mathbb{Q}_p and its finite extensions (Non-Archimedean, char = 0)
4. The field $\mathbb{F}_q(T)$ of **formal Laurent power series** in the variable T over a **finite field** \mathbb{F}_q , where q is a power of p . (Non-Archimedean, char = p)

Proposition 1.3. The fields \mathbb{Q}_p and \mathbb{R} are not isomorphic.

(WTS: It suffices to show \mathbb{Q}_p and \mathbb{R} is not a ring homomorphism, which we will do by counterexample/contradiction with \mathbb{Q}_5 .)

Proof:

1. **In \mathbb{R} , the equation $x^2 = -1$ has no solution.** For any real number x , $x^2 \geq 0$, so $x^2 \neq -1$.
2. **Compare with \mathbb{Q}_p , for certain primes p , the equation $x^2 = -1$ DOES have a solution.** For example, in \mathbb{Q}_5 , there exists an element x such that $x^2 = -1$. This is because the group of units in \mathbb{Q}_p has torsion elements, unlike \mathbb{R} .

3. ("Forward Iso") Supposing $\phi : \mathbb{R} \rightarrow \mathbb{Q}_p$ is a ring iso, then $\phi(1) = 1$ in order to preserve structure. Then $\phi(-1)$ would be $\phi(-1) = -1$. If an element $i \in \mathbb{R}$ satisfied $i^2 = -1$, then $\phi(i)^2 = \phi(i^2) = \phi(-1) = -1$. If $p = 5$, this is possible in \mathbb{Q}_5 .
4. ("Backward Iso": **Contradiction:**) \mathbb{Q}_5 contains an element u such that $u^2 = -1$. A hypothetical isomorphism ϕ would map u to $\phi(u) \in \mathbb{R}$, which would satisfy $\phi(u)^2 = \phi(u^2) = \phi(-1) = -1$, which is impossible in \mathbb{R} .

■

Next week's talk should introduce **Hensel's Lemma** [Cona], a handy "algebraic lifting tool" which allows us to verify local existence of roots. In conjunction with Hasse's **Local-Global Principle** [Conb], one can study problems over the global field \mathbb{Q} by studying it in \mathbb{R} and all of \mathbb{Q}_p . While beyond the intended scope of this seminar, the local-global principle captures much of the essence of **Class Field Theory**, with Milne's CFT [Mil20] as a popular graduate-level reference.

For now, we continue with a review of ring theory so that we may understand the algebraic structure of p -adic fields.

Definition 8. **Ideal of a Ring**

An ideal $I \subseteq R$ satisfies:

- As an Additive Subgroup
- Closure
- Absorption

Remark. Ideals are often used to construct **quotient rings**, which can show up quite a bit in algebraic NT.

Non-Example 10. Note that \mathbb{Z} is not an ideal of \mathbb{R} nor \mathbb{Q} , even though it is a subring of both.

Definition 9. **Principal Ideal**

We call an ideal I of R *principal* if there is an element a of R such that

$$I = aR = \{ar \mid r \in R\}.$$

In other words, the ideal is **generated by a single element** a of R through multiplication by every element of R .

Example 11. The even integers $2\mathbb{Z}$ of \mathbb{Z} is a principal ideal.

Example 12. More generally, the set of all integers divisible by a fixed integer n , denoted $n\mathbb{Z}$, is a principal ideal in \mathbb{Z} .

Example 13. "To divide is to contain" for Dedekind domains, a "prime factorizable" **integral domain**. All **PIDS** are Dedekind domains.

Definition 10. **Principal Ideal Domain (PID)**

A PID is an **integral domain** in which every ideal is principal.

Example 14. \mathbb{Z}

Definition 11. Maximal Ideal of a Ring

A maximal ideal of a ring R is a proper ideal I such that there are no ideals "in between" I and R . In other words, if J is an ideal which contains I , then either $J = I$ or $J = R$.

Example 15. In the ring \mathbb{Z} of integers, the maximal ideals are the principal ideals generated by a prime number.

1.2.2 The ring \mathbb{Z}_p

Proposition 1.4. [Kat07] The ring \mathbb{Z}_p is an integral domain.

Proof: Follows from $\mathbb{Z}_p \subset \mathbb{Q}_p$ which is a field and has no zero divisors. ■

Corollary. The ring \mathbb{Z}_p has a unique maximal ideal, namely

$$p\mathbb{Z}_p = \mathbb{Z}_p / \mathbb{Z}_p^\times.$$

Proof: Suppose I is another max ideal. Since $p\mathbb{Z}_p$ is max in \mathbb{Z}_p , I must contain element from its complement $a \in \mathbb{Z}_p^\times$. As an ideal, $1 = a \cdot a^{-1} \in I$, but then $I = \mathbb{Z}_p$. ■

Remark. We call \mathbb{Z}_p a local ring.

Proposition 1.5. [Kat07] The ring \mathbb{Z}_p is a PID. More precisely, its ideals are the principal ideals $\{0\}$ and $p^k\mathbb{Z}_p$ for all $k \in \mathbb{N}$.

Proof: $p^k\mathbb{Z}_p \subset I$

Let I be a nonzero ideal in \mathbb{Z}_p and $0 \neq a \in I$ be an element of max norm. Assume $|a|_p = p^{-k}$ for some $k \in \mathbb{N}$. Then $a = \varepsilon p^k$, where ε is a unit, by

$$|a|_p = |\varepsilon p^k|_p = |\varepsilon|_p |p^k|_p = 1 \cdot p^{-k} = p^{-k}$$

using $v_p(p^k) = k$. Then $p^k = \varepsilon^{-1}a \in I$. Hence $p^k\mathbb{Z}_p \subset I$.

