The Predicate of the Current Mathematical Knowledge Substantially Increases the Constructive and Informal Mathematics and Why It Cannot Be Adapted to Any Empirical Science

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Abstract: We assume that the current mathematical knowledge $\mathcal{K}$ is a finite set of statements in the public domain which is time-dependent. This set exists only theoretically. Ignoring $\mathcal{K}$ and its subsets, sets exist formally in *ZFC* theory although their properties can be time-dependent (when they depend on $\mathcal{K}$) or informal. In every branch of mathematics, the set of all knowable truths is the set of all theorems. This set exists independently of $\mathcal{K}$. Algorithms always terminate. We explain the distinction between algorithms whose existence is provable in *ZFC* and constructively defined algorithms which are currently known. By using this distinction, we obtain non-trivial statements on decidable sets $X \subseteq \mathbb{N}$ that belong to constructive and informal mathematics and refer to the current mathematical knowledge on X. This and the next sentence justify the article title. For any empirical science, we can identify the current knowledge with that science because truths from the empirical sciences are not necessary truths but working models of truth from a particular context.

Keywords: conjecturally infinite sets $X \subseteq \mathbb{N}$; constructive algorithms; current mathematical knowledge; informal notions; known algorithms; known elements of $\mathbb{N}$

MSC: 03A05; 03F55

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1. Introduction and Why Such Title of the Article

This article is a continuation of [16]–[18]. The main mathematical results of this article were presented at the 25th Conference Applications of Logic in Philosophy and the Foundations of Mathematics, see http://applications-of-logic.uni.wroc.pl/XXV-Konferencja-Zastosowania-Logiki-w-Filozofii-i-Podstawach-Matematyki. We assume that the current mathematical knowledge $\mathcal{K}$ is a finite set of statements in the public domain which is time-dependent. This set exists only theoretically. Ignoring $\mathcal{K}$ and its subsets, sets exist formally in *ZFC* theory although their properties can be time-dependent (when they depend on $\mathcal{K}$) or informal. In every branch of mathematics, the set of all knowable truths is the set of all theorems. This set exists independently of $\mathcal{K}$. Algorithms always terminate. We explain the distinction between algorithms whose existence is provable in *ZFC* and constructively defined algorithms which are currently known. By using this distinction, we obtain non-trivial statements on decidable sets $X \subseteq \mathbb{N}$ that belong to constructive and informal mathematics and refer to the current mathematical knowledge on X. This and the next sentence justify the article title. For any empirical science, we can identify the current knowledge with that science because truths from the empirical sciences are not necessary truths but working models of truth from a particular context, see [19, p. 610].

2. Summary of the Main Mathematical Results

For a set $X \subseteq \mathbb{N}$ whose infiniteness is false or unproven, we define which elements of X are classified as known. No known set $X \subseteq \mathbb{N}$ satisfies Conditions `(1)-(4)` and is widely known in number theory or naturally defined, where this term has only informal meaning.

`(1)` A known algorithm with no input returns an integer n satisfying $\mathrm{card}(X) < \omega \Rightarrow X \subseteq (-\infty, n]$.

(2) A known algorithm for every $k \in \mathbb{N}$ decides whether or not $k \in \mathcal{X}$.

(3) No known algorithm with no input returns the logical value of the statement $\text{card}(\mathcal{X}) = \omega$.

(4) There are many elements of $\mathcal{X}$ and it is conjectured, though so far unproven, that $\mathcal{X}$ is infinite.

(5) $\mathcal{X}$ is naturally defined. The infiniteness of $\mathcal{X}$ is false or unproven. $\mathcal{X}$ has the simplest definition among known sets $\mathcal{Y} \subseteq \mathbb{N}$ with the same set of known elements.

