

# The physical limits of computation inspire an open problem that concerns abstract computable sets $\mathcal{X} \subseteq \mathbb{N}$ and cannot be formalized in the set theory ZFC as it refers to our current knowledge on $\mathcal{X}$

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**Abstract.** Let  $f(1) = 2$ ,  $f(2) = 4$ , and let  $f(n+1) = f(n)!$  for every integer  $n \geq 2$ . Edmund Landau's conjecture states that the set  $\mathcal{P}_{n^2+1}$  of primes of the form  $n^2 + 1$  is infinite. Landau's conjecture implies the following unproven statement  $\Phi$ :  $\text{card}(\mathcal{P}_{n^2+1}) < \omega \Rightarrow \mathcal{P}_{n^2+1} \subseteq [2, f(7)]$ . Let  $B$  denote the system of equations:  $\{x_i! = x_k : i, k \in \{1, \dots, 9\}\} \cup \{x_i \cdot x_j = x_k : i, j, k \in \{1, \dots, 9\}\}$ . We write down a system  $\mathcal{U} \subseteq B$  of 9 equations which has exactly two solutions in positive integers, namely  $(1, \dots, 1)$  and  $(f(1), \dots, f(9))$ . Let  $\Psi$  denote the statement: *if a system  $\mathcal{S} \subseteq B$  has at most finitely many solutions in positive integers  $x_1, \dots, x_9$ , then each such solution  $(x_1, \dots, x_9)$  satisfies  $x_1, \dots, x_9 \leq f(9)$* . We write down a system  $\mathcal{A} \subseteq B$  of 8 equations. The statement  $\Psi$  restricted to the system  $\mathcal{A}$  is equivalent to the statement  $\Phi$ . Open Problem: *Is there a set  $\mathcal{X} \subseteq \mathbb{N}$  that satisfies conditions (1)–(5)?* (1) *There are many elements of  $\mathcal{X}$  and it is conjectured that  $\mathcal{X}$  is infinite.* (2) *No known algorithm decides the finiteness/infiniteness of  $\mathcal{X}$ .* (3) *There is a known algorithm that for every  $k \in \mathbb{N}$  decides whether or not  $k \in \mathcal{X}$ .* (4) *There is a known algorithm that computes an integer  $n$  satisfying  $\text{card}(\mathcal{X}) < \omega \Rightarrow \mathcal{X} \subseteq (-\infty, n]$ .* (5) *There is a naturally defined condition  $C$ , which can be formalized in ZFC, such that for almost all  $k \in \mathbb{N}$ ,  $k$  satisfies the condition  $C$  if and only if  $k \in \mathcal{X}$ . The simplest known such condition  $C$  defines in  $\mathbb{N}$  the set  $\mathcal{X}$ .* We define a set  $\mathcal{X} \subseteq \mathbb{N}$ . The set  $\mathcal{X}$  satisfies conditions (1)–(5) except the requirement that  $\mathcal{X}$  is naturally defined. The statement  $\Phi$  implies that the set  $\mathcal{X} = \{1\} \cup \mathcal{P}_{n^2+1}$  satisfies conditions (1)–(5). Proving Landau's conjecture will disprove the last two statements. No set  $\mathcal{X} \subseteq \mathbb{N}$  will satisfy conditions (1)–(4) forever, if for every algorithm with no inputs that operates on integers, at some future day, a computer will be able to execute this algorithm in 1 second or less. Physics disproves this assumption.

**2020 Mathematics Subject Classification:** 03D20.

**Key words and phrases:** computable set  $\mathcal{X} \subseteq \mathbb{N}$ , conjecturally infinite set  $\mathcal{X} \subseteq \mathbb{N}$ , current knowledge on  $\mathcal{X}$ , naturally defined set  $\mathcal{X} \subseteq \mathbb{N}$ , no known algorithm decides the finiteness/infiniteness of  $\mathcal{X}$ , physical limits of computation, primes of the form  $n^2 + 1$ .

