On ZFC-formulae $\varphi(x)$ for which we know a non-negative integer n such that $\{x \in \mathbb{N}\colon \varphi(x)\} \subseteq \{x \in \mathbb{N}\colon x \leqslant n-1\}$ if the set $\{x \in \mathbb{N}\colon \varphi(x)\}$ is finite

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Abstract

We say that a non-negative integer m is a threshold number of a set $\mathcal{X} \subseteq \mathbb{N}$, if $\mathcal{X}$ is infinite if and only if $\mathcal{X}$ contains an element greater than m. We formulate hypothetical statements $\Psi_3, \ldots, \Psi_{16}$. The statement Ψ_9 implies that a simple formula computes a gigantic threshold number of the set of primes of the form n^2+1. The statement Ψ_9 implies that a simple formula computes a gigantic threshold number of the set of primes of the form $n!+1$. The statement Ψ_{16} implies that a simple formula computes a gigantic threshold number of the set of twin primes. The following problem is open: define a set $\mathcal{X} \subseteq \mathbb{N}$ that satisfies the following conditions: (1) a known algorithm for every $n \in \mathbb{N}$ decides whether or not $n \in \mathcal{X}$, (2) a known algorithm returns a threshold number of $\mathcal{X}$, (3) new elements of $\mathcal{X}$ are still discovered, (4) we do not know any algorithm deciding the inequality $\mathrm{card}(\mathcal{X}) < \infty$.

Key words and phrases: arithmetical consistency of ZFC, Brocard-Ramanujan equation $x!+1=y^2$, composite Fermat numbers, finiteness/infiniteness of a set, incompleteness of ZFC, oracle for the halting problem, prime numbers of the form n^2+1, prime numbers of the form $n!+1$, twin primes, Sophie Germain primes.

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1 Introduction

The phrase "*we know a non-negative integer n*" in the title means that we know an algorithm which returns n. The title cannot be formalised in ZFC because the phrase "*we know a non-negative integer n*" refers to currently known non-negative integers n with some property. A formally stated title may look like this: *On ZFC-formulae $\varphi(x)$ for which there exists a non-negative integer n such that ZFC proves that*

$$\mathrm{card}(\{x \in \mathbb{N}\colon \varphi(x)\}) < \infty \Longrightarrow \{x \in \mathbb{N}\colon \varphi(x)\} \subseteq \{x \in \mathbb{N}\colon x \leqslant n-1\}$$

Unfortunately, this formulation admits formulae $\varphi(x)$ without any known non-negative integer n such that ZFC proves the above implication.

Lemma 1. *For every non-negative integer n,* $\mathrm{card}(\{x \in \mathbb{N}\colon x \leqslant n-1\}) = n$.

Corollary 1. *The title altered to* "ZFC-formulae $\varphi(x)$ for which we know a non-negative integer n such that $\mathrm{card}(\{x \in \mathbb{N}\colon \varphi(x)\}) \leqslant n$ if the set $\{x \in \mathbb{N}\colon \varphi(x)\}$ is finite" *involves a weaker assumption on $\varphi(x)$.*

2 Subsets of $\mathbb{N}$ and their threshold numbers

We say that a non-negative integer m is a threshold number of a set $\mathcal{X} \subseteq \mathbb{N}$, if $\mathcal{X}$ is infinite if and only if $\mathcal{X}$ contains an element greater than m, cf. [25] and [26]. If a set $\mathcal{X} \subseteq \mathbb{N}$ is empty or infinite, then any non-negative integer m 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 $\{\max(\mathcal{X}), \max(\mathcal{X}) + 1, \max(\mathcal{X}) + 2, \ldots\}$.

It is conjectured that the set of prime numbers of the form $n^2 + 1$ is infinite, see [15, pp. 37–38]. It is conjectured that the set of prime numbers of the form $n! + 1$ is infinite, see [3, p. 443]. A twin prime is a prime number that differs from another prime number by 2. The twin prime conjecture states that the set of twin primes is infinite, see [15, p. 39]. It is conjectured that the set of composite numbers of the form $2^{2^n} + 1$ is infinite, see [11, p. 23] and [12, pp. 158–159]. A prime p is said to be a Sophie Germain prime if both p and $2p + 1$ are prime, see [23]. It is conjectured that the set of Sophie Germain primes is infinite, see [18, p. 330]. For each of these sets, we do not know any threshold number.

Open Problem 1. *Define a set $\mathcal{X} \subseteq \mathbb{N}$ that satisfies the following conditions:* (1) *a known algorithm for every $n \in \mathbb{N}$ decides whether or not $n \in \mathcal{X}$,* (2) *a known algorithm returns a threshold number of $\mathcal{X}$,* (3) *new elements of $\mathcal{X}$ are still discovered,* (4) *we do not know any algorithm deciding the inequality* $\mathrm{card}(\mathcal{X}) < \infty$.

The following statement:

$$\text{for every non-negative integer } n \text{ there exist}$$

$$\text{prime numbers } p \text{ and } q \text{ such that } p + 2 = q \text{ and } p \in \left[10^n, 10^{n+1}\right] \tag{T}$$

is a Π_1 statement which strengthens the twin prime conjecture, see [4, p. 43]. C. H. Bennett claims that most mathematical conjectures can be settled indirectly by proving stronger Π_1 statements, see [1]. The statement (T) is equivalent to the non-halting of a Turing machine. If a set $\mathcal{X} \subseteq \mathbb{N}$ is computable and we know a threshold number of $\mathcal{X}$, then the infinity of $\mathcal{X}$ is equivalent to the halting of a Turing machine.

The height of a rational number $\frac{p}{q}$ is denoted by $H\left(\frac{p}{q}\right)$ and equals $\max(|p|, |q|)$ provided $\frac{p}{q}$ is written in lowest terms. The height of a rational tuple $(x_1, \ldots, x_n)$ is denoted by $H(x_1, \ldots, x_n)$ and equals $\max(H(x_1), \ldots, H(x_n))$.

Observation 1. *The equation $x^5 - x = y^2 - y$ has only finitely many rational solutions, see [14, p. 212]. The known rational solutions are $(x, y) = (-1, 0)$, $(-1, 1)$, $(0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, $(2, -5)$, $(2, 6)$, $(3, -15)$, $(3, 16)$, $(30, -4929)$, $(30, 4930)$, $\left(\frac{1}{4}, \frac{15}{32}\right)$, $\left(\frac{1}{4}, \frac{17}{32}\right)$, $\left(-\frac{15}{16}, -\frac{185}{1024}\right)$, $\left(-\frac{15}{16}, \frac{1209}{1024}\right)$, and the existence of other solutions is an open question, see [19, pp. 223–224].*

Corollary 2. *The set*

$$\mathcal{T} = \{n \in \mathbb{N} : \text{the equation } x^5 - x = y^2 - y \text{ has a rational solution of height } n\}$$

is finite. We know an algorithm which for every $n \in \mathbb{N}$ decides whether or not $n \in \mathcal{T}$. We do not know any algorithm which returns a threshold number of $\mathcal{T}$.

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

$$\begin{cases} x^2 + y^2 &= s^2 \\ x^2 + z^2 &= t^2 \\ y^2 + z^2 &= u^2 \\ x^2 + y^2 + z^2 &= v^2 \end{cases}$$

Let

$$\mathcal{F} = \Big\{n \in \mathbb{N} \setminus \{0\} : \Big(\text{the system } \mathcal{L} \text{ has no solutions in } \{1, \ldots, n\}^7\Big) \wedge$$
$$\Big(\text{the system } \mathcal{L} \text{ has a solution in } \{1, \ldots, n+1\}^7\Big)\Big\}$$

A perfect cuboid is a cuboid having integer side lengths, integer face diagonals, and an integer space diagonal.

Observation 2. *([22]) No perfect cuboids are known.*

Corollary 3. *We know an algorithm which for every $n \in \mathbb{N}$ decides whether or not $n \in \mathcal{F}$. ZFC proves that* $\mathrm{card}(\mathcal{F}) \in \{0, 1\}$. *We do not know any algorithm which returns* $\mathrm{card}(\mathcal{F})$. *We do not know any algorithm which returns a threshold number of $\mathcal{F}$.*

Let

$$\mathcal{H} = \begin{cases} \mathbb{N}, \text{ if } \sin\left(9^{9^{9^{9^{9}}}}\right) < 0 \\ \mathbb{N} \cap \left[0, \ \sin\left(9^{9^{9^{9^{9}}}}\right) \cdot 9^{9^{9^{9^{9}}}}\right) \text{ otherwise} \end{cases}$$

We do not know whether or not the set $\mathcal{H}$ is finite.