We prove that the set

$$\mathcal{X} = \{n \in \mathbb{N} : \textit{the interval } [-1, n] \textit{ contains more than}$$

$$\frac{11!}{3n+1} \cdot \sin(n) \textit{ primes of the form } k! + 1\}$$

satisfies Conditions (1)–(5) except the requirement that $\mathcal{X}$ is naturally defined. If we add to $\mathcal{X}$ some set $\mathcal{W}$ satisfying $14 \leqslant \text{card}(\mathcal{W}) \leqslant 23$, then the following statements hold:

$\mathcal{X}$ does not satisfy Condition (1),

$159827 + 14 \leqslant \text{card}(\mathcal{X})$,

the above lower bound is currently the best known,

$\text{card}(\mathcal{X}) < \omega \Rightarrow \text{card}(\mathcal{X}) \leqslant 159827 + 23$,

the above upper bound is currently the best known,

$\mathcal{X}$ satisfies Conditions (2)–(5) except the requirement that $\mathcal{X}$ is naturally defined.

We present a table that shows satisfiable conjunctions of the form

$$\#(\text{Condition 1}) \wedge (\text{Condition 2}) \wedge \#(\text{Condition 3}) \wedge (\text{Condition 4}) \wedge \#(\text{Condition 5})$$

where # denotes the negation ¬ or the absence of any symbol.

3. Basic Definitions and Examples

Algorithms always terminate. Semi-algorithms may not terminate. There is the distinction between *existing algorithms* (i.e. algorithms whose existence is provable in *ZFC*) and *known algorithms* (i.e. algorithms whose definition is constructive and currently known), see [2], [10], [12, p. 9]. A definition of an integer n is called *constructive*, if it provides a known algorithm with no input that returns n. Definition 1 applies to sets $\mathcal{X} \subseteq \mathbb{N}$ whose infiniteness is false or unproven.

Definition 1. *We say that a non-negative integer k is a known element of $\mathcal{X}$, if $k \in \mathcal{X}$ and we know an algebraic expression that defines k and consists of the following signs: 1 (one), $+$ (addition), $-$ (subtraction), $\cdot$ (multiplication), $\hat{}$ (exponentiation with exponent in $\mathbb{N}$), $!$ (factorial of a non-negative integer), $($ (left parenthesis), $)$ (right parenthesis).*

The set of known elements of $\mathcal{X}$ is finite and time-dependent, so cannot be defined in the formal language of classical mathematics. Let t denote the largest twin prime that is smaller than $(((((((((9!)!)!)!)!)!)!)!)!$. The number t is an unknown element of the set of twin primes.

Definition 2. *Conditions* (1) – (5) *concern sets* $X \subseteq \mathbb{N}$.

(1) *A known algorithm with no input returns an integer n satisfying* $\mathrm{card}(X) < \omega \Rightarrow X \subseteq (-\infty, n]$.

(2) *A known algorithm for every* $k \in \mathbb{N}$ *decides whether or not* $k \in X$.

(3) *No known algorithm with no input returns the logical value of the statement* $\mathrm{card}(X) = \omega$.

(4) *There are many elements of X and it is conjectured, though so far unproven, that X is infinite.*

(5) *X is naturally defined. The infiniteness of X is false or unproven. X has the simplest definition among known sets* $\mathcal{Y} \subseteq \mathbb{N}$ *with the same set of known elements.*

Condition (3) implies that no known proof shows the finiteness/infiniteness of X. No known set $X \subseteq \mathbb{N}$ satisfies Conditions (1) – (4) and is widely known in number theory or naturally defined, where this term has only informal meaning.

Let $[\cdot]$ denote the integer part function.

Example 1. *The set* $X = \begin{cases} \mathbb{N}, & \text{if } \left[\frac{(((((((((9!)!)!)!)!)!)!)!)!}{\pi}\right] \text{ is odd} \\ \emptyset, & \text{otherwise} \end{cases}$ *does not satisfy Condition* (3) *because we know an algorithm with no input that computes* $\left[\frac{(((((((((9!)!)!)!)!)!)!)!)!}{\pi}\right]$. *The set of known elements of X is empty. Hence, Condition* (5) *fails for X.*

Example 2. *(*[2]*,* [10]*,* [12, p. 9]*). The function*

$$\mathbb{N} \ni n \xrightarrow{h} \begin{cases} 1, & \text{if the decimal expansion of } \pi \text{ contains } n \text{ consecutive zeros} \\ 0, & \text{otherwise} \end{cases}$$

is computable because $h = \mathbb{N} \times \{1\}$ *or there exists* $k \in \mathbb{N}$ *such that*

$$h = (\{0, \ldots, k\} \times \{1\}) \cup (\{k+1, \ k+2, \ k+3, \ \ldots\} \times \{0\})$$

No known algorithm computes the function h.

