

# On sets $\mathcal{X} \subseteq \mathbb{N}$ for which we know an algorithm that computes a threshold number $t(\mathcal{X}) \in \mathbb{N}$ such that $\mathcal{X}$ is infinite if and only if $\mathcal{X}$ contains an element greater than $t(\mathcal{X})$

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## Abstract

Let  $\Gamma_{\lfloor n \rfloor}(k)$  denote  $(k-1)!$ , where  $n \in \{3, \dots, 16\}$  and  $k \in \{2\} \cup \{2^{2^{n-3}} + 1, 2^{2^{n-3}} + 2, 2^{2^{n-3}} + 3, \dots\}$ . For an integer  $n \in \{3, \dots, 16\}$ , let  $\Sigma_n$  denote the following statement: if a system of equations  $\mathcal{S} \subseteq \{\Gamma_{\lfloor n \rfloor}(x_i) = x_k : i, k \in \{1, \dots, n\}\} \cup \{x_i \cdot x_j = x_k : i, j, k \in \{1, \dots, n\}\}$  has only finitely many solutions in positive integers  $x_1, \dots, x_n$ , then each such solution  $(x_1, \dots, x_n)$  satisfies  $x_1, \dots, x_n \leq 2^{2^{n-2}}$ . The statement  $\Sigma_6$  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  $\{(1, 2), (2, 3)\}$ . The statement  $\Sigma_6$  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  $\{(4, 5), (5, 11), (7, 71)\}$ . The statement  $\Sigma_9$  implies the infinitude of primes of the form  $n^2 + 1$ . The statement  $\Sigma_9$  implies that any prime of the form  $n! + 1$  with  $n \geq 2^{2^{9-3}}$  proves the infinitude of primes of the form  $n! + 1$ . The statement  $\Sigma_{14}$  implies the infinitude of twin primes. The statement  $\Sigma_{16}$  implies the infinitude of Sophie Germain primes. A modified statement  $\Sigma_7$  implies the infinitude of Wilson primes.

**Key words and phrases:** Brocard's problem, Brocard-Ramanujan equation  $x! + 1 = y^2$ , composite Fermat numbers, Erdős' equation  $x(x+1) = y!$ , prime numbers of the form  $n^2 + 1$ , prime numbers of the form  $n! + 1$ , Richert's lemma, Sophie Germain primes, Wilson primes, twin prime conjecture.

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## 1 Introduction

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 [18, p. 39]. The following statement

- (1) "For every non-negative integer  $n$  there exist prime exist numbers  $p$  and  $q$  such that  $p + 2 = q$  and  $p \in [10^n, 10^n + 1]$ "

is a  $\Pi_1$  statement which strengthens the twin prime conjecture, see [5, p. 43], cf. [7, pp. 337–338]. Statement (1) is equivalent to the non-halting of a Turing machine. C. H. Bennett claims that most mathematical conjectures can be settled indirectly by proving stronger  $\Pi_1$  statements, see [1].

In this article, we study sets  $\mathcal{X} \subseteq \mathbb{N}$  for which we know an algorithm that computes a threshold number  $t(\mathcal{X}) \in \mathbb{N}$  such that  $\mathcal{X}$  is infinite if and only if  $\mathcal{X}$  contains an element greater than  $t(\mathcal{X})$ . If  $\mathcal{X}$  is computable, then this property implies that the infinity of  $\mathcal{X}$  is equivalent to the halting of a Turing machine. 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  $\{\max(\mathcal{X}), \max(\mathcal{X}) + 1, \max(\mathcal{X}) + 2, \dots\}$ .

The classes of the infinite recursively enumerable sets and of the infinite recursive sets are not recursively enumerable, see [19, p. 234].

**Corollary 1.** *If an algorithm  $\text{Alg}_1$  for every recursive set  $\mathcal{R} \subseteq \mathbb{N}$  finds a non-negative integer  $\text{Alg}_1(\mathcal{R})$ , then there exists a finite set  $\mathcal{W} \subseteq \mathbb{N}$  such that  $\mathcal{W} \cap [\text{Alg}_1(\mathcal{W}) + 1, \infty) \neq \emptyset$ . If an algorithm  $\text{Alg}_2$  for*

every recursively enumerable set  $\mathcal{R} \subseteq \mathbb{N}$  finds a non-negative integer  $\text{Alg}_2(\mathcal{R})$ , then there exists a finite set  $\mathcal{W} \subseteq \mathbb{N}$  such that  $\mathcal{W} \cap [\text{Alg}_2(\mathcal{W}) + 1, \infty) \neq \emptyset$ .

## 2 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.

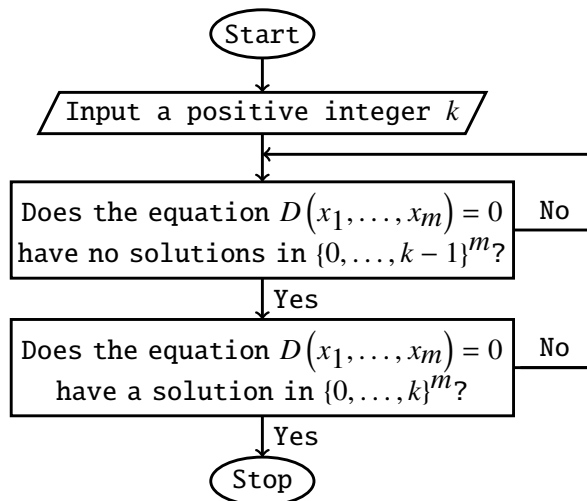
**Theorem 1.** ([6, p. 35]). *There exists a polynomial  $D(x_1, \dots, x_m)$  with integer coefficients such that if ZFC is arithmetically consistent, then the sentences "The equation  $D(x_1, \dots, x_m) = 0$  is solvable in non-negative integers" and "The equation  $D(x_1, \dots, x_m) = 0$  is not solvable in non-negative integers" are not provable in ZFC.*

Let  $\mathcal{Y}$  denote the set of all non-negative integers  $k$  such that the equation  $D(x_1, \dots, x_m) = 0$  has no solutions in  $\{0, \dots, k\}^m$ . Since the set  $\{0, \dots, k\}^m$  is finite, we know an algorithm which for every  $n \in \mathbb{N}$  decides whether or not  $n \in \mathcal{Y}$ . Let  $\gamma: \mathbb{N}^{m+1} \rightarrow \mathbb{N}$  be a computable bijection, and let  $\mathcal{E} \subseteq \mathbb{N}^{m+1}$  be the solution set of the equation  $D(x_1, \dots, x_m) + 0 \cdot x_{m+1} = 0$ . Theorem 1 implies Theorems 2 and 3.

**Theorem 2.** *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.*

**Theorem 3.** *We know an algorithm which for every  $n \in \mathbb{N}$  decides whether or not  $n \in \gamma(\mathcal{E})$ . The set  $\gamma(\mathcal{E})$  is empty or infinite. In both cases, every non-negative integer  $n$  is a threshold number of  $\gamma(\mathcal{E})$ . If ZFC is arithmetically consistent, then the sentences " $\gamma(\mathcal{E})$  is empty", " $\gamma(\mathcal{E})$  is not empty", " $\gamma(\mathcal{E})$  is finite", and " $\gamma(\mathcal{E})$  is infinite" are not provable in ZFC.*

In Figure 1,  $D(x_1, \dots, x_m)$  stands for the polynomial described in Theorem 1. Let  $\mathcal{K}$  denote the set of all positive integers  $k$  such that the algorithm in Figure 1 halts for  $k$  on the input. If ZFC is consistent, then  $\mathcal{K} = \emptyset$ . Otherwise,  $\text{card}(\mathcal{K}) = 1$ .



**Fig. 1** The algorithm which may halt only when ZFC is inconsistent

**Theorem 4.** *If ZFC is consistent, then for every positive integer  $n$ , the inclusion  $\mathcal{K} \subseteq \{1, \dots, n\}$  is not provable in ZFC.*

*Proof.* It follows from Gödel's second incompleteness theorem because the inclusion  $\mathcal{K} \subseteq \{1, \dots, n\}$  implies  $\mathcal{K} = \emptyset$  and the consistency of ZFC.  $\square$

**Theorem 5.** (cf. Theorem 28). *If ZFC is consistent and a computer program halts for at most finitely many positive integers  $k$  on the input, then not always we can write the decimal expansion of a positive integer  $n$  which is not smaller than every such number  $k$ .*

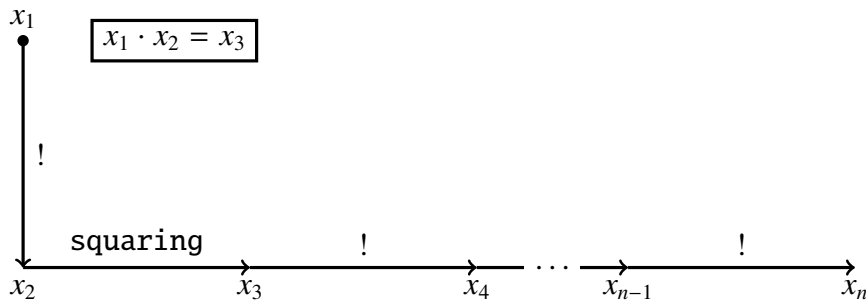
*Proof.* We write a computer program which implements the algorithm in Figure 1. This program halts exactly for elements of  $\mathcal{K}$  on the input. The set  $\mathcal{K}$  is finite as  $\text{card}(\mathcal{K}) \leq 1$ . By Theorem 4, if  $ZFC$  is consistent, then for every positive integer  $n$ , the inclusion  $\mathcal{K} \subseteq \{1, \dots, n\}$  is not provable in  $ZFC$ .  $\square$

### 3 Hypothetical statements $\Psi_3, \dots, \Psi_{16}$ and number-theoretic lemmas

For a positive integer  $n$ , let  $\Gamma(n)$  denote  $(n-1)!$ . Let  $f(1) = 2, f(2) = 4$ , and let  $f(n+1) = f(n)!$  for every integer  $n \geq 2$ . Let  $h(1) = 1$ , and let  $h(n+1) = 2^{2^{h(n)}}$  for every positive integer  $n$ . Let  $g(3) = 4$ , and let  $g(n+1) = g(n)!$  for every integer  $n \geq 3$ . For an integer  $n \geq 3$ , let  $\mathcal{U}_n$  denote the following system of equations:

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

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



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

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

Let

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

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

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

**Theorem 6.** 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.  $\square$

**Theorem 7.** For every statement  $\Psi_n$ , the bound  $g(n)$  cannot be decreased.

*Proof.* It follows from Lemma 1 because  $\mathcal{U}_n \subseteq B_n$ .  $\square$

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

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

**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 positive integers  $x$  and  $y$ ,  $x+1 = y$  if and only if

$$(1 \neq y) \wedge (x! \cdot y = y!)$$

**Lemma 5.** For every non-negative integers  $b$  and  $c$ ,  $b + 1 = c$  if and only if  $2^{2^b} \cdot 2^{2^b} = 2^{2^c}$ .

Let  $\mathcal{P}$  denote the set of prime numbers.

**Lemma 6.** (Wilson's theorem, [9, p. 89]). For every positive integer  $x$ ,  $x$  divides  $(x - 1)! + 1$  if and only if  $x \in \{1\} \cup \mathcal{P}$ .

## 4 Heuristic arguments against the statement $\forall n \in \mathbb{N} \setminus \{0, 1, 2\} \Psi_n$

Let

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

**Hypothesis 2.** ([33, p. 109]. If a system  $\mathcal{S} \subseteq G_n$  has only finitely many solutions in non-negative integers  $x_1, \dots, x_n$ , then each such solution  $(x_1, \dots, x_n)$  satisfies  $x_1, \dots, x_n \leq h(2n)$ .

**Hypothesis 3.** If a system  $\mathcal{S} \subseteq G_n$  has only finitely many solutions in positive integers  $x_1, \dots, x_n$ , then each such solution  $(x_1, \dots, x_n)$  satisfies  $x_1, \dots, x_n \leq f(2n)$ .

Observations 1 and 2 heuristically justify Hypothesis 3.

**Observation 1.** (cf. [33, p. 110, Observation 1]). For every system  $\mathcal{S} \subseteq G_n$  which involves all the variables  $x_1, \dots, x_n$ , the following new system

$$\left( \bigcup_{x_i \cdot x_j = x_k \in \mathcal{S}} \{x_i \cdot x_j = x_k\} \right) \cup \{x_k! = y_k : k \in \{1, \dots, n\}\} \cup \left( \bigcup_{x_i + 1 = x_k \in \mathcal{S}} \{1 \neq x_k, y_i \cdot x_k = y_k\} \right)$$

is equivalent to  $\mathcal{S}$ . If the system  $\mathcal{S}$  has only finitely many solutions in positive integers  $x_1, \dots, x_n$ , then the new system has only finitely many solutions in positive integers  $x_1, \dots, x_n, y_1, \dots, y_n$ .