Observation 3. *The number $9^{9^{9^{9^{9}}}}$ is a threshold number of $\mathcal{H}$. We know an algorithm which decides the equality $\mathcal{H} = \mathbb{N}$. If $\mathcal{H} \neq \mathbb{N}$, then the set $\mathcal{H}$ consists of all integers from 0 to a non-negative integer which can be computed by a known algorithm. We know an algorithm which for every $n \in \mathbb{N}$ decides whether or not $n \in \mathcal{H}$.*

Let

$$\mathcal{K} = \begin{cases} \{n\}, \text{ if } (n \in \mathbb{N}) \wedge \left(2^{\aleph_0} = \aleph_{n+1}\right) \\ \{0\}, \text{ if } 2^{\aleph_0} \geqslant \aleph_\omega \end{cases}$$

Theorem 1. *ZFC proves that* $\mathrm{card}(\mathcal{K}) = 1$. *If ZFC is consistent, then for every $n \in \mathbb{N}$ the sentences* "n is a threshold number of $\mathcal{K}$" *and* "n is not a threshold number of $\mathcal{K}$" *are not provable in ZFC.*

Proof. It suffices to observe that $2^{\aleph_0}$ can attain every value from the set $\{\aleph_1, \aleph_2, \aleph_3, \ldots\}$, see [7] and [10, p. 232]. □

3 A Diophantine equation whose non-solvability expresses the consistency of ZFC

Gödel's second incompleteness theorem and the Davis-Putnam-Robinson-Matiyasevich theorem imply the following theorem.

Theorem 2. *([5, p. 35]) There exists a polynomial $D(x_1, \ldots, x_m)$ with integer coefficients such that if ZFC is arithmetically consistent, then the sentences* "The equation $D(x_1, \ldots, x_m) = 0$ is solvable in non-negative integers" *and* "The equation $D(x_1, \ldots, x_m) = 0$ is not solvable in non-negative integers" *are not provable in ZFC.*

Observation 4. *([9, p. 53]) The polynomial $D(x_1, \ldots, x_m)$ is not effectively known.*

Let $\mathcal{Y}$ denote the set of all non-negative integers k such that the equation $D(x_1, \ldots, x_m) = 0$ has no solutions in $\{0, \ldots, k\}^m$. Since the set $\{0, \ldots, k\}^m$ is finite, there exists an algorithm which for every $n \in \mathbb{N}$ decides whether or not $n \in \mathcal{Y}$. Theorem 2 implies the next theorem.

Theorem 3. *For every $n \in \mathbb{N}$, ZFC proves that $n \in \mathcal{Y}$. If ZFC is arithmetically consistent, then the sentences* "$\mathcal{Y}$ is finite" *and* "$\mathcal{Y}$ is infinite" *are not provable in ZFC. If ZFC is arithmetically consistent, then for every $n \in \mathbb{N}$ the sentences* "n is a threshold number of $\mathcal{Y}$" *and* "n is not a threshold number of $\mathcal{Y}$" *are not provable in ZFC.*

Let $\mathcal{E}$ denote the set of all non-negative integers k such that the equation $D(x_1, \ldots, x_m) = 0$ has a solution in $\{0, \ldots, k\}^m$. Since the set $\{0, \ldots, k\}^m$ is finite, there exists an algorithm which for every $n \in \mathbb{N}$ decides whether or not $n \in \mathcal{E}$. Theorem 2 implies the next theorem.

Theorem 4. *The set $\mathcal{E}$ is empty or infinite. In both cases, every non-negative integer n is a threshold number of $\mathcal{E}$. If ZFC is arithmetically consistent, then the sentences* "$\mathcal{E}$ is empty", "$\mathcal{E}$ is not empty", "$\mathcal{E}$ is finite", *and* "$\mathcal{E}$ is infinite" *are not provable in ZFC.*

Let

$$\mathcal{V} = \Big\{n \in \mathbb{N} : \Big(\text{the polynomial } D(x_1, \ldots, x_m) \text{ has no solutions in } \{0, \ldots, n\}^m\Big) \wedge$$

$$\Big(\text{the polynomial } D(x_1, \ldots, x_m) \text{ has a solution in } \{0, \ldots, n+1\}^m\Big)\Big\}$$

Since the sets $\{0, \ldots, n\}^m$ and $\{0, \ldots, n+1\}^m$ are finite, there exists an algorithm which for every $n \in \mathbb{N}$ decides whether or not $n \in \mathcal{V}$. According to Observation 4, at present we are not able to write a computer program that realizes such an algorithm. Theorem 2 implies the next theorem.

Theorem 5. `(5)` *ZFC proves that* $\mathrm{card}(\mathcal{V}) \in \{0, 1\}$. `(6)` *For every $n \in \mathbb{N}$, ZFC proves that $n \notin \mathcal{V}$.* `(7)` *ZFC does not prove the emptiness of $\mathcal{V}$, if ZFC is arithmetically consistent.* `(8)` *For every $n \in \mathbb{N}$, the sentence* "n is a threshold number of $\mathcal{V}$" *is not provable in ZFC, if ZFC is arithmetically consistent.* `(9)` *For every $n \in \mathbb{N}$, the sentence* "n is not a threshold number of $\mathcal{V}$" *is not provable in ZFC, if ZFC is arithmetically consistent.*

Open Problem 2. *Define a simple algorithm* `A` *such that* `A` *returns* 0 *or* 1 *on every input $k \in \mathbb{N}$ and the set*

$$\mathcal{V} = \{k \in \mathbb{N} : \text{ the program } \mathtt{A} \text{ returns } 1 \text{ on input } k\}$$

satisfies conditions `(5)-(9)`.

4 Number-theoretic lemmas

Lemma 2. *For every positive integers x and y, $x! \cdot y = y!$ if and only if*

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

Let $\Gamma(k)$ denote $(k-1)!$.

Lemma 3. *For every positive integers x and y, $x \cdot \Gamma(x) = \Gamma(y)$ if and only if*

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

Lemma 4. *For every non-negative integers b and c, $b+1=c$ if and only if* $2^{2^b} \cdot 2^{2^b} = 2^{2^c}$.

Lemma 5. *(Wilson's theorem, [8, p. 89]). For every positive integer x, x divides $(x-1)!+1$ if and only if $x=1$ or x is prime.*

5 Hypothetical statements $\Psi_3, \ldots, \Psi_{16}$

For an integer $n \geqslant 3$, let $\mathcal{U}_n$ denote the following system of equations:

$$\begin{cases} \forall i \in \{1,\ldots,n-1\} \setminus \{2\}\ x_i! &= x_{i+1} \\ x_1 \cdot x_2 &= x_3 \\ x_2 \cdot x_2 &= x_3 \end{cases}$$

The diagram in Figure 1 illustrates the construction of the system $\mathcal{U}_n$.

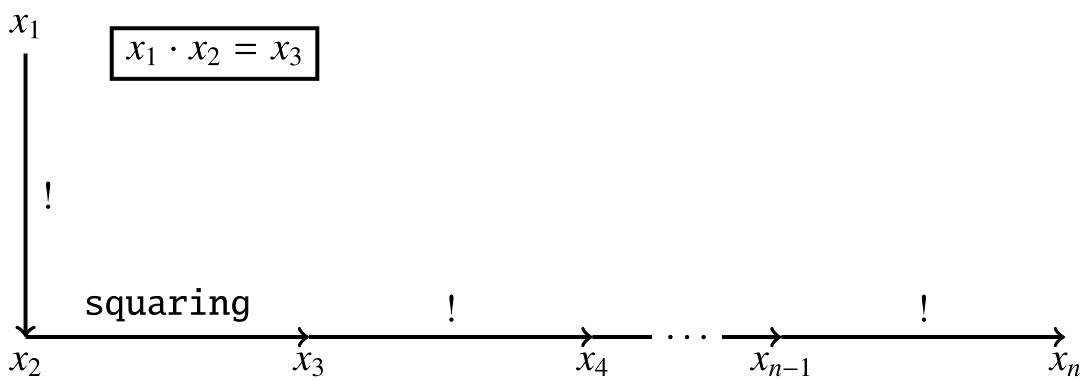

Fig. 1 Construction of the system $\mathcal{U}_n$

Let $g(3)=4$, and let $g(n+1)=g(n)!$ for every integer $n \geqslant 3$.

Lemma 6. *For every integer $n \geqslant 3$, the system $\mathcal{U}_n$ has exactly two solutions in positive integers, namely $(1,\ldots,1)$ and $\big(2,2,g(3),\ldots,g(n)\big)$.*

Let

$$B_n = \Big\{x_i! = x_k :\ (i,k \in \{1,\ldots,n\}) \wedge (i \neq k)\Big\} \cup \Big\{x_i \cdot x_j = x_k :\ i,j,k \in \{1,\ldots,n\}\Big\}$$

For an integer $n \geqslant 3$, let Ψ_n denote the following statement: *if a system of equations $\mathcal{S} \subseteq B_n$ has only finitely many solutions in positive integers $x_1,\ldots,x_n$, then each such solution $(x_1,\ldots,x_n)$ satisfies $x_1,\ldots,x_n \leqslant g(n)$.* The statement Ψ_n says that for subsystems of B_n the largest known solution is indeed the largest possible.

Hypothesis 1. *The statements* $\Psi_3, \ldots, \Psi_{16}$ *are true.*

Lemma 7. *Every statement* Ψ_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. □

Lemma 8. *For every statement* Ψ_n*, the bound* $g(n)$ *cannot be decreased.*

Proof. It follows from Lemma 6 because $\mathcal{U}_n \subseteq B_n$. □

6 The Brocard-Ramanujan equation $x! + 1 = y^2$

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

$$\begin{cases} x_1! &= x_2 \\ x_2! &= x_3 \\ x_5! &= x_6 \\ x_4 \cdot x_4 &= x_5 \\ x_3 \cdot x_5 &= x_6 \end{cases}$$

Lemma 2 and the diagram in Figure 2 explain the construction of the system $\mathcal{A}$.

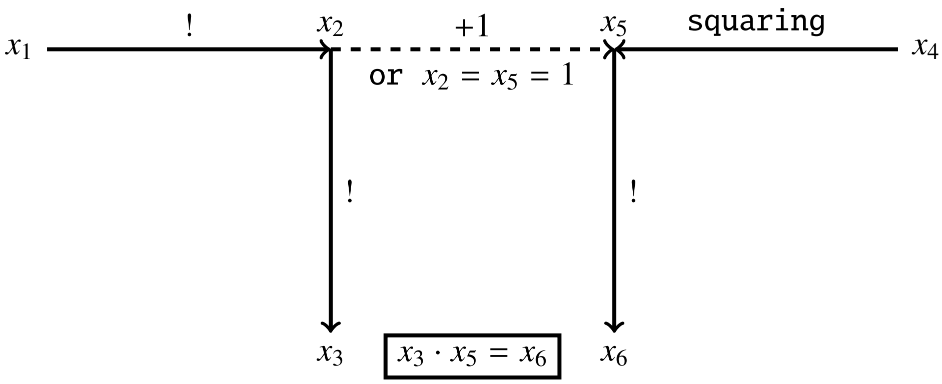

Fig. 2 Construction of the system $\mathcal{A}$

Lemma 9. *For every* $x_1, x_4 \in \mathbb{N} \setminus \{0, 1\}$*, the system* $\mathcal{A}$ *is solvable in positive integers* x_2*,* x_3*,* x_5*,* x_6 *if and only if* $x_1! + 1 = x_4^2$*. In this case, the integers* x_2, x_3, x_5, x_6 *are uniquely determined by the following equalities:*

$$\begin{aligned} x_2 &= x_1! \\ x_3 &= (x_1!)! \\ x_5 &= x_1! + 1 \\ x_6 &= (x_1! + 1)! \end{aligned}$$

Proof. It follows from Lemma 2. □

It is conjectured that $x! + 1$ is a perfect square only for $x \in \{4, 5, 7\}$, see [21, p. 297]. A weak form of Szpiro's conjecture implies that there are only finitely many solutions to the equation $x! + 1 = y^2$, see [16].

Theorem 6. *If the equation* $x_1! + 1 = x_4^2$ *has only finitely many solutions in positive integers, then the statement* Ψ_6 *guarantees that each such solution* (x_1, x_4) *belongs to the set* $\{(4, 5), (5, 11), (7, 71)\}$.

Proof. Suppose that the antecedent holds. Let positive integers x_1 and x_4 satisfy $x_1! + 1 = x_4^2$. Then, $x_1, x_4 \in \mathbb{N} \setminus \{0, 1\}$. By Lemma 9, the system $\mathcal{A}$ is solvable in positive integers x_2, x_3, x_5, x_6. Since $\mathcal{A} \subseteq B_6$, the statement Ψ_6 implies that $x_6 = (x_1! + 1)! \leqslant g(6) = g(5)!$. Hence, $x_1! + 1 \leqslant g(5) = g(4)!$. Consequently, $x_1 < g(4) = 24$. If $x_1 \in \{1, \ldots, 23\}$, then $x_1! + 1$ is a perfect square only for $x_1 \in \{4, 5, 7\}$. □

7 Are there infinitely many prime numbers of the form $n^2 + 1$?

Edmund Landau's conjecture states that there are infinitely many primes of the form $n^2 + 1$, see [15, pp. 37–38]. Let $\mathcal{B}$ denote the following system of equations:

$$\begin{cases} x_2! = x_3 \\ x_3! = x_4 \\ x_5! = x_6 \\ x_8! = x_9 \\ x_1 \cdot x_1 = x_2 \\ x_3 \cdot x_5 = x_6 \\ x_4 \cdot x_8 = x_9 \\ x_5 \cdot x_7 = x_8 \end{cases}$$

Lemma 2 and the diagram in Figure 3 explain the construction of the system $\mathcal{B}$.

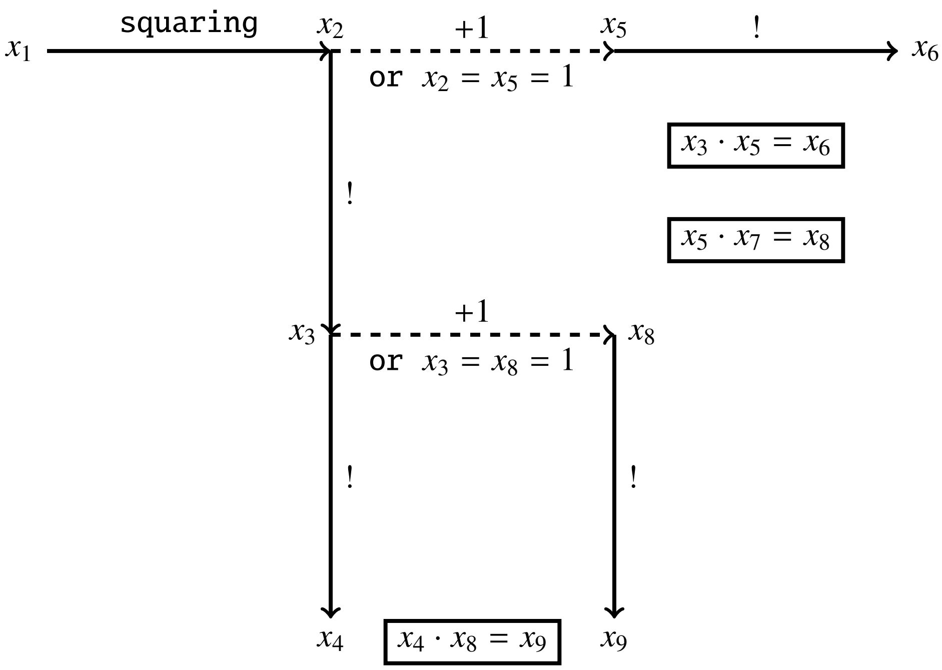

Fig. 3 Construction of the system $\mathcal{B}$

Lemma 10. *For every integer $x_1 \geqslant 2$, the system $\mathcal{B}$ is solvable in positive integers $x_2, \ldots, x_9$ if and only if $x_1^2 + 1$ is prime. In this case, the integers $x_2, \ldots, x_9$ 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 2, for every integer $x_1 \geqslant 2$, the system $\mathcal{B}$ is solvable in positive integers $x_2, \ldots, x_9$ if and only if $x_1^2 + 1$ divides $(x_1^2)! + 1$. Hence, the claim of Lemma 10 follows from Lemma 5. □

Lemma 11. *There are only finitely many tuples* $(x_1, \ldots, x_9) \in (\mathbb{N} \setminus \{0\})^9$ *which solve the system* $\mathcal{B}$ *and satisfy* $x_1 = 1$.

Proof. If a tuple $(x_1, \ldots, x_9) \in (\mathbb{N} \setminus \{0\})^9$ solves the system $\mathcal{B}$ and $x_1 = 1$, then $x_1, \ldots, x_9 \leqslant 2$. Indeed, $x_1 = 1$ implies that $x_2 = x_1^2 = 1$. Hence, for example, $x_3 = x_2! = 1$. Therefore, $x_8 = x_3 + 1 = 2$ or $x_8 = 1$. Consequently, $x_9 = x_8! \leqslant 2$. □

Theorem 7. *The statement* Ψ_9 *proves the following implication: if there exists an integer* $x_1 \geqslant 2$ *such that* $x_1^2 + 1$ *is prime and greater than* $g(7)$*, then there are infinitely many primes of the form* $n^2 + 1$.

Proof. Suppose that the antecedent holds. By Lemma 10, there exists a unique tuple $(x_2, \ldots, x_9) \in (\mathbb{N} \setminus \{0\})^8$ such that the tuple $(x_1, x_2, \ldots, x_9)$ solves the system $\mathcal{B}$. Since $x_1^2 + 1 > g(7)$, we obtain that $x_1^2 \geqslant g(7)$. Hence, $(x_1^2)! \geqslant g(7)! = g(8)$. Consequently,

$$x_9 = ((x_1^2)! + 1)! \geqslant (g(8) + 1)! > g(8)! = g(9)$$

Since $\mathcal{B} \subseteq B_9$, the statement Ψ_9 and the inequality $x_9 > g(9)$ imply that the system $\mathcal{B}$ has infinitely many solutions $(x_1, \ldots, x_9) \in (\mathbb{N} \setminus \{0\})^9$. According to Lemmas 10 and 11, there are infinitely many primes of the form $n^2 + 1$. □

Corollary 4. *Let* $\mathcal{X}_9$ *denote the set of primes of the form* $n^2 + 1$*. The statement* Ψ_9 *implies that we know an algorithm such that it returns a threshold number of* $\mathcal{X}_9$*, and this number equals* $\max(\mathcal{X}_9)$*, if* $\mathcal{X}_9$ *is finite. Assuming the statement* Ψ_9*, a single query to an oracle for the halting problem decides the infinity of* $\mathcal{X}_9$*. Assuming the statement* Ψ_9*, the infinity of* $\mathcal{X}_9$ *is decidable in the limit.*

Proof. We consider an algorithm which computes $\max(\mathcal{X}_9 \cap [1, g(7)])$. □

8 Are there infinitely many prime numbers of the form $n! + 1$?

It is conjectured that there are infinitely many primes of the form $n! + 1$, see [3, p. 443].

Theorem 8. *(cf. Theorem 12). The statement* Ψ_9 *proves the following implication: if there exists an integer* $x_1 \geqslant g(6)$ *such that* $x_1! + 1$ *is prime, then there are infinitely many primes of the form* $n! + 1$.

Proof. We leave the analogous proof to the reader. □

9 The twin prime conjecture

A twin prime is a prime number that differs from another prime number by 2. The twin prime conjecture states that there are infinitely many twin primes, see [15, p. 39]. Let C denote the following system of equations:

$$\begin{cases} x_1! &= x_2 \\ x_2! &= x_3 \\ x_4! &= x_5 \\ x_6! &= x_7 \\ x_7! &= x_8 \\ x_9! &= x_{10} \\ x_{12}! &= x_{13} \\ x_{15}! &= x_{16} \\ x_2 \cdot x_4 &= x_5 \\ x_5 \cdot x_6 &= x_7 \\ x_7 \cdot x_9 &= x_{10} \\ x_4 \cdot x_{11} &= x_{12} \\ x_3 \cdot x_{12} &= x_{13} \\ x_9 \cdot x_{14} &= x_{15} \\ x_8 \cdot x_{15} &= x_{16} \end{cases}$$

Lemma 2 and the diagram in Figure 4 explain the construction of the system C.

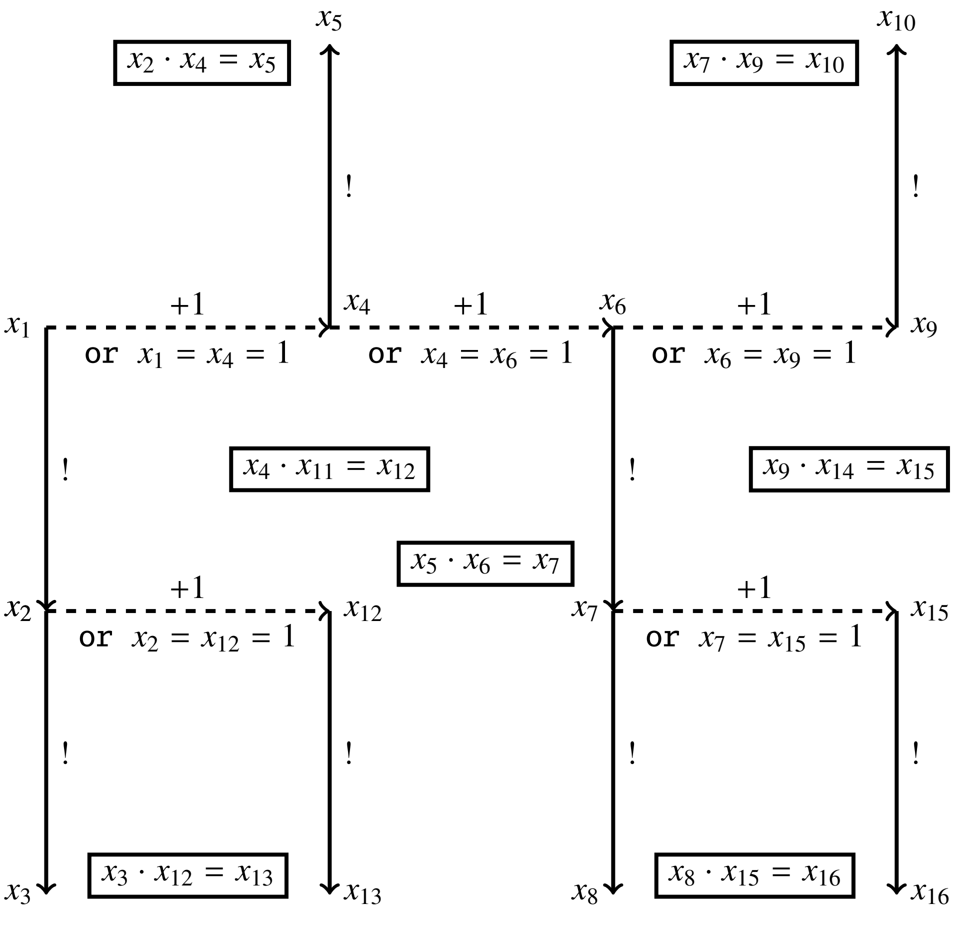

Fig. 4 Construction of the system C

Lemma 12. *For every $x_4, x_9 \in \mathbb{N} \setminus \{0,1,2\}$, the system C is solvable in positive integers $x_1, x_2, x_3, x_5, x_6, x_7, x_8, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}$ if and only if x_4 and x_9 are prime and $x_4 + 2 = x_9$. In this case, the integers $x_1, x_2, x_3, x_5, x_6, x_7, x_8, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}$ are uniquely determined by the following equalities:*

$$\begin{array}{rcl}
x_1 &=& x_4 - 1 \\
x_2 &=& (x_4 - 1)! \\
x_3 &=& ((x_4 - 1)!)! \\
x_5 &=& x_4! \\
x_6 &=& x_9 - 1 \\
x_7 &=& (x_9 - 1)! \\
x_8 &=& ((x_9 - 1)!)! \\
x_{10} &=& x_9! \\
x_{11} &=& \dfrac{(x_4 - 1)! + 1}{x_4} \\
x_{12} &=& (x_4 - 1)! + 1 \\
x_{13} &=& ((x_4 - 1)! + 1)! \\
x_{14} &=& \dfrac{(x_9 - 1)! + 1}{x_9} \\
x_{15} &=& (x_9 - 1)! + 1 \\
x_{16} &=& ((x_9 - 1)! + 1)!
\end{array}$$