Example 3. *The set*
$$X = \begin{cases} \mathbb{N}, & \text{if the continuum hypothesis holds} \\ \emptyset, & \text{otherwise} \end{cases}$$

is decidable. This X satisfies Conditions (1) *and* (3) *and does not satisfy Conditions* (2), (4), *and* (5). *These facts will hold forever.*

4. Number-theoretic results

Edmund Landau's conjecture states that the set $\mathcal{P}_{n^2+1}$ of primes of the form $n^2 + 1$ is infinite, see [14,15,21].

Statement 1. *Condition* (1) *remains unproven for* $X = \mathcal{P}_{n^2+1}$.

Proof. For every set $X \subseteq \mathbb{N}$, there exists an algorithm $\mathtt{Alg}(X)$ with no input that returns

$$n = \begin{cases} 0, & \text{if } \mathrm{card}(X) \in \{0, \omega\} \\ \max(X), & \text{otherwise} \end{cases}$$

This n satisfies the implication in Condition (1), but the algorithm $\mathtt{Alg}(\mathcal{P}_{n^2+1})$ is unknown because its definition is ineffective. □

Statement 2. *The statement*

$$\exists n \in \mathbb{N} \ (\mathrm{card}(\mathcal{P}_{n^2+1}) < \omega \Rightarrow \mathcal{P}_{n^2+1} \subseteq [2, n+3])$$

remains unproven in ZFC and classical logic without the law of excluded middle.

Let $f(1) = 10^6$, and let $f(n+1) = f(n)^{f(n)}$ for every positive integer n.

Statement 3. *The set*

$$X = \{k \in \mathbb{N} : (10^6 < k) \Rightarrow (f(10^6), f(k)) \cap \mathcal{P}_{n^2+1} \neq \emptyset\}$$

satisfies Conditions (1)–(4)*. Condition* (5) *fails for* X.

Proof. Condition (4) holds as $X \supseteq \{0, \ldots, 10^6\}$ and the set $\mathcal{P}_{n^2+1}$ is conjecturally infinite. 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 $f(10^6)$, see [7]. Thus Condition (3) holds. Condition (2) holds trivially. Since the set

$$\{k \in \mathbb{N} : (10^6 < k) \wedge (f(10^6), f(k)) \cap \mathcal{P}_{n^2+1} \neq \emptyset\}$$

is empty or infinite, Condition (1) holds with $n = 10^6$. Condition (5) fails as the set of known elements of X equals $\{0, \ldots, 10^6\}$. □

Statements 4 and 7 provide stronger examples.

Conjecture 1. *([1,4, p. 443]). The are infinitely many primes of the form $k! + 1$.*

For a non-negative integer n, let $\rho(n)$ denote $29.5 + \dfrac{11!}{3n+1} \cdot \sin(n)$.

Statement 4. *The set*

$$X = \{n \in \mathbb{N} : \text{the interval } [-1, n] \text{ contains more than } \rho(n) \text{ primes of the form } k! + 1\}$$

satisfies Conditions (1)–(5) *except the requirement that X is naturally defined. $501893 \in X$. Condition* (1) *holds with $n = 501893$. $\mathrm{card}(X \cap [0, 501893]) = 159827$. $X \cap [501894, \infty) = \{n \in \mathbb{N} : \text{the interval } [-1, n]$ contains at least 30 primes of the form $k! + 1\}$.*