*Proof.* It follows from Lemma 4. □

**Observation 2.** The equation  $x_1! = x_1$  has exactly two solutions in positive integers, namely  $x_1 = 1$  and  $x_1 = f(1)$ . The system  $\begin{cases} x_1! = x_1 \\ x_1 \cdot x_1 = x_2 \end{cases}$  has exactly two solutions in positive integers, namely  $(1, 1)$  and  $(f(1), f(2))$ . For every integer  $n \geq 3$ , the following system

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

has exactly two solutions in positive integers, namely  $(1, \dots, 1)$  and  $(f(1), \dots, f(n))$ .

For a positive integer  $n$ , let  $\Phi_n$  denote the following statement: if a system

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

has only finitely many solutions in positive integers  $x_1, \dots, x_n$ , then each such solution  $(x_1, \dots, x_n)$  satisfies  $x_1, \dots, x_n \leq f(n)$ .

**Theorem 8.** The statement  $\forall n \in \mathbb{N} \setminus \{0\} \Phi_n$  implies Hypothesis 3.

*Proof.* It follows from Lemma 4. □

Let  $\mathcal{R}ng$  denote the class of all rings  $\mathbf{K}$  that extend  $\mathbb{Z}$ , and let

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

Th. Skolem proved that every Diophantine equation can be algorithmically transformed into an equivalent system of Diophantine equations of degree at most 2, see [25, pp. 2–3] and [15, pp. 3–4]. The following result strengthens Skolem's theorem.

**Lemma 7.** ([31, p. 720]). Let  $D(x_1, \dots, x_p) \in \mathbb{Z}[x_1, \dots, x_p]$ . Assume that  $\deg(D, x_i) \geq 1$  for each  $i \in \{1, \dots, p\}$ . We can compute a positive integer  $n > p$  and a system  $T \subseteq E_n$  which satisfies the following two conditions:

**Condition 1.** If  $\mathbf{K} \in \mathcal{Rng} \cup \{\mathbb{N}, \mathbb{N} \setminus \{0\}\}$ , then

$$\forall \tilde{x}_1, \dots, \tilde{x}_p \in \mathbf{K} \left( D(\tilde{x}_1, \dots, \tilde{x}_p) = 0 \iff \exists \tilde{x}_{p+1}, \dots, \tilde{x}_n \in \mathbf{K} (\tilde{x}_1, \dots, \tilde{x}_p, \tilde{x}_{p+1}, \dots, \tilde{x}_n) \text{ solves } T \right)$$

**Condition 2.** If  $\mathbf{K} \in \mathcal{Rng} \cup \{\mathbb{N}, \mathbb{N} \setminus \{0\}\}$ , then for each  $\tilde{x}_1, \dots, \tilde{x}_p \in \mathbf{K}$  with  $D(\tilde{x}_1, \dots, \tilde{x}_p) = 0$ , there exists a unique tuple  $(\tilde{x}_{p+1}, \dots, \tilde{x}_n) \in \mathbf{K}^{n-p}$  such that the tuple  $(\tilde{x}_1, \dots, \tilde{x}_p, \tilde{x}_{p+1}, \dots, \tilde{x}_n)$  solves  $T$ .

Conditions 1 and 2 imply that for each  $\mathbf{K} \in \mathcal{Rng} \cup \{\mathbb{N}, \mathbb{N} \setminus \{0\}\}$ , the equation  $D(x_1, \dots, x_p) = 0$  and the system  $T$  have the same number of solutions in  $\mathbf{K}$ .

Let  $\alpha, \beta$ , and  $\gamma$  denote variables.

**Lemma 8.** ([23, p. 100]) For each positive integers  $x, y, z$ ,  $x + y = z$  if and only if

$$(zx + 1)(zy + 1) = z^2(xy + 1) + 1$$

**Corollary 2.** We can express the equation  $x + y = z$  as an equivalent system  $\mathcal{F}$ , where  $\mathcal{F}$  involves  $x, y, z$  and 9 new variables, and where  $\mathcal{F}$  consists of equations of the forms  $\alpha + 1 = \gamma$  and  $\alpha \cdot \beta = \gamma$ .

*Proof.* The new 9 variables express the following polynomials:

$$zx, \quad zx + 1, \quad zy, \quad zy + 1, \quad z^2, \quad xy, \quad xy + 1, \quad z^2(xy + 1), \quad z^2(xy + 1) + 1$$

□

**Lemma 9.** (cf. [33, p. 110, Lemma 4]). Let  $D(x_1, \dots, x_p) \in \mathbb{Z}[x_1, \dots, x_p]$ . Assume that  $\deg(D, x_i) \geq 1$  for each  $i \in \{1, \dots, p\}$ . We can compute a positive integer  $n > p$  and a system  $T \subseteq G_n$  which satisfies the following two conditions:

**Condition 3.** For every positive integers  $\tilde{x}_1, \dots, \tilde{x}_p$ ,

$$D(\tilde{x}_1, \dots, \tilde{x}_p) = 0 \iff \exists \tilde{x}_{p+1}, \dots, \tilde{x}_n \in \mathbb{N} \setminus \{0\} (\tilde{x}_1, \dots, \tilde{x}_p, \tilde{x}_{p+1}, \dots, \tilde{x}_n) \text{ solves } T$$

**Condition 4.** If positive integers  $\tilde{x}_1, \dots, \tilde{x}_p$  satisfy  $D(\tilde{x}_1, \dots, \tilde{x}_p) = 0$ , then there exists a unique tuple  $(\tilde{x}_{p+1}, \dots, \tilde{x}_n) \in (\mathbb{N} \setminus \{0\})^{n-p}$  such that the tuple  $(\tilde{x}_1, \dots, \tilde{x}_p, \tilde{x}_{p+1}, \dots, \tilde{x}_n)$  solves  $T$ .

Conditions 3 and 4 imply that the equation  $D(x_1, \dots, x_p) = 0$  and the system  $T$  have the same number of solutions in positive integers.

*Proof.* Let the system  $T$  be given by Lemma 7. We replace in  $T$  each equation of the form  $1 = x_k$  by the equation  $x_k \cdot x_k = x_k$ . Next, we apply Corollary 2 and replace in  $T$  each equation of the form  $x_i + x_j = x_k$  by an equivalent system of equations of the forms  $\alpha + 1 = \gamma$  and  $\alpha \cdot \beta = \gamma$ . □

**Theorem 9.** Hypothesis 3 implies that there is an algorithm which takes as input a Diophantine equation, and returns an integer such that this integer is greater than the solutions in positive integers, if these solutions form a finite set.

*Proof.* It follows from Lemma 9. □

**Open Problem 1.** Is there an algorithm which takes as input a Diophantine equation, and returns an integer such that this integer is greater than the moduli of integer (non-negative integer, positive integer) solutions, if the solution set is finite?

Matiyasevich's conjecture on finite-fold Diophantine representations ([17]) implies a negative answer to Open Problem 1, see [16, p. 42].

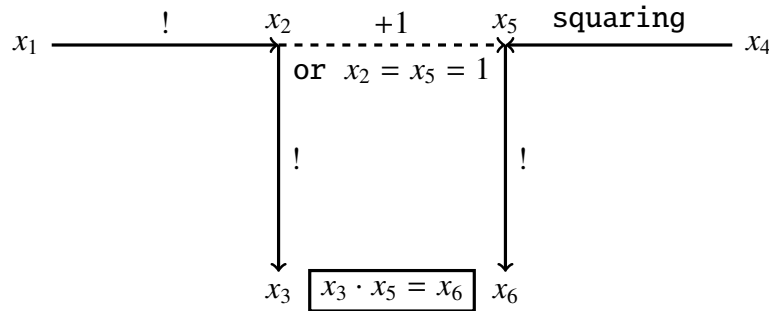
The statement  $\forall n \in \mathbb{N} \setminus \{0\} \Phi_n$  implies that there is an algorithm which takes as input a factorial Diophantine equation, and returns an integer such that this integer is greater than the solutions in positive integers, if these solutions form a finite set. This conclusion is a bit strange because a computable upper bound on non-negative integer solutions does not exist for exponential Diophantine equations with a finite number of solutions, see [14, p. 300].

## 5 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 3 explain the construction of the system  $\mathcal{A}$ .



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

**Lemma 10.** 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 [34, 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 [20].

**Theorem 10.** If the equation  $x_1! + 1 = x_4^2$  has only finitely many solutions in positive integers, then the statement  $\Psi_6$  guarantees that each such solution  $(x_1, x_4)$  belongs to the set  $\{(4, 5), (5, 11), (7, 71)\}$ .

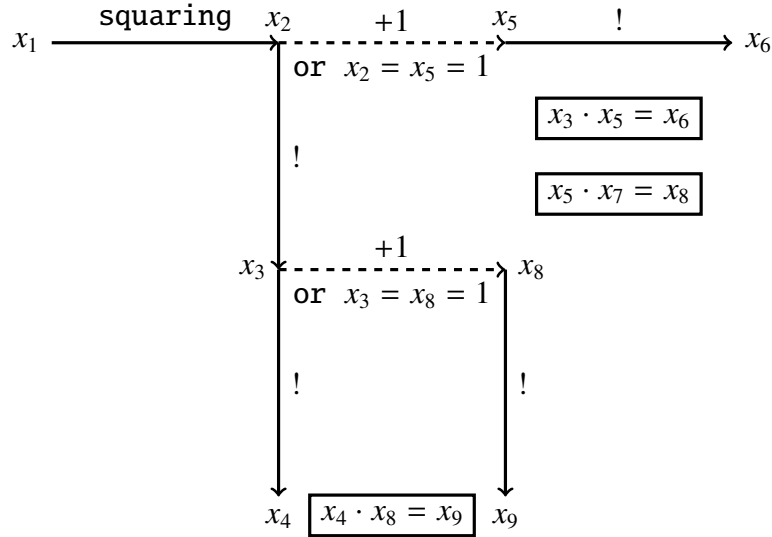
*Proof.* Suppose that the antecedent holds. Let positive integers  $x_1$  and  $x_4$  satisfy  $x_1! + 1 = x_4^2$ . Then,  $x_1, x_4 \in \mathbb{N} \setminus \{0, 1\}$ . By Lemma 10, the system  $\mathcal{A}$  is solvable in positive integers  $x_2, x_3, x_5, x_6$ . Since  $\mathcal{A} \subseteq B_6$ , the statement  $\Psi_6$  implies that  $x_6 = (x_1! + 1)! \leq g(6) = g(5)!$ . Hence,  $x_1! + 1 \leq g(5) = g(4)!$ . Consequently,  $x_1 < g(4) = 24$ . If  $x_1 \in \{1, \dots, 23\}$ , then  $x_1! + 1$  is a perfect square only for  $x_1 \in \{4, 5, 7\}$ . □

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

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 4 explain the construction of the system  $\mathcal{B}$ .



**Fig. 4** Construction of the system  $\mathcal{B}$

**Lemma 11.** For every integer  $x_1 \geq 2$ , the system  $\mathcal{B}$  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 2, for every integer  $x_1 \geq 2$ , the system  $\mathcal{B}$  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 11 follows from Lemma 6.  $\square$

**Lemma 12.** There are only finitely many tuples  $(x_1, \dots, x_9) \in (\mathbb{N} \setminus \{0\})^9$  which solve the system  $\mathcal{B}$  and satisfy  $x_1 = 1$ .

*Proof.* If a tuple  $(x_1, \dots, x_9) \in (\mathbb{N} \setminus \{0\})^9$  solves the system  $\mathcal{B}$  and  $x_1 = 1$ , then  $x_1, \dots, x_9 \leq 2$ . 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,  $x_9 = x_8! \leq 2$ .  $\square$

Edmund Landau's conjecture states that there are infinitely many primes of the form  $n^2 + 1$ , see [18, pp. 37–38].