Proof. By Lemma 2, for every $x_4, x_9 \in \mathbb{N} \setminus \{0,1,2\}$, the system C is solvable in positive integers x_1, x_2, x_3, x_5, x_6, x_7, x_8, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16} if and only if

$$\Big(x_4 + 2 = x_9\Big) \wedge \Big(x_4 | (x_4 - 1)! + 1\Big) \wedge \Big(x_9 | (x_9 - 1)! + 1\Big)$$

Hence, the claim of Lemma 12 follows from Lemma 5. □

Lemma 13. *There are only finitely many tuples $(x_1, \ldots, x_{16}) \in (\mathbb{N} \setminus \{0\})^{16}$ which solve the system C and satisfy $(x_4 \in \{1,2\}) \vee (x_9 \in \{1,2\})$.*

Proof. If a tuple $(x_1, \ldots, x_{16}) \in (\mathbb{N} \setminus \{0\})^{16}$ solves the system C and $(x_4 \in \{1,2\}) \vee (x_9 \in \{1,2\})$, then $x_1, \ldots, x_{16} \leqslant 7!$. Indeed, for example, if $x_4 = 2$ then $x_6 = x_4 + 1 = 3$. Hence, $x_7 = x_6! = 6$. Therefore, $x_{15} = x_7 + 1 = 7$. Consequently, $x_{16} = x_{15}! = 7!$. □

Theorem 9. *The statement Ψ_{16} proves the following implication: if there exists a twin prime greater than $g(14)$, then there are infinitely many twin primes.*

Proof. Suppose that the antecedent holds. Then, there exist prime numbers x_4 and x_9 such that $x_9 = x_4 + 2 > g(14)$. Hence, $x_4, x_9 \in \mathbb{N} \setminus \{0,1,2\}$. By Lemma 12, there exists a unique tuple $(x_1, x_2, x_3, x_5, x_6, x_7, x_8, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}) \in (\mathbb{N} \setminus \{0\})^{14}$ such that the tuple $(x_1, \ldots, x_{16})$ solves the system C. Since $x_9 > g(14)$, we obtain that $x_9 - 1 \geqslant g(14)$. Therefore, $(x_9 - 1)! \geqslant g(14)! = g(15)$. Hence, $(x_9 - 1)! + 1 > g(15)$. Consequently,

$$x_{16} = ((x_9 - 1)! + 1)! > g(15)! = g(16)$$

Since $C \subseteq B_{16}$, the statement Ψ_{16} and the inequality $x_{16} > g(16)$ imply that the system C has infinitely many solutions in positive integers $x_1, \ldots, x_{16}$. According to Lemmas 12 and 13, there are infinitely many twin primes. □

Corollary 5. *(cf. [6]). Let $\mathcal{X}_{16}$ denote the set of twin primes. The statement Ψ_{16} implies that we know an algorithm such that it returns a threshold number of $\mathcal{X}_{16}$, and this number equals* $\max(\mathcal{X}_{16})$*, if $\mathcal{X}_{16}$ is finite. Assuming the statement Ψ_{16}, a single query to an oracle for the halting problem decides the infinity of $\mathcal{X}_{16}$. Assuming the statement Ψ_{16}, the infinity of $\mathcal{X}_{16}$ is decidable in the limit.*

Proof. We consider an algorithm which computes $\max(\mathcal{X}_{16} \cap [1, g(14)])$. □

10 Hypothetical statements $\Delta_5, \ldots, \Delta_{14}$ and their consequences

Let $\lambda(5) = \Gamma(25)$, and let $\lambda(n+1) = \Gamma(\lambda(n))$ for every integer $n \geqslant 5$. For an integer $n \geqslant 5$, let $\mathcal{J}_n$ denote the following system of equations:

$$\begin{cases} \forall i \in \{1, \ldots, n-1\} \setminus \{3\} \; \Gamma(x_i) & = & x_{i+1} \\ x_1 \cdot x_1 & = & x_4 \\ x_2 \cdot x_3 & = & x_5 \end{cases}$$

Lemma 3 and the diagram in Figure 5 explain the construction of the system $\mathcal{J}_n$.

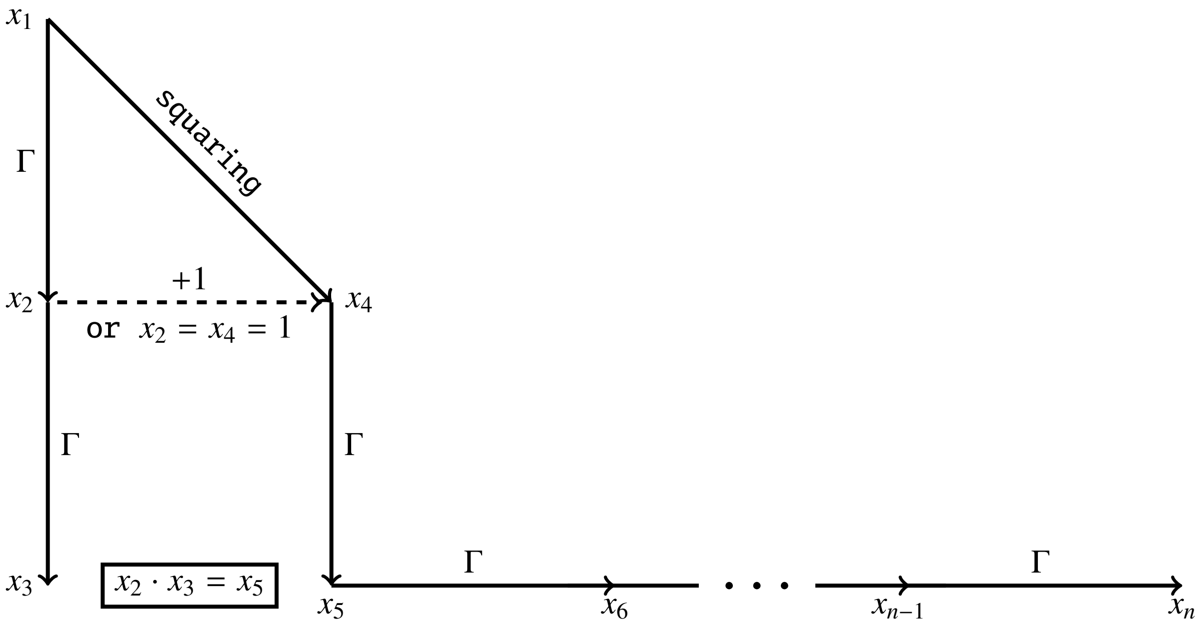

Fig. 5 Construction of the system $\mathcal{J}_n$

For every integer $n \geqslant 5$, the system $\mathcal{J}_n$ has exactly two solutions in positive integers, namely $(1, \ldots, 1)$ and $(5, 24, 23!, 25, \lambda(5), \ldots, \lambda(n))$. For an integer $n \geqslant 5$, let Δ_n denote the following statement: *if a system of equations* $\mathcal{S} \subseteq \Big\{\Gamma(x_i) = x_k : i, k \in \{1, \ldots, n\}\Big\} \cup \Big\{x_i \cdot x_j = x_k : i, j, k \in \{1, \ldots, n\}\Big\}$ *has only finitely many solutions in positive integers* $x_1, \ldots, x_n$*, then each such solution* $(x_1, \ldots, x_n)$ *satisfies* $x_1, \ldots, x_n \leqslant \lambda(n)$*.*

Hypothesis 2. *The statements* $\Delta_5, \ldots, \Delta_{14}$ *are true.*

Lemmas 3 and 5 imply that the statements Δ_n have similar consequences as the statements Ψ_n.

Theorem 10. *The statement* Δ_6 *implies that any prime number* $p \geqslant 25$ *proves the infinitude of primes.*

Proof. It follows from Lemmas 3 and 5. We leave the details to the reader. $\square$

11 Hypothetical statements $\Sigma_3, \ldots, \Sigma_{16}$ and their consequences

Let $\Gamma_n(k)$ denote $(k-1)!$, where $n \in \{3, \ldots, 16\}$ and $k \in \{2\} \cup [2^{2^{n-3}}+1, \infty) \cap \mathbb{N}$. For an integer $n \in \{3, \ldots, 16\}$, let

$$Q_n = \{\Gamma_n(x_i) = x_k : \ i, k \in \{1, \ldots, n\}\} \cup \{x_i \cdot x_j = x_k : \ i, j, k \in \{1, \ldots, n\}\}$$

For an integer $n \in \{3, \ldots, 16\}$, let P_n denote the following system of equations:

$$\begin{cases} \qquad\qquad\qquad\quad x_1 \cdot x_1 &= x_1 \\ \qquad\qquad\qquad\quad \Gamma_n(x_2) &= x_1 \\ \forall i \in \{2, \ldots, n-1\} \ x_i \cdot x_i &= x_{i+1} \end{cases}$$

Lemma 14. *For every integer $n \in \{3, \ldots, 16\}$, $P_n \subseteq Q_n$ and the system P_n with Γ instead of Γ_n has exactly one solution in positive integers $x_1, \ldots, x_n$, namely $\left(1, 2^{2^0}, \ 2^{2^1}, 2^{2^2}, \ldots, 2^{2^{n-2}}\right)$.*

For an integer $n \in \{3, \ldots, 16\}$, let Σ_n denote the following statement: if a system of equations $\mathcal{S} \subseteq Q_n$ with Γ instead of Γ_n has only finitely many solutions in positive integers $x_1, \ldots, x_n$, then every tuple $(x_1, \ldots, x_n) \in (\mathbb{N} \setminus \{0\})^n$ that solves the original system $\mathcal{S}$ satisfies $x_1, \ldots, x_n \leqslant 2^{2^{n-2}}$.

Hypothesis 3. *The statements $\Sigma_3, \ldots, \Sigma_{16}$ are true.*

Lemma 15. *(cf. Lemma 3). For every integer $n \in \{4, \ldots, 16\}$ and for every positive integers x and y, $x \cdot \Gamma_n(x) = \Gamma_n(y)$ if and only if $(x+1 = y) \wedge \left(x \geqslant 2^{2^{n-3}} + 1\right)$.*

Let $\mathcal{Z}_9 \subseteq Q_9$ be the system of equations in Figure 6.

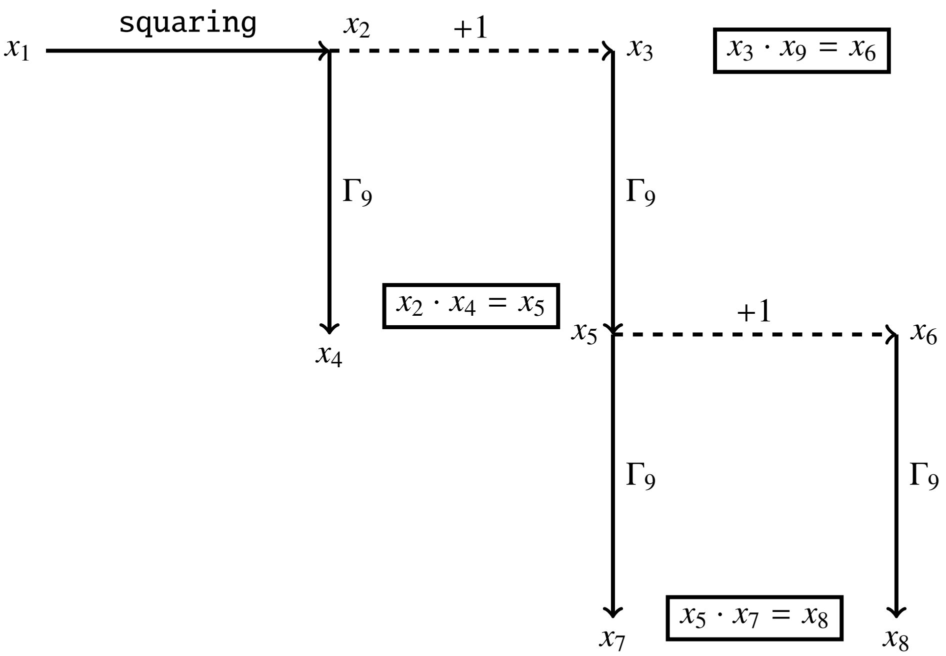

Fig. 6 Construction of the system $\mathcal{Z}_9$

Lemma 16. *For every positive integer x_1, the system $\mathcal{Z}_9$ is solvable in positive integers $x_2, \ldots, x_9$ if and only if $x_1 > 2^{2^{9-4}}$ and $x_1^2 + 1$ is prime. In this case, positive integers $x_2, \ldots, x_9$ are uniquely determined by x_1. For every positive integer n, at most finitely many tuples $(x_1, \ldots, x_9) \in (\mathbb{N} \setminus \{0\})^9$ begin with n and solve the system $\mathcal{Z}_9$ with Γ instead of Γ_9.*

Proof. It follows from Lemmas 3, 5, and 15. □

Lemma 17. *([20]). The number* $(13!)^2 + 1 = 38775788043632640001$ *is prime.*

Lemma 18. $\left((13!)^2 \geqslant 2^{2^{9-3}} + 1 = 18446744073709551617\right) \wedge \left(\Gamma_9((13!)^2) > 2^{2^{9-2}}\right)$.

Theorem 11. *The statement* Σ_9 *implies the infinitude of primes of the form* $n^2 + 1$.

Proof. It follows from Lemmas 16–18. □

Theorem 12. *(cf. Theorem 8). The statement* Σ_9 *implies that any prime of the form* $n! + 1$ *with* $n \geqslant 2^{2^{9-3}}$ *proves the infinitude of primes of the form* $n! + 1$.

Proof. We leave the proof to the reader. □

Corollary 6. *Let* $\mathcal{Y}_9$ *denote the set of primes of the form* $n! + 1$*. The statement* Σ_9 *implies that we know an algorithm such that it returns a threshold number of* $\mathcal{Y}_9$*, and this number equals* $\max(\mathcal{Y}_9)$*, if* $\mathcal{Y}_9$ *is finite. Assuming the statement* Σ_9*, a single query to an oracle for the halting problem decides the infinity of* $\mathcal{Y}_9$*. Assuming the statement* Σ_9*, the infinity of* $\mathcal{Y}_9$ *is decidable in the limit.*

Proof. We consider an algorithm which computes $\max(\mathcal{Y}_9 \cap [1, (2^{2^{9-3}} - 1)! + 1])$. □

Let $\mathcal{Z}_{14} \subseteq Q_{14}$ be the system of equations in Figure 7.