Proof. For every integer $n \geq 11!$, 30 is the smallest integer greater than $\rho(n)$. By this, if $n \in X \cap [11!, \infty)$, then $n+1$, $n+2$, $n+3$, ... $\in X$. Hence, Condition (1) holds with $n = 11! - 1$. We explicitly know 24 positive integers k such that $k! + 1$ is prime, see [3]. The inequality $\mathrm{card}(\{k \in \mathbb{N} \setminus \{0\} : k! + 1 \text{ is prime}\}) > 24$ remains unproven. Since $24 < 30$, Condition (3) holds. The interval $[-1, 11! - 1]$ contains exactly three primes of the form $k! + 1$: $1! + 1$, $2! + 1$, $3! + 1$. For every integer $n > 503000$, the inequality $\rho(n) > 3$ holds. Therefore, the execution of the following *MuPAD* code

```
m:=0:
for n from 0.0 to 503000.0 do
if n<1!+1 then r:=0 end_if:
if n>=1!+1 and n<2!+1 then r:=1 end_if:
if n>=2!+1 and n<3!+1 then r:=2 end_if:
if n>=3!+1 then r:=3 end_if:
if r>29.5+(11!/(3*n+1))*sin(n) then
m:=m+1:
```

```
    print([n,m]):
    end_if:
    end_for:
```

displays the all known elements of X. The output ends with the line $[501893.0, \ 159827]$, which proves Condition (1) with $n = 501893$ and Condition (4) with $\mathrm{card}(X) \geqslant 159827$.   □

T. Nagell proved in [8] (cf. [13, p. 104]) that the equation $x^2 - 17 = y^3$ has exactly 16 integer solutions, namely $(\pm 3, -2)$, $(\pm 4, -1)$, $(\pm 5, 2)$, $(\pm 9, 4)$, $(\pm 23, 8)$, $(\pm 282, 43)$, $(\pm 375, 52)$, $(\pm 378661, 5234)$. The set

$$\bigcup_{\substack{(x,y) \in \mathbb{Z} \times \mathbb{Z} \\ (x^2 - y^3 - 17) \cdot (y^2 - x^3 - 17) = 0}} \{(x+8)^8\}$$

has exactly 23 elements. Among them, there are 14 integers from the interval $[1, 2199894223892]$. Let $\mathcal{W}$ denote the set

$$\bigcup_{\substack{(x,y) \in \mathbb{Z} \times \mathbb{Z} \\ (x^2 - y^3 - 17) \cdot (y^2 - x^3 - 17) = 0}} \{k \in \mathbb{N} : \ k \text{ is the } (x+8)^8 - th \text{ element of } \mathcal{P}_{n^2+1}\}$$

From [15], it is known that $\mathrm{card}(\mathcal{P}_{n^2+1} \cap [2, 10^{28})) = 2199894223892$. Hence, $\mathrm{card}(\mathcal{W} \cap [2, 10^{28})) = 14$ and 14 elements of $\mathcal{W}$ can be practically computed. The inequality $\mathrm{card}(\mathcal{P}(n^2 + 1)) \geqslant (378661 + 8)^8$ remains unproven. The last two sentences and Statement 4 imply the following corollary.

Corollary 1. *If we add $\mathcal{W}$ to X, then the following statements hold:*

  X does not satisfy Condition (1),

  $159827 + 14 \leqslant \mathrm{card}(X)$,

  the above lower bound is currently the best known,

  $\mathrm{card}(X) < \omega \Rightarrow \mathrm{card}(X) \leqslant 159827 + 23$,

  the above upper bound is currently the best known,

  X satisfies Conditions (2) − (5) *except the requirement that X is naturally defined.*

Definition 3. *Conditions* (1a) − (5a) *concern sets $X \subseteq \mathbb{N}$.*
(1a) *A known algorithm with no input returns a positive integer n satisfying $\mathrm{card}(X) < \omega \Rightarrow X \subseteq (-\infty, n]$.*
(2a) *A known algorithm for every $k \in \mathbb{N}$ decides whether or not $k \in X$.*
(3a) *No known algorithm with no input returns the logical value of the statement $\mathrm{card}(X) < \omega$.*
(4a) *There are many elements of X and it is conjectured, though so far unproven, that X is finite.*
(5a) *X is naturally defined. The finiteness of X is false or unproven. X has the simplest definition among known sets $\mathcal{Y} \subseteq \mathbb{N}$ with the same set of known elements.*

