

# Proof of the Hardy-Littlewood K-tuple Conjecture in the Distribution of Numbers Coprime with the Primorial

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## Abstract

In the symmetries in the numbers that are coprime with the primorial we find proof of the Hardy-Littlewood K-tuple Conjecture and, consequently, the Twin Prime Conjecture. Using a primorial-based sieve, called the *bitstring sieve*, we prove that the number of prime k-tuples of size  $k$  between  $p_n^2$  and  $p_{n+1}^2$ , where  $p_n$  is the  $n$ -th prime, increases on average with increasing  $n$ . Hardy and Littlewood's statistical predictions concerning prime k-tuples and twin primes are correct.

## 1 Introduction

The Hardy-Littlewood K-tuple Conjecture, or the First Hardy–Littlewood Conjecture, is a long-standing problem in analytic number theory. Proposed by G. H. Hardy and J. E. Littlewood in their 1923 paper *Some problems of ‘Partitio numerorum’; III: On the expression of a number as a sum of primes* [1], as part of their investigations into the distribution of primes, using their circle method approach, the conjecture predicts the asymptotic frequency with which prime k-tuples of size  $k$  appear.

In this paper, we present a proof of the Hardy-Littlewood K-tuple Conjecture. The tool we use for our proof is the *bitstring sieve*. The bitstring sieve is the smallest program of binary digit instructions that generates the primes, given a digital computing machine with unlimited memory. The bitstring sieve is similar to the Sieve of Pritchard, or wheel sieve, and identical to the sieve first conceived by Pete Quinn [2], posted on [primegrid.com](http://primegrid.com) in 2011.

The bitstring sieve is a recurrence relation, such that its output is fed as input for the next iteration. Its output, and therefore its input, is a **bitstring**, a string of bits. The 1s in the bitstrings correspond with numbers that are coprime with the primorial, numbers we call *candidate primes*. The visual pattern of the 1s in the bitstrings show the periodicities and symmetries in the numbers that are coprime with the primorial. These patterns, often called

*primorial patterns*, are well known. Primorial patterns are directly visible in the sequence of least prime factors ([OEIS A020639](#)). Examples of work on primorial patterns are Dennis R. Martin's *Proofs Regarding Primorial Patterns* 2006 [3] and Fred B. Holt's *Patterns among the Primes* 2022 [4].

## 2 The Bitstring Sieve

The bitstring sieve is the smallest program of binary digit instructions that generates the primes, running on a computer with unlimited memory. The bitstring sieve is defined as a recurrence relation, such that its output is fed as input for the next iteration. Each iteration corresponds with a prime. Per iteration, the first step is to obtain the next prime from the input, and the second step is to calculate the output.

Let  $S$  be the set of all outputs generated by the bitstring sieve, starting from prime 2. For each  $p_n$ , where  $p_n$  is the  $n$ -th prime, there is a bitstring  $S_{p_n} \in S$ :

$$S = \{S_2, S_3, S_5, S_7, S_{11}, \dots\}$$

A bitstring  $S_{p_n}$  is a finite-length sequence of binary digits  $S_{p_n} \in \{0, 1\}^*$ .

Notation:

- $(b_1, b_2, \dots, b_n)$ : Represents individual bits in the bitstring, where  $b_i \in \{0, 1\}$  and  $n$  is the length of the bitstring. For example, bitstring  $(1, 0, 0, 0, 1, 0)$  has length 6.
- $|s|$ : The length of the bitstring  $s$ .
- $s[i]$ : The  $i$ -th bit in the bitstring  $s$ , where indexing starts from 1.

The bitstrings of  $S$  are defined and generated by the following recurrence relation.

### Initial condition:

Let  $S_1$  be the bitstring (1).  $S_1$  is not a member of  $S$ , but it serves to get the recurrence relation started. We can regard 1 as the zeroth prime  $p_0$ .

$$S_1 = (1)$$

### Recurrence relation:

Given bitstring  $S_{p_n}$ , where  $p_n$  is the  $n$ -th prime, the next bitstring  $S_{p_{n+1}}$  is obtained by:

$$\begin{aligned} p_{n+1} &= NEXT1(S_{p_n}) \\ S_{p_{n+1}} &= AND(CONCAT(S_{p_n}, p_{n+1}), NOT(STRETCH(S_{p_n}, p_{n+1}))) \end{aligned} \tag{1}$$

The functions *NEXT1*, *AND*, *CONCAT*, *NOT* and *STRETCH* are defined below.

### **NEXT1**

Let  $\text{NEXT1}(s) : \{0, 1\}^* \rightarrow \mathbb{Z}^+$  be a function that takes as input bitstring  $s$ , and returns the (1-based) index of the second occurrence of 1 in  $s$  (skipping the first 1 at index 1), or the length of the bitstring  $s$  plus 1 if such an occurrence does not exist (which only happens for  $\text{NEXT1}(S_1)$  and  $\text{NEXT1}(S_2)$ ), as defined in:

$$\text{NEXT1}(s) = \begin{cases} \text{index of second 1 in } s, & \text{if such 1 exists} \\ |s| + 1, & \text{otherwise} \end{cases}$$

### **AND**

Let  $\text{AND}(s1, s2) : \{0, 1\}^* \times \{0, 1\}^* \rightarrow \{0, 1\}^*$  be a function that takes as input bitstrings  $s1$  and  $s2$ , where  $|s1| = |s2|$ , and returns a new bitstring with the same length, where each bit is the result of the logical AND operator applied to the corresponding bits in  $s1$  and  $s2$ , as defined in:

$$\text{OR}(s1, s2) = (s1[1] \wedge s2[1], s1[2] \wedge s2[2], \dots, s1[|s1|] \wedge s2[|s2|])$$

Where  $\wedge$  represents the logical AND operator.

### **CONCAT**

Let  $\text{CONCAT}(s, n) : \{0, 1\}^* \times \mathbb{Z}^+ \rightarrow \{0, 1\}^*$  be a function that takes as input bitstring  $s$  and positive integer  $n > 0$ , and returns a new bitstring with length  $|s| \times n$ , filled with  $n$  concatenated copies of  $s$ , as defined in:

$$\text{CONCAT}(s, n) = s \circ s \circ \dots \circ s \quad (\text{n times})$$

Where  $\circ$  denotes concatenation.

### **NOT**

Let  $\text{NOT}(s) : \{0, 1\}^* \rightarrow \{0, 1\}^*$  be a function that takes as input bitstring  $s$ , and returns a new bitstring with the same length, where each bit is the logical inverse of corresponding bit in  $s$ , as defined in:

$$\text{NOT}(s) = (\neg s[1], \neg s[2], \dots, \neg s[|s|])$$

Where  $\neg$  represents the logical NOT operator.

### **STRETCH**

Let  $\text{STRETCH}(s, n) : \{0, 1\}^* \times \mathbb{Z}^+ \rightarrow \{0, 1\}^*$  be a function that takes as input bitstring  $s$  and positive integer  $n > 0$ , and returns a new bitstring with length  $|s| \times n$ , where the bits from  $s$  are mapped to a position  $n$  times farther than their original position, and the positions in between are padded with 0s, as defined in:

$$STRETCH(s, n) = (b_1, b_2, b_3, \dots, b_{|s| \times n})$$

Where:

$$b_i = \begin{cases} s[\frac{i}{n}], & \text{if } i \text{ is a multiple of } n \\ 0, & \text{otherwise} \end{cases}$$

The first bitstrings generated by the recurrence relation are:

$$S_2 = (1, 0)$$

$$S_3 = (1, 0, 0, 0, 1, 0)$$

$$S_5 = (1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 1, 0, 1, 0, 0, 0, 1, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0)$$

$$S_7 = (1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 1, 0, 0, 0, 1, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 1, 0, \dots)$$

The indices of the 1s in bitstring  $S_{p_n}$  are the numbers that are coprime with  $p_n\#$ .

Equivalently, and more compactly, a bitstring  $S_{p_n}$  can be defined and interpreted as follows:

$$S_{p_n} = (b_1, b_2, b_3, \dots, b_{p_n\#})$$

Where  $p_n$  is the  $n$ -th prime,  $p_n\#$  is the product of all the primes up to and including the  $n$ -th prime, and:

$$b_i = \begin{cases} 1, & \text{if } i = 1 \\ 1, & \text{if } i \text{ is coprime with } p_n\# \\ 0, & \text{otherwise} \end{cases}$$

Figure 1 shows the operations performed by the bitstring sieve when advancing from bitstring  $S_3$  to bitstring  $S_5$ . The 0s are represented as white squares with black text, and the 1s are represented as black squares with white text (a convention used throughout this paper). The numbers in the squares indicate the 1-based index of the bit in the bitstring.  $A$ ,  $B$  and  $C$  are intermediate registers to show what happens at each step. Note that intermediate step  $B$  marks the periodic pattern of integers which have  $p_n$  as its least prime factor. The periodic pattern of prime  $p_n$  in the sequence of least prime factors ([OEIS A020639](#)) is exactly bitstring  $S_{p_{n-1}}$  stretched by a factor of  $p_n$ .

$S_3$ <table border="1" style="border-collapse: collapse; text-align: center;"> <tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td></tr> </table> $NEXT1(S_3) = 5$	1	2	3	4	5	6	<p style="text-align: right;">key</p> <table border="1" style="border-collapse: collapse; text-align: right;"> <tr><td>i</td><td>0</td></tr> <tr><td>■</td><td>1</td></tr> <tr><td>i</td><td>index</td></tr> </table>	i	0	■	1	i	index																		
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$B = STRETCH(S_3, 5)$ <table border="1" style="border-collapse: collapse; text-align: center;"> <tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td></tr> </table>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30		
$C = NOT(B)$ <table border="1" style="border-collapse: collapse; text-align: center;"> <tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td></tr> </table>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
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$S_5 = AND(A, C)$ <table border="1" style="border-collapse: collapse; text-align: center;"> <tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td></tr> </table>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
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Figure 1: Recurrence relation applied to  $S_3$  to obtain  $S_5$

The 0s (the white squares) in a bitstring  $S_{p_n}$  have indices that are not coprime with  $p_n\#$ , which are either the numbers between 1 and  $p_n$ , or the numbers we call *definite composites*. The indices of the 1s (the black squares) in a bitstring  $S_{p_n}$  are the numbers that are coprime with  $p_n\#$ . The 1s after index 1 represent the *candidate primes*. A candidate prime is either a composite, in which case it will at some iteration be marked as a definite composite, or it is a prime, in which case it will survive all iterations until it is found by the *NEXT1* operation, and eliminated in the next bitstring.

### 3 Symmetry in the bitstrings

The length of bitstring  $S_{p_n}$ , where  $p_n$  is the  $n$ -th prime, is equal to the primorial function  $p_n\#$ , the product of all primes up to and including the  $n$ -th prime.

$$|S_{p_n}| = p_n\# = \prod_{i=1}^n p_i \quad (2)$$

The sequence of primorial numbers is listed in [OEIS A002110](#).

The index of the bit halfway a bitstring at  $\frac{|S_{p_n}|}{2}$  is its *index of symmetry*. The pattern of 1s and 0s are mirror-symmetric on either side of this index. In other words, each bitstring  $S_{p_n}$  is palindromic. This is because the functions

*CONCAT*, *NOT*, *STRETCH* and *AND* in the recurrence relation (1) conserves symmetry given symmetric input.

A method of visualizing the overall structure and symmetry of the bitstrings in  $S$  is to render the bitstrings as rows of black and white squares, where each bitstring is scaled to a common width, and drawn beneath each other. The symmetry in this fractal-like structure becomes apparent when aligning the indices of symmetry in each bitstring, by shifting each bitstring by half a square width to the right, in modular fashion (as if the structure is cylindrical). The result is shown in Figure 2. Each horizontal row corresponds to a bitstring in  $S$ . The first row is  $S_2$ , the next row is  $S_3$ , the next row is  $S_5$ , and so forth.

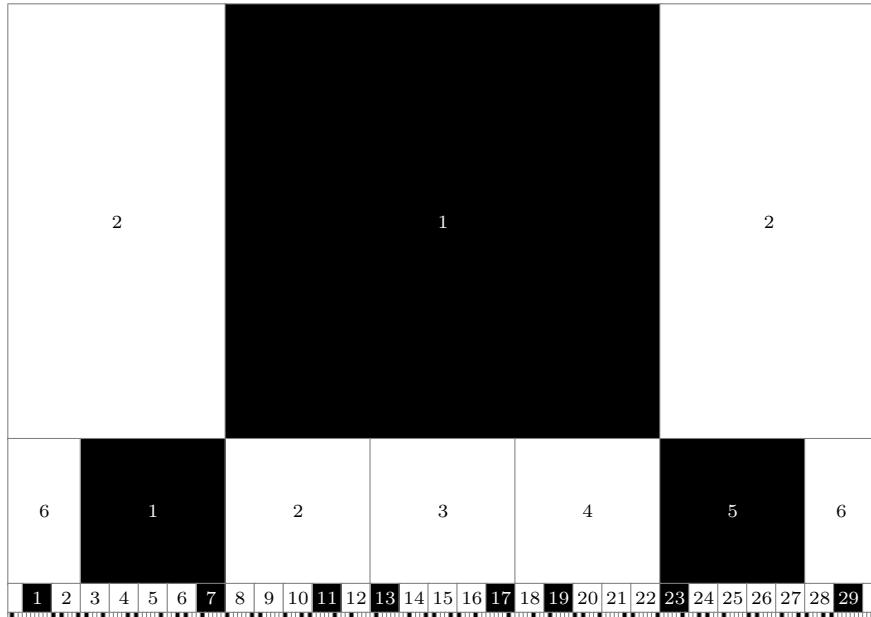


Figure 2: Fractal-like structure and symmetry in the bitstrings.

The heights of the bitstrings after  $S_7$  are too small for print, so in Figure 2 we represent this convergent area at the bottom as a blue horizontal line. That blue line, slightly thickened to make it visible, contains all the bitstrings from  $S_{11}$  to  $S_{p_\infty}$ . The surface of the bottom of this structure is undefined, as there is no such thing as the largest prime.

The ratio of the width and height of this fractal-like structure is 1 : the sum of the reciprocals of the primorials, which converges to a value of  $0.70523\cdots$ .

$$\sum_{n=1}^{\infty} \frac{1}{p_n \#} \approx 0.70523 \dots$$

The Engel expansion of this value is the sequence of prime numbers. See its decimal expansion in [OEIS A064648](#).

## 4 Candidate prime k-tuples

Let us investigate the recurrence relation (1) and derive formulations for the distribution of 1s in the bitstrings of  $S$  (i.e. coprimes with the primorial).

When iterating from  $S_{p_n}$  to  $S_{p_{n+1}}$ , the *CONCAT* function outputs  $p_{n+1}$  times as many 1s as there are in  $S_{p_n}$ , and the *NOT-STRETCH* operation eliminates as many 1s as there are in  $S_{p_n}$ . Therefore, the number of 1s in bitstring  $S_{p_n}$ , denoted as  $p_n \#_1$ , is as follows:

$$p_n \#_1 = \prod_{i=1}^n (p_i - 1) \tag{3}$$

The sequence of  $p_n \#_1$  per  $n$  is listed in [OEIS A005867](#).

$p_n \#_1$  relates to Euler's totient function  $\phi$  as follows:

$$\begin{aligned} p_n \#_1 &= \prod_{i=1}^n (p_i - 1) \\ &= \prod_{i=1}^n p_i \prod_{i=1}^n \left(1 - \frac{1}{p_i}\right) \\ &= p_n \# \prod_{i=1}^n \left(1 - \frac{1}{p_i}\right) \\ &= \phi(p_n \#) \end{aligned}$$

Let a *candidate twin prime* be a sequence in a bitstring that matches  $(1, 0, 1)$ . When iterating from  $S_{p_n}$  to  $S_{p_{n+1}}$ , the *CONCAT* function creates  $p_{n+1}$  copies of the candidate twin primes in  $S_{p_n}$ , and the *NOT-STRETCH* operation eliminates 2 candidate twin primes for each candidate twin prime in  $S_{p_n}$ . Therefore, the number of candidate twin primes in  $S_{p_n}$ , denoted as  $p_n \#_2$ , where  $p_n > 2$ , is as follows:

$$\begin{aligned}
p_n \#_2 &= \prod_{i=2}^n (p_i - 2) \\
&= \prod_{i=2}^n \left( p_i - \frac{2 \cdot p_i}{p_i} \right) \\
&= \prod_{i=2}^n p_i \prod_{i=2}^n \left( 1 - \frac{2}{p_i} \right) \\
&= \frac{p_n \#}{2} \prod_{i=2}^n \left( 1 - \frac{2}{p_i} \right)
\end{aligned}$$

A bitstring  $S_{p_n}$  is periodic over the entire natural number line, beyond the length of the bitstring, so we include in our count the candidate twin prime that would be formed at index 1 and index  $(p_n \# - 1)$ . Note that  $p_1 \#_2 = 1$ , because in  $S_2$  we encounter (3, 5) when wrapping around in modular fashion. The sequence of  $p_n \#_2$  per  $n$  is listed in [OEIS A059861](#). In addition to counting the number of candidate twin primes,  $p_n \#_2$  also counts the number of *candidate cousin primes*, that is, occurrences of bit pattern (1, 0, 0, 0, 1), and also the number of *candidate sexy primes*, that is, occurrences of bit pattern (1, 0, 0, 0, 0, 1).

The bit sequence (1,0,1,0,0,0,1,0,1) is a *candidate prime quadruplet*. For example, this sequence can be found in  $S_5$  at index 11, corresponding with prime quadruplet (11, 13, 17, 19), a constellation of the form  $(p, p + 2, p + 6, p + 8)$ . This candidate prime quadruplet is copied 7 times into  $S_7$ , of which  $(7 - (4 \cdot 1)) = 3$  survive, at indices 11, 101, 191. These 3 candidate prime quadruplets are copied 11 times into  $S_{11}$ , of which  $(33 - (4 \cdot 3)) = 21$  survive. These 21 candidate prime sextuplets are copied 13 times into  $S_{13}$ , of which 189 survive. In general, the number of candidate prime quadruplets in  $S_{p_n}$ , where  $p_n > 4$ , denoted as  $p_n \#_4$ , is as follows:

$$p_n \#_4 = \prod_{i=3}^n (p_i - 4)$$

We define  $2 \#_3 = 1$  and  $3 \#_3 = 1$ , because in  $S_2$  we encounter (3, 5, 7, 9, 11), and in  $S_3$  we encounter (5, 7, 11, 13). The sequence of  $p_n \#_4$  per  $n$  is listed in [OEIS A059863](#).

The bit sequence (1,0,0,0,1,0,1,0,0,0,1,0,1,0,0,0,1) is a *candidate prime sextuplet*. For example, this sequence can be found in  $S_5$  at index 7, corresponding with the prime sextuplet (7, 11, 13, 17, 19, 23), a constellation of the form  $(p, p + 4, p + 6, p + 10, p + 12, p + 16)$ . This candidate prime sextuplet is copied 7 times into  $S_7$ , of which only 1 survives, at index 97. This candidate prime sextuplet is copied 11 times into  $S_{11}$ , of which 5 survive. These 5

candidate prime sextuplets are copied 13 times into  $S_{13}$ , of which 35 survive. In general, the number of candidate prime sextuplets in  $S_{p_n}$ , denoted as  $p_n\#_6$ , where  $p_n > 6$ , is as follows:

$$p_n\#_6 = \prod_{i=4}^n (p_i - 6)$$

The sequence of  $p_n\#_6$  per  $n$  is listed in [OEIS A059865](#).

In general, for all *candidate prime k-tuples*, in the bitstrings we observe the following:

*Whatever pattern of 1s and 0s can be found in bitstring  $S_{p_n}$ , all occurrences of this pattern is copied  $p_{n+1}$  times into  $S_{p_{n+1}}$ , and eliminated as many times as the number of occurrences of this pattern in the original  $S_{p_n}$  multiplied by the number of 1s in the pattern.*

The number of candidate prime k-tuples in bitstring  $S_{p_n}$ , denoted as  $p_n\#_k$ , where  $k > 0$  is the number of 1s in the common pattern, is as follows:

$$p_n\#_k = \prod_{i=\pi(k+1)}^n (p_i - k) \quad (4)$$

A candidate prime k-tuple is a pattern in a bitstring  $S_{p_n}$  that is counted by the function  $p_n\#_k$ . For each  $k > 0$  there may be more than one pattern that is counted, such as when  $k = 2$  it counts candidate twin primes, candidate cousin primes, candidate sexy primes, and so on.

## 5 Density of candidate prime k-tuples and the Twin Prime Constant

The average distance between the centers of two nearest candidate prime k-tuples of size  $k > 0$  in bitstring  $S_{p_n}$ , denoted as  $G_{p_n,k}$ , is simply the length of the bitstring divided by the number of occurrences of candidate prime k-tuples of size  $k$ .

$$\begin{aligned}
G_{p_n, k} &= \frac{p_n \#}{p_n \#_k} \\
&= \frac{\prod_{i=1}^n p_i}{\prod_{i=\pi(k+1)}^n (p_i - k)} \\
&= \frac{p_{(\pi(k+1)-1)} \# \cdot \prod_{i=\pi(k+1)}^n p_i}{\prod_{i=\pi(k+1)}^n (p_i - k)} \\
&= p_{(\pi(k+1)-1)} \# \cdot \prod_{i=\pi(k+1)}^n \frac{p_i}{p_i - k} \\
&= p_{(\pi(k+1)-1)} \# \cdot \prod_{i=\pi(k+1)}^n \frac{1}{1 - \frac{k}{p_i}}
\end{aligned} \tag{5}$$

Where  $\pi$  is the prime counting function.

When  $k = 1$ , i.e. 1-tuples,  $G_{p_n, 1}$  equals the average distance between candidate primes in bitstring  $S_{p_n}$ .

$$\begin{aligned}
G_{p_n, 1} &= p_{(\pi(2)-1)} \# \cdot \prod_{i=\pi(2)}^n \frac{1}{1 - \frac{1}{p_i}} \\
&= p_0 \# \cdot \prod_{i=1}^n \frac{1}{1 - \frac{1}{p_i}} \\
&= \prod_{i=1}^n \frac{1}{1 - \frac{1}{p_i}}
\end{aligned}$$

Note that  $G_{p_\infty, 1}$  is equivalent to  $\zeta(1)$ , the pole of the Riemann zeta function  $\zeta$ , the harmonic series.

Let  $\rho_{p_n, k}$  be the reciprocal of  $G_{p_n, k}$ , such that  $\rho_{p_n, k}$  is a measure for the average density of candidate prime k-tuples in bitstring  $S_{p_n}$ .

$$\begin{aligned}
\rho_{p_n, k} &= \frac{1}{G_{p_n, k}} \\
&= \frac{p_n \#_k}{p_n \#} \\
&= \frac{1}{p_{(\pi(k+1)-1)} \#} \cdot \prod_{i=\pi(k+1)}^n \left(1 - \frac{k}{p_i}\right)
\end{aligned} \tag{6}$$

The density of candidate prime k-tuples tends to zero as  $n$  goes to infinity. For any  $k > 0$ :

$$\lim_{n \rightarrow \infty} \rho_{p_n, k} = \lim_{n \rightarrow \infty} \frac{1}{p_{(\pi(k+1)-1)} \#} \cdot \prod_{i=\pi(k+1)}^n \left(1 - \frac{k}{p_i}\right) = 0$$

$\rho_{p_n, k}$  is never zero because for any value of  $n$  there is a slice of candidate primes that is being eliminated from the number line. Consider the distribution of the least prime factors on the natural number line, as in [OEIS A020639](#). Let  $\rho_{lpf, p_n}$  be the general density of positive integers that have  $p_n$  as its least prime factor. We define  $\rho_{lpf, p_n}$  as follows:

$$\begin{aligned} \rho_{lpf, p_n} &= \frac{p_{n-1} \#_1}{p_n \#} = \frac{\phi(p_{n-1} \#)}{p_n \#} \\ &= \prod_{i=1}^n \frac{1}{p_i} \cdot \prod_{i=1}^{n-1} (p_i - 1) \\ &= \frac{1}{p_n - 1} \cdot \prod_{i=1}^n \frac{p_i - 1}{p_i} \\ &= \frac{1}{p_n - 1} \cdot \prod_{i=1}^n \left(1 - \frac{1}{p_i}\right) \end{aligned} \tag{7}$$

Every positive integer has exactly one least prime factor; therefore, the sum of densities  $\rho_{lpf, p_n}$  over all  $n > 0$  converges to 1.

$$\sum_{n=1}^{\infty} \frac{p_{n-1} \#_1}{p_n \#} = \sum_{n=1}^{\infty} \left( \frac{1}{p_n - 1} \cdot \prod_{i=1}^n \left(1 - \frac{1}{p_i}\right) \right) = 1 \tag{8}$$

Where  $p_0 \#_1 = 1$ .

The expression above shows that, for each iteration of the recurrence relation, a thin slice of the candidate primes is eliminated from the concatenated bitstring. For any iteration, the candidate primes eliminated are the composites with the new prime as its least prime factor. The pattern of eliminations is just a scaled-up version of the pattern of candidate primes in the previous bitstring, and just as symmetric and uniform. We therefore observe the following pattern.

*During the sieving process, as the candidate primes are gradually being thinned out, the average distance between nearest candidate prime k-tuples gradually increases, resulting in ever sparser clusters of intact candidate prime k-tuples, of which a deterministic number survive in each iteration.*

The rate of change in average distance between neighboring candidate prime k-tuples depends on  $k$  because a candidate prime k-tuple has  $k$  opportunities

of getting eliminated per iteration. A candidate single prime has one opportunity of getting eliminated per iteration, and a candidate twin prime has two opportunities of getting eliminated per iteration (and never a double elimination in a single iteration). This implies that, per iteration, the rate of change in distance between candidate twin primes is proportional to the rate of change in distance between single candidate primes squared. We can express this as follows.

$$G_{p_n,2} \approx \frac{G_{p_n,1}^2}{2 \cdot C_2}$$

Here  $C_2$  is the Hardy-Littlewood twin prime constant, and the factor of 2 in the denominator is to align with their formulation. Solving for  $C_2$ :

$$\begin{aligned} C_2 &= \lim_{n \rightarrow \infty} \frac{1}{2} \cdot G_{p_n,1}^2 \cdot \frac{1}{G_{p_n,2}} \\ &= \lim_{n \rightarrow \infty} \frac{1}{2} \cdot \left( \frac{p_n \#}{p_n \#_1} \right)^2 \cdot \frac{p_n \#_2}{p_n \#} \\ &= \lim_{n \rightarrow \infty} \frac{1}{2} \cdot \left( \prod_{i=1}^n \frac{p_i}{p_i - 1} \right)^2 \cdot 2 \cdot \prod_{i=2}^n \frac{p_i - 2}{p_i} \\ &\equiv \prod_{i=2}^{\infty} \frac{p_i}{p_i - 1} \cdot \prod_{i=2}^{\infty} \frac{p_i}{p_i - 1} \cdot \prod_{i=2}^{\infty} \frac{p_i - 2}{p_i} \\ &\equiv \prod_{i=2}^{\infty} \frac{p_i}{p_i - 1} \cdot \prod_{i=2}^{\infty} \frac{p_i - 2}{p_i - 1} \\ &\equiv \prod_{i=2}^{\infty} \frac{p_i \cdot (p_i - 2)}{(p_i - 1)^2} \\ &\equiv \prod_{i=2}^{\infty} \left( 1 - \frac{1}{(p_i - 1)^2} \right) \\ &\approx 0.6601618 \dots \end{aligned} \tag{9}$$

## 6 At the border of candidate prime elimination

The candidate primes (the 1s) in bitstring  $S_{p_n}$  after index  $p_n$  and before  $p_n^2$ , are all prime numbers. These candidate primes are definitely prime because in  $S_{p_n}$  the first 1 that is composite is at index  $p_{n+1}^2$ . The next composite after  $p_{n+1}^2$  is at index  $(p_{n+1} \cdot p_{n+2})$ , followed by either  $p_{n+2}^2$  or  $(p_{n+1} \cdot p_{n+3})$ . After that the combinatorics of either-or possibilities explode in size. Figure 3 shows the general anatomy of a bitstring.

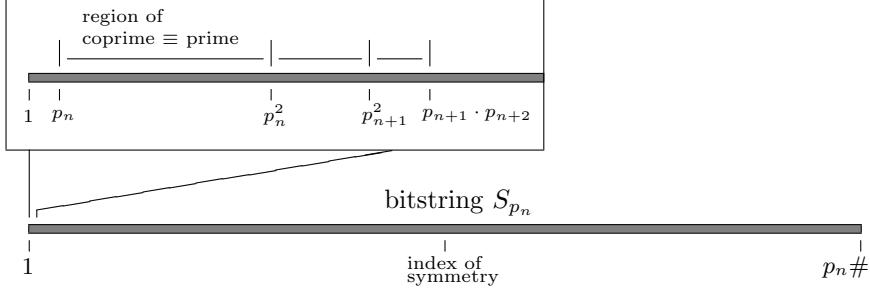


Figure 3: Generic structure of a bitstring  $S_{p_n}$

When the bitstring sieve (the recurrence relation) completes its task of generating output bitstring  $S_{p_n}$ , then from the sieve's perspective, not yet knowing  $p_{n+1}$ , the candidate primes between  $p_n$  and  $p_n^2$  are *definite primes*, and for any candidate prime after  $p_n^2$  it is not yet known whether it is a definite prime or a definite composite.  $p_n^2$  is at the border between definite primes and candidate primes, which we call the *border of candidate prime elimination*. In the progression of the bitstrings  $S_{p_n}$  as  $n$  increases, the border of candidate prime elimination travels with a "speed" of  $p_n^2$  along the number line, over a structure that is gradually being thinned out throughout. At each iteration, the border of candidate prime elimination passes over a non-empty set of 1s, which in itself proves there are infinitely many primes. In this way, the proof of the infinitude of primes can be written as follows:

#### (Yet another) proof of the infinitude of primes

The distance between  $p_n^2$  and  $p_{n+1}^2$ , or the sequence [OEIS A069482](#), is relatively smallest when  $p_n$  and  $p_{n+1}$  are twin primes, at which point the distance between  $p_n^2$  and  $p_{n+1}^2$  is  $4p_n + 4$ , or  $4p_{n+1} - 4$ . A jump from  $p_n^2$  to  $p_{n+1}^2$  therefore always covers a distance of at least  $4p_n + 4$ . The largest distance between candidate primes in  $S_{p_n}$  is  $2p_{n-1}$ . Therefore, the number of candidate primes between  $p_n^2$  and  $p_{n+1}^2$  is at least  $\frac{4p_n+4}{2p_{n-1}}$ , which is at least 2, which is more than 1.  $\square$

The largest distance between candidate twin primes is not always smaller than  $4p + 4$ , so there is no equivalent and easy proof for the twin primes. For example, in  $S_{17}$  the largest distance between candidate twin primes (from center to center) is 108, which is greater than  $19^2 - 17^2 = 72$ . The largest distance between candidate twin primes (from center to center) in  $S_{p_n}$  per  $n$  is listed in [OEIS A144311](#) (plus 1).

Statistically, however, the average number of candidate twin primes per randomly selected region of size  $(p_{n+1}^2 - p_n^2)$  increases with increasing  $n$ . In

other words, with ever more iterations of the bitstring sieve, we expect ever more candidate twin primes to survive the border of candidate elimination at  $p_n^2$ . Assuming a uniform distribution of candidate twin primes throughout a bitstring, which on the primorial scale is so, an estimate for how many candidate twin primes exist on average in the region between  $p_n^2$  and  $p_{n+1}^2$  is as follows:

$$\pi_2(p_{n+1}^2) - \pi_2(p_n^2) \approx \frac{p_{n+1}^2 - p_n^2}{2} \cdot \prod_{i=2}^n \frac{p_i - 2}{p_i} \quad (10)$$

Where  $\pi_2(x)$  is the actual number of twin primes less than  $x$ .

On average, assuming a uniform distribution of candidate twin primes throughout  $S_{p_n}$ , which on the primorial scale is so, the region swept by  $p_n^2$  at each iteration captures ever more candidate twin primes with increasing  $n$ .

$$\lim_{n \rightarrow \infty} \left( \frac{p_{n+1}^2 - p_n^2}{2} \cdot \prod_{i=2}^n \frac{p_i - 2}{p_i} \right) = \infty \quad (11)$$

Let us extend this approach to candidate k-tuples of any size  $k > 0$ .

Assuming the candidate prime k-tuples of size  $k$  are, on average, uniformly distributed throughout bitstring  $S_{p_n}$ , which on the primorial scale is so, then  $A_{k,p_n}$ , the average number of candidate prime k-tuples between  $p_n^2$  and  $p_{n+1}^2$ , is as follows:

$$\begin{aligned} \pi_k(p_{n+1}^2) - \pi_k(p_n^2) &\approx A_{k,p_n} \\ A_{k,p_n} &= \frac{p_{n+1}^2 - p_n^2}{G_{p_n,k}} \\ &= \frac{p_{n+1}^2 - p_n^2}{\frac{p_n \#}{p_n \#_k}} \\ &= (p_{n+1}^2 - p_n^2) \cdot \frac{p_n \#_k}{p_n \#} \\ &= \frac{p_{n+1}^2 - p_n^2}{p_{(\pi(k+1)-1)\#}} \cdot \prod_{i=\pi(k+1)}^n \frac{p_i - k}{p_i} \end{aligned} \quad (12)$$

Where  $\pi_k(x)$  is the actual number of prime k-tuples of size  $k$  with a center index less than  $x$ .

$A_{k,p_n}$  increases with increasing  $n$ , albeit slowly for large  $k$ . On average, assuming a uniform distribution of candidate prime k-tuples throughout  $S_{p_n}$ , the region swept by  $p_n^2$  at each iteration captures ever more candidate prime k-tuples with increasing  $n$ . For any prime k-tuple of size  $k > 0$ :

$$\lim_{n \rightarrow \infty} A_{k,p_n} = \lim_{n \rightarrow \infty} \left( \frac{p_{n+1}^2 - p_n^2}{p_{(\pi(k+1)-1)} \#} \cdot \prod_{i=\pi(k+1)}^n \frac{p_i - k}{p_i} \right) = \infty \quad (13)$$

This result is very close to a proof of the K-tuple Conjecture. The above result states that if the density of candidate prime k-tuples of size  $k$  in the region between  $p_n^2$  and  $p_{n+1}^2$  in bitstring  $S_{p_n}$  is, on average and in the long run, representative of its density in the whole bitstring, then the K-tuple Conjecture is true. The remaining step is to prove that the micro region between  $p_n^2$  and  $p_{n+1}^2$  is statistically representative of the whole bitstring. The only way for the K-tuple Conjecture to be false is if after some large prime there somehow emerges an everlasting local wave of bias toward eliminating all candidate prime k-tuples of particular size  $k$  just ahead of  $p_n^2$ , thus preventing any of them from becoming prime. To investigate whether such phenomena are even possible, our approach is to delve deeper into the elimination process, by rearranging the bitstrings into *bitmatrices*.

## 7 The Bitmatrix Sieve

A bitstring  $S_{p_n}$  of length  $p_n \#$  can be shaped into a  $p_n \times p_{n-1} \#$  matrix. Such a matrix we call a *bitmatrix*. The *bitmatrix sieve* is defined as follows.

Let  $M$  be the set of outputs generated by the bitmatrix sieve at each iteration, starting with bitmatrix  $M_2$ . For each prime  $p_n$  there is a matrix  $M_{p_n}$  in  $M$ :

$$M = \{M_2, M_3, M_5, M_7, M_{11}, \dots\}$$

Each matrix  $M_{p_n}$  is a *bitmatrix*, a matrix of binary digits. The referencing of entries in the bitmatrix is by a single 1-based index, where  $index = column + ((row - 1) \times width)$ . For example, in bitmatrix  $M_3$  with 6 columns, bit  $b_7$  at  $M[7]$  refers to the first bit (column 1) in the second row. The format of a bitmatrix is:

$$\begin{bmatrix} b_1 & \dots & b_{columns} \\ \dots & \dots & \dots \\ b_{((rows-1) \times columns)+1} & \dots & b_{rows \times columns} \end{bmatrix}$$

Where  $b_i \in \{0, 1\}$ .

The recurrence relation that generates the bitmatrices is as follows.

**Initial condition:**

Let  $M_2$  be this  $2 \times 1$  bitmatrix:

$$\mathbf{M}_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

**Recurrence relation:**

Given bitmatrix  $M_{p_n}$ , where  $p_n$  is the  $n$ -th prime, the next bitmatrix  $M_{p_{n+1}}$  is obtained by:

- In bitmatrix  $M_{p_n}$ , starting after index 1, locate the index of the next occurrence of bit value 1. Let  $p_{n+1}$  be this index.
- Let  $M_{p_{n+1}}$  be a  $p_{n+1} \times p_n\#$  bitmatrix. The contents of  $M_{p_{n+1}}$  is filled as follows.
  - Fill each row in  $M_{p_{n+1}}$  with a flattened copy of  $M_{p_n}$ . To flatten is to reshape the matrix such that all rows are concatenated to form a single row (effectively forming bitstring  $S_{p_n}$ ).
  - For each column in  $M_{p_{n+1}}$  that contains 1s, zero the entry that has an index that is divisible by  $p_{n+1}$ .

Equivalently, bitmatrix  $M_{p_n}$  can be defined as:

$$\mathbf{M}_{p_n} = \begin{bmatrix} b_1 & \dots & b_{p_{n-1}\#} \\ \dots & \dots & \dots \\ b_{((p_n-1)\times p_{n-1}\#)+1} & \dots & b_{p_n\#} \end{bmatrix}$$

Where:

$$b_i = \begin{cases} 1, & \text{if } i \text{ is coprime with } p_n\# \\ 0, & \text{otherwise} \end{cases}$$

The bitmatrices  $M_5$  and  $M_7$  are shown in Figure 4.

$M_5$						key	
1	2	3	4	5	6	i	0
7	8	9	10	11	12	i	1
13	14	15	16	17	18	i index	
19	20	21	22	23	24		
25	26	27	28	29	30		

$M_7$																													
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	50
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150
151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180
181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210

Figure 4: Bitmatrices  $M_5$  and  $M_7$

Zooming out, we can just about get bitmatrix  $M_{11}$  in full view, as shown in Figure 5.

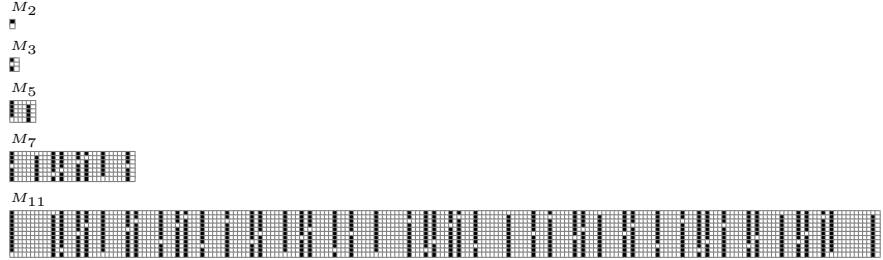


Figure 5: Bitmatrices  $M_2$  -  $M_{11}$

A bitmatrix's index of symmetry is halfway its bitstring length. For example, the index of symmetry of  $M_7$  is at index  $\frac{7\#}{2} = 105$ . A bitmatrix is centrosymmetric, meaning that pairs of entries that are on opposite sides of the index of symmetry, i.e. having indices that add up to  $p\#$ , always have the same bit value. A bitmatrix has an even number of columns, and its index of symmetry lies half a column width to the left of its geometric center.

In this matrix format, the candidate primes (black squares) are arranged in columns. Each black column has exactly one white square, because exactly one of these indices will be divisible by prime  $p_n$ . These single white squares per black column is the process of eliminating candidate primes in action. The multiples of  $p_n$  are distributed as diagonal lines across the table because the width of the table is not divisible by its height.

## 8 Residue Systems and the Candidate Prime Eliminator

As is visible in Figure 4 and Figure 5, the candidate primes (black squares) are grouped in *black columns*. In bitmatrix  $M_{p_n}$  there are  $p_{n-1}\#_1$  such black columns. Each black column has exactly one white square because the indices in each column of  $M_{p_n}$  form a complete residue system  $(\text{mod } p_n)$ , such that each column has exactly one entry that is divisible by  $p_n$ . Furthermore, any horizontal sequence of  $p_n$  entries also form a complete residue system  $(\text{mod } p_n)$ . Therefore, any  $p_n \times p_n$  section of  $M_{p_n}$  contains a set of all rotations of the complete residue system  $(\text{mod } p_n)$ . We can therefore interpret the elimination process as a  $p_n \times p_n$  *elimination mask* being applied sequentially along the matrix.

In bitmatrix  $M_{p_n}$ , the elimination mask is applied  $\frac{p_{n-1}\#}{p_n}$  many times, which is never a whole number, leaving a relatively small fractional part of  $\frac{p_n \text{ mod } p_{n-1}\#}{p_n}$ . The elimination masks are center-aligned around the index of symmetry. The eliminations are therefore centrosymmetrically placed around the bitmatrix's index of symmetry. Note that the elimination mask is similar to the *NOT-STRETCH* operation in the bitstring sieve, except that it will eliminate numbers that were already marked as composite, whereas the *NOT-STRETCH* operation does not.

Figure 6 shows the  $E_7$  elimination masks highlighted in green in bitmatrix  $M_7$ . Red borders are drawn around each elimination mask.

The elimination mask  $E_{p_n}$  for  $M_{p_n}$  is a  $p_n \times p_n$  bitmatrix, defined as:

$$E_{p_n} = \begin{bmatrix} b_1 & \dots & b_{p_n} \\ \dots & \dots & \dots \\ b_{((p_n-1)\times p_n)+1} & \dots & b_{p_n \times p_n} \end{bmatrix}$$

Where:

$$b_i = \begin{cases} 0, & \text{if } T_{p_n}(i) \text{ is divisible by } p_n \\ 1, & \text{otherwise} \end{cases}$$

$M_7$ 

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	50
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150
151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180
181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210

Figure 6:  $M_7$  with  $E_7$  elimination masks (i.e. multiples of 7) highlighted in green

Where:

$$T_{p_n}(i) = \frac{p_{n-1}\#}{2} - \frac{p_n - 1}{2} + ((i - 1) \bmod p_n) + \left\lfloor \frac{i - 1}{p_n} \right\rfloor \cdot p_{n-1}\#$$

Alternatively, the candidate prime eliminator (the green squares in Figure 6) can be described as a diagonal line wrapping as a coil around a cylinder. A bitmatrix is modular in horizontal and vertical directions, such that its ends can be joined together in two ways to form a cylinder, either by joining the horizontal ends, or by joining the vertical ends. In this way, a bitmatrix is a torus. There are two ways of wrapping the coil of elimination around the bitmatrix and end up with the same result, either by  $(\bmod p_{n-1}\#)$  or by  $(\bmod p_n)$ . We can either wrap around the bitmatrix in horizontal direction while stepping down, or wrap around vertically while stepping right. The first option rotates around the cylinder with a period of  $(\bmod p_{n-1}\#)$  steps, while the second option rotates around the cylinder with a period of  $(\bmod p_n)$  steps. We shall focus on the second option, because we are interested in an expression for determining which row in a given black column is eliminated in the next iteration.

The right side of Figure 7 shows an illustration of the candidate prime eliminator of  $M_7$ . The other side of the cylinder (within the same torus), shown on the left, hosts the candidate primes (before the elimination step). The coordinate systems of the two cylinders are inverses of each other, and transforming one into the other is akin to turning a punctured torus inside out, whilst ensuring the symmetries are maintained.

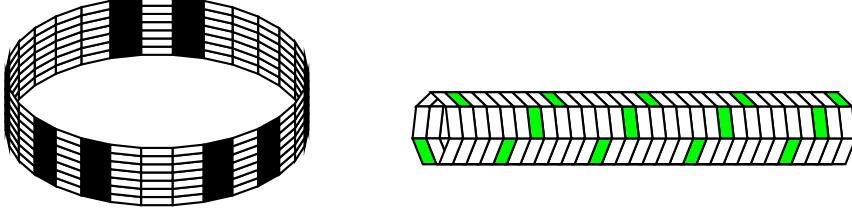


Figure 7: The two cylinders in the torus of  $M_7$ . The left cylinder contains the candidate primes (before the elimination step), and the right cylinder contains the candidate prime eliminator.

Let  $J_{p_n}$  be a function that returns the increment in row index modulo  $p_n$  per increment in column index of bitmatrix  $M_{p_n}$ . We know that  $J_{p_n}$  is an integer greater than 0 and less than  $p_n$ . The congruence relations are as follows.

$$\begin{aligned} T_{p_n}\left(\frac{p_n^2}{2} + 1\right) &\equiv 0 \pmod{p_n} \\ T_{p_n}\left(\frac{p_n^2}{2} + 1\right) + 1 + J_{p_n} \cdot p_{n-1}\# &\equiv 0 \pmod{p_n} \end{aligned}$$

Therefore:

$$1 + J_{p_n} \cdot p_{n-1}\# \equiv 0 \pmod{p_n} \quad (14)$$

The candidate prime eliminator in bitmatrix  $M_{p_n}$  can be modeled as a rotating object that passes from left to right over the bitmatrix, rotating with a frequency of  $\frac{2\pi \cdot J_{p_n}}{p_n}$  radians per column shift.  $J_{p_n}$  can be any integer value greater than 0 and less than  $p_n$ , any choice will ensure a periodic visit to each row per shift in  $p_n$  columns, but  $J_{p_n}$  is the only integer greater than 0 and less than  $p_n$  such that the eliminator passes through both  $p_n$  and the index of symmetry.

$J_{p_n}$  answers the question: how many times to add  $p_{n-1}\#$  to  $p_n$  for it to be divisible by  $p_n$ . To calculate  $J_{p_n}$  requires finding the modular inverse of  $p_{n-1}\#$  modulo  $p_n$ . Finding the modular inverse requires knowing the specific numbers of the congruence relations, implying there is no simple or direct formula for calculating  $J_{p_n}$ . It is a puzzle that you can only start to attempt solving after first knowing  $p_{n-1}\#$ . When  $p_{n-1}\#$  and  $p_n$  are both known,  $J_{p_n}$  can be calculated by an algorithm, such as by sieving, or by exhaustively searching by adding and checking divisibility, or by the Extended Euclidean Algorithm.

When  $J_{p_n}$  is known, we have a formula for  $R_{p_n}(c)$ , the "row index of elimination" in  $M_{p_n}$ , for any given column index  $c \geq 1, c \leq p_{n-1}\#$ .

$$R_{p_n}(c) = 1 + ((J_{p_n} \cdot c) \bmod p_n)$$

Values of  $J_p$  for the first 6 primes are:

$$\begin{aligned} J_2 &= 1 \\ J_3 &= 1 \\ J_5 &= 4 \\ J_7 &= 3 \\ J_{11} &= 10 \\ J_{13} &= 10 \end{aligned}$$

The sequence of  $J_{p_n}$  per  $n$  is listed in [A081617](#).