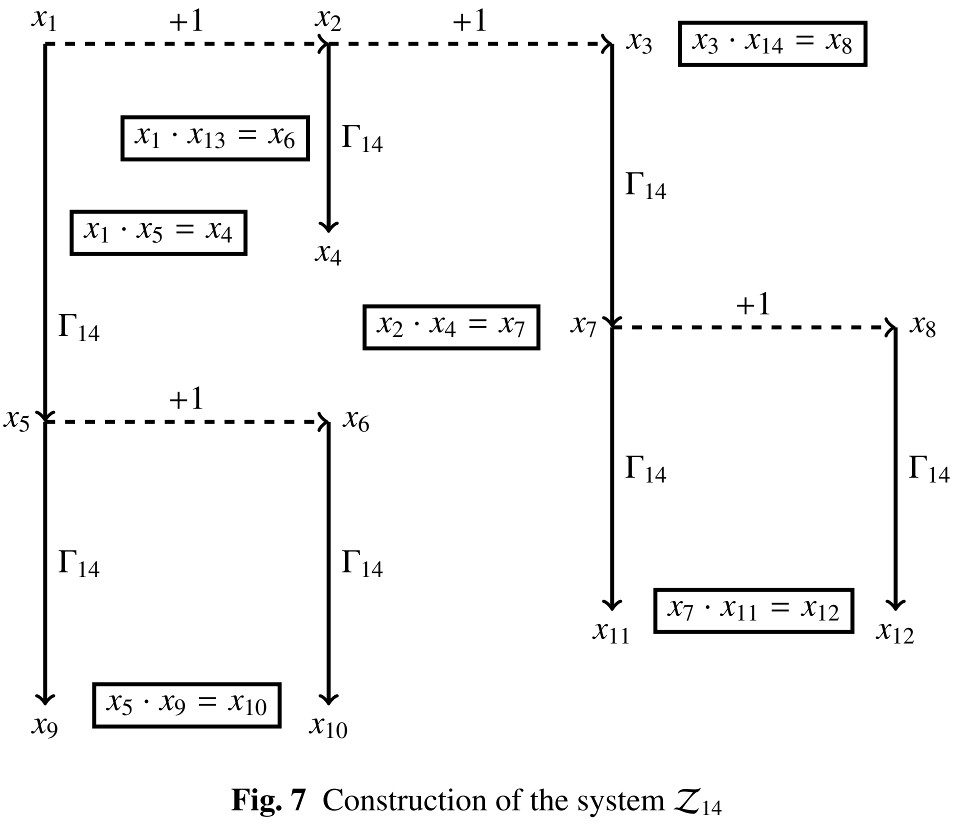

Fig. 7 Construction of the system $\mathcal{Z}_{14}$

Lemma 19. *For every positive integer* x_1*, the system* $\mathcal{Z}_{14}$ *is solvable in positive integers* $x_2, \ldots, x_{14}$ *if and only if* x_1 *and* $x_1 + 2$ *are prime and* $x_1 \geqslant 2^{2^{14-3}} + 1$*. In this case, positive integers* $x_2, \ldots, x_{14}$ *are uniquely determined by* x_1*. For every positive integer n, at most finitely many tuples* $(x_1, \ldots, x_{14}) \in (\mathbb{N} \setminus \{0\})^{14}$ *begin with n and solve the system* $\mathcal{Z}_{14}$ *with* Γ *instead of* Γ_{14}.

Proof. It follows from Lemmas 3, 5, and 15. □

Lemma 20. *([24, p. 87]). The numbers* $459 \cdot 2^{8529} - 1$ *and* $459 \cdot 2^{8529} + 1$ *are prime (Harvey Dubner).*

Lemma 21. $459 \cdot 2^{8529} - 1 > 2^{2^{14-2}} = 2^{4096}$.

Theorem 13. *The statement* Σ_{14} *implies the infinitude of twin primes.*

Proof. It follows from Lemmas 19–21. □

A prime p is said to be a Sophie Germain prime if both p and $2p + 1$ are prime, see [23]. It is conjectured that there are infinitely many Sophie Germain primes, see [18, p. 330]. Let $\mathcal{Z}_{16} \subseteq Q_{16}$ be the system of equations in Figure 8.

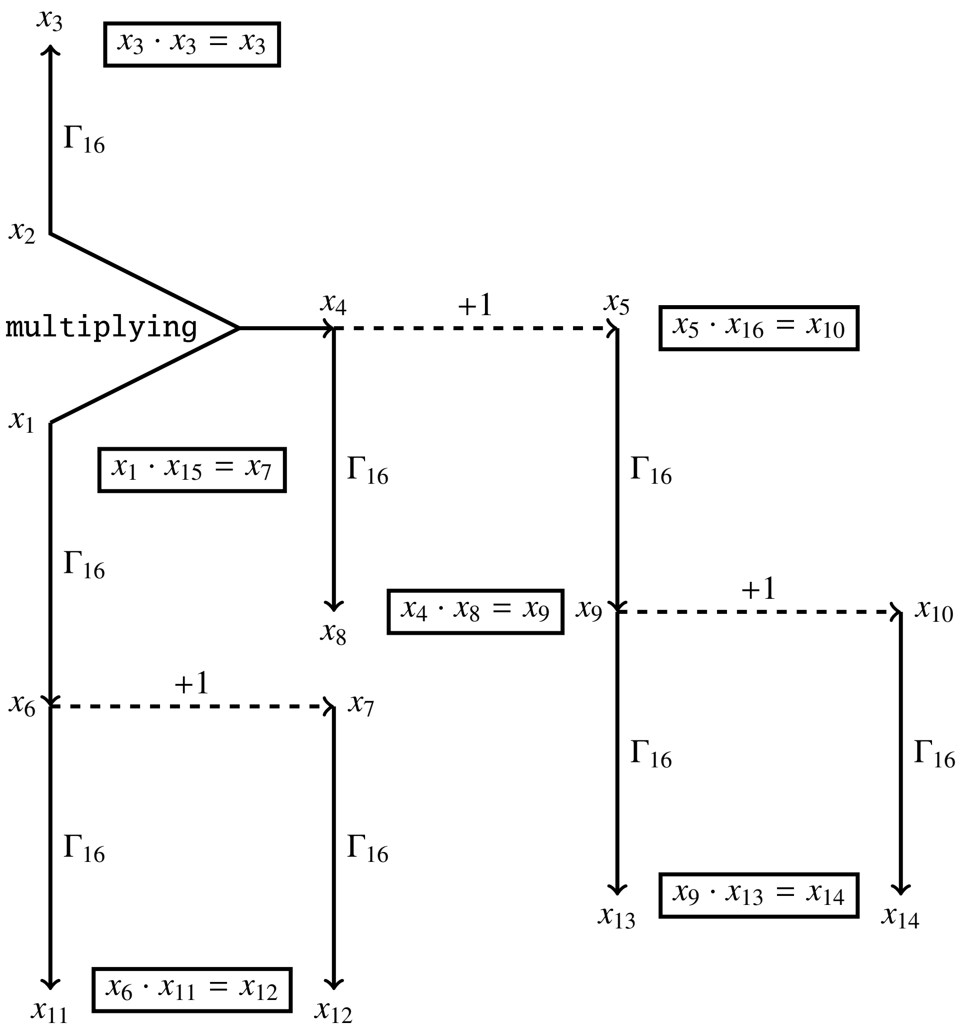

Fig. 8 Construction of the system $\mathcal{Z}_{16}$

Lemma 22. *For every positive integer* x_1*, the system* $\mathcal{Z}_{16}$ *is solvable in positive integers* $x_2, \ldots, x_{16}$ *if and only if* x_1 *is a Sophie Germain prime and* $x_1 \geqslant 2^{2^{16-3}} + 1$*. In this case, positive integers* $x_2, \ldots, x_{16}$ *are uniquely determined by* x_1*. For every positive integer n, at most finitely many tuples* $(x_1, \ldots, x_{16}) \in (\mathbb{N} \setminus \{0\})^{16}$ *begin with n and solve the system* $\mathcal{Z}_{16}$ *with* Γ *instead of* Γ_{16}.

Proof. It follows from Lemmas 3, 5, and 15. □

Lemma 23. *([18, p. 330]).* $8069496435 \cdot 10^{5072} - 1$ *is a Sophie Germain prime (Harvey Dubner).*

Lemma 24. $8069496435 \cdot 10^{5072} - 1 > 2^{2^{16-2}}$.

Theorem 14. *The statement* Σ_{16} *implies the infinitude of Sophie Germain primes.*

Proof. It follows from Lemmas 22–24. □

Theorem 15. *The statement* Σ_6 *proves the following implication: if the equation* $x(x+1) = y!$ *has only finitely many solutions in positive integers x and y, then each such solution* (x, y) *belongs to the set* $\{(1, 2), (2, 3)\}$.

Proof. We leave the proof to the reader. □

The question of solving the equation $x(x+1) = y!$ was posed by P. Erdös, see [2]. F. Luca proved that the *abc* conjecture implies that the equation $x(x+1) = y!$ has only finitely many solutions in positive integers, see [13].

Theorem 16. *The statement* Σ_6 *proves the following implication: if the equation* $x! + 1 = y^2$ *has only finitely many solutions in positive integers x and y, then each such solution* (x, y) *belongs to the set* $\{(4, 5), (5, 11), (7, 71)\}$.

Proof. We leave the proof to the reader. □

12 Hypothetical statements $\Omega_3, \ldots, \Omega_{16}$ and their consequences

For an integer $n \in \{3, \ldots, 16\}$, let Ω_n denote the following statement: *if a system of equations* $\mathcal{S} \subseteq \Big\{\Gamma(x_i) = x_k : i, k \in \{1, \ldots, n\}\Big\} \cup \Big\{x_i \cdot x_j = x_k : i, j, k \in \{1, \ldots, n\}\Big\}$ *has a solution in integers* $x_1, \ldots, x_n$ *greater than* $2^{2^{n-2}}$, *then* $\mathcal{S}$ *has infinitely many solutions in positive integers* $x_1, \ldots, x_n$. For every $n \in \{3, \ldots, 16\}$, the statement Σ_n implies the statement Ω_n.

Lemma 25. *The number* $(65!)^2 + 1$ *is prime and* $65! > 2^{2^{9-2}}$.