Statement 5. *The set*

$$X = \left\{ n \in \mathbb{N} : \ the \ interval \ [-1, n] \ contains \ more \ than \right.$$

$$\left. 6.5 + \frac{10^6}{3n+1} \cdot \sin(n) \ squares \ of \ the \ form \ k! + 1 \right\}$$

satisfies Conditions (1a) − (5a) *except the requirement that X is naturally defined.* $95151 \in X$. *Condition* (1a) *holds with $n = 95151$.* $\mathrm{card}(X \cap [0, 95151]) = 30311$. $X \cap [95152, \infty) = \{n \in \mathbb{N} : the \ interval \ [-1, n] \ contains \ at \ least \ 7 \ squares \ of \ the \ form \ k! + 1\}$.

Proof. For every integer $n > 10^6$, 7 is the smallest integer greater than $6.5 + \frac{10^6}{3n+1} \cdot \sin(n)$. By this, if $n \in X \cap (10^6, \infty)$, then $n+1$, $n+2$, $n+3$, ... $\in X$. Hence, Condition (1a) holds with $n = 10^6$. It is conjectured that $k! + 1$ is a square only for $k \in \{4, 5, 7\}$, see [20, p. 297]. Hence, the inequality $\text{card}(\{k \in \mathbb{N} \setminus \{0\} : k! + 1 \text{ is a square}\}) > 3$ remains unproven. Since $3 < 7$, Condition (3a) holds. The interval $[-1, 10^6]$ contains exactly three squares of the form $k! + 1$: $4! + 1$, $5! + 1$, $7! + 1$. Therefore, the execution of the following *MuPAD* code

```
m:=0:
for n from 0.0 to 1000000.0 do
if n<25 then r:=0 end_if:
if n>=25 and n<121 then r:=1 end_if:
if n>=121 and n<5041 then r:=2 end_if:
if n>=5041 then r:=3 end_if:
if r>6.5+(1000000/(3*n+1))*sin(n) then
m:=m+1:
print([n,m]):
end_if:
end_for:
```

displays the all known elements of X. The output ends with the line $[95151.0, 30311]$, which proves Condition (1a) with $n = 95151$ and Condition (4a) with $\text{card}(X) \geqslant 30311$. □

Statement 6. *The set*

$$X = \{k \in \mathbb{N} : \text{card}([-1, k] \cap \mathcal{P}_{n^2+1}) < 10^{10000}\}$$

satisfies the conjunction

$$\neg(\textit{Condition 1a}) \wedge (\textit{Condition 2a}) \wedge (\textit{Condition 3a}) \wedge (\textit{Condition 4a}) \wedge (\textit{Condition 5a})$$

To formulate Statement 7 and its proof, we need some lemmas. For a non-negative integer n, let $\theta(n)$ denote the largest integer divisor of $10^{10^{10}}$ smaller than n. For a non-negative integer n, let $\theta_1(n)$ denote the largest integer divisor of 10^{10} smaller than n.

Lemma 1. *For every integer $j > 10^{10^{10}}$, $\theta(j) = 10^{10^{10}}$. For every integer $j > 10^{10}$, $\theta_1(j) = 10^{10}$.*

Lemma 2. *For every integer $j \in (6553600, 7812500]$, $\theta(j) = 6553600$.*

Proof. 6553600 equals $2^{18} \cdot 5^2$ and divides $10^{10^{10}}$. $7812500 < 2^{24}$. $7812500 < 5^{10}$. We need to prove that every integer $j \in (6553600, 7812500)$ does not divide $10^{10^{10}}$. It holds as the set

$$\left\{ 2^u \cdot 5^v : (u \in \{0, \ldots, 23\}) \wedge (v \in \{0, \ldots, 9\}) \right\}$$

contains 6553600 and 7812500 as consecutive elements. □

Lemma 3. *The number $6553600^2 + 1$ is prime.*

Proof. The following PARI/GP ([9]) command

```
isprime(6553600^2+1,{flag=2})
```

returns 1. This command performs the APRCL primality test, the best deterministic primality test algorithm ([22, p. 226]). It rigorously shows that the number $6553600^2 + 1$ is prime. □