## 1. Basic definitions and the aim of the article

**Definition 1.** *Conditions (1)–(5) concern sets  $X \subseteq \mathbb{N}$ .*

- (1) *There are many elements of  $X$  and it is conjectured that  $X$  is infinite.*
- (2) *No known algorithm decides the finiteness/infiniteness of  $X$ .*
- (3) *There is a known algorithm that for every  $k \in \mathbb{N}$  decides whether or not  $k \in X$ .*
- (4) *There is a known algorithm that computes an integer  $n$  satisfying  $\text{card}(X) < \omega \Rightarrow X \subseteq (-\infty, n]$ .*
- (5) *There is a naturally defined condition  $C$ , which can be formalized in  $ZFC$ , such that for almost all  $k \in \mathbb{N}$ ,  $k$  satisfies the condition  $C$  if and only if  $k \in X$ . The simplest known such condition  $C$  defines in  $\mathbb{N}$  the set  $X$ .*

**Definition 2.** *We say that an integer  $n$  is a threshold number of a set  $X \subseteq \mathbb{N}$ , if  $\text{card}(X) < \omega \Rightarrow X \subseteq (-\infty, n]$ , cf. [6] and [7].*

If a set  $X \subseteq \mathbb{N}$  is empty or infinite, then any integer  $n$  is a threshold number of  $X$ . If a set  $X \subseteq \mathbb{N}$  is non-empty and finite, then the all threshold numbers of  $X$  form the set  $[\max(X), \infty) \cap \mathbb{N}$ .

Edmund Landau's conjecture states that the set  $\mathcal{P}_{n^2+1}$  of primes of the form  $n^2 + 1$  is infinite, see [3]–[5].

**Definition 3.** *Let  $\Phi$  denote the following unproven statement:*

$$\text{card}(\mathcal{P}_{n^2+1}) < \omega \Rightarrow \mathcal{P}_{n^2+1} \subseteq (-\infty, (((24!)!)!)!]$$

Landau's conjecture implies the statement  $\Phi$ . In Section 4, we heuristically justify the statement  $\Phi$  without invoking Landau's conjecture.

**Statement 1.** *No known algorithm computes an integer  $k$  such that*

$$\text{card}(\mathcal{P}_{n^2+1}) < \omega \Rightarrow \mathcal{P}_{n^2+1} \subseteq (-\infty, k]$$

Proving the statement  $\Phi$  will disprove Statement 1. Statement 1 cannot be formalized in  $ZFC$  because it refers to the current mathematical knowledge. The same is true for Statements 2–4 and for Open Problem 1 on abstract computable sets  $X \subseteq \mathbb{N}$ , see the next sections. Summarizing, Open Problem 1 is a new open problem in computability theory that cannot be formalized in  $ZFC$  and is related to fundamental concepts of mathematics.

## 2. The physical limits of computation inspire Open Problem 1

**Definition 4.** Let  $\beta = (((24!)!)!)!$ .

**Lemma 1.**  $\log_2(\log_2(\log_2(\log_2(\log_2(\log_2(\log_2(\beta))))))) \approx 1.42298$ .

*Proof.* We ask Wolfram Alpha at <http://wolframalpha.com>. □

**Statement 2.** *The set*

$$\mathcal{X} = \{k \in \mathbb{N} : (\beta < k) \Rightarrow (\beta, k) \cap \mathcal{P}_{n^2+1} \neq \emptyset\}$$

*satisfies conditions (1)–(4).*

*Proof.* Condition (1) holds as  $\mathcal{X} \supseteq \{0, \dots, \beta\}$  and the set  $\mathcal{P}_{n^2+1}$  is conjecturally infinite. By Lemma 1, due to known physics we are not able to confirm by a direct computation that some element of  $\mathcal{P}_{n^2+1}$  is greater than  $\beta$ , see [2]. Thus condition (2) holds. Condition (3) holds trivially. Since the set

$$\{k \in \mathbb{N} : (\beta < k) \wedge (\beta, k) \cap \mathcal{P}_{n^2+1} \neq \emptyset\}$$

is empty or infinite, the integer  $\beta$  is a threshold number of  $\mathcal{X}$ . Thus condition (4) holds. □

Let  $[\cdot]$  denote the integer part function. For a non-negative integer  $n$ , let  $g(n)$  denote the number of positive integers  $k$  such that  $n \geq \beta$  and  $2^k$  divides  $2^\beta \cdot \left[\frac{n}{\beta}\right]$ .

**Lemma 2.** *The function  $g : \mathbb{N} \rightarrow \mathbb{N}$  satisfies  $g(0) = \dots = g(\beta - 1) = 0$  and maps  $\mathbb{N} \cap [\beta, \infty)$  onto itself taking every value in  $\mathbb{N} \cap [\beta, \infty)$  infinitely many times.*

**Statement 3.** *The set*

$$\mathcal{X} = \left\{n \in \mathbb{N} : g(n)^2 + 1 \text{ has no divisors greater than } 1 \text{ and smaller than } g(n)^2 + 1\right\}$$

*satisfies conditions (1)–(5) except the requirement that  $\mathcal{X}$  is naturally defined.*

*Proof.* We use Lemma 2 and argue as in the proof of Statement 2. □

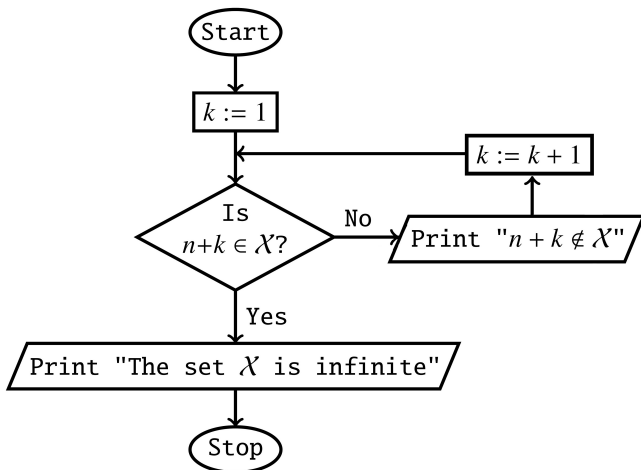
Proving Landau's conjecture will disprove Statements 2 and 3.

**Open Problem 1.** *Is there a set  $\mathcal{X} \subseteq \mathbb{N}$  that satisfies conditions (1)–(5)?*

**Theorem 1.** *No set  $\mathcal{X} \subseteq \mathbb{N}$  will satisfy conditions (1)–(4) forever, if for every algorithm with no inputs that operates on integers, at some future day, a computer will be able to execute this algorithm in 1 second or less.*

*Proof.* The proof goes by contradiction. We fix an integer  $n$  that satisfies condition (4). Since conditions (2)–(4) will hold forever, the semi-algorithm in Figure 1 never terminates and sequentially prints the following sentences:

$$n + 1 \notin \mathcal{X}, n + 2 \notin \mathcal{X}, n + 3 \notin \mathcal{X}, \dots \tag{T}$$



**Fig. 1** A semi-algorithm that halts if and only if the set  $X$  is infinite

The sentences from the sequence (T) and our assumption imply that for every integer  $m > n$  computed by a known algorithm, at some future day, a computer will be able to confirm in 1 second or less that  $(n, m] \cap X = \emptyset$ . Thus, at some future day, numerical evidence will support the conjecture that the set  $X$  is finite, contrary to the conjecture in condition (1).  $\square$

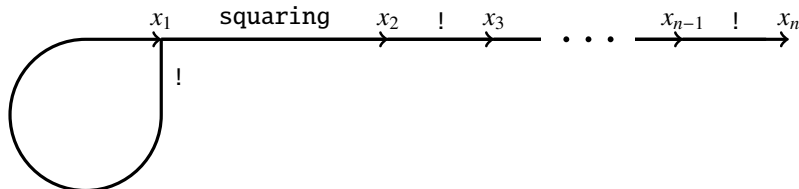
Physics disproves the assumption of Theorem 1.

### 3. Number-theoretic statements $\Psi_n$

Let  $f(1) = 2, f(2) = 4$ , and let  $f(n + 1) = f(n)!$  for every integer  $n \geq 2$ . Let  $\mathcal{U}_1$  denote the system of equations which consists of the equation  $x_1! = x_1$ . For an integer  $n \geq 2$ , let  $\mathcal{U}_n$  denote the following system of equations:

$$\begin{cases} x_1! = x_1 \\ x_1 \cdot x_1 = x_2 \\ \forall i \in \{2, \dots, n-1\} x_i! = x_{i+1} \end{cases}$$

The diagram in Figure 2 illustrates the construction of the system  $\mathcal{U}_n$ .



**Fig. 2** Construction of the system  $\mathcal{U}_n$

**Lemma 3.** For every positive integer  $n$ , the system  $\mathcal{U}_n$  has exactly two solutions in positive integers, namely  $(1, \dots, 1)$  and  $(f(1), \dots, f(n))$ .

Let  $B_n$  denote the following system of equations:

$$\{x_i! = x_k : i, k \in \{1, \dots, n\}\} \cup \{x_i \cdot x_j = x_k : i, j, k \in \{1, \dots, n\}\}$$

For a positive integer  $n$ , let  $\Psi_n$  denote the following statement: *if a system of equations  $\mathcal{S} \subseteq B_n$  has at most finitely many solutions in positive integers  $x_1, \dots, x_n$ , then each such solution  $(x_1, \dots, x_n)$  satisfies  $x_1, \dots, x_n \leq f(n)$ .* The statement  $\Psi_n$  says that for subsystems of  $B_n$  with a finite number of solutions, the largest known solution is indeed the largest possible. The statements  $\Psi_1$  and  $\Psi_2$  hold trivially. There is no reason to assume the validity of the statement  $\forall n \in \mathbb{N} \setminus \{0\} \Psi_n$ .

**Theorem 2.** *For every statement  $\Psi_n$ , the bound  $f(n)$  cannot be decreased.*

*Proof.* It follows from Lemma 3 because  $\mathcal{U}_n \subseteq B_n$ . □

**Theorem 3.** *For every integer  $n \geq 2$ , the statement  $\Psi_{n+1}$  implies the statement  $\Psi_n$ .*

*Proof.* If a system  $\mathcal{S} \subseteq B_n$  has at most finitely many solutions in positive integers  $x_1, \dots, x_n$ , then for every integer  $i \in \{1, \dots, n\}$  the system  $\mathcal{S} \cup \{x_i! = x_{n+1}\}$  has at most finitely many solutions in positive integers  $x_1, \dots, x_{n+1}$ . The statement  $\Psi_{n+1}$  implies that  $x_i! = x_{n+1} \leq f(n+1) = f(n)!$ . Hence,  $x_i \leq f(n)$ . □

**Theorem 4.** *Every statement  $\Psi_n$  is true with an unknown integer bound that depends on  $n$ .*

*Proof.* For every positive integer  $n$ , the system  $B_n$  has a finite number of subsystems. □

## 4. A conjectural solution to Open Problem 1

**Lemma 4.** *For every positive integers  $x$  and  $y$ ,  $x! \cdot y = y!$  if and only if*

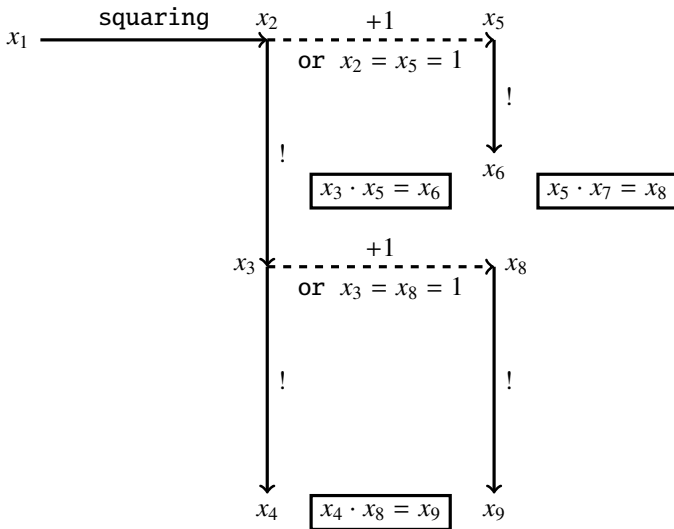
$$(x + 1 = y) \vee (x = y = 1)$$

**Lemma 5.** (*Wilson's theorem*, [1, p. 89]). *For every integer  $x \geq 2$ ,  $x$  is prime if and only if  $x$  divides  $(x - 1)! + 1$ .*

Let  $\mathcal{A}$  denote the following system of equations:

$$\left\{ \begin{array}{l} x_2! = x_3 \\ x_3! = x_4 \\ x_5! = x_6 \\ x_8! = x_9 \\ x_1 \cdot x_1 = x_2 \\ x_3 \cdot x_5 = x_6 \\ x_4 \cdot x_8 = x_9 \\ x_5 \cdot x_7 = x_8 \end{array} \right.$$

Lemma 4 and the diagram in Figure 3 explain the construction of the system  $\mathcal{A}$ .



**Fig. 3** Construction of the system  $\mathcal{A}$

**Lemma 6.** For every integer  $x_1 \geq 2$ , the system  $\mathcal{A}$  is solvable in positive integers  $x_2, \dots, x_9$  if and only if  $x_1^2 + 1$  is prime. In this case, the integers  $x_2, \dots, x_9$  are uniquely determined by the following equalities:

$$\begin{aligned}
 x_2 &= x_1^2 \\
 x_3 &= (x_1^2)! \\
 x_4 &= ((x_1^2)!)! \\
 x_5 &= x_1^2 + 1 \\
 x_6 &= (x_1^2 + 1)! \\
 x_7 &= \frac{(x_1^2)! + 1}{x_1^2 + 1} \\
 x_8 &= (x_1^2)! + 1 \\
 x_9 &= ((x_1^2)! + 1)!
 \end{aligned}$$

*Proof.* By Lemma 4, for every integer  $x_1 \geq 2$ , the system  $\mathcal{A}$  is solvable in positive integers  $x_2, \dots, x_9$  if and only if  $x_1^2 + 1$  divides  $(x_1^2)! + 1$ . Hence, the claim of Lemma 6 follows from Lemma 5.  $\square$

**Lemma 7.** There are only finitely many tuples  $(x_1, \dots, x_9) \in (\mathbb{N} \setminus \{0\})^9$ , which solve the system  $\mathcal{A}$  and satisfy  $x_1 = 1$ . This is true as every such tuple  $(x_1, \dots, x_9)$  satisfies  $x_1, \dots, x_9 \in \{1, 2\}$ .

*Proof.* The equality  $x_1 = 1$  implies that  $x_2 = x_1 \cdot x_1 = 1$ . Hence,  $x_3 = x_2! = 1$ . Therefore,  $x_4 = x_3! = 1$ . The equalities  $x_5! = x_6$  and  $x_5 = 1 \cdot x_5 = x_3 \cdot x_5 = x_6$  imply that  $x_5, x_6 \in \{1, 2\}$ . The equalities  $x_8! = x_9$  and  $x_8 = 1 \cdot x_8 = x_4 \cdot x_8 = x_9$  imply that  $x_8, x_9 \in \{1, 2\}$ . The equality  $x_5 \cdot x_7 = x_8$  implies that  $x_7 = \frac{x_8}{x_5} \in \left\{ \frac{1}{1}, \frac{1}{2}, \frac{2}{1}, \frac{2}{2} \right\} \cap \mathbb{N} = \{1, 2\}$ .  $\square$

**Conjecture 1.** *The statement  $\Psi_9$  is true when is restricted to the system  $\mathcal{A}$ .*

**Theorem 5.** *Conjecture 1 proves the following implication: if there exists an integer  $x_1 \geq 2$  such that  $x_1^2 + 1$  is prime and greater than  $f(7)$ , then the set  $\mathcal{P}_{n^2+1}$  is infinite.*

*Proof.* Suppose that the antecedent holds. By Lemma 6, there exists a unique tuple  $(x_2, \dots, x_9) \in (\mathbb{N} \setminus \{0\})^8$  such that the tuple  $(x_1, x_2, \dots, x_9)$  solves the system  $\mathcal{A}$ . Since  $x_1^2 + 1 > f(7)$ , we obtain that  $x_1^2 \geq f(7)$ . Hence,  $(x_1^2)! \geq f(7)! = f(8)$ . Consequently,

$$x_9 = ((x_1^2)! + 1)! \geq (f(8) + 1)! > f(8)! = f(9)$$

Conjecture 1 and the inequality  $x_9 > f(9)$  imply that the system  $\mathcal{A}$  has infinitely many solutions  $(x_1, \dots, x_9) \in (\mathbb{N} \setminus \{0\})^9$ . According to Lemmas 6 and 7, the set  $\mathcal{P}_{n^2+1}$  is infinite.  $\square$

**Theorem 6.** *Conjecture 1 implies the statement  $\Phi$ .*

*Proof.* It follows from Theorem 5 and the equality  $f(7) = (((24!)!)!)!$ .  $\square$

**Theorem 7.** *The statement  $\Phi$  implies Conjecture 1.*

*Proof.* By Lemmas 6 and 7, if positive integers  $x_1, \dots, x_9$  solve the system  $\mathcal{A}$ , then

$$(x_1 \geq 2) \wedge (x_5 = x_1^2 + 1) \wedge (x_5 \text{ is prime})$$

or  $x_1, \dots, x_9 \in \{1, 2\}$ . In the first case, Lemma 6 and the statement  $\Phi$  imply that the inequality  $x_5 \leq (((24!)!)!)! = f(7)$  holds when the system  $\mathcal{A}$  has at most finitely many solutions in positive integers  $x_1, \dots, x_9$ . Hence,  $x_2 = x_5 - 1 < f(7)$  and  $x_3 = x_2! < f(7)! = f(8)$ . Continuing this reasoning in the same manner, we can show that every  $x_i$  does not exceed  $f(9)$ .  $\square$

**Statement 4.** *The statement  $\Phi$  implies that the set  $\mathcal{X} = \{1\} \cup \mathcal{P}_{n^2+1}$  satisfies conditions (1)–(5).*

*Proof.* The set  $\mathcal{P}_{n^2+1}$  is conjecturally infinite. There are 2199894223892 primes of the form  $n^2 + 1$  in the interval  $[2, 10^{28})$ , see [4]. These two facts imply condition (1). By Lemma 1, due to known physics we are not able to confirm by a direct computation that some element of  $\{1\} \cup \mathcal{P}_{n^2+1}$  is greater than  $f(7) = (((24!)!)!)! = \beta$ , see [2]. Thus condition (2) holds. Condition (3) holds trivially. The statement  $\Phi$  implies that  $\beta$  is a threshold number of  $\mathcal{X} = \{1\} \cup \mathcal{P}_{n^2+1}$ . Thus condition (4) holds. The following condition:

*$k - 1$  is a square and  $k$  has no divisors greater than 1 and smaller than  $k$*

defines in  $\mathbb{N}$  the set  $\{1\} \cup \mathcal{P}_{n^2+1}$ . This proves condition (5).  $\square$

Proving Landau's conjecture will disprove Statement 4.

**Acknowledgment.** Sławomir Kurpaska prepared three diagrams in TikZ. Apolnusz Tyszka wrote the article.

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