**Theorem 11.** The statement  $\Psi_9$  proves the following implication: if there exists an integer  $x_1 \geq 2$  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 11, 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  $\mathcal{B}$ . Since  $x_1^2 + 1 > g(7)$ , we obtain that  $x_1^2 \geq g(7)$ . Hence,  $(x_1^2)! \geq g(7)! = g(8)$ . Consequently,

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

Since  $\mathcal{B} \subseteq \mathcal{B}_9$ , the statement  $\Psi_9$  and the inequality  $x_9 > g(9)$  imply that the system  $\mathcal{B}$  has infinitely many solutions  $(x_1, \dots, x_9) \in (\mathbb{N} \setminus \{0\})^9$ . According to Lemmas 11 and 12, there are infinitely many primes of the form  $n^2 + 1$ .  $\square$

## 7 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 [4, p. 443] and [26].

**Theorem 12.** (cf. Theorem 17). *The statement  $\Psi_9$  proves the following implication: if there exists an integer  $x_1 \geq g(6)$  such that  $x_1! + 1$  is prime, then there are infinitely many primes of the form  $n! + 1$ .*

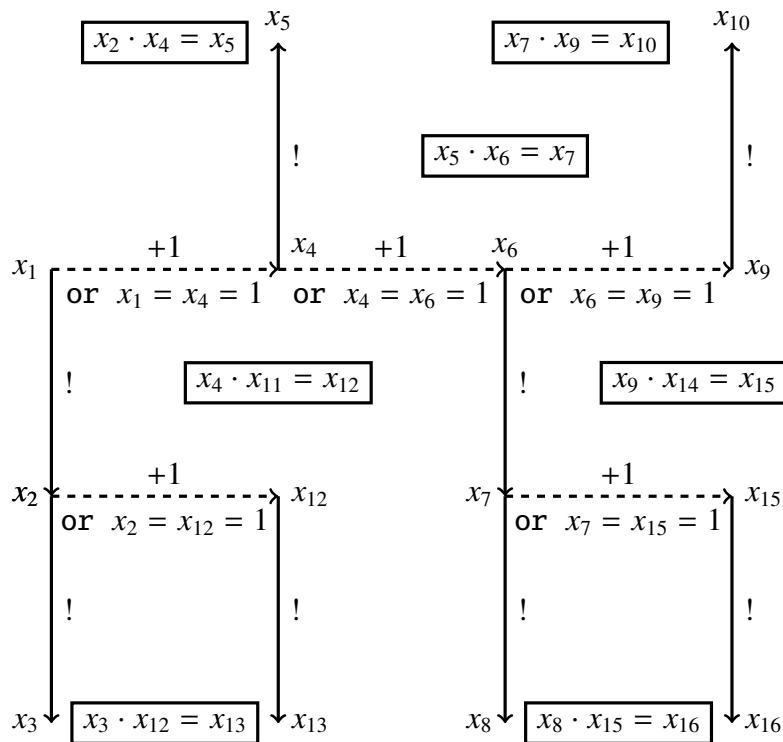
*Proof.* We leave the analogous proof to the reader. □

## 8 The twin prime conjecture

Let  $C$  denote the following system of equations:

$$\left\{ \begin{array}{l} x_1! = x_2 \\ x_2! = x_3 \\ x_4! = x_5 \\ x_6! = x_7 \\ x_7! = x_8 \\ x_9! = x_{10} \\ x_{12}! = x_{13} \\ x_{15}! = x_{16} \\ x_2 \cdot x_4 = x_5 \\ x_5 \cdot x_6 = x_7 \\ x_7 \cdot x_9 = x_{10} \\ x_4 \cdot x_{11} = x_{12} \\ x_3 \cdot x_{12} = x_{13} \\ x_9 \cdot x_{14} = x_{15} \\ x_8 \cdot x_{15} = x_{16} \end{array} \right.$$

Lemma 2 and the diagram in Figure 5 explain the construction of the system  $C$ .



**Fig. 5** Construction of the system  $C$



**Lemma 13.** 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:

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

*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

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

Hence, the claim of Lemma 13 follows from Lemma 6.  $\square$

**Lemma 14.** There are only finitely many tuples  $(x_1, \dots, x_{16}) \in (\mathbb{N} \setminus \{0\})^{16}$  which solve the system  $C$  and satisfy

$$(x_4 \in \{1, 2\}) \vee (x_9 \in \{1, 2\})$$

*Proof.* If a tuple  $(x_1, \dots, x_{16}) \in (\mathbb{N} \setminus \{0\})^{16}$  solves the system  $C$  and

$$(x_4 \in \{1, 2\}) \vee (x_9 \in \{1, 2\})$$

then  $x_1, \dots, x_{16} \leq 7!$ . 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,  $x_{16} = x_{15}! = 7!$ .  $\square$

**Theorem 13.** The statement  $\Psi_{16}$  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 13, there exists a unique tuple  $(x_1, x_2, x_3, x_5, x_6, x_7, x_8, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}) \in (\mathbb{N} \setminus \{0\})^{16}$  such that the tuple  $(x_1, \dots, x_{16})$  solves the system  $C$ . Since  $x_9 > g(14)$ , we obtain that  $x_9 - 1 \geq g(14)$ . Therefore,  $(x_9 - 1)! \geq g(14)! = g(15)$ . 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  $\Psi_{16}$  and the inequality  $x_{16} > g(16)$  imply that the system  $C$  has infinitely many solutions in positive integers  $x_1, \dots, x_{16}$ . According to Lemmas 13 and 14, there are infinitely many twin primes.  $\square$

Let  $\mathbb{P}(x)$  denote the predicate " $x$  is a prime number". Dickson's conjecture ([18, p. 36], [36, p. 109]) implies that the existential theory of  $(\mathbb{N}, =, +, \mathbb{P})$  is decidable, see [36, Theorem 2, p. 109]. For a positive integer  $n$ , let  $\Theta_n$  denote the following statement: for every system  $\mathcal{S} \subseteq \{x_i + 1 = x_k : i, k \in \{1, \dots, n\}\} \cup \{\mathbb{P}(x_i) : i \in \{1, \dots, n\}\}$  the solvability of  $\mathcal{S}$  in non-negative integers is decidable.

**Lemma 15.** *If the existential theory of  $(\mathbb{N}, =, +, \mathbb{P})$  is decidable, then the statements  $\Theta_n$  are true.*

*Proof.* For every non-negative integers  $x$  and  $y$ ,  $x + 1 = y$  if and only if

$$\exists u, v \in \mathbb{N} ((u + u = v) \wedge \mathbb{P}(v) \wedge (x + u = y))$$

□

**Theorem 14.** *The conjunction of the implication (\*) and the statement  $\Theta_{g(14)+2}$  implies that the twin prime conjecture is decidable.*

*Proof.* By the statement  $\Theta_{g(14)+2}$ , we can decide the truth of the sentence

$$\exists x_1 \dots \exists x_{g(14)+2} ((\forall i \in \{1, \dots, g(14) + 1\} x_i + 1 = x_{i+1}) \wedge \mathbb{P}(x_{g(14)}) \wedge \mathbb{P}(x_{g(14)+2})) \quad (2)$$

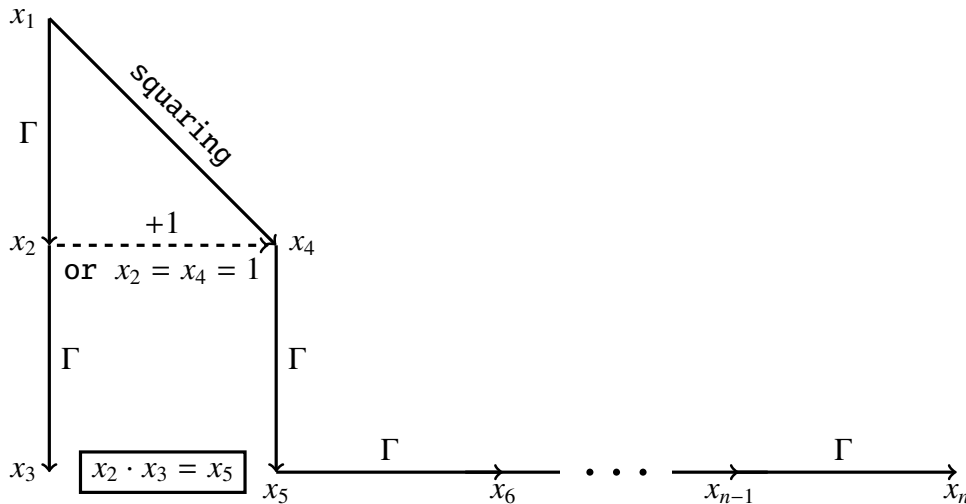
If sentence (2) is false, then the twin prime conjecture is false. If sentence (2) is true, then there exists a twin prime greater than  $g(14)$ . In this case, the twin prime conjecture follows from Theorem 13. □

## 9 Hypothetical statements $\Delta_5, \dots, \Delta_{14}$ about the Gamma function and their consequences

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

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

Lemma 3 and the diagram in Figure 6 explain the construction of the system  $\mathcal{J}_n$ .



**Fig. 6** Construction of the system  $\mathcal{J}_n$

**Observation 3.** *For every integer  $n \geq 5$ , the system  $\mathcal{J}_n$  has exactly two solutions in positive integers, namely  $(1, \dots, 1)$  and  $(5, 24, 23!, 25, \lambda(5), \dots, \lambda(n))$ .*

For an integer  $n \geq 5$ , let  $\Delta_n$  denote the following statement: *if a system  $\mathcal{S} \subseteq \{\Gamma(x_i) = x_k : i, k \in \{1, \dots, n\}\} \cup \{x_i \cdot x_j = x_k : i, j, k \in \{1, \dots, n\}\}$  has only finitely many solutions in positive integers  $x_1, \dots, x_n$ , then each such solution  $(x_1, \dots, x_n)$  satisfies  $x_1, \dots, x_n \leq \lambda(n)$ .*

**Hypothesis 4.** *The statements  $\Delta_5, \dots, \Delta_{14}$  are true.*

Lemmas 3 and 6 imply that the statements  $\Delta_n$  have similar consequences as the statements  $\Psi_n$ .

**Theorem 15.** *The statement  $\Delta_6$  implies that any prime number  $p \geq 25$  proves the infinitude of primes.*

*Proof.* It follows from Lemmas 3 and 6. We leave the details to the reader. □

## 10 Hypothetical statements $\Sigma_3, \dots, \Sigma_{16}$ about the Gamma function and their consequences

Let  $\Gamma_{\boxed{n}}(k)$  denote  $(k-1)!$ , where  $n \in \{3, \dots, 16\}$  and  $k \in \{2\} \cup \{2^{2^{n-3}} + 1, 2^{2^{n-3}} + 2, 2^{2^{n-3}} + 3, \dots\}$ . For an integer  $n \in \{3, \dots, 16\}$ , let

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

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

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

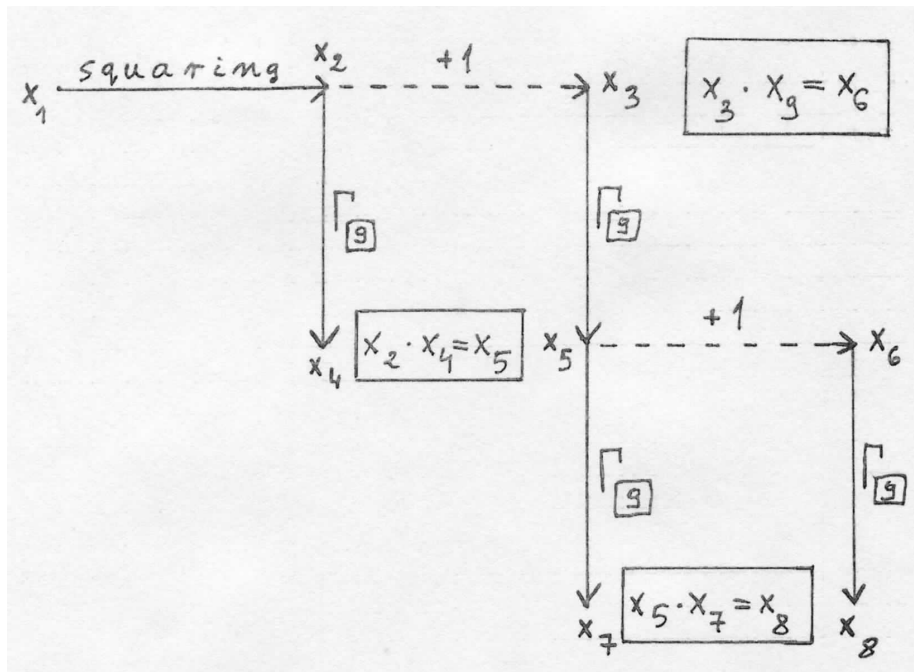
**Lemma 16.** For every integer  $n \in \{3, \dots, 16\}$ ,  $P_n \subseteq Q_n$  and the system  $P_n$  has exactly one solution in positive integers  $x_1, \dots, x_n$ , namely  $(1, 2^{2^0}, 2^{2^1}, 2^{2^2}, \dots, 2^{2^{n-2}})$ .

For an integer  $n \in \{3, \dots, 16\}$ , let  $\Sigma_n$  denote the following statement: if a system of equations  $S \subseteq Q_n$  has only finitely many solutions in positive integers  $x_1, \dots, x_n$ , then each such solution  $(x_1, \dots, x_n)$  satisfies  $x_1, \dots, x_n \leq 2^{2^{n-2}}$ .

**Hypothesis 5.** The statements  $\Sigma_3, \dots, \Sigma_{16}$  are true.

**Lemma 17.** (cf. Lemma 3). For every integer  $n \in \{4, \dots, 16\}$  and for every positive integers  $x$  and  $y$ ,  $x \cdot \Gamma_{\boxed{n}}(x) = \Gamma_{\boxed{n}}(y)$  if and only if  $(x+1 = y) \wedge (x \geq 2^{2^{n-3}} + 1)$ .

Let  $Z_9 \subseteq Q_9$  be the system of equations in Figure 7.



**Fig. 7** Construction of the system  $Z_9$

**Lemma 18.** For every positive integer  $x_1$ , the system  $Z_9$  is solvable in positive integers  $x_2, \dots, x_9$  if and only if  $x_1 > 2^{2^{9-4}}$  and  $x_1^2 + 1$  is prime. In this case, positive integers  $x_2, \dots, x_9$  are uniquely determined by  $x_1$ .

*Proof.* It follows from Lemmas 6 and 17. □

**Lemma 19.** ([29]). The number  $(13!)^2 + 1 = 38775788043632640001$  is prime.

**Lemma 20.**  $\left( (13!)^2 \geq 2^{2^{9-3}} + 1 = 18446744073709551617 \right) \wedge \left( \Gamma_{\boxed{9}}((13!)^2) > 2^{2^{9-2}} \right)$ .

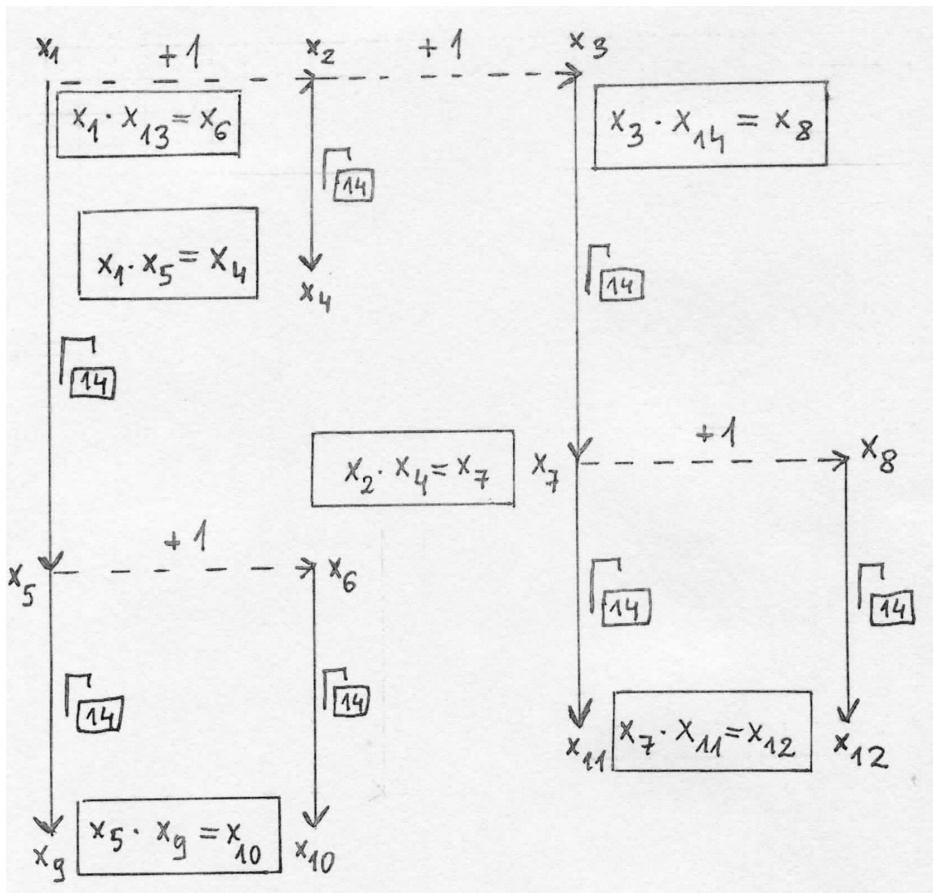
**Theorem 16.** The statement  $\Sigma_9$  implies the infinitude of primes of the form  $n^2 + 1$ .

*Proof.* It follows from Lemmas 18–20. □

**Theorem 17.** (cf. Theorem 12). The statement  $\Sigma_9$  implies that any prime of the form  $n! + 1$  with  $n \geq 2^{2^{9-3}}$  proves the infinitude of primes of the form  $n! + 1$ .

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

Let  $\mathcal{Z}_{14} \subseteq \mathcal{Q}_{14}$  be the system of equations in Figure 8.



**Fig. 8** Construction of the system  $\mathcal{Z}_{14}$

**Lemma 21.** For every positive integer  $x_1$ , the system  $\mathcal{Z}_{14}$  is solvable in positive integers  $x_2, \dots, x_{14}$  if and only if  $x_1$  and  $x_1 + 2$  are prime and  $x_1 \geq 2^{2^{14-3}} + 1$ . In this case, positive integers  $x_2, \dots, x_{14}$  are uniquely determined by  $x_1$ .

*Proof.* It follows from Lemmas 6 and 17. □

**Lemma 22.** ([37, p. 87]). The numbers  $459 \cdot 2^{8529} - 1$  and  $459 \cdot 2^{8529} + 1$  are prime (Harvey Dubner).

**Lemma 23.**  $459 \cdot 2^{8529} - 1 > 2^{2^{14-2}} = 2^{4096}$ .

**Theorem 18.** The statement  $\Sigma_{14}$  implies the infinitude of twin primes.

*Proof.* It follows from Lemmas 21–23. □

A prime  $p$  is said to be a Sophie Germain prime if both  $p$  and  $2p + 1$  are prime, see [35]. Let  $\mathcal{Z}_{16} \subseteq \mathcal{Q}_{16}$  be the system of equations in Figure 9.

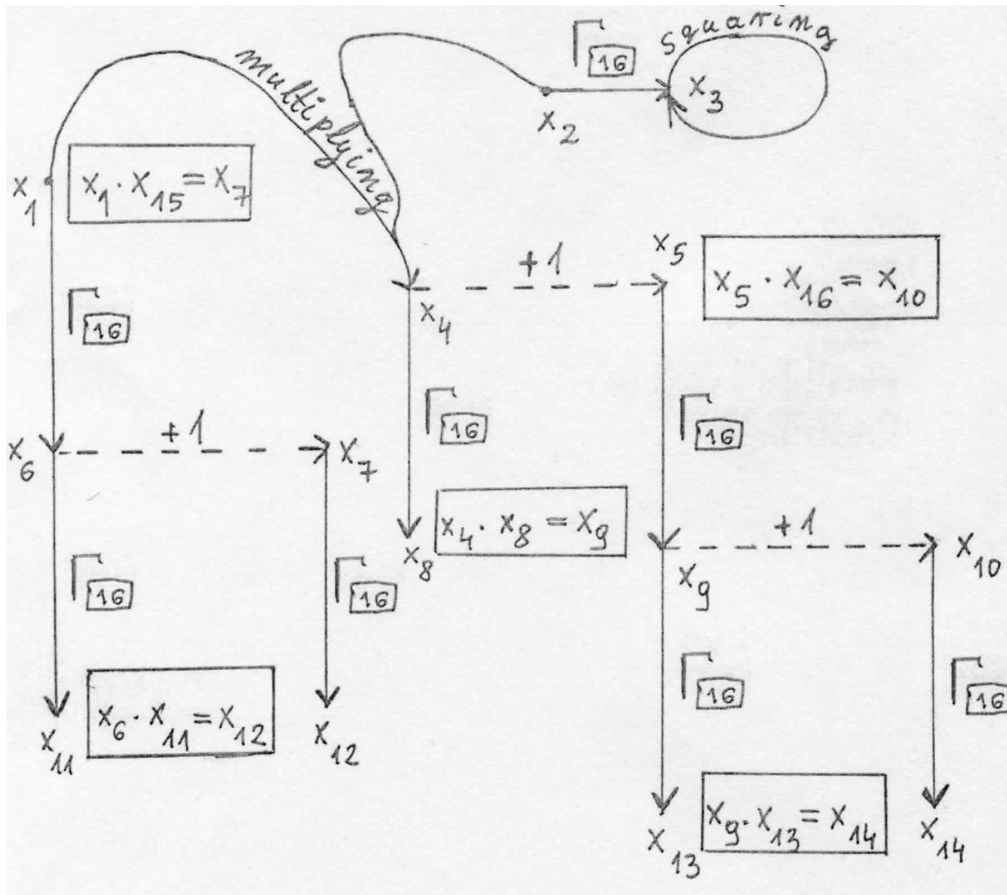


Fig. 9 Construction of the system  $\mathcal{Z}_{16}$

**Lemma 24.** For every positive integer  $x_1$ , the system  $\mathcal{Z}_{16}$  is solvable in positive integers  $x_2, \dots, x_{16}$  if and only if  $x_1$  is a Sophie Germain prime and  $x_1 \geq 2^{2^{16-3}} + 1$ . In this case, positive integers  $x_2, \dots, x_{16}$  are uniquely determined by  $x_1$ .

*Proof.* It follows from Lemmas 6 and 17. □

**Lemma 25.** ([21, p. 330]).  $8069496435 \cdot 10^{5072} - 1$  is a Sophie Germain prime (Harvey Dubner).

**Lemma 26.**  $8069496435 \cdot 10^{5072} - 1 > 2^{2^{16-2}}$ .

**Theorem 19.** The statement  $\Sigma_{16}$  implies the infinitude of Sophie Germain primes.

*Proof.* It follows from Lemmas 24–26. □

**Theorem 20.** The statement  $\Sigma_6$  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. Erdős, 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 21.** The statement  $\Sigma_6$  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. □

## 11 A hypothesis which implies the infinitude of Wilson primes

Let

$$\mathcal{V}_7 = \{\Gamma_5(x_i) = x_k : i, k \in \{1, \dots, 7\}\} \cup \{x_i \cdot x_j = x_k : i, j, k \in \{1, \dots, 7\}\}$$

Let  $I_7$  denote the following system of equations:

$$\left\{ \begin{array}{l} x_1 \cdot x_1 = x_1 \\ \Gamma_5(x_2) = x_1 \\ x_2 \cdot x_2 = x_3 \\ x_3 \cdot x_3 = x_4 \\ x_4 \cdot x_4 = x_5 \\ \Gamma_5(x_5) = x_6 \\ \Gamma_5(x_6) = x_7 \end{array} \right.$$

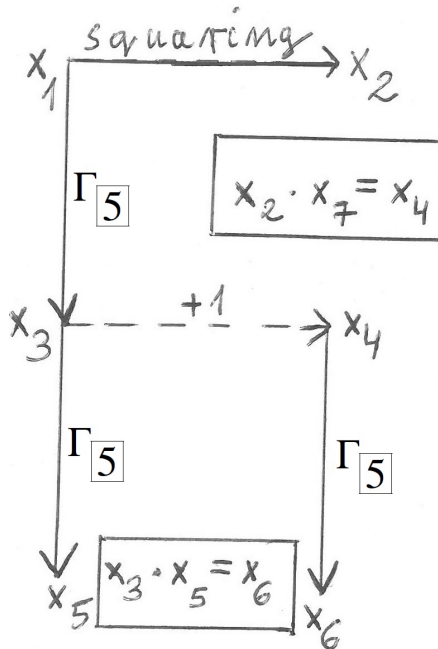
**Lemma 27.**  $I_7 \subseteq \mathcal{V}_7$  and the system  $I_7$  has exactly one solution in positive integers  $x_1, \dots, x_7$ , namely  $(1, 2, 4, 16, 256, 255!, (255! - 1)!)$ .

Let  $\Xi_7$  denote the following statement: if a system of equations  $S \subseteq \mathcal{V}_7$  has only finitely many solutions in positive integers  $x_1, \dots, x_7$ , then each such solution  $(x_1, \dots, x_7)$  satisfies  $x_1, \dots, x_7 \leq (255! - 1)!$ .

**Hypothesis 6.** The statement  $\Xi_7$  is true.

**Lemma 28.** (cf. Lemma 3). For every positive integers  $x$  and  $y$ ,  $x \cdot \Gamma_5(x) = \Gamma_5(y)$  if and only if  $(x + 1 = y) \wedge (x \geq 17)$ .