In the next lemmas, the execution of the command `isprime(n,{flag=2})` proves the primality of n. Let κ denote the function

$$\mathbb{N} \ni n \xrightarrow{\kappa} \text{the exponent of } 2 \text{ in the prime factorization of } \underbrace{n+1} \in \mathbb{N}$$

Lemma 4. *The set* $X_1 = \{n \in \mathbb{N} : (\theta_1(n) + \kappa(n))^2 + 1 \text{ is prime}\}$ *is infinite.*

Proof. Let $i = 142101504$. By the inequality $2^i \geqslant 2 + 10^{10}$ and Lemma 1, for every non-negative integer m, the number

$$\left(\theta_1\left(2^i \cdot (2m+1) - 1\right) + \kappa\left(2^i \cdot (2m+1) - 1\right)\right)^2 + 1 = \left(10^{10} + i\right)^2 + 1$$

is prime. $\square$

Before Open Problem 1, X denotes the set $\{n \in \mathbb{N} : (\theta(n) + \kappa(n))^2 + 1 \text{ is prime}\}$.

Lemma 5. *For every* $n \in X \cap \left(10^{10^{10}}, \infty\right)$ *and for every non-negative integer* j, $3^j \cdot (n+1) - 1 \in X \cap \left(10^{10^{10}}, \infty\right)$.

Proof. By the inequality $3^j \cdot (n+1) - 1 \geqslant n$ and Lemma 1,

$$\theta\left(3^j \cdot (n+1) - 1\right) + \kappa\left(3^j \cdot (n+1) - 1\right) = 10^{10^{10}} + \kappa(n) = \theta(n) + \kappa(n)$$

$\square$

Lemma 6. $\text{card}(X) \geqslant 629450$.

Proof. By Lemmas 2 and 3, for every even integer $j \in (6553600, 7812500]$, the number $(\theta(j) + \kappa(j))^2 + 1 = (6553600 + 0)^2 + 1$ is prime. Hence,

$$\{2k : k \in \mathbb{N}\} \cap (6553600, 7812500] \subseteq X$$

Consequently,

$$\text{card}(X) \geqslant \text{card}(\{2k : k \in \mathbb{N}\} \cap (6553600, 7812500]) = \frac{7812500 - 6553600}{2} = 629450$$

$\square$

Lemma 7. $10242 \in X$ *and* $10242 \notin X_1$.

Proof. The number $10240 = 2^{11} \cdot 5$ divides $10^{10^{10}}$. Hence, $\theta(10242) = 10240$. The number $(\theta(10242) + \kappa(10242))^2 + 1 = (10240 + 0)^2 + 1$ is prime. The set

$$\left\{2^u \cdot 5^v : (u \in \{0, \ldots, 10\}) \wedge (v \in \{0, \ldots, 10\})\right\}$$

contains 10000 and 12500 as consecutive elements. Hence, $\theta_1(10242) = 10000$. The number $(\theta_1(10242) + \kappa(10242))^2 + 1 = (10000 + 0)^2 + 1 = 17 \cdot 5882353$ is composite. $\square$

Statement 7. *The set* X *satisfies Conditions* (1) − (5) *except the requirement that* X *is naturally defined.*

Proof. Condition (2) holds trivially. Let δ denote $10^{10^{10}}$. By Lemma 5, Condition (1) holds for $n = \delta$. Lemma 5 and the unproven statement $\mathcal{P}_{n^2+1} \cap \left[\delta^2 + 1, \infty\right) \neq \emptyset$ show Condition (3). The same argument and Lemma 6 yield Condition (4). By Lemma 4, the set $\mathcal{X}_1$ is infinite. Since Definition 1 applies to sets $X \subseteq \mathbb{N}$ whose infiniteness is false or unproven, Condition (5) holds except the requirement that X is naturally defined. □

The set X satisfies Condition (5) except the requirement that X is naturally defined. It is true because $\mathcal{X}_1$ is infinite by Lemma 4 and Definition 1 applies only to sets $X \subseteq \mathbb{N}$ whose infiniteness is false or unproven. Ignoring this restriction, X still satisfies the same identical condition due to Lemma 7.