$I \subset p^k\mathbb{Z}_p$

Conversely for any $b \in I$, $|b|_p = p^{-w} \leq p^{-k}$ and we can write

$$b = p^w \varepsilon' = p^k p^{w-k} \varepsilon' \in p^k\mathbb{Z}_p.$$

Therefore $I \subset p^k\mathbb{Z}_p$. ■

Theorem 1.2. For any $x \in \mathbb{Z}_p$, the **Teichmüller character**³ $\omega(x) = \lim_{n \rightarrow \infty} x^{p^n}$ exists. This limit is denoted by $\omega(x)$ and has properties

1. **Dependence on Residue Class:** $\omega(x)$ depends only on x_0 of x in the p -adic expansion

$$x = x_0 + x_1p + x_2p^2 \dots$$

2. **Multiplicativity:** $\omega(xy) = \omega(x) \cdot \omega(y)$
3. **Root of Unity:** $\omega(x) = 0$ if $x_0 = 0$, and it is a $(p-1)$ th root of 1 if $x_0 \neq 0$

(WTS: The sequence $\{x_0^{p^n}\}$ is Cauchy and converges to the desired limit in \mathbb{Z}_p . We use a **lemma** to show that the limit exists for all $x \in \mathbb{Z}_p$ and is defined by x_0 to prove 1) and swiftly proceed to prove 2) and 3).)

Proof:

1. We will use **Euler's Totient Function** $\varphi(n)$ which counts the rel. prime integers up to n and **Euler's Theorem** $x^{\varphi(n)} \equiv 1 \pmod{n}$ if $\gcd(x, n) = 1$.
 Applying to our case, $x_0^{\varphi(p^n)} \equiv 1 \pmod{p^n}$.

2. Since p is prime, the totient function $\varphi(p^n) = p^n - p^{n-1}$.

3. Sub

$$\begin{aligned} x_0^{p^n - p^{n-1}} &\equiv 1 \pmod{p^n} \\ x_0^{p^n} &\equiv x_0^{p^{n-1}} \pmod{p^n}, \end{aligned}$$

which means that the difference between consecutive terms becomes divisible by increasingly higher powers p , so

$$|x_0^{p^n} - x_0^{p^{n-1}}|_p$$

tends to zero as $n \rightarrow \infty$ and $\{x_0^{p^n}\}$ is Cauchy. By **completeness of \mathbb{Z}_p** , $\{x_0^{p^n}\}$ **converges** to $\omega(x_0) = \lim_{n \rightarrow \infty} x_0^{p^n}$.

We use a lemma to prove existence of a limit for all $x \in \mathbb{Z}_p$, **defined by digit x_0 of x** .

Lemma 1.1. [Kat07] Suppose $x \in \mathbb{Z}_p$ with first digit x_0 . Then we have $|x^p - x_0^p|_p \leq p^{-1}|x - x_0|_p$.

³By Remark 3.1.8 of [Ked21], some may prefer the non-eponymous (yet non-standardized) terminology and notation for what is historically known as the Teichmüller character. We thank Gabriel Ong for pointing out the discrepancy to us.

Proof: Let $x = x_0 + \alpha$ with $|\alpha|_p \leq p^{-1}$. We **expand** $x^p - x_0^p$ using the **binomial theorem**:

$$\begin{aligned} & \binom{p}{1} x_0^{p-1} \alpha + \binom{p}{2} x_0^{p-2} \alpha^2 + \binom{p}{p} \alpha^p \\ &= x - x_0 \left(\binom{p}{1} x_0^{p-1} + \binom{p}{2} x_0^{p-2} \alpha + \binom{p}{p} \alpha^{p-1} \right) \end{aligned}$$

Since $|\binom{p}{j} x_0^{p-j} \alpha^{j-1}|_p \leq p^{-1}$ for $j \geq 1$, by **strong tri inequality** we obtain

$$|x^p - x_0^p|_p \leq p^{-1} |x - x_0|_p.$$

■

Applying 1.1, we obtain

$$|x^{p^n} - x_0^{p^n}|_p \leq p^{-1} |x^{p^{n-1}} - x_0^{p^{n-1}}|_p \leq \dots \leq p^{-n} |x - x_0|_p,$$

implying existence of $\lim_{n \rightarrow \infty} x^{p^n} = \lim_{n \rightarrow \infty} x_0^{p^n}$. **Thus we have proved Property 1).**

- Property 2) follows from the product law for limits.
- Applying property 2 and FLT, obtain

$$\omega_p^{p-1}(x_0) = \omega(x_0^{p-1}) = \omega(1) = 1.$$

Thus the values of $\omega(x)$ are solutions to $y^p - y = 0$. Since \mathbb{Q}_p is a field, this equation cannot have more than p solutions in \mathbb{Q}_p , nor in \mathbb{Z}_p . Consequently, the only solutions are values of ω , verifying Property 3).

■

While also beyond the intended scope of this seminar, we find it worthwhile to note that the Teichmüller character plays a necessary role in the construction and theory of **Witt vectors** [Rab07]. By their “lifting” ability, the **commutative ring** of Witt vectors $W(\mathbb{F}_p) \cong \mathbb{Z}_p$.

Warning: Avoid $\text{char} = p$ at all costs :)

JK, it has its pros and cons [Conc, BHK⁺19], promise there are lots of successful mathematicians working in characteristic p !

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