A Wilson prime is a prime number  $p$  such that  $p^2$  divides  $(p - 1)! + 1$ , see [3], [21, p. 346], and [30]. It is conjectured that the set of Wilson primes is infinite, see [3]. Let  $\mathcal{Z}_7 \subseteq \mathcal{V}_7$  be the system of equations in Figure 10.



**Fig. 10** Construction of the system  $\mathcal{Z}_7$

**Lemma 29.** For every positive integer  $x_1$ , the system  $\mathcal{Z}_7$  is solvable in positive integers  $x_2, \dots, x_7$  if and only if  $x_1$  is a Wilson prime and  $x_1 \geq 17$ . In this case, positive integers  $x_2, \dots, x_7$  are uniquely determined by  $x_1$ .

*Proof.* It follows from Lemmas 6 and 28. □

**Lemma 30.** ([3], [21, p. 346], [30]). 563 is a Wilson prime.

**Lemma 31.**  $\Gamma_{\boxed{5}}(\Gamma_{\boxed{5}}(563) + 1) > (255! - 1)!$

**Theorem 22.** The statement  $\Xi_7$  implies the infinitude of Wilson primes.

*Proof.* It follows from Lemmas 29–31. □

## 12 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 2.** ([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  $n \geq 5$ , see [11, p. 23].

**Theorem 23.** ([32]). An unproven inequality stated in [32] implies that  $2^{2^n} + 1$  is composite for every integer  $n \geq 5$ .

Let

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

**Lemma 32.** The following subsystem of  $H_n$

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

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

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

**Hypothesis 7.** The statements  $\Gamma_1, \dots, \Gamma_{13}$  are true.

The truth of the statement  $\forall n \in \mathbb{N} \setminus \{0\} \Gamma_n$  is doubtful because a computable upper bound on non-negative integer solutions does not exist for exponential Diophantine equations with a finite number of solutions, see [14, p. 300].

**Theorem 24.** Every statement  $\Gamma_n$  is true with an unknown integer bound that depends on  $n$ .

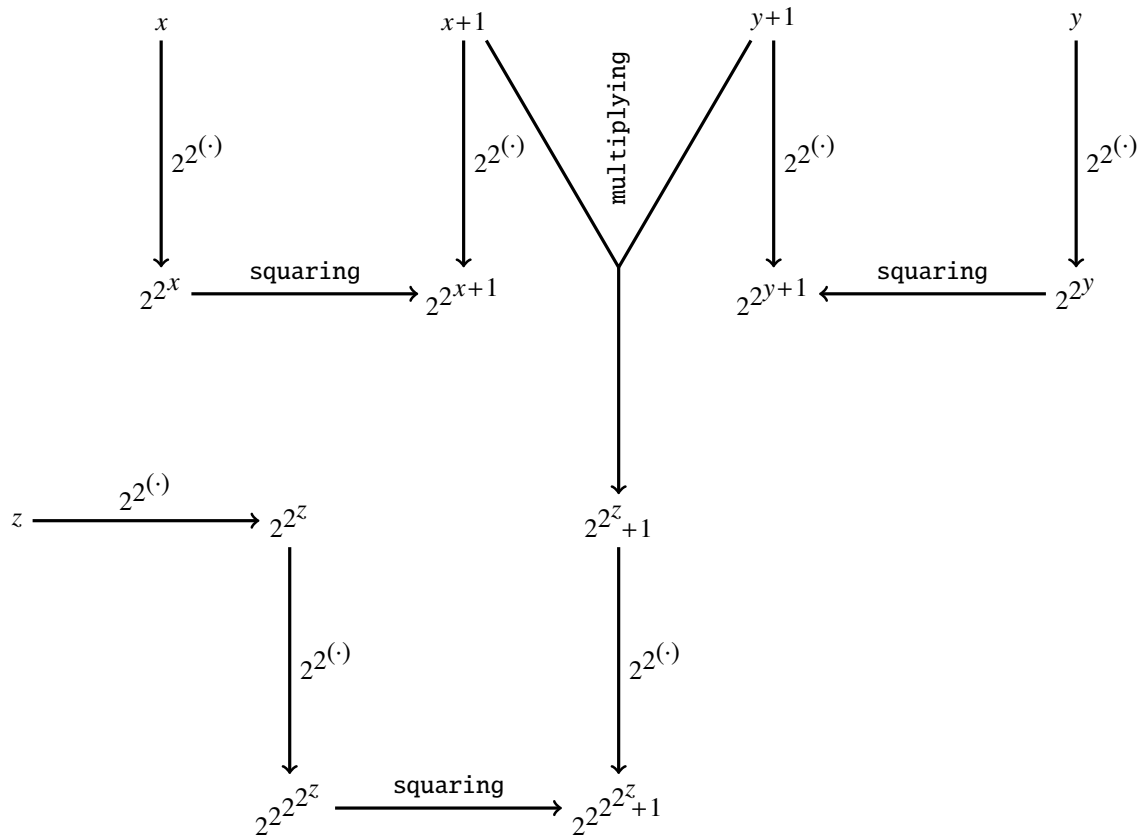
*Proof.* For every positive integer  $n$ , the system  $H_n$  has a finite number of subsystems. □

**Theorem 25.** The statement  $\Gamma_{13}$  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

$$(x + 1)(y + 1) = 2^{2^z} + 1 \tag{3}$$

in positive integers. By Lemma 5, we can transform equation (3) into an equivalent system  $\mathcal{G}$  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 11.



**Fig. 11** Construction of the system  $\mathcal{G}$

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

### 13 Subsets of $\mathbb{N}$ whose infinitude is unconditionally equivalent to the halting of a Turing machine

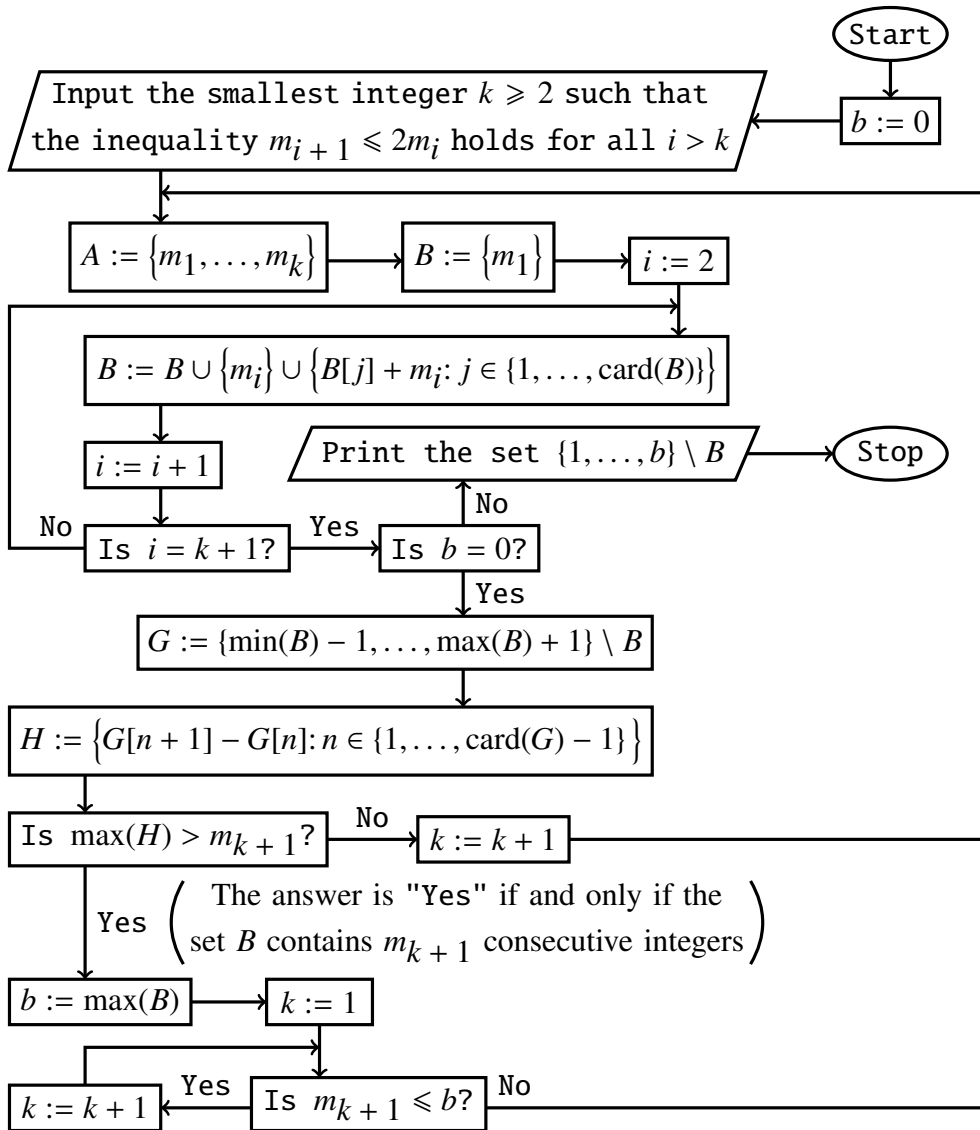
The following lemma is known as Richert's lemma.

**Lemma 33.** ([8], [22], [24, p. 152]). *Let  $\{m_i\}_{i=1}^{\infty}$  be an increasing sequence of positive integers such that for some positive integer  $k$  the inequality  $m_{i+1} \leq 2m_i$  holds for all  $i > k$ . Suppose there exists a non-negative integer  $b$  such that the numbers  $b + 1, b + 2, b + 3, \dots, b + m_{k+1}$  are all expressible as sums of one or more distinct elements of the set  $\{m_1, \dots, m_k\}$ . Then every integer greater than  $b$  is expressible as a sum of one or more distinct elements of the set  $\{m_1, m_2, m_3, \dots\}$ .*

Let  $\mathcal{T}$  denote the set of all positive integers  $i$  such that every integer  $j \geq i$  is expressible as a sum of one or more distinct elements of the set  $\{m_1, m_2, m_3, \dots\}$ . Obviously,  $\mathcal{T} = \emptyset$  or  $\mathcal{T} = [d, \infty) \cap \mathbb{N}$  for some positive integer  $d$ .

**Corollary 3.** *If the sequence  $\{m_i\}_{i=1}^{\infty}$  is computable and the algorithm in Figure 12 terminates, then almost all positive integers are expressible as a sum of one or more distinct elements of the set  $\{m_1, m_2, m_3, \dots\}$ . In particular, if the sequence  $\{m_i\}_{i=1}^{\infty}$  is computable and the algorithm in Figure 12 terminates, then the set  $\mathcal{T}$  is infinite. In this case, the algorithm in Figure 12 prints all positive integers which are not expressible as a sum of one or more distinct elements of the set  $\{m_1, m_2, m_3, \dots\}$ .*





**Fig. 12** The algorithm which uses Richert's lemma

**Theorem 26.** ([10, Theorem 2.3]). *If there exists  $\varepsilon > 0$  such that the inequality  $m_{i+1} \leq (2 - \varepsilon) \cdot m_i$  holds for every sufficiently large  $i$ , then the algorithm in Figure 12 terminates if and only if almost all positive integers are expressible as a sum of one or more distinct elements of the set  $\{m_1, m_2, m_3, \dots\}$ .*

**Corollary 4.** *If there exists  $\varepsilon > 0$  such that the inequality  $m_{i+1} \leq (2 - \varepsilon) \cdot m_i$  holds for every sufficiently large  $i$ , then the algorithm in Figure 12 terminates if and only if the set  $\mathcal{T}$  is infinite.*

We show how the algorithm in Figure 12 works for a concrete sequence  $\{m_i\}_{i=1}^{\infty}$ . Let  $[\cdot]$  denote the integer part function. For a positive integer  $i$ , let  $t_i = \frac{(i + 19)^{i + 19}}{(i + 19)! \cdot 2^i + 19}$ , and let  $m_i = [t_i]$ .