In the long run, with ever increasing  $n$ , the distribution of  $J_{p_n}$  over  $n$  is statistically the same as the distribution of throwing  $(p_n - 1)$ -sided dice, because, by definition, primes do not divide each other. The distribution of  $J_{p_n}$  is stochastic, such that:

$$\lim_{n \rightarrow \infty} \frac{\sum_{q=1}^n \frac{J_{p_q}}{p_q}}{n} = \frac{1}{2} \quad (15)$$

On average, especially so when  $p_n$  is large, each row in a bitmatrix will have near-equal numbers of eliminations, implying that there cannot emerge a sustained bias for near-future eliminations over far-future eliminations, and therefore it is impossible for some everlasting rogue wave of bias to appear after some large prime, that somehow purposely eliminates all candidate prime k-tuples of chosen size  $k > 0$  just ahead of  $p_n^2$ . Furthermore, even if the values of  $J_{p_n}$  were not stochastic, its impact is not enough to create any significant bias. The value of  $J_{p_n}$ , particularly when  $n$  is large, has very little impact on the distribution of eliminations per row in the bitmatrix. With increasing  $n$ , whatever the behavior is of  $J_{p_n}$ , the number of eliminations in each row approaches the average value of  $\frac{p_{n-1}\#_1}{p_n}$ .

To illustrate this, imagine there is a demon in the sieve that manipulates the values of  $J_{p_n}$ , in an attempt to eliminate the candidate prime k-tuples of size  $k$  that lie ahead of  $p_n^2$ , by targeting more prime k-tuples of size  $k$  in the first row than in the other rows. The demon will find that, particularly when  $n$  is large, the number of eliminations per row remains nearly the same for each setting of  $J$ . Table 1 shows the number of candidate primes eliminated per row in bitmatrix  $M_{11}$ , for all possible manipulations of  $J$ . The column  $J_{11} = 10$

represents the actual value for  $J_{11}$ . Notice that, in this model, manipulating  $J$  has no impact on the number of eliminations in the first row, only from the second row onward.

row	1	manipulated $J$									$J_{11}$
		2	3	4	5	6	7	8	9	10	
1	4	4	4	4	4	4	4	4	4	4	4
2	4	5	6	3	5	5	4	4	3	4	
3	5	4	4	5	4	6	3	3	4	5	
4	3	4	4	5	3	5	5	4	6	4	
5	6	5	3	4	3	4	4	5	5	4	
6	3	4	5	6	4	4	4	5	3	5	
7	5	3	5	4	4	4	6	5	4	3	
8	4	5	5	4	4	3	4	3	5	6	
9	4	6	4	5	5	3	5	4	4	3	
10	5	4	3	3	6	4	5	4	4	5	
11	4	3	4	4	5	5	3	6	5	4	

Table 1: Number of candidate prime eliminations per row in  $M_{11}$  per manipulation of  $J$ . Actual value of  $J_{11} = 10$ .

In the above table for bitmatrix  $M_{11}$ , with 11 being a low prime, the differences in the number of eliminations per row are still relatively large compared to the average value of  $4\frac{4}{11}$ , but in the tables for larger primes the differences in the number of eliminations per row get relatively smaller, with all rows gradually approaching the average value of  $\frac{p_{n-1}\#_1}{p_n}$  as  $n$  increases. As an indication, in  $M_{19}$  the average number of eliminations per row is  $4850\frac{10}{19}$ , and the actual values range from 4846 to 4854.

We can summarize this as follows. Let  $E_{p_n, \text{row}(r)}$  be the number of eliminations in row index  $r \in \mathbb{N}; r \geq 1, r \leq p_n$  in bitmatrix  $M_{p_n}$ . Then, as  $n$  increases, the number of eliminations in each row converges to the same value:

$$\begin{aligned} \lim_{n \rightarrow \infty} E_{p_n, \text{row}(x)} &= \frac{p_{n-1}\#_1}{p_n} \\ &= \frac{1}{p_n} \prod_{i=1}^{n-1} (p_i - 1) \end{aligned} \tag{16}$$

The numbers which have  $p_n$  as its least prime factor are uniformly distributed at the primorial scale, as is evident in the sequence of least prime factors. This rules out any possibility for a sustained local phenomenon to appear after

some large prime. This means that the density of a pattern of 1s in bitstring  $S_{p_n}$  just ahead of  $p_n^2$  is statistically representative of the density of the same pattern throughout the entire bitstring. Therefore, we can say for sure that the number of prime k-tuples of size  $k$  between  $p_n^2$  and  $p_{n+1}^2$  increases on average with increasing  $n$ . There are infinitely many prime k-tuples, which are distributed as statistically predicted by Hardy and Littlewood.

## 9 Proof of the Hardy-Littlewood K-tuple Conjecture

In the recurrence relation that defines the primes, such as in the bitstring sieve or bitmatrix sieve, symmetry and modularity of the candidate primes (coprimes with the primorial) is conserved at the primorial scale. During the sieving process, as the candidate primes are gradually being thinned out, the average distance between nearest candidate prime k-tuples gradually increases, resulting in ever sparser clusters of intact candidate prime k-tuples, of which a deterministic number survive in each iteration. The "border of candidate prime elimination" passes over this structure with a "speed" of  $p_n^2$ , stepping over gradually increasing numbers of prime k-tuples of any size at each iteration.

$A_{k,p_n}$ , the average number of prime k-tuples of size  $k$  in  $S_{p_n}$  between  $p_n^2$  and  $p_{n+1}^2$ , increases with increasing  $n$ .

$$\lim_{n \rightarrow \infty} A_{k,p_n} = \lim_{n \rightarrow \infty} \left( \frac{p_{n+1}^2 - p_n^2}{p_{(\pi(k+1)-1)} \#} \cdot \prod_{i=\pi(k+1)}^n \frac{p_i - k}{p_i} \right) = \infty$$

As  $n$  increases, the region between  $p_n^2$  and  $p_{n+1}^2$  contains ever more expected candidate k-tuples. The distribution of primes in the sequence of least prime factors, which account for the eliminations in the bitstring sieve, are also uniform at the primorial scale. The candidate creation process and candidate elimination process are both symmetric and uniform at the primorial scale, but the candidate creation process is always one step ahead of the candidate elimination process.

The symmetry maintained by the recurrence relation prohibit any possibility of a sustained local phenomenon, such as a rogue "bow wave" of elimination, to somehow emerge ahead of  $p_n^2$  after some large  $n$ . Such sustained local phenomena are guaranteed not to happen, guaranteed by the fact that primes do not divide each other. In the recurrence relation that defines the primes there is no mechanism to target and stop all candidate k-tuples of size  $k$  from becoming definitely prime at  $p_n^2$ .

## 10 Conclusion

In the recurrence relation that defines the primes there is no mechanism to target and stop all candidate k-tuples of size  $k$  from becoming definite primes at  $p_n^2$ . There exist infinitely many twin primes and prime k-tuples, occurring at asymptotic frequency, as predicted by Hardy and Littlewood.

## References

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