Proposition 1. *No set $X \subseteq \mathbb{N}$ will satisfy Conditions* (1) – (4) *forever, if for every algorithm with no input, 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 (1). Since Conditions (1) – (3) will hold forever, the semi-algorithm in Figure 1 never terminates and sequentially prints the following sentences:

$$n + 1 \notin X, \; n + 2 \notin X, \; n + 3 \notin X, \; \ldots \tag{T}$$
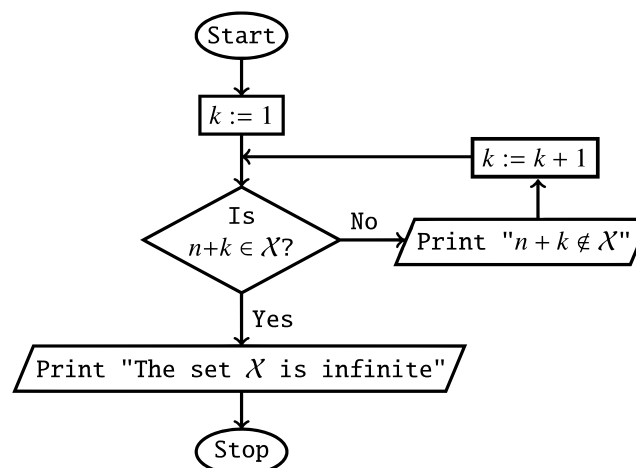
Figure 1. Semi-algorithm that terminates if and only if X is infinite

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 (4). □

The physical limits of computation ([7]) disprove the assumption of Proposition 1.

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

Open Problem 1 asks about the existence of a year $t \geqslant 2023$ in which the conjunction

$$(Condition\ 1) \wedge (Condition\ 2) \wedge (Condition\ 3) \wedge (Condition\ 4) \wedge (Condition\ 5)$$

will hold for some $X \subseteq \mathbb{N}$. For every year $t \geqslant 2023$ and for every $i \in \{1, 2, 3\}$, a positive solution to Open Problem i in the year t may change in the future. Currently, the answers to Open Problems 1–5 are negative.

5. Satisfiable Conjunctions Which Consist of Conditions (1)-(5) **and Their Negations**

The set $X = \mathcal{P}_{n^2+1}$ satisfies the conjunction

$$\neg(Condition\ 1) \wedge (Condition\ 2) \wedge (Condition\ 3) \wedge (Condition\ 4) \wedge (Condition\ 5)$$

The set $X = \{0, \ldots, 10^6\} \cup \mathcal{P}_{n^2+1}$ satisfies the conjunction

$$\neg(Condition\ 1) \wedge (Condition\ 2) \wedge (Condition\ 3) \wedge (Condition\ 4) \wedge \neg(Condition\ 5)$$

The numbers $2^{2^k} + 1$ are prime for $k \in \{0, 1, 2, 3, 4\}$. It is open whether or not there are infinitely many primes of the form $2^{2^k} + 1$, see [6, p. 158] and [11, p. 74]. It is open whether or not there are infinitely many composite numbers of the form $2^{2^k} + 1$, see [6, p. 159] and [11, p. 74]. Most mathematicians believe that $2^{2^k} + 1$ is composite for every integer $k \geqslant 5$, see [5, p. 23]. The set

$$X = \begin{cases} \mathbb{N}, & if\ 2^{2^{f(9^9)}} + 1\ is\ composite \\ \{0, \ldots, 10^6\}, & otherwise \end{cases}$$

satisfies the conjunction

$$(Condition\ 1) \wedge (Condition\ 2) \wedge \neg(Condition\ 3) \wedge (Condition\ 4) \wedge \neg(Condition\ 5)$$

Open Problem 2. *Is there a set $X \subseteq \mathbb{N}$ that satisfies the conjunction*

$$(Condition\ 1) \wedge (Condition\ 2) \wedge \neg(Condition\ 3) \wedge (Condition\ 4) \wedge (Condition\ 5)?$$