**Lemma 34.** *The inequality  $m_{i+1} \leq 2m_i$  holds for every positive integer  $i$ .*

*Proof.* For every positive integer  $i$ ,

$$\frac{m_i}{m_{i+1}} = \frac{[t_i]}{[t_{i+1}]} > \frac{t_i - 1}{t_{i+1}} = \frac{t_i}{t_{i+1}} - \frac{1}{t_{i+1}} \geq \frac{t_i}{t_{i+1}} - \frac{1}{t_2} =$$

$$2 \cdot \frac{i + 20}{i + 19} \cdot \left(1 - \frac{1}{i + 20}\right)^{i+20} - \frac{21! \cdot 2^{21}}{21^{21}} > 2 \cdot \left(1 - \frac{1}{21}\right)^{21} - \frac{21! \cdot 2^{21}}{21^{21}} = \frac{4087158528442715204485120000}{5842587018385982521381124421}$$

The last fraction was computed by MuPAD and is greater than  $\frac{1}{2}$ . □

**Theorem 27.** *The algorithm in Figure 12 terminates for the sequence  $\{m_i\}_{i=1}^{\infty}$ .*

*Proof.* By Lemma 34, we take  $k = 2$  as the initial value of  $k$ . The following *MuPAD* code

```

k:=2:
repeat
A:={floor((i+19)^(i+19)/((i+19)!*2^(i+19))) $i=1..k+1}:
B:={A[1]}:
for i from 2 to nops(A)-1 do
B:=B union {A[i]} union {B[j]+A[i] $j=1..nops(B)}:
end_for:
G:={y $y=B[1]-1..B[nops(B)]+1} minus B:
H:={G[n+1]-G[n] $n=1..nops(G)-1}:
k:=k+1:
until H[nops(H)]>A[nops(A)] end_repeat:
b:=B[nops(B)]:
k:=1:
while floor((k+20)^(k+20)/((k+20)!*2^(k+20)))<=b do
k:=k+1:
end_while:
A:={floor((i+19)^(i+19)/((i+19)!*2^(i+19))) $i=1..k}:
B:={A[1]}:
for i from 2 to nops(A)-1 do
B:=B union {A[i]} union {B[j]+A[i] $j=1..nops(B)}:
end_for:
print({n $n=1..b} minus B):

```

implements the algorithm in Figure 12 because *MuPAD* automatically orders every finite set of integers and the inequality  $H[nops(H)] > A[nops(A)]$  holds true if and only if the set  $B$  contains  $m_{k+1}$  consecutive integers. The code returns the following output:

```

{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20,
21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38,
39, 40, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 55, 56, 57, 58,
59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 73, 74, 75, 76, 77,
78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 97,
98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111,
112, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 127,
129, 130, 131, 132, 133, 134, 135, 136, 138, 139, 140, 141, 142, 143,
144, 145, 146, 147, 148, 149, 151, 152, 153, 154, 155, 156, 157, 158,
159, 160, 161, 162, 163, 164, 165, 166, 171, 172, 173, 174, 175, 176,
177, 178, 179, 180, 181, 183, 184, 185, 186, 187, 188, 189, 190, 192,
193, 194, 195, 196, 197, 198, 199, 201, 202, 203, 204, 205, 206, 207,

```

208, 210, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 225, 226,  
228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 243,  
244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 255, 256, 257, 258,  
259, 260, 261, 262, 264, 267, 269, 270, 271, 272, 273, 274, 275, 276,  
277, 279, 280, 282, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293,  
294, 297, 300, 301, 302, 304, 305, 306, 308, 309, 310, 311, 312, 313,  
314, 315, 316, 317, 318, 321, 324, 325, 326, 327, 328, 329, 330, 331,  
332, 333, 334, 335, 336, 341, 342, 343, 345, 346, 347, 348, 349, 351,  
354, 356, 358, 359, 360, 362, 363, 365, 366, 367, 368, 369, 371, 372,  
373, 374, 376, 378, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389,  
390, 400, 401, 402, 403, 405, 406, 407, 408, 410, 412, 413, 414, 415,  
417, 419, 420, 421, 422, 423, 425, 426, 428, 430, 432, 434, 437, 439,  
441, 442, 443, 444, 446, 447, 452, 454, 455, 456, 457, 459, 460, 461,  
462, 463, 464, 467, 474, 475, 477, 478, 479, 480, 482, 483, 484, 486,  
487, 488, 491, 495, 496, 497, 498, 501, 502, 504, 506, 508, 509, 511,  
513, 515, 516, 518, 519, 521, 524, 528, 529, 531, 533, 535, 536, 537,  
538, 539, 542, 543, 548, 549, 550, 551, 552, 553, 555, 556, 558, 559,  
560, 562, 563, 567, 570, 575, 576, 578, 580, 582, 583, 585, 587, 589,  
590, 591, 592, 593, 596, 600, 603, 605, 607, 608, 609, 611, 614, 616,  
617, 624, 629, 630, 632, 633, 634, 637, 639, 644, 647, 648, 649, 650,  
652, 654, 657, 659, 661, 663, 665, 671, 674, 676, 678, 679, 681, 683,  
684, 686, 688, 689, 691, 701, 704, 705, 706, 713, 715, 717, 718, 719,  
720, 725, 728, 729, 732, 733, 735, 737, 745, 746, 750, 755, 758, 760,  
766, 770, 773, 775, 777, 778, 780, 785, 786, 787, 789, 790, 791, 804,  
807, 809, 811, 812, 814, 816, 819, 824, 827, 829, 830, 832, 834, 841,  
845, 846, 851, 856, 858, 861, 865, 866, 871, 881, 883, 886, 887, 888,

899, 902, 903, 905, 906, 908, 912, 920, 925, 928, 940, 942, 943, 947,  
 952, 953, 955, 957, 959, 960, 962, 974, 977, 979, 982, 984, 986, 994,  
 997, 999, 1004, 1015, 1028, 1031, 1035, 1036, 1048, 1049, 1051, 1053,  
 1056, 1058, 1069, 1073, 1076, 1078, 1080, 1082, 1088, 1089, 1090, 1093,  
 1095, 1107, 1110, 1122, 1123, 1127, 1129, 1130, 1132, 1147, 1152, 1154,  
 1164, 1169, 1174, 1179, 1184, 1201, 1205, 1206, 1218, 1219, 1223, 1224,  
 1226, 1228, 1246, 1250, 1255, 1257, 1258, 1259, 1260, 1275, 1277, 1280,  
 1298, 1300, 1302, 1307, 1315, 1322, 1329, 1331, 1346, 1351, 1352, 1354,  
 1356, 1372, 1374, 1376, 1381, 1383, 1385, 1387, 1396, 1398, 1403, 1405,  
 1426, 1427, 1428, 1450, 1457, 1468, 1472, 1477, 1482, 1497, 1499, 1526,  
 1529, 1533, 1549, 1551, 1573, 1580, 1583, 1603, 1605, 1610, 1625, 1627,  
 1647, 1667, 1679, 1681, 1699, 1701, 1721, 1753, 1773, 1775, 1780, 1795,  
 1817, 1832, 1849, 1852, 1869, 1871, 1886, 1923, 1925, 1943, 1945, 1950,  
 1997, 2022, 2039, 2073, 2120, 2174, 2221, 2246, 2297, 2369, 2416, 2591,  
 2761}

□

**Corollary 5.**  $\mathcal{T} = [2762, \infty) \cap \mathbb{N}$ .

*MuPAD* is a general-purpose computer algebra system. *MuPAD* is no longer available as a stand-alone computer program, but only as the *Symbolic Math Toolbox* of *MATLAB*. Fortunately, the presented code can be executed by *MuPAD Light*, which was offered for free for research and education until autumn 2005.

## 14 A hypothetical infinitude of various classes of primes via computer programs which halt for at most finitely many positive integers on the input

Let  $\text{fact}^{-1}: \{1, 2, 6, 24, \dots\} \rightarrow \mathbb{N} \setminus \{0\}$  denote the inverse function to the factorial function. For positive integers  $x$  and  $y$ , let  $\text{rem}(x, y)$  denote the remainder from dividing  $x$  by  $y$ .

**Definition.** For a positive integer  $n$ , by a program of length  $n$  we understand any sequence of terms  $x_1, \dots, x_n$  such that  $x_1$  is defined as the variable  $x$ , and for every integer  $i \in \{2, \dots, n\}$ ,  $x_i$  is defined as  $\Gamma(x_{i-1})$ , or  $\text{fact}^{-1}(x_{i-1})$ , or  $\text{rem}(x_{i-1}, x_{i-2})$  – but only if  $i \geq 3$  and  $x_{i-1}$  is defined as  $\Gamma(x_{i-2})$ .

Let  $\delta(4) = 3$ , and let  $\delta(n+1) = \delta(n)!$  for every integer  $n \geq 4$ . For an integer  $n \geq 4$ , let  $\Omega_n$  denote the following statement: if a program of length  $n$  returns positive integers  $x_1, \dots, x_n$  for at most finitely many positive integers  $x$ , then every such  $x$  does not exceed  $\delta(n)$ .

**Theorem 28.** (cf. Theorem 5). For every integer  $n \geq 4$ , the statement  $\Omega_n$  is true with an unknown integer bound that depends on  $n$ .

*Proof.* For every positive integer  $n$ , there are only finitely many programs of length  $n$ .  $\square$

**Lemma 35.** ([24, pp. 214–215]). For every positive integer  $x$ ,  $\text{rem}(\Gamma(x), x) \in \mathbb{N} \setminus \{0\}$  if and only if  $x \in \{4\} \cup \mathcal{P}$ .

**Theorem 29.** For every integer  $n \geq 4$  and for every positive integer  $x$ , the following program  $\mathcal{H}_n$

$$\left\{ \begin{array}{l} x_1 := x \\ \forall i \in \{2, \dots, n-3\} x_i := \text{fact}^{-1}(x_{i-1}) \\ x_{n-2} := \Gamma(x_{n-3}) \\ x_{n-1} := \Gamma(x_{n-2}) \\ x_n := \text{rem}(x_{n-1}, x_{n-2}) \end{array} \right.$$

returns positive integers  $x_1, \dots, x_n$  if and only if  $x = \delta(n)$ .

*Proof.* We make three observations.

**Observation 4.** If  $x_{n-3} = 3$ , then  $x_1, \dots, x_{n-3} \in \mathbb{N} \setminus \{0\}$  and  $x = x_1 = \delta(n)$ .

If  $x = \delta(n)$ , then  $x_1, \dots, x_{n-3} \in \mathbb{N} \setminus \{0\}$  and  $x_{n-3} = 3$ .

Hence,  $x_{n-2} = \Gamma(x_{n-3}) = 2$  and  $x_{n-1} = \Gamma(x_{n-2}) = 1$ . Therefore,  $x_n = \text{rem}(x_{n-1}, x_{n-2}) = 1$ .

**Observation 5.** If  $x_{n-3} = 2$ , then  $x = x_1 = \dots = x_{n-3} = 2$ .

If  $x = 2$ , then  $x_1 = \dots = x_{n-3} = 2$ . Hence,  $x_{n-2} = \Gamma(x_{n-3}) = 1$  and  $x_{n-1} = \Gamma(x_{n-2}) = 1$ .

Therefore,  $x_n = \text{rem}(x_{n-1}, x_{n-2}) = 0 \notin \mathbb{N} \setminus \{0\}$ .

**Observation 6.** If  $x_{n-3} = 1$ , then  $x_{n-2} = \Gamma(x_{n-3}) = 1$ . Hence,  $x_{n-1} = \Gamma(x_{n-2}) = 1$ .

Therefore,  $x_n = \text{rem}(x_{n-1}, x_{n-2}) = 0 \notin \mathbb{N} \setminus \{0\}$ .

Observations 4–6 cover the case when  $x_{n-3} \in \{1, 2, 3\}$ . If  $x_{n-3} \geq 4$ , then  $x_{n-2} = \Gamma(x_{n-3})$  is greater than 4 and composite. By Lemma 35,  $x_n = \text{rem}(x_{n-1}, x_{n-2}) = \text{rem}(\Gamma(x_{n-2}), x_{n-2}) = 0 \notin \mathbb{N} \setminus \{0\}$ .  $\square$

**Corollary 6.** For every integer  $n \geq 4$ , the bound  $\delta(n)$  in the statement  $\Omega_n$  cannot be decreased.

**Lemma 36.** If  $x \in \mathcal{P}$ , then  $\text{rem}(\Gamma(x), x) = x - 1$ .

*Proof.* It follows from Lemma 6.  $\square$

**Lemma 37.** For every positive integer  $x$ , the following program  $\mathcal{A}$

$$\left\{ \begin{array}{l} x_1 := x \\ x_2 := \Gamma(x_1) \\ x_3 := \text{rem}(x_2, x_1) \\ x_4 := \text{fact}^{-1}(x_3) \end{array} \right.$$

returns positive integers  $x_1, \dots, x_4$  if and only if  $x = 4$  or  $x$  is a prime number of the form  $n! + 1$ .

