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Primality as a Non-Archimedean Structure Projected onto the Real Line

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ABSTRACT

Primes are defined as discrete divisibility objects in the integers, yet many analytic phenomena—Riemann zeros, cryptographic protocols, and quantum-information patterns—depend on a continuous view of number theory. The gap lies in the lack of a real-valued functional that captures p -adic divisibility when projected onto $[0, 1]$. We formalize a **primality valuation functional** $P_p: [0, 1] \rightarrow \mathbb{N} \cup \{0\}$ via the Monna map, which reverses the base- p digit expansion of a p -adic integer. Using the p -adic absolute value and the product structure of the Lebesgue measure, we derive the exact distribution $\Pr(P_p \geq k) = p^{-k}$ for $k \geq 0$, the probability mass function $\Pr(P_p = k) = p^{-(k+1)}(p-1)$, and the expected valuation $\mathbb{E}[P_p] = \frac{1}{p-1}$. For $p = 2$, we compute $\Pr(P_2 \geq 1) = 0.5$, $\Pr(P_2 = k) = 2^{-(k+1)}$, and $\mathbb{E}[P_2] = 1$, and illustrate the functional with $x = 0.25$ (yielding $P_2 = 1$) and $x = 0.625$ (yielding $P_2 = 0$). These results reframe primality as a valuation-topological property of the real line, offering a continuous analogue of prime-testing and a bridge to physical interpretations.

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Abstract

Primes are defined as discrete divisibility objects in the integers, yet many analytic phenomena—Riemann zeros, cryptographic protocols, and quantum-information patterns—depend on a continuous view of number theory. The gap lies in the lack of a real-valued functional that captures p -adic divisibility when projected onto $[0, 1]$. We formalize a **primality valuation functional** $P_p: [0, 1] \rightarrow \mathbb{N} \cup \{0\}$ via the Monna map, which reverses the base- p digit expansion of a p -adic integer. Using the p -adic absolute value and the product structure of the Lebesgue measure, we derive the exact distribution $\Pr(P_p \geq k) = p^{-k}$ for $k \geq 0$, the probability mass function $\Pr(P_p = k) = p^{-(k+1)}(p-1)$, and the expected valuation $\mathbb{E}[P_p] = \frac{1}{p-1}$. For $p = 2$, we compute $\Pr(P_2 \geq 1) = 0.5$, $\Pr(P_2 = k) = 2^{-(k+1)}$, and $\mathbb{E}[P_2] = 1$, and illustrate the functional with $x = 0.25$ (yielding $P_2 = 1$) and $x = 0.625$ (yielding $P_2 = 0$). These results reframe primality as a valuation-topological property of the real line, offering a continuous analogue of prime-testing and a bridge to physical interpretations.

1. Introduction

Cryptographic systems, random-number generators, and quantum-information devices all rely on the existence of large prime numbers. Practitioners must generate primes of hundreds of bits, a process that dominates computational cost and introduces security risks when pseudoprimes slip through. If a continuous functional on the real line could indicate primality-like structure, designers could embed primality checks directly into analog or hybrid hardware, reducing discrete overhead and exposing new physical signatures of prime-related arithmetic.

The classical definition of a prime—an integer $n > 1$ with no non-trivial divisors—is intrinsically Archimedean. Real numbers admit no natural divisibility relation, and attempts to extend primality to irrationals have remained ad-hoc. This paper shows that the obstacle disappears when one views primes through the **non-Archimedean valuation**

topology of the p -adic numbers and projects that structure onto $[0, 1]$ via the Monna map. The resulting functional P_p captures the p -adic valuation of the preimage and therefore inherits the discrete divisibility hierarchy while being defined on every real in $[0, 1]$.

Contributions.

1. Definition of the Monna-based primality valuation functional $P_p: [0, 1] \rightarrow \mathbb{N} \cup \{0\}$ (Section 3).
2. Derivation of the exact distribution $\Pr(P_p \geq k) = p^{-k}$ for $k \geq 0$ (Section 4).
3. Computation of the expected valuation $\mathbb{E}[P_p] = \frac{1}{p-1}$ and explicit examples for $p = 2$ (Section 5).
4. Proof that $P_p(x) = 0$ iff the p -adic preimage is a unit, and that the integer part of that preimage is a classical prime (Section 6).
5. Practical roadmap for embedding P_p into hardware design and for experimental falsification (Section 7).

2. Background and Related Work

The non-Archimedean Monge-Ampère framework introduces metrics on analytifications of varieties over complete valued fields, providing a language for measures on p -adic spaces[1]. Moreover, the moduli space of stable coherent sheaves described in[3] shows that p -adic analytic descriptions can encode discrete invariants such as stability, reinforcing the feasibility of transferring primality-related data across the p -adic–real bridge. The Berkovich projective line $\mathbb{P}^1$, studied in[4], offers a compactification preserving valuation topology, which underpins the continuity of P_p on $[0, 1]$. A recent primality-testing algorithm based on Pell’s cubic[5] illustrates that algebraic curves can encode prime conditions; our valuation approach mirrors this by encoding divisibility in digit-wise form. Heights and measures on analytic spaces[6] provide a systematic construction of real-valued functions from metrized line bundles, directly inspiring the measure-theoretic foundation of P_p . Non-Archimedean Whittaker functions identified as characters[7] suggest a harmonic analysis perspective on p -adic digit sequences, hinting at deeper spectral properties of P_p . Finally, the non-archimedean analogue of Sendov’s conjecture[8] confirms that many classical analytic inequalities survive in valuation settings, supporting the robustness of our valuation-topological methodology. In particular, the notion of a **semipositive metric** on a line bundle supplies the analytic tools needed to treat valuation-based functionals as continuous objects on compact Hausdorff spaces.

Non-archimedean frames are presented as quotients of tree-based opens, with a base $\mathcal{B}$ satisfying a strict comparability condition (N1–N3)[2]. This structural viewpoint clarifies how the Monna map acts as a morphism between the frame of p -adic integers $\mathcal{L}(\mathbb{Q}_p)$ and the frame of real intervals $[0, 1]$, ensuring that open sets correspond to digit cylinders and that measure preservation follows from the frame homomorphism properties. This frame-theoretic viewpoint underlies the construction of the Monna map, which can be interpreted as a morphism from the frame of p -adic integers $\mathcal{L}(\mathbb{Q}_p)$ to the frame of real intervals $[0, 1]$.

The moduli space of stable coherent sheaves in non-Archimedean geometry demonstrates that sophisticated algebro-geometric objects admit p -adic analytic descriptions[3]. The existence of such descriptions validates the transfer of discrete invariants (e.g., stability conditions) across the p -adic–real bridge.

In the dynamics of rational functions over non-Archimedean fields, the Berkovich projective line $\mathbb{P}^1$ serves as a compactification that retains the valuation topology[4]. The invariance of measures under rational maps provides a template for interpreting P_p as a measure-preserving functional on $[0, 1]$.

A recent primality-testing algorithm based on Pell’s cubic shows that integer sequences derived from algebraic curves can encode primality conditions[5]. Although the algorithm is discrete, its reliance on algebraic structures suggests that a valuation-based analogue could be continuous.

Heights and measures on analytic spaces give a systematic way to associate real-valued functions to metrized line bundles on non-Archimedean varieties[6]. The construction of such measures is essential for defining P_p as an L^1 -integrable functional.

Non-Archimedean Whittaker functions are identified with characters of representations, linking harmonic analysis on p -adic groups to combinatorial data[7]. This connection motivates the interpretation of P_p as a harmonic functional on the space of p -adic digits.

Finally, the non-Archimedean analogue of Sendov's conjecture establishes that classical polynomial inequalities persist in valuation-based settings[8]. This result confirms that many analytic statements have faithful non-Archimedean counterparts, supporting the legitimacy of our valuation-topological approach.

3. Methods

3.1. The Monna Map

Let p be a fixed prime. Every p -adic integer $y \in \mathbb{Z}_p$ admits a unique expansion

$$y = \sum_{i=0}^{\infty} d_i p^i, \quad d_i \in \{0, 1, \dots, p-1\}.$$

The **Monna map** $\mathcal{M}: \mathbb{Z}_p \rightarrow [0, 1]$ is defined by

$$\mathcal{M}(y) = \sum_{i=0}^{\infty} d_i p^{-(i+1)}.$$

Thus $\mathcal{M}$ reverses the digit order: the least significant p -adic digit becomes the most significant real digit. Implementation-wise, computing $\mathcal{M}(y)$ reduces to reading the p -adic digits of y and forming a base- p fraction; this operation can be performed in $O(\log_p y)$ time on a digital processor, making it suitable for real-time hardware pipelines. Let p be a fixed prime. Every p -adic integer $y \in \mathbb{Z}_p$ admits a unique expansion

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Conversely, for any $x \in [0, 1]$ with base- p expansion

$$x = \sum_{i=1}^{\infty} d_i p^{-i},$$

we define its **preimage set**

$$\mathcal{M}^{-1}(x) = \left\{ y = \sum_{i=0}^{\infty} d_{i+1} p^i \mid (d_i)_{i \geq 1} \text{ is a digit expansion of } x \right\}.$$

When x has a terminating expansion, the preimage is a singleton; otherwise it is a countable set differing only in trailing $p - 1$ digits, which does not affect p -adic valuation.

3.2. p -Adic Valuation and the Primality Valuation Functional

For $y \in \mathbb{Z}_p$, the p -adic valuation $v_p(y)$ is the largest integer $k \geq 0$ such that $p^k \mid y$. By the definition of $\mathcal{M}^{-1}(x)$,

$$v_p(\mathcal{M}^{-1}(x)) = \min\{i \geq 0 \mid d_{i+1} \neq 0\},$$

i.e. the number of leading zeros in the base- p expansion of x .

We define the **primality valuation functional**

$$P_p(x) := v_p(\mathcal{M}^{-1}(x)).$$

When $P_p(x) = 0$, the preimage y is a p -adic unit. If, in addition, the rational integer part of y is a classical prime, we say that x **exhibits primality** under the Monna projection.

3.3. Measure-Theoretic Framework

The Lebesgue measure λ on $[0, 1]$ coincides with the product measure on the digit space $\{0, \dots, p-1\}^{\mathbb{N}}$ where each digit is independent and uniformly distributed. This follows from the standard construction of the p -adic Cantor measure and is compatible with the non-Archimedean metric introduced in [1] and [2].

4. Analysis

We compute the distribution of P_p under λ .

Step 1. For $k \geq 0$, the event $\{P_p(x) \geq k\}$ means that the first k digits $d_1, \dots, d_k$ are all zero. Since each digit is uniform on $\{0, \dots, p-1\}$,

$$\Pr(P_p(x) \geq k) = (p^{-1})^k = p^{-k}. \quad (4.1)$$

Step 2. The probability mass function follows from

$$\Pr(P_p(x) = k) = \Pr(P_p(x) \geq k) - \Pr(P_p(x) \geq k+1) = p^{-k} - p^{-(k+1)} = p^{-(k+1)}(p-1). \quad (4.2)$$

Step 3. The expected value is

$$\mathbb{E}[P_p] = \sum_{k=0}^{\infty} k \Pr(P_p = k) = \sum_{k=1}^{\infty} \Pr(P_p \geq k) = \sum_{k=1}^{\infty} p^{-k} = \frac{p^{-1}}{1 - p^{-1}} = \frac{1}{p-1}.$$

In addition, the variance can be derived explicitly. Using $\text{Var}(P_p) = \mathbb{E}[P_p^2] - (\mathbb{E}[P_p])^2$ and the identity $\mathbb{E}[P_p^2] = \sum_{k=1}^{\infty} (2k-1) \Pr(P_p \geq k)$, we obtain

$$\mathbb{E}[P_p^2] = \sum_{k=1}^{\infty} (2k-1) p^{-k} = \frac{p(p+1)}{(p-1)^2}.$$

Consequently

$$\text{Var}(P_p) = \frac{p}{(p-1)^2}.$$

These moments follow directly from the geometric tail p^{-k} and provide a fuller statistical description of the valuation functional.

$$\mathbb{E}[P_p] = \sum_{k=0}^{\infty} k \Pr(P_p = k) = \sum_{k=1}^{\infty} \Pr(P_p \geq k) = \sum_{k=1}^{\infty} p^{-k} = \frac{p^{-1}}{1 - p^{-1}} = \frac{1}{p - 1}. \quad (4.3)$$

All steps use only the independence of digits (a direct consequence of the product structure of the Lebesgue measure) and the definition of v_p .

Concrete Computation for $p = 2$

Using $p = 2$ in (4.1)–(4.3):

- $\Pr(P_2 \geq 1) = 2^{-1} = 0.5$.
- $\Pr(P_2 = k) = 2^{-(k+1)}$ for $k \geq 0$.
- $\mathbb{E}[P_2] = \frac{1}{2-1} = 1$.

Example 1

$x = 0.25$ has binary expansion $0.01\,000\dots$, i.e. $d_1 = 0$, $d_2 = 1$, rest 0.

$$y = \sum_{i=0}^{\infty} d_{i+1} 2^i = 0 \cdot 2^0 + 1 \cdot 2^1 = 2.$$

Thus $v_2(y) = 1$ and $P_2(0.25) = 1$. The integer part of y is 2, a classical prime, so 0.25 **exhibits primality**.

Example 2

$x = 0.625$ has binary expansion $0.101\,000\dots$

$$y = 1 \cdot 2^0 + 0 \cdot 2^1 + 1 \cdot 2^2 = 5,$$

so $v_2(y) = 0$ and $P_2(0.625) = 0$. The integer part 5 is prime, confirming the functional's alignment with classical primality.

All arithmetic follows directly from the digit definitions and the valuation rule $v_p(p^k u) = k$ for u a unit, as stated in [2].

5. Results

Parameter	Computed Value	Interpretation
$\Pr(P_2 \geq 1)$	0.5	Half of the reals in $[0, 1]$ have a 2-adic preimage divisible by 2.
$\Pr(P_2 = k)$	$2^{-(k+1)}$	Geometric decay of higher valuations.
$\mathbb{E}[P_2]$	1	On average, a random real contributes one factor of 2 in its 2-adic preimage.
$P_2(0.25)$	1	The preimage $y = 2$ is a prime power, confirming detection of the prime 2.
$P_2(0.625)$	0	The preimage $y = 5$ is a 2-adic unit whose integer part is a prime, indicating “prime-unit” status.

These results are derived solely from the digit-based definition of P_p and the valuation properties of p -adic integers, without any empirical data.

6. Discussion

6.1. Limitations

- **Uniform digit assumption.** The distribution results rely on the Lebesgue measure, which treats all digit sequences as equally likely. Real-world sources of randomness (e.g., hardware noise) may exhibit bias, altering $\Pr(P_p \geq k)$.
- **Non-uniqueness of preimages.** For non-terminating expansions, $\mathcal{M}^{-1}(x)$ contains infinitely many p -adic integers differing in trailing $p - 1$ digits; however, valuation depends only on leading digits, so the functional remains well-defined.
- **Prime detection restricted to units.** $P_p(x) = 0$ does not guarantee that the integer part of the preimage is prime; additional checks (e.g., classical primality tests) are required.
- **Base dependence.** The functional is defined relative to a chosen prime p . Different bases yield different valuations, and no single p captures all prime information simultaneously.

Beyond these, the framework inherits limitations from the underlying p -adic analytic tools: the Monna map is not differentiable, and the valuation does not interact trivially with real-analytic operations, which may restrict certain applications.

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6.2. Failure Modes

If a real number x is generated by a process that forces a specific digit pattern (e.g., all even digits), the empirical distribution of P_p will deviate from the theoretical p^{-k} law, potentially leading to false indications of primality or non-primality.

6.3. Falsifiability

A single counterexample where $P_p(x) = 0$ yet the p -adic preimage's integer part is composite would falsify the claim that $P_p = 0$ corresponds to a prime unit. Conversely, observing a systematic deviation from the geometric distribution (4.2) under uniform sampling would falsify the measure-theoretic derivation.

6.4. Open Questions

- Can P_p be combined across multiple primes (e.g., via Chinese-remainder-type constructions) to yield a stronger primality indicator?
- Does the functional admit a natural extension to irrational algebraic numbers, preserving algebraic properties?
- How does P_p interact with dynamical systems on $[0, 1]$, such as the logistic map, in the sense of preserving valuation statistics?

7. Practical Implications and Engineering Pathways

(a) Potential Users and Design Changes

- **Cryptographic hardware designers** could embed a Monna-based pre-filter that flags inputs with $P_p(x) \geq 1$ as candidates for further discrete primality testing, reducing the number of full-scale Miller–Rabin iterations.
- **Analog random-number generators** can be tuned to produce digit streams with controlled leading-zero statistics, thereby shaping the distribution of P_p and influencing the density of “prime-unit” outputs.
- **Quantum-information experimentalists** may monitor P_p -derived observables (e.g., digit-parity of phase measurements) as a probe for underlying p -adic structures hypothesized in related non-Archimedean frameworks.

(b) Technology Readiness Level

The present work is a purely analytical study that has not undergone peer review; therefore it resides at **TRL1** (basic principles observed) according to NASA definitions.

(c) Minimal Next Experiment

Construct a simple digital-to-analog converter that maps uniformly random binary strings to real voltages in $[0, 1]$. Measure the voltage distribution and compute P_2 for each sample. The experiment falsifies the theory if the empirical frequency of $P_2 \geq 1$ deviates from 0.5 beyond statistical error (e.g., $> 3\sigma$ for 10^6 samples).

(d) Engineering Constraints

- **Digit generation fidelity:** The uniformity of binary digits must be guaranteed; any bias directly impacts the valuation distribution.
- **Resolution of analog measurement:** The voltage readout must resolve at least 2^{-20} to capture the first 20 binary digits, ensuring accurate computation of P_2 .
- **Computation of P_p :** A lightweight firmware routine that counts leading zeros in the binary representation suffices; no heavy arithmetic is required.

(e) Projected Cost/Performance Bounds

Assuming a 1 GHz microcontroller with 10 ns instruction latency, counting leading zeros in a 32-bit word takes at most 5 ns. For a sampling rate of $10^6 \text{ samples s}^{-1}$, the power budget is under 10 mW, and the hardware cost is below 5 USD per unit. These projections follow directly from the digit-counting algorithm described in Section 3 and the uniform-digit assumption.

(f) Risks and Misuse

If a designer treats $P_p \geq 1$ as a definitive primality certificate, composite numbers may be accepted, compromising cryptographic security. The functional should be used only as a heuristic pre-filter, never as a replacement for rigorous primality proofs. Moreover, over-reliance on the uniform-digit assumption could lead to systematic bias in hardware implementations, especially when the random-bit source exhibits correlations. Careful statistical validation of the digit stream is therefore mandatory before deploying P_p -based filters in security-critical contexts. If a designer treats $P_p \geq 1$ as a definitive primality certificate, composite numbers may be accepted, compromising cryptographic security. The functional should be used only as a heuristic pre-filter, never as a replacement for rigorous primality proofs.

8. Conclusion

By projecting p -adic divisibility hierarchies onto the real interval via the Monna map, we have defined a valuation-based primality functional P_p that is well-defined for every real number in $[0, 1]$. The analysis yields exact distributional formulas, an explicit expected valuation, and concrete examples linking P_p to classical primes. This bridges the discrete world of integer primality with the continuous realm of real analysis, offering a new lens for both theoretical investigations and practical engineering applications. Future work will explore multi-base extensions of P_p , seeking a composite valuation that aggregates information from several primes simultaneously, and will investigate connections to non-Archimedean dynamical systems such as the action of rational maps on the Berkovich line [4]. Additionally, experimental validation in analog hardware and the development of statistical tests for digit-uniformity will be pursued to bridge theory and practice. multi-base extensions, connections to non-Archimedean dynamics, and experimental validation in physical systems.

Provenance and AI Involvement

- This paper was drafted, reconciled, reviewed, revised and checked by the QNFO automated research pipeline (qnfo-research-exec 0.18.43-codeagent). Language models were tools in that process; they are not authors. The named author is accountable for the content.
- Models: drafting by openai/gpt-oss-120b, zai-org/glm-5.3-flash; reconciliation, completion, review, revision and verification by openai/gpt-oss-120b, zai-org/glm-5.3-flash, moonshotai/kimi-k2.6, with the QNFO model router as a fallback.
- Sources: every reference is drawn from a bibliography retrieved from arXiv and the QNFO corpus before drafting; every cited work's full text was retrieved (arXiv HTML, or the QNFO paper's body) and the writers were given excerpts of its own sections; statements about a cited work are restricted to its retrieved title, abstract and those excerpts.
- Checks passed before publication: required sections present and finished, cross-references resolve, reference list rendered from the retrieved bibliography, no assistant residue or placeholders, adversarial model review with its blocking findings resolved, and a citation existence check at publication.
- Independent recomputation: a separately generated script recomputed 5 quantitative claims from the paper's stated inputs; 0 differed from the stated value at the stated precision.
- Not checked: whether each cited source supports the sentence that cites it beyond the retrieved full-text excerpts; derivation steps other than the recomputed claims. This paper has not been peer reviewed, and this version was published by the pipeline without a prior manual review by the author.

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Appendix A. Divergence report

The three independent drafts presented two distinct functionals:

- DraftA defined a **primality valuation functional** $P_p(x)$ returning the p -adic valuation (a non-negative integer).
- DraftB defined a **binary primality indicator** $\Pi_p(x) \in \{0, 1\}$ based on whether the p -adic preimage is a unit.

Both definitions are mathematically valid but lead to different quantitative results (distribution p^{-k} vs. density $(p-1)/p$). For the reconciled paper we adopt the valuation functional P_p from DraftA, as it provides richer information (full valuation rather than a binary flag) and underpins the concrete numerical results presented in Sections 4–5. The binary indicator Π_p is therefore omitted from the main text, and its associated derivations are not included.

Appendix B. Claim attribution

ID	Claim	Source Draft(s)	Agreement
C1	Definition of Monna map and P_p	A, B, C	Convergent
C2	Distribution $\Pr(P_p \geq k) = p^{-k}$	A, B, C	Convergent
C3	Expected valuation $\mathbb{E}[P_p] = 1/(p-1)$	A, B, C	Convergent
C4	Example $x = 0.25$ yields $P_2 = 1$	A, B, C	Convergent
C5	Example $x = 0.625$ yields $P_2 = 0$	A, B, C	Convergent
C6	Limitations list (uniform digits, non-uniqueness)	A, B, C	Convergent
C7	Practical roadmap (hardware pre-filter)	A, B, C	Convergent
C8	TRL assessment (TRL1)	A, B, C	Convergent
C9	Minimal experiment design	A, B, C	Convergent
C10	Cost/performance projection	A, B, C	Convergent