

Beyond The Sieve: A Survey of Artificial Intelligence Approaches for Prime Number Prediction and Structural Analysis

¹Asheesh Patel*, ²Pradeep Kumar Maurya, ³Ajay Kumar Kushawaha

^{1/2/3}Ashoka Institute of Technology and Management, Varanasi, Pahariya (UP) India

¹ashishkumarpatel178@gmail.com

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Abstract

The study of prime numbers, the essential structural blocks of number theory, has been the area of rigorous logical and algebraic methods. While effective for showing general properties, these standard methods often struggle to identify delicate, high-dimensional patterns within the arrangement of primes that may not be simply expressible in closed-form mathematical language. This report studies the developing paradigm of using Artificial Intelligence (AI), mostly deep learning, to balance classical number theory. We survey key methodologies, including the application of recurrent neural networks (RNNs) and transformers for next-prime calculation, and the use of unsupervised learning for uncovering latent structures in prime distributions. We discuss important successes, such as models that complete high truth in expecting subsequent primes within unnatural sequences and the identification of potential novel inter-prime relationships. However, we also address serious limitations, most particularly the models' leaning toward speaking rather than true extrapolation, their absence of interpretability, and the important challenge of moving from pattern credit to mathematically generalizable proof. The deduction suggests that AI serves not as a replacement for standard theory, but as a powerful investigative tool for generating novel hypotheses about prime distribution, possibly guiding mathematicians toward new theorems and a deeper understanding of the primes.

Keywords: Prime Numbers, Artificial Intelligence, Deep Learning, Recurrent Neural Networks, Changers, Unverified Learning, Number Theory, Pattern Acknowledgment.

Introduction

Prime numbers have fascinated mathematicians for areas. Their distribution, ruled by the Prime Number Theorem, appears random at a local scale yet displays deep total regularity (Apostol, 1976). Standard tools like filter methods, logical number theory, and linked forms have produced monumental results. However, these methods often rely on asymptotic behaviour and are less adept at capturing complex, local patterns or making precise predictions for very large primes where computational confirmation becomes infeasible.

The start of powerful AI and machine learning techniques offers a new lens system (Nanda et al., 2024). Instead of looking for a deterministic formula, AI models can be skilled to estimate the fundamental function that maps the order of natural numbers to the binary classification of "prime" or "composite" (He & Yámana, 2021). The principal hypothesis is that deep neural networks, with their ability to model highly non-linear and compound

relationships, may enable intelligent buildings in the prime place that have eluded standard description.

This report is intended to:

1. Summary of the main AI buildings being applied to prime number analysis.
2. Present and discuss the results of key research on the next-prime guess.
3. Discover the possibilities for AI to expose hidden structures.
4. Analyse the important challenges and logical limitations of this method.

Methodologies: AI Designs for Prime Study

Problem Preparation

The problem can be outlined in two primary concerns:

- **Organization:** Given an integer n , order it as prime or compound. This is a supervised learning duty.
- **Arrangement Prediction:** Given a sequence of preceding primes $[x_1, x_2, \dots, x_k]$, predict the next prime x_{k+1} or the prime gap $y_k = x_{k+1} - x_k$. This is naturally mounted as a regression or a next-step calculation duty (Zanisi et al., 2021).

Important Constructions:

- **Recurrent Neural Networks (RNNs):** These networks are understandably right for successive data. An LSTM (Long Short-Term Memory) network can be expert on measures of prime numbers to study the ancient dependencies between them (He & Yámana, 2021). The model's interior public acts as a remembrance of the classification history, which it uses to type the next calculation.
- **Messenger Images:** The building behind current great language representations (LLMs), convertors use a self-attention device to weigh the position of all preceding elements in a sequence when generating the next. This allows them to capture long-range dependencies more successfully than RNNs. A convertor can be qualified on a "language" of primes, where the "terminology" is the set of numbers or prime breaches (Zanisi et al., 2021; Vaswani et al., 2017).
- **Unconfirmed Education (Clustering & Dimensionality Reduction):** Methods like Primary Component Analysis (PCA) or t-SNE can be practical to vectorize signs of primes (e.g., based on their remains modulo different numbers) to picture if they form groups or manifolds in a high-dimensional space, suggesting fundamental geometric structure.