Proof. The following `PARI/GP` ([17]) command

```
(04:04) gp > isprime((65!)^2+1,{flag=2})
%1 = 1
```

is shown together with its output. This command performs the `APRCL` primality test, the best deterministic primality test algorithm ([24, p. 226]). It rigorously shows that the number $(65!)^2 + 1$ is prime. □

Lemma 26. *If positive integers* $x_1, \ldots, x_9$ *solve the system* $\mathcal{Z}_9$ *and* $x_1 > 2^{2^{9-2}}$, *then* $x_1 = \min(x_1, \ldots, x_9)$.

Theorem 17. *The statement* Ω_9 *implies the infinitude of primes of the form* $n^2 + 1$.

Proof. It follows from Lemmas 16 and 25–26. □

Lemma 27. *If positive integers $x_1, \ldots, x_{14}$ solve the system $\mathcal{Z}_{14}$ and $x_1 > 2^{2^{14-2}}$, then $x_1 = \min(x_1, \ldots, x_{14})$.*

Theorem 18. *The statement Ω_{14} implies the infinitude of twin primes.*

Proof. It follows from Lemmas 19–21 and 27. □

13 Are there infinitely many composite Fermat numbers?

Integers of the form $2^{2^n} + 1$ are called Fermat numbers. Primes of the form $2^{2^n} + 1$ are called Fermat primes, as Fermat conjectured that every integer of the form $2^{2^n} + 1$ is prime, see [12, p. 1]. Fermat correctly remarked that $2^{2^0} + 1 = 3$, $2^{2^1} + 1 = 5$, $2^{2^2} + 1 = 17$, $2^{2^3} + 1 = 257$, and $2^{2^4} + 1 = 65537$ are all prime, see [12, p. 1].

Open Problem 3. *([12, p. 159]) Are there infinitely many composite numbers of the form $2^{2^n} + 1$?*

Most mathematicians believe that $2^{2^n} + 1$ is composite for every integer $n \geqslant 5$, see [11, p. 23]. Let

$$H_n = \left\{x_i \cdot x_j = x_k : \; i, j, k \in \{1, \ldots, n\}\right\} \cup \left\{2^{2^{x_i}} = x_k : \; i, k \in \{1, \ldots, n\}\right\}$$

Let $h(1) = 1$, and let $h(n + 1) = 2^{2^{h(n)}}$ for every positive integer n.

Lemma 28. *The following subsystem of H_n*

$$\begin{cases} x_1 \cdot x_1 & = & x_1 \\ \forall i \in \{1, \ldots, n-1\} \; 2^{2^{x_i}} & = & x_{i+1} \end{cases}$$

has exactly one solution $(x_1, \ldots, x_n) \in (\mathbb{N} \setminus \{0\})^n$, namely $(h(1), \ldots, h(n))$.

For a positive integer n, let ξ_n denote the following statement: *if a system of equations $S \subseteq H_n$ has only finitely many solutions in positive integers $x_1, \ldots, x_n$, then each such solution $(x_1, \ldots, x_n)$ satisfies $x_1, \ldots, x_n \leqslant h(n)$.* The statement ξ_n says that for subsystems of H_n the largest known solution is indeed the largest possible.

Hypothesis 4. *The statements $\xi_1, \ldots, \xi_{13}$ are true.*

Lemma 29. *Every statement ξ_n is true with an unknown integer bound that depends on n.*

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

Theorem 19. *The statement ξ_{13} proves the following implication: if $z \in \mathbb{N} \setminus \{0\}$ and $2^{2^z} + 1$ is composite and greater than $h(12)$, then $2^{2^z} + 1$ is composite for infinitely many positive integers z.*

Proof. Let us consider the equation

$$(x+1)(y+1) = 2^{2^z} + 1 \tag{E}$$

in positive integers. By Lemma 4, we can transform the equation `(E)` into an equivalent system of equations $\mathcal{G}$ which has 13 variables (x, y, z, and 10 other variables) and which consists of equations of the forms $\alpha \cdot \beta = \gamma$ and $2^{2^\alpha} = \gamma$, see the diagram in Figure 9.

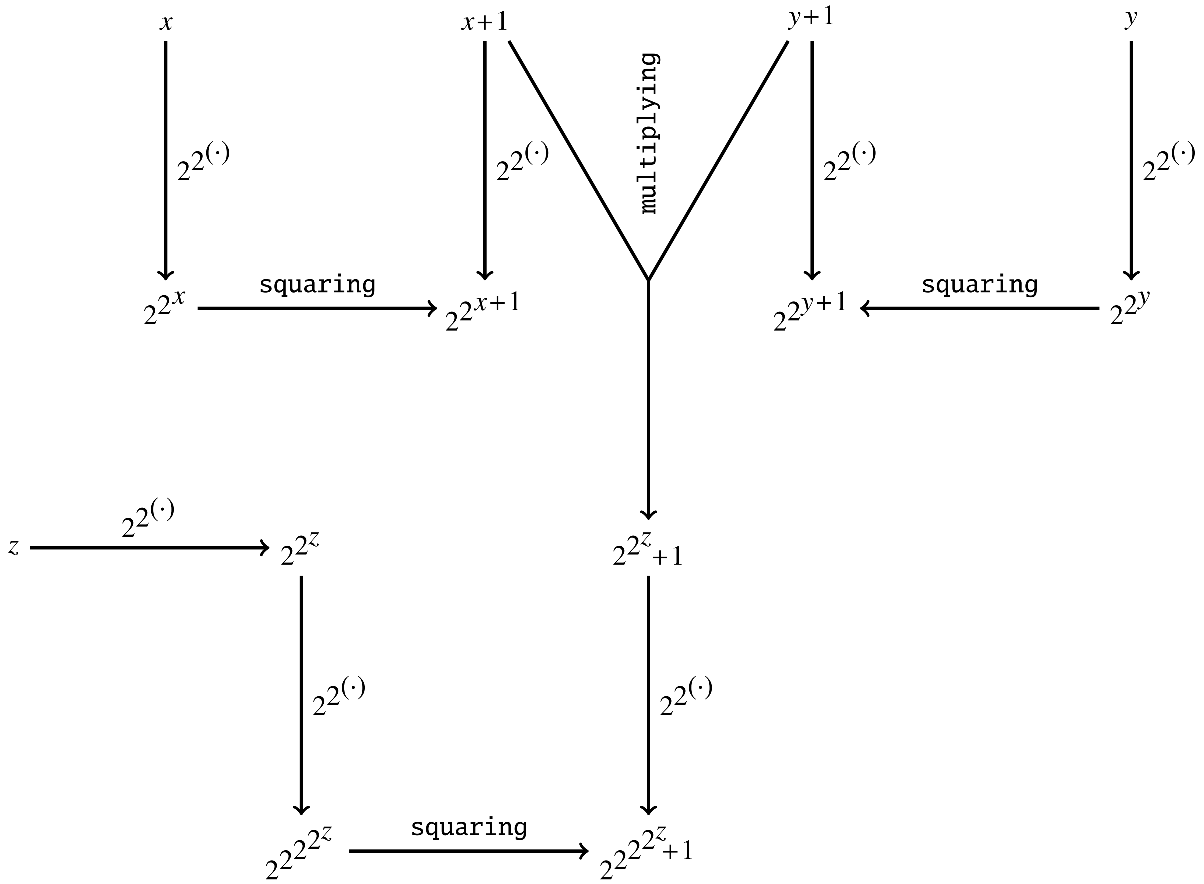

Fig. 9 Construction of the system $\mathcal{G}$

Since $2^{2^z}+1 > h(12)$, we obtain that $2^{2^{2^{2^z}+1}} > h(13)$. By this, the statement ξ_{13} implies that the system $\mathcal{G}$ has infinitely many solutions in positive integers. It means that there are infinitely many composite Fermat numbers. □

Corollary 7. *Let $\mathcal{W}_{13}$ denote the set of composite Fermat numbers. The statement ξ_{13} implies that we know an algorithm such that it returns a threshold number of $\mathcal{W}_{13}$, and this number equals* $\max(\mathcal{W}_{13})$*, if $\mathcal{W}_{13}$ is finite. Assuming the statement ξ_{13}, a single query to an oracle for the halting problem decides the infinity of $\mathcal{W}_{13}$. Assuming the statement ξ_{13}, the infinity of $\mathcal{W}_{13}$ is decidable in the limit.*

Proof. We consider an algorithm which computes $\max(\mathcal{W}_{13} \cap [1, h(12)])$. □

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