An attempt to prove the Strong Goldbach Conjecture
by the Principle of Mathematical Induction

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Abstract

A Recursive Algorithm described here generates consecutive sequences of Goldbach sets \( \{G_k \mid 3 \leq k \leq m\} \) toward the proof of the Strong Goldbach Conjecture.

Approach suggested here is based on the fundamental principle of mathematical induction and uses rather elementary set-theoretical technique. It does not involve any sophisticated powerful tools and results of contemporary Number Theory, Algebraic Geometry, or Theory of Dynamical Systems with applications to measure preserving groups of transformations on the appropriate topological spaces [7].

This work might cause beforehand certain suspicions among specialists in this area regarding the validity of the proof (perhaps inspired by the notorious ‘Uncle Petros’ phenomenon [8]). The main idea of this work is to develop a recursive algorithm toward building the sequence of consecutive Goldbach sets \( \{G_k \mid 3 \leq k \leq m\} \) that represent solutions to the system of Goldbach equations \( \{x + y = 2 \cdot k \mid 3 \leq k \leq m\} \) in the intervals \( I_k = [3, 2 \cdot k - 3] \). Validity of the algorithm is based on the proved here recurrent formula

\[
\bigcup_{k=3}^{m} \left( G_k \mathbb{P} + 2 \cdot (m+1-k) \right) \cap S_m = G_{m+1} \mathbb{P} \neq \emptyset ,
\]

given the inductive assumption that \( G_k \mathbb{P} \neq \emptyset \) for all \( k : 3 \leq k \leq m \), where \( S_m = I_m \cap \mathbb{P} \), and \( \mathbb{P} \) is a set of all odd prime numbers.
"The most interesting facts are those which can be used several times, those which have a chance of recurring ...."

(Henry Poincaré, The Value of Science)

We approach here one of old classical problems in Number Theory known as the strong form of Goldbach Conjecture (SGC) [1, 5]. According to the conjecture stated by Goldbach in his letter to Euler in 1742, “every even number $2m \geq 6$ is the sum of two odd primes” [1]. Regