The smallest gap between primes

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Abstract

A prime gap is the difference between two successive prime numbers.
Two is the smallest possible gap between primes. A twin prime is a prime
that has a prime gap of two. The twin prime conjecture states that there
are infinitely many twin primes. This conjecture has been one of the
great open problems in number theory for many years. In May 2013,
the popular Yitang Zhang's paper was accepted by the journal Annals
of Mathematics where it was announced that for some integer N that
is less than 70 million, there are infinitely many pairs of primes that
differ by N. A few months later, James Maynard gave a different proof
of Yitang Zhang's theorem and showed that there are infinitely many
prime gaps with size of at most 600. A collaborative effort in the Poly-
math Project, led by Terence Tao, reduced to the lower bound 246 just
using Zhang and Maynard results as the main theoretical background.
In this note, using arithmetic operations, we prove that the twin prime
conjecture is true. Indeed, this is a trivial and short note very easy to
check and understand which is a breakthrough result at the same time.

Keywords: Twin prime conjecture, Prime numbers, Prime gap

MSC Classification: 11A41 , 11A25

1 Introduction

Leonhard Euler studied the following value of the Riemann zeta function
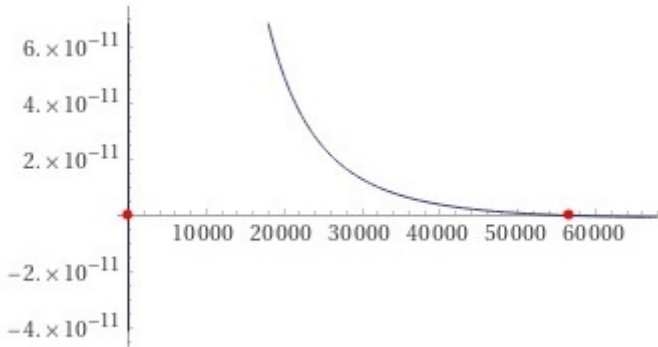(1734).

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Fig. 1   Roots of $H_2(x)$ [5]

Proposition 1 *It is known that[1, (1) pp. 1070]:*

$$\zeta(2) = \prod_{k=1}^{\infty} \frac{p_k^2}{p_k^2 - 1} = \frac{\pi^2}{6},$$

where p_k is the kth prime number (We also use the notation p_n to denote the nth prime number.).

Franz Mertens obtained some important results about the constants B and H (1874). We define $H = \gamma - B$ such that $B \approx 0.2614972128$ is the Meissel-Mertens constant and $\gamma \approx 0.57721$ is the Euler-Mascheroni constant [2, (17.) pp. 54].

Proposition 2 *We have [3, Lemma 2.1 (1) pp. 359]:*

$$\sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) - \frac{1}{p_k} \right) = \gamma - B = H,$$

where $\log$ *is the natural logarithm.*

For $x \geq 2$, the function $u(x)$ is defined as follows [4, pp. 379]:

$$u(x) = \sum_{p_k > x} \left(\log(\frac{p_k}{p_k - 1}) - \frac{1}{p_k} \right).$$

We use the following function:

Definition 1 For all $x > 1$ and $a \geq 0$, we define the function:

$$H_a(x) = \log(\frac{x}{x - 1}) - \frac{1}{x + a} + \log(\frac{x^2 - \frac{\log(x)+1}{\sqrt{x}}}{x^2}).$$

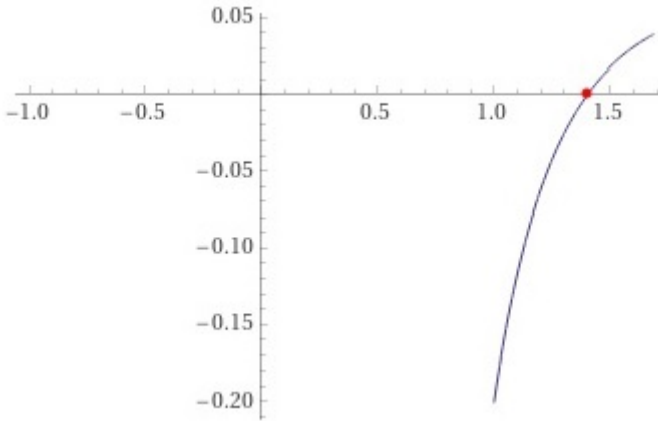We state the following Propositions:

Fig. 2   Roots of $H_4(x)$ [6]

Proposition 3 *For a sufficiently large positive value x, we have $H_2(x) < 0$. Certainly, $H_2(x)$ is negative for all $x \geq 60000$ since it is negative for $x = 60000$, strictly decreasing for $x \geq 60000$ (because its derivative is lesser than 0 for $x \geq 60000$) and its greatest root is between 50000 and 60000 (See Figure 1).*

Proposition 4 *For a sufficiently large positive value x, we have $H_4(x) > 0$. Certainly, $H_4(x)$ is positive for all $x \geq 1.5$ since it is positive for $x = 1.5$ and its unique root is between 1.4 and 1.5 (See Figure 2).*

The following property is based on natural logarithms:

Proposition 5   *[7, pp. 1]. For $x > -1$:*

$$\log(1 + x) \leq x.$$

Putting all together yields the proof of the main theorem.

Theorem 1 *The twin prime conjecture is true.*

2 Infinite Sums

Lemma 1
$$\sum_{k=1}^{\infty} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) \right) = \log(\zeta(2)) - H.$$

Proof We obtain that

$$\log(\zeta(2)) - H = \log(\prod_{k=1}^{\infty} \frac{p_k^2}{p_k^2 - 1}) - H$$

$$= \sum_{k=1}^{\infty} \left(\log(\frac{p_k^2}{(p_k^2 - 1)}) \right) - H$$

$$= \sum_{k=1}^{\infty} \left(\log(\frac{p_k^2}{(p_k - 1) \cdot (p_k + 1)}) \right) - H$$

$$= \sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) + \log(\frac{p_k}{p_k + 1}) \right) - H$$

$$= \sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) - \log(\frac{p_k + 1}{p_k}) \right) - H$$

$$= \sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_k}) \right) - \sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) - \frac{1}{p_k} \right)$$

$$= \sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_k}) - \log(\frac{p_k}{p_k - 1}) + \frac{1}{p_k} \right)$$

$$= \sum_{k=1}^{\infty} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) \right)$$

by Propositions 1 and 2. □

Lemma 2

$$\sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_{k+1}}) \right) = \log(\zeta(2)) + \log(\frac{3}{2}).$$

Proof We obtain that

$$\log(\zeta(2)) + \log(\frac{3}{2}) = \log(\zeta(2)) - H + H + \log(\frac{3}{2})$$

$$= \sum_{k=1}^{\infty} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) \right) + H + \log(\frac{3}{2})$$

$$= \sum_{k=1}^{\infty} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) \right) + \sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) - \frac{1}{p_k} \right) + \log(\frac{3}{2})$$

$$= \sum_{k=1}^{\infty} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) + \log(\frac{p_k}{p_k - 1}) - \frac{1}{p_k} \right) + \log(\frac{3}{2})$$

$$= \sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_k}) \right) + \log(\frac{3}{2})$$

$$= \sum_{k=1}^{\infty} \left(\log(1 + \frac{1}{p_k}) - \log(\frac{p_{k+1}}{p_{k+1} - 1}) \right)$$

by Lemma 1. □

3 Partial Sums

Lemma 3

$$\sum_{p_k \leq x} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) \right) = \log(\prod_{p_k \leq x} \frac{p_k^2}{p_k^2 - 1}) - H + u(x).$$

Proof We obtain that

$$\log(\prod_{p_k \leq x} \frac{p_k^2}{p_k^2 - 1}) - H + u(x) = \sum_{p_k \leq x} \left(\log(\frac{p_k^2}{(p_k^2 - 1)}) \right) - H + u(x)$$

$$= \sum_{p_k \leq x} \left(\log(\frac{p_k^2}{(p_k - 1) \cdot (p_k + 1)}) \right) - H + u(x)$$

$$= \sum_{p_k \leq x} \left(\log(\frac{p_k}{p_k - 1}) + \log(\frac{p_k}{p_k + 1}) \right) - H + u(x)$$

$$= \sum_{p_k \leq x} \left(\log(\frac{p_k}{p_k - 1}) - \log(\frac{p_k + 1}{p_k}) \right) - H + u(x)$$

$$= \sum_{p_k \leq x} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_k}) \right) - \sum_{p_k \leq x} \left(\log(\frac{p_k}{p_k - 1}) - \frac{1}{p_k} \right)$$

$$= \sum_{p_k \leq x} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_k}) - \log(\frac{p_k}{p_k - 1}) + \frac{1}{p_k} \right)$$

$$= \sum_{p_k \leq x} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) \right)$$

by Propositions 1 and 2. $\qquad\square$

Lemma 4

$$\sum_{p_k < p_n} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_{k+1}}) \right) = \log(\frac{3}{2}) + \log(\prod_{p_k \leq p_{n-1}} \frac{p_k^2}{p_k^2 - 1}) - \log(1 + \frac{1}{p_n}).$$

Proof We obtain that

$$\log(\frac{3}{2}) + \log(\prod_{p_k \leq p_{n-1}} \frac{p_k^2}{p_k^2 - 1}) - \log(1 + \frac{1}{p_n})$$

$$= \log(\frac{3}{2}) + \log(\prod_{p_k \leq p_{n-1}} \frac{p_k^2}{p_k^2 - 1}) - H + u(p_{n-1}) + H - u(p_{n-1}) - \log(1 + \frac{1}{p_n})$$

$$= \log(\frac{3}{2}) + \sum_{p_k \leq p_{n-1}} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) \right) + H - u(p_{n-1}) - \log(1 + \frac{1}{p_n})$$

$$= \log(\frac{3}{2}) + \sum_{p_k \leq p_{n-1}} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) \right) + \sum_{p_k \leq p_{n-1}} \left(\log(\frac{p_k}{p_k - 1}) - \frac{1}{p_k} \right) - \log(1 + \frac{1}{p_n})$$

$$= \log(\frac{3}{2}) + \sum_{p_k \leq p_{n-1}} \left(\frac{1}{p_k} - \log(1 + \frac{1}{p_k}) + \log(\frac{p_k}{p_k - 1}) - \frac{1}{p_k} \right) - \log(1 + \frac{1}{p_n})$$

$$= \log(\frac{3}{2}) + \sum_{p_k \leq p_{n-1}} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_k}) \right) - \log(1 + \frac{1}{p_n})$$

$$= \sum_{p_k < p_n} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_{k+1}}) \right)$$

by Lemma 3.   □

4 Main Insight

Lemma 5

$$\sum_{p_k \geq p_n} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_{k+1}}) \right) = \log(1 + \frac{1}{p_n}) + \log\left(\prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2 - 1} \right).$$

Proof We obtain that

$$\sum_{p_k \geq p_n} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_{k+1}}) \right)$$

$$= \sum_{k=1}^{\infty} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_{k+1}}) \right) - \sum_{p_k < p_n} \left(\log(\frac{p_k}{p_k - 1}) - \log(1 + \frac{1}{p_{k+1}}) \right)$$

$$= \log(\zeta(2)) + \log(\frac{3}{2}) - \log(\frac{3}{2}) - \log\left(\prod_{p_k \leq p_{n-1}} \frac{p_k^2}{p_k^2 - 1} \right) + \log(1 + \frac{1}{p_n})$$

$$= \log(1 + \frac{1}{p_n}) + \log\left(\prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2 - 1} \right)$$

by Lemmas 2 and 4.   □

5 Proof of Theorem 1

Proof Suppose that the twin prime conjecture is false. Then, there would exist a sufficiently large prime number p_n such that for all prime gaps starting from p_n, this implies that they are greater than or equal to 4. First, we need prove that

$$\log(1 + \frac{1}{p_n}) + \log\left(\prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2 - 1} \right) + \sum_{p_k \geq p_n} \log\left(\frac{p_k^2 - \frac{\log(p_k)+1}{\sqrt{p_k}}}{p_k^2} \right) \leq 0$$

when p_n is large enough. That is the same as

$$\log(1 + \frac{1}{p_n}) + \log\left(\prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2 - 1} \right) \leq \sum_{p_k \geq p_n} \log\left(\frac{p_k^2}{p_k^2 - \frac{\log(p_k)+1}{\sqrt{p_k}}} \right).$$

That is equivalent to

$$\frac{p_n + 1}{p_n} \cdot \prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2 - 1} \leq \prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2 - \frac{\log(p_k)+1}{\sqrt{p_k}}}.$$

So,

$$\frac{p_n+1}{p_n} \cdot \prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2-1} \leq \prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2 - \left(\sqrt[\log(p_k)+1]{p_k}\right)^{\frac{\log(p_k)}{\log(p_k)}}}$$

which is

$$\frac{p_n+1}{p_n} \cdot \prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2-1} \leq \prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2 - \sqrt[\frac{\log(p_k)+1}{\log(p_k)}]{e}}$$

since $x^{\frac{1}{\log x}} = e$ for $x > -1$. Hence, it is enough to show that

$$\prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2-2.71828} \leq \prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2 - \sqrt[\frac{\log(p_k)+1}{\log(p_k)}]{e}}$$

for a sufficiently large prime number p_n. Indeed, we see that

$$(p_n+1) \cdot \prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2-1} \leq p_n \cdot \prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2-2.71828}$$

trivially holds for large enough p_n since

$$1 \gg \prod_{p_k \geq p_n} \frac{p_k^2 - 2.71828}{p_k^2-1} \quad and \quad \frac{p_n}{p_n+1} \to 1 \quad when \quad (n \to \infty),$$

where the symbol $\gg$ means "much greater than". Consequently, we can assure that

$$\log(1+\frac{1}{p_n}) + \log(\prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2-1}) + \sum_{p_k \geq p_n} \log(\frac{p_k^2 - \sqrt[\log(p_k)+1]{p_k}}{p_k^2}) \leq 0$$

whenever p_n is large enough. In this way, we have

$$\sum_{p_k \geq p_n} \left(\log(\frac{p_k}{p_k-1}) - \log(1+\frac{1}{p_{k+1}})\right) + \sum_{p_k \geq p_n} \log(\frac{p_k^2 - \sqrt[\log(p_k)+1]{p_k}}{p_k^2}) \leq 0$$

by Lemma 5. We verify that

$$\sum_{p_k \geq p_n} \left(\log(\frac{p_k}{p_k-1}) - \log(1+\frac{1}{p_{k+1}})\right) + \sum_{p_k \geq p_n} \log(\frac{p_k^2 - \sqrt[\log(p_k)+1]{p_k}}{p_k^2})$$

$$\geq \sum_{p_k \geq p_n} \left(\log(\frac{p_k}{p_k-1}) - \frac{1}{p_{k+1}}\right) + \sum_{p_k \geq p_n} \log(\frac{p_k^2 - \sqrt[\log(p_k)+1]{p_k}}{p_k^2})$$

since $-\log(1+\frac{1}{p_{k+1}}) \geq -\frac{1}{p_{k+1}}$ by Proposition 5. Under our assumption, we notice that

$$\sum_{p_k \geq p_n} \left(\log(\frac{p_k}{p_k-1}) - \frac{1}{p_{k+1}}\right) + \sum_{p_k \geq p_n} \log(\frac{p_k^2 - \sqrt[\log(p_k)+1]{p_k}}{p_k^2}) \geq \sum_{p_k \geq p_n} H_4(p_k)$$

since $-\frac{1}{p_{k+1}} \geq -\frac{1}{p_k+4}$. However, we know that

$$\sum_{p_k \geq p_n} H_4(p_k) > 0$$

due to Proposition 4. Hence, the inequality

$$\log(1+\frac{1}{p_n}) + \log(\prod_{p_k \geq p_n} \frac{p_k^2}{p_k^2-1}) + \sum_{p_k \geq p_n} \log(\frac{p_k^2 - \sqrt[\log(p_k)+1]{p_k}}{p_k^2}) \leq 0$$

would not hold by transitivity. For that reason, we obtain a contradiction under the supposition that the twin prime conjecture is false. By reductio ad absurdum, we prove that the twin prime conjecture is true. □

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