Consequences and Conversation: Successes and Findings

Next-Prime Calculation

Several lessons have confirmed that AI models can attain high accuracy in forecasting the next major within a bounded range.

- **High Intra-Dataset Accuracy:** When trained on primes up to, for example, 1,000,000, an LSTM or transformer model can learn to predict the next prime with remarkable accuracy (e.g., >99.5%) on a test set from the same range (He

& Yamana, 2021). The model effectively learns a complex approximation of the prime-counting function and local gap distributions.

- **Learning Known Properties:** Analysis of successful models shows they implicitly learn known properties. For instance, they quickly learn that no prime (except 2) is even, and they capture the tendency for primes to avoid multiples of small primes, reflecting the principles of sieve methods.

Uncovering Potential Structures

- **Prime Gap Patterns:** AI models have been shown to predict prime gaps more exactly than simple numerical models based on normal gap size. This proposes that the models are finding subtle, non-random designs in the order of gaps (e.g., correlations between following gaps) (Zanussi et al., 2021).
- **Hypothesis Group:** The disappointment modes of AI models can be informative. If a classical steady makes mistakes at primes that are part of known collections (like identical primes), or at very big primes near the bounds of known tables, it may point to areas where the circulation deviates from the model's learned pattern, potentially indicating areas for new theoretical examination. This approach is similar to AI systems like Alpha Zero determining novel strategies in games (Silver et al., 2017).

Critical Limitations and Challenges

Despite these promising results, significant hurdles remain.

Interpolation vs. Extrapolation

The most critical restriction is that these mockups are masters of exclamation, not extrapolation. They outshine in education patterns inside the data they are competent in, but fail to oversimplify to numbers for outdoor their training series. A model trained on primes up to N has no inherent understanding of primality and will fail catastrophically when asked about primes near $10N$ or N^2 . These differences with a classical theorem, which, once proven, holds for all integers (Apostol, 1976).

The Black Box Problem

Deep learning models are often "black boxes." While they can predict accurately, it is extremely difficult to translate the millions of parameters in a neural network into a human-comprehensible mathematical conjecture or proof. The "hidden structure" remains hidden within the model's weights, posing a significant challenge for explainable AI (XAI) (Marcus, 2018).

Data Dependency and Computational Cost

The performance is heavily dependent on the quality and scope of the training data (known primes) (Yadav et al., 2025). Generating this data for very large primes is computationally expensive, relying on the very classical processes (e.g., AKS, ECPP) that AI aims to complement (The OEIS Foundation, 2023).

Lack of Mathematical Rigor

An AI model's forecast, no matter how accurate, is not proof. It is an arithmetical inference. Mathematics needs deductive reasoning. An AI can suggest *where* a decoration might exist, but it cannot explicate *why*.

Supposition and Future Directions

The submission of AI to prime number investigation represents an attractive and productive connection of computation and pure mathematics. While current AI models cannot exceed classical number theory in providing general, proven actualities about primes, they have demonstrated to be exceptionally controlling tools for investigative data analysis on an enormous scale.

The most promising path forward is a cooperative approach:

1. **AI as a Hypothesis Author:** Use AI to sense strange patterns, associations, or clusters in prime orders and gaps. These productions are not formulae but rather captivating guesses for mathematicians to investigate.
2. **Symbolic Degeneration and Explainable AI (XAI):** Future research should attention on integrating AI with representative mathematics. Approaches that can distil a neural network's 9 determination into a simpler, representative appearance could connection the gap between decoration acknowledgment and formal mathematics (Udrescu & Tegmark, 2020).
3. **Superintendent Investigative Efforts:** By identifying regions of the number line where prime circulation behaves in unanticipated ways, AI can attendant scholars to focus their investigative efforts more successfully (Kumari et al., 2022).

In supposition, AI does not concentrate classical number model obsolete. Instead, it delivers a new, controlling telescope for measuring the vast and complex countryside of the primes. The designs it detects may well be principal to the instinctive leaps that have continually been at the heart of mathematical encounter, eventually demanding classical methods to be congealed into enduring truth.

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