*Proof.* For an integer  $i \in \{1, \dots, 4\}$ , let  $A_i$  denote the set of positive integers  $x$  such that the first  $i$  instructions of the program  $\mathcal{A}$  returns positive integers  $x_1, \dots, x_i$ . We show that

$$A_4 = \{4\} \cup \{n! + 1 : n \in \mathbb{N} \setminus \{0\}\} \cap \mathcal{P} \quad (4)$$

For every positive integer  $x$ , the terms  $x_1$  and  $x_2$  belong to  $\mathbb{N} \setminus \{0\}$ . By Lemma 35, the term  $x_3$  (which equals  $\text{rem}(\Gamma(x), x)$ ) belongs to  $\mathbb{N} \setminus \{0\}$  if and only if  $x \in \{4\} \cup \mathcal{P}$ . Hence,  $A_3 = \{4\} \cup \mathcal{P}$ . If  $x = 4$ , then  $x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\}$ . Hence,  $4 \in A_4$ . If  $x \in \mathcal{P}$ , then Lemma 36 implies that  $x_3 = \text{rem}(\Gamma(x), x) = x - 1 \in \mathbb{N} \setminus \{0\}$ . Therefore, for every  $x \in \mathcal{P}$ , the term  $x_4 = \text{fact}^{-1}(x_3)$  belongs to  $\mathbb{N} \setminus \{0\}$  if and only if  $x \in \{n! + 1 : n \in \mathbb{N} \setminus \{0\}\}$ . This proves equality (4).  $\square$

**Theorem 30.** The statement  $\Omega_4$  implies that the set of primes of the form  $n! + 1$  is infinite.

*Proof.* The number  $3! + 1 = 7$  is prime. By Lemma 37, for  $x = 7$  the program  $\mathcal{A}$  returns positive integers  $x_1, \dots, x_4$ . Since  $x = 7 > 3 = \delta(4)$ , the statement  $\Omega_4$  guarantees that the program  $\mathcal{A}$  returns positive integers  $x_1, \dots, x_4$  for infinitely many positive integers  $x$ . By Lemma 37, there are infinitely many primes of the form  $n! + 1$ .  $\square$

**Lemma 38.** *If  $x \in \mathbb{N} \setminus \{0, 1\}$ , then  $\text{fact}^{-1}(\Gamma(x)) = x - 1$ .*

**Theorem 31.** *If the set of primes of the form  $n! + 1$  is infinite, then the statement  $\Omega_4$  is true.*

*Proof.* There exist exactly 10 programs of length 4 that differ from  $\mathcal{H}_4$  and  $\mathcal{A}$ , see Figure 13. For every such program  $\mathcal{F}_i$ , we determine the set  $S_i$  of all positive integers  $x$  such that the program  $\mathcal{F}_i$  outputs positive integers  $x_1, \dots, x_4$  on input  $x$ . We omit 10 easy proofs which use Lemmas 35 and 38. The sets  $S_i$  are infinite, see Figure 13.

$\mathcal{F}_1$	$x_1 := x$	$x_2 := \Gamma(x_1)$	$x_3 := \Gamma(x_2)$	$x_4 := \Gamma(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \mathbb{N} \setminus \{0\} = S_1$
$\mathcal{F}_2$	$x_1 := x$	$x_2 := \Gamma(x_1)$	$x_3 := \Gamma(x_2)$	$x_4 := \text{fact}^{-1}(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \mathbb{N} \setminus \{0\} = S_2$
$\mathcal{H}_4$	$x_1 := x$	$x_2 := \Gamma(x_1)$	$x_3 := \Gamma(x_2)$	$x_4 := \text{rem}(x_3, x_2)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x = 3$
$\mathcal{F}_3$	$x_1 := x$	$x_2 := \Gamma(x_1)$	$x_3 := \text{fact}^{-1}(x_2)$	$x_4 := \Gamma(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \mathbb{N} \setminus \{0\} = S_3$
$\mathcal{F}_4$	$x_1 := x$	$x_2 := \Gamma(x_1)$	$x_3 := \text{fact}^{-1}(x_2)$	$x_4 := \text{fact}^{-1}(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \{1\} \cup \{n! + 1 : n \in \mathbb{N} \setminus \{0\}\} = S_4$
$\mathcal{F}_5$	$x_1 := x$	$x_2 := \Gamma(x_1)$	$x_3 := \text{rem}(x_2, x_1)$	$x_4 := \Gamma(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \{4\} \cup \mathcal{P} = S_5$
$\mathcal{A}$	$x_1 := x$	$x_2 := \Gamma(x_1)$	$x_3 := \text{rem}(x_2, x_1)$	$x_4 := \text{fact}^{-1}(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \{4\} \cup \{n! + 1 : n \in \mathbb{N} \setminus \{0\}\} \cap \mathcal{P}$
$\mathcal{F}_6$	$x_1 := x$	$x_2 := \text{fact}^{-1}(x_1)$	$x_3 := \Gamma(x_2)$	$x_4 := \Gamma(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \{n! : n \in \mathbb{N} \setminus \{0\}\} = S_6$
$\mathcal{F}_7$	$x_1 := x$	$x_2 := \text{fact}^{-1}(x_1)$	$x_3 := \Gamma(x_2)$	$x_4 := \text{fact}^{-1}(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \{n! : n \in \mathbb{N} \setminus \{0\}\} = S_7$
$\mathcal{F}_8$	$x_1 := x$	$x_2 := \text{fact}^{-1}(x_1)$	$x_3 := \Gamma(x_2)$	$x_4 := \text{rem}(x_3, x_2)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \{4!\} \cup \{p! : p \in \mathcal{P}\} = S_8$
$\mathcal{F}_9$	$x_1 := x$	$x_2 := \text{fact}^{-1}(x_1)$	$x_3 := \text{fact}^{-1}(x_2)$	$x_4 := \Gamma(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \{(n!)! : n \in \mathbb{N} \setminus \{0\}\} = S_9$
$\mathcal{F}_{10}$	$x_1 := x$	$x_2 := \text{fact}^{-1}(x_1)$	$x_3 := \text{fact}^{-1}(x_2)$	$x_4 := \text{fact}^{-1}(x_3)$	$x_1, \dots, x_4 \in \mathbb{N} \setminus \{0\} \iff x \in \{((n!)!)! : n \in \mathbb{N} \setminus \{0\}\} = S_{10}$

**Fig. 13** 12 programs of length 4,  $x \in \mathbb{N} \setminus \{0\}$

This completes the proof.  $\square$

**Hypothesis 8.** *The statements  $\Omega_4, \dots, \Omega_7$  are true.*

**Lemma 39.** *For every positive integer  $x$ , the following program  $\mathcal{B}$*

$$\begin{cases} x_1 := x \\ x_2 := \Gamma(x_1) \\ x_3 := \text{rem}(x_2, x_1) \\ x_4 := \text{fact}^{-1}(x_3) \\ x_5 := \Gamma(x_4) \\ x_6 := \text{rem}(x_5, x_4) \end{cases}$$

*returns positive integers  $x_1, \dots, x_6$  if and only if  $x \in \{4\} \cup \{p! + 1 : p \in \mathcal{P}\} \cap \mathcal{P}$*

*Proof.* For an integer  $i \in \{1, \dots, 6\}$ , let  $B_i$  denote the set of positive integers  $x$  such that the first  $i$  instructions of the program  $\mathcal{B}$  returns positive integers  $x_1, \dots, x_i$ . Since the programs  $\mathcal{A}$  and  $\mathcal{B}$  have the same first four instructions, the equality  $B_i = A_i$  holds for every  $i \in \{1, \dots, 4\}$ . In particular,

$$B_4 = \{4\} \cup \{n! + 1 : n \in \mathbb{N} \setminus \{0\}\} \cap \mathcal{P}$$

We show that

$$B_6 = \{4\} \cup \{p! + 1 : p \in \mathcal{P}\} \cap \mathcal{P} \quad (5)$$

If  $x = 4$ , then  $x_1, \dots, x_6 \in \mathbb{N} \setminus \{0\}$ . Hence,  $4 \in B_6$ . Let  $x \in \mathcal{P}$ , and let  $x = n! + 1$ , where  $n \in \mathbb{N} \setminus \{0\}$ . Hence,  $n \neq 4$ . Lemma 36 implies that  $x_3 = \text{rem}(\Gamma(x), x) = x - 1 = n!$ . Hence,  $x_4 = \text{fact}^{-1}(x_3) = n$  and  $x_5 = \Gamma(x_4) = \Gamma(n) \in \mathbb{N} \setminus \{0\}$ . By Lemma 35, the term  $x_6$  (which equals  $\text{rem}(\Gamma(n), n)$ ) belongs to  $\mathbb{N} \setminus \{0\}$  if and only if  $n \in \{4\} \cup \mathcal{P}$ . This proves equality (5) as  $n \neq 4$ .  $\square$

**Theorem 32.** *The statement  $\Omega_6$  implies that for infinitely many primes  $p$  the number  $p! + 1$  is prime.*

*Proof.* The numbers 11 and  $11! + 1$  are prime, see [4, p. 441] and [28]. By Lemma 39, for  $x = 11! + 1$  the program  $\mathcal{B}$  returns positive integers  $x_1, \dots, x_6$ . Since  $x = 11! + 1 > 6! = \delta(6)$ , the statement  $\Omega_6$  guarantees that the program  $\mathcal{B}$  returns positive integers  $x_1, \dots, x_6$  for infinitely many positive integers  $x$ . By Lemma 39, for infinitely many primes  $p$  the number  $p! + 1$  is prime.  $\square$

**Lemma 40.** *For every positive integer  $x$ , the following program  $\mathcal{C}$*

$$\begin{cases} x_1 & := & x \\ x_2 & := & \Gamma(x_1) \\ x_3 & := & \Gamma(x_2) \\ x_4 & := & \text{fact}^{-1}(x_3) \\ x_5 & := & \Gamma(x_4) \\ x_6 & := & \text{rem}(x_5, x_4) \end{cases}$$

*returns positive integers  $x_1, \dots, x_6$  if and only if  $(x - 1)! - 1$  is prime.*

*Proof.* For an integer  $i \in \{1, \dots, 6\}$ , let  $C_i$  denote the set of positive integers  $x$  such that the first  $i$  instructions of the program  $\mathcal{C}$  returns positive integers  $x_1, \dots, x_i$ . If  $x \in \{1, 2, 3\}$ , then  $x_6 = 0$ . Therefore,  $C_6 \subseteq \mathbb{N} \setminus \{0, 1, 2, 3\}$ . By Lemma 38, for every integer  $x \geq 4$ ,  $x_4 = (x - 1)! - 1$ ,  $x_5 = \Gamma((x - 1)! - 1)$ , and  $x_1, \dots, x_5 \in \mathbb{N} \setminus \{0\}$ . By Lemma 35, for every integer  $x \geq 4$ ,

$$x_6 = \text{rem}(\Gamma((x - 1)! - 1), (x - 1)! - 1)$$

belongs to  $\mathbb{N} \setminus \{0\}$  if and only if  $(x - 1)! - 1 \in \{4\} \cup \mathcal{P}$ . The last condition equivalently expresses that  $(x - 1)! - 1$  is prime as  $(x - 1)! - 1 \geq 5$  for every integer  $x \geq 4$ . Hence,

$$C_6 = (\mathbb{N} \setminus \{0, 1, 2, 3\}) \cap \{x \in \mathbb{N} \setminus \{0, 1, 2, 3\} : (x - 1)! - 1 \in \mathcal{P}\} = \{x \in \mathbb{N} \setminus \{0\} : (x - 1)! - 1 \in \mathcal{P}\}$$

$\square$

It is conjectured that there are infinitely many primes of the form  $n! - 1$ , see [4, p. 443] and [27].

**Theorem 33.** *The statement  $\Omega_6$  implies that there are infinitely many primes of the form  $x! - 1$ .*

*Proof.* The number  $(975 - 1)! - 1$  is prime, see [4, p. 441] and [27]. By Lemma 40, for  $x = 975$  the program  $\mathcal{C}$  returns positive integers  $x_1, \dots, x_6$ . Since  $x = 975 > 720 = \delta(6)$ , the statement  $\Omega_6$  guarantees that the program  $\mathcal{C}$  returns positive integers  $x_1, \dots, x_6$  for infinitely many positive integers  $x$ . By Lemma 40, the set  $\{x \in \mathbb{N} \setminus \{0\} : (x - 1)! - 1 \in \mathcal{P}\}$  is infinite.  $\square$

**Lemma 41.** *For every positive integer  $x$ , the following program  $\mathcal{D}$*

$$\begin{cases} x_1 & := & x \\ x_2 & := & \Gamma(x_1) \\ x_3 & := & \text{rem}(x_2, x_1) \\ x_4 & := & \Gamma(x_3) \\ x_5 & := & \text{fact}^{-1}(x_4) \\ x_6 & := & \Gamma(x_5) \\ x_7 & := & \text{rem}(x_6, x_5) \end{cases}$$

*returns positive integers  $x_1, \dots, x_7$  if and only if both  $x$  and  $x - 2$  are prime.*

*Proof.* For an integer  $i \in \{1, \dots, 7\}$ , let  $D_i$  denote the set of positive integers  $x$  such that the first  $i$  instructions of the program  $\mathcal{D}$  returns positive integers  $x_1, \dots, x_i$ . If  $x = 1$ , then  $x_3 = 0$ . Hence,  $D_7 \subseteq D_3 \subseteq \mathbb{N} \setminus \{0, 1\}$ . If  $x \in \{2, 3, 4\}$ , then  $x_7 = 0$ . Therefore,

$$D_7 \subseteq (\mathbb{N} \setminus \{0, 1\}) \cap (\mathbb{N} \setminus \{0, 2, 3, 4\}) = \mathbb{N} \setminus \{0, 1, 2, 3, 4\}$$

By Lemma 35, for every integer  $x \geq 5$ , the term  $x_3$  (which equals  $\text{rem}(\Gamma(x), x)$ ) belongs to  $\mathbb{N} \setminus \{0\}$  if and only if  $x \in \mathcal{P} \setminus \{2, 3\}$ . By Lemma 36, for every  $x \in \mathcal{P} \setminus \{2, 3\}$ ,  $x_3 = x - 1 \in \mathbb{N} \setminus \{0, 1, 2, 3\}$ . By Lemma 38, for every  $x \in \mathcal{P} \setminus \{2, 3\}$ , the terms  $x_4$  and  $x_5$  belong to  $\mathbb{N} \setminus \{0\}$  and  $x_5 = x_3 - 1 = x - 2$ . By Lemma 35, for every  $x \in \mathcal{P} \setminus \{2, 3\}$ , the term  $x_7$  (which equals  $\text{rem}(\Gamma(x_5), x_5)$ ) belongs to  $\mathbb{N} \setminus \{0\}$  if and only if  $x_5 = x - 2 \in \{4\} \cup \mathcal{P}$ . From these facts, we obtain that

$$D_7 = (\mathbb{N} \setminus \{0, 1, 2, 3, 4\}) \cap (\mathcal{P} \setminus \{2, 3\}) \cap (\{6\} \cup \{p + 2 : p \in \mathcal{P}\}) = \{p \in \mathcal{P} : p - 2 \in \mathcal{P}\}$$

□

**Theorem 34.** *The statement  $\Omega_7$  implies that there are infinitely many twin primes.*

*Proof.* Harvey Dubner proved that the numbers  $459 \cdot 2^{8529} - 1$  and  $459 \cdot 2^{8529} + 1$  are prime, see [37, p. 87]. By Lemma 41, for  $x = 459 \cdot 2^{8529} + 1$  the program  $\mathcal{D}$  returns positive integers  $x_1, \dots, x_7$ . Since  $x > 720! = \delta(7)$ , the statement  $\Omega_7$  guarantees that the program  $\mathcal{D}$  returns positive integers  $x_1, \dots, x_7$  for infinitely many positive integers  $x$ . By Lemma 41, there are infinitely many twin primes. □

We can transform every program of length  $n$  into a computer program with  $n$  instructions which for every  $x \in \mathbb{N} \setminus \{0\}$  does the same if  $(x_1, \dots, x_n) \in (\mathbb{N} \setminus \{0\})^n$ , and never halts if  $(x_1, \dots, x_n) \notin (\mathbb{N} \setminus \{0\})^n$  or the tuple  $(x_1, \dots, x_n)$  is undefined. To do so, we perform the following steps:

a) We replace the instruction  $x_1 := x$  by the following instruction:

$$x_1 := x \ \& \ \text{PRINT}(x_1)$$

b) We replace every instruction of the form  $x_i = \Gamma(x_{i-1})$  by the following instruction:

$$x_i := \Gamma(x_{i-1}) \ \& \ \text{PRINT}(x_i)$$

c) We replace every instruction of the form  $x_i := \text{fact}^{-1}(x_{i-1})$  by the following instruction:

$$\text{IF } \text{fact}^{-1}(x_{i-1}) \in \mathbb{N} \setminus \{0\} \ \text{THEN } x_i := \text{fact}^{-1}(x_{i-1}) \ \& \ \text{PRINT}(x_i) \ \text{ELSE GOTO Instruction 1}$$

d) We replace every instruction of the form  $x_i := \text{rem}(x_{i-1}, x_{i-2})$  by the following instruction:

$$\text{IF } \text{rem}(x_{i-1}, x_{i-2}) \in \mathbb{N} \setminus \{0\} \ \text{THEN } x_i := \text{rem}(x_{i-1}, x_{i-2}) \ \& \ \text{PRINT}(x_i) \ \text{ELSE GOTO Instruction 1}$$

## References

- [1] C. H. Bennett, *Chaitin's Omega*, in: *Fractal music, hypercards, and more ...* (M. Gardner, ed.), W. H. Freeman, New York, 1992, 307–319.
- [2] D. Berend and J. E. Harmse, *On polynomial-factorial Diophantine equations*, *Trans. Amer. Math. Soc.* 358 (2006), no. 4, 1741–1779.
- [3] C. K. Caldwell, *The Prime Glossary: Wilson prime*, <http://primes.utm.edu/glossary/xpage/WilsonPrime.html>.
- [4] C. K. Caldwell and Y. Gallot, *On the primality of  $n! \pm 1$  and  $2 \times 3 \times 5 \times \dots \times p \pm 1$* , *Math. Comp.* 71 (2002), no. 237, 441–448, <http://doi.org/10.1090/S0025-5718-01-01315-1>.
- [5] C. S. Calude, H. Jürgensen, S. Legg, *Solving problems with finite test sets*, in: *Finite versus Infinite: Contributions to an Eternal Dilemma* (C. Calude and G. Păun, eds.), 39–52, Springer, London, 2000.



- [6] N. C. A. da Costa and F. A. Doria, *On the foundations of science (LIVRO): essays, first series*, E-papers Serviços Editoriais Ltda, Rio de Janeiro, 2013.
- [7] M. Davis, Yu. Matiyasevich, J. Robinson, *Hilbert's tenth problem. Diophantine equations: positive aspects of a negative solution*; in: Mathematical developments arising from Hilbert problems (ed. F. E. Browder), Proc. Sympos. Pure Math., vol. 28, Part 2, Amer. Math. Soc., Providence, RI, 1976, 323–378, <http://dx.doi.org/10.1090/pspum/028.2>; reprinted in: The collected works of Julia Robinson (ed. S. Feferman), Amer. Math. Soc., Providence, RI, 1996, 269–324.
- [8] R. E. Dressler, A. Małowski, T. Parker, *Sums of distinct primes from congruence classes modulo 12*, Math. Comp. 28 (1974), 651–652.
- [9] M. Erickson, A. Vazzana, D. Garth, *Introduction to number theory*, 2nd ed., CRC Press, Boca Raton, FL, 2016.
- [10] T. Kløve, *Sums of distinct elements from a fixed set*, Math. Comp. 29 (1975), 1144–1149.
- [11] J.-M. De Koninck and F. Luca, *Analytic number theory: Exploring the anatomy of integers*, American Mathematical Society, Providence, RI, 2012.
- [12] M. Křížek, F. Luca, L. Somer, *17 lectures on Fermat numbers: from number theory to geometry*, Springer, New York, 2001.
- [13] F. Luca, *The Diophantine equation  $P(x) = n!$  and a result of M. Overholt*, Glas. Mat. Ser. III 37 (57) (2002), no. 2, 269–273
- [14] Yu. Matiyasevich, *Existence of noneffectivizable estimates in the theory of exponential Diophantine equations*, J. Sov. Math. vol. 8, no. 3, 1977, 299–311, <http://dx.doi.org/10.1007/bf01091549>.
- [15] Yu. Matiyasevich, *Hilbert's tenth problem*, MIT Press, Cambridge, MA, 1993.
- [16] Yu. Matiyasevich, *Hilbert's tenth problem: what was done and what is to be done*; in: Hilbert's tenth problem: relations with arithmetic and algebraic geometry (Ghent, 1999), 1–47, Contemp. Math. 270, Amer. Math. Soc., Providence, RI, 2000, <http://dx.doi.org/10.1090/conm/270>.
- [17] Yu. Matiyasevich, *Towards finite-fold Diophantine representations*, J. Math. Sci. (N. Y.) vol. 171, no. 6, 2010, 745–752, <http://dx.doi.org/10.1007%2Fs10958-010-0179-4>.
- [18] W. Narkiewicz, *Rational number theory in the 20th century: From PNT to FLT*, Springer, London, 2012.
- [19] P. Odifreddi, *Classical recursion theory: the theory of functions and sets of natural numbers*, North-Holland, Amsterdam, 1989.
- [20] M. Overholt, *The Diophantine equation  $n! + 1 = m^2$* , Bull. London Math. Soc. 25 (1993), no. 2, 104.
- [21] P. Ribenboim, *The new book of prime number records*, Springer, New York, 1996, <http://doi.org/10.1007/978-1-4612-0759-7>.
- [22] H.-E. Richert, *Über Zerlegungen in paarweise verschiedene Zahlen*, Norsk Mat. Tidsskr. 31 (1949), 120–122.
- [23] J. Robinson, *Definability and decision problems in arithmetic*, J. Symbolic Logic 14 (1949), no. 2, 98–114, <http://dx.doi.org/10.2307/2266510>; reprinted in: The collected works of Julia Robinson (ed. S. Feferman), Amer. Math. Soc., Providence, RI, 1996, 7–23
- [24] W. Sierpiński, *Elementary theory of numbers*, 2nd ed. (ed. A. Schinzel), PWN – Polish Scientific Publishers and North-Holland, Warsaw-Amsterdam, 1987.

- [25] Th. Skolem, *Diophantische Gleichungen*, Julius Springer, Berlin, 1938.
- [26] N. J. A. Sloane, *The On-Line Encyclopedia of Integer Sequences*, A002981, Numbers  $n$  such that  $n! + 1$  is prime, <http://oeis.org/A002981>.
- [27] N. J. A. Sloane, *The On-Line Encyclopedia of Integer Sequences*, A002982, Numbers  $n$  such that  $n! - 1$  is prime, <http://oeis.org/A002982>.
- [28] N. J. A. Sloane, *The On-Line Encyclopedia of Integer Sequences*, A093804, Primes  $p$  such that  $p! + 1$  is also prime, <http://oeis.org/A093804>.
- [29] N. J. A. Sloane, *The On-Line Encyclopedia of Integer Sequences*, Smallest prime factor of  $A020549(n) = (n!)^2 + 1$ , <http://oeis.org/A282706>.
- [30] N. J. A. Sloane, *The On-Line Encyclopedia of Integer Sequences*, A007540, Wilson primes: primes  $p$  such that  $(p - 1)! \equiv -1 \pmod{p^2}$ , <http://oeis.org/A007540>.
- [31] A. Tyszka, *Conjecturally computable functions which unconditionally do not have any finite-fold Diophantine representation*, Inform. Process. Lett. 113 (2013), no. 19–21, 719–722, <http://dx.doi.org/10.1016/j.ipl.2013.07.004>.
- [32] A. Tyszka, *Is there a computable upper bound for the height of a solution of a Diophantine equation with a unique solution in positive integers?*, Open Comput. Sci. 7 (2017), no. 1, 17–23, <http://doi.org/10.1515/comp-2017-0003>.
- [33] A. Tyszka, *A hypothetical upper bound on the heights of the solutions of a Diophantine equation with a finite number of solutions*, Open Comput. Sci. 8 (2018), no. 1, 109–114, <http://dx.doi.org/10.1515/comp-2018-0012>.
- [34] E. W. Weisstein, *CRC Concise Encyclopedia of Mathematics*, 2nd ed., Chapman & Hall/CRC, Boca Raton, FL, 2002.
- [35] Wolfram MathWorld, *Sophie Germain prime*, <http://mathworld.wolfram.com/SophieGermainPrime.html>.
- [36] A. R. Woods, *Some problems in logic and number theory, and their connections*, Ph.D. thesis, University of Manchester, Manchester, 1981, <http://staffhome.ecm.uwa.edu.au/~00017049/thesis/WoodsPhDThesis.pdf>; reprinted in: *New studies in weak arithmetics* (eds. P. Cégielski, C. Cornaros, C. Dimitracopoulos), CSLI Lecture Notes, vol. 211, 271–388, CSLI Publ., Stanford, CA, 2013.
- [37] S. Y. Yan, *Number theory for computing*, 2nd ed., Springer, Berlin, 2002.

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