The set

$$X = \begin{cases} \mathbb{N}, & if\ 2^{2^{f(9^9)}} + 1\ is\ composite \\ \{0, \ldots, 10^6\} \cup \\ \{n \in \mathbb{N} : n\ is\ the\ sixth\ prime\ number\ of\ the\ form\ 2^{2^k} + 1\}, & otherwise \end{cases}$$

satisfies the conjunction

$$\neg(Condition\ 1) \wedge (Condition\ 2) \wedge \neg(Condition\ 3) \wedge (Condition\ 4) \wedge \neg(Condition\ 5)$$

Open Problem 3. *Is there a set $X \subseteq \mathbb{N}$ that satisfies the conjunction*

$$\neg(Condition\ 1) \wedge (Condition\ 2) \wedge \neg(Condition\ 3) \wedge (Condition\ 4) \wedge (Condition\ 5)?$$

It is possible, although very doubtful, that at some future day, the set $X = \mathcal{P}_{n^2+1}$ will solve Open Problem 2. The same is true for Open Problem 3. It is possible, although very doubtful, that at some future day, the set $X = \{k \in \mathbb{N} : 2^{2^k} + 1\ is\ composite\}$ will solve Open Problem 1. The same is true for Open Problems 2 and 3.

Table 1 shows satisfiable conjunctions of the form

$$\#(Condition\ 1) \wedge (Condition\ 2) \wedge \#(Condition\ 3) \wedge (Condition\ 4) \wedge \#(Condition\ 5)$$

where # denotes the negation $\neg$ or the absence of any symbol.

Table 1. Five satisfiable conjunctions.

	(Cond. 2) ∧ (Cond. 3) ∧ (Cond. 4)	(Cond. 2) ∧ ¬(Cond. 3) ∧ (Cond. 4)
(Cond. 1) ∧ (Cond. 5)	Open Problem 1	Open Problem 2
(Cond. 1) ∧ ¬(Cond. 5)	$\mathcal{X} = \{n \in \mathbb{N} : \text{ the interval } [-1, n] \text{ contains more than } 29.5 + \frac{11!}{3n+1} \cdot \sin(n) \text{ primes of the form } k! + 1\}$	$\mathcal{X} = \begin{cases} \mathbb{N}, \text{ if } 2^{2^{f(9^9)}} + 1 \text{ is composite} \\ \{0, \ldots, 10^6\}, \text{ otherwise} \end{cases}$
¬(Cond. 1) ∧ (Cond. 5)	$\mathcal{X} = \mathcal{P}_{n^2+1}$	Open Problem 3
¬(Cond. 1) ∧ ¬(Cond. 5)	$\mathcal{X} = \{0, \ldots, 10^6\} \cup \mathcal{P}_{n^2+1}$	$\mathcal{X} = \begin{cases} \mathbb{N}, \text{ if } 2^{2^{f(9^9)}} + 1 \text{ is composite} \\ \{0, \ldots, 10^6\} \cup \{n \in \mathbb{N} : n \text{ is} \\ \text{the sixth prime number of} \\ \text{the form } 2^{2^k} + 1\}, \text{ otherwise} \end{cases}$

Definition 4. *We say that an integer n is a threshold number of a set $\mathcal{X} \subseteq \mathbb{N}$, if $\mathrm{card}(\mathcal{X}) < \omega \Rightarrow \mathcal{X} \subseteq (-\infty, n]$.*

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

Open Problem 4. *Is there a known threshold number of $\mathcal{P}_{n^2+1}$?*

Open Problem 4 asks about the existence of a year $t \geqslant 2023$ in which the implication $\mathrm{card}(\mathcal{P}_{n^2+1}) < \omega \Rightarrow \mathcal{P}_{n^2+1} \subseteq (-\infty, n]$ will hold for some known integer n.

Let $\mathcal{T}$ denote the set of twin primes.

Open Problem 5. *Is there a known threshold number of $\mathcal{T}$?*

Open Problem 5 asks about the existence of a year $t \geqslant 2023$ in which the implication $\mathrm{card}(\mathcal{T}) < \omega \Rightarrow \mathcal{T} \subseteq (-\infty, n]$ will hold for some known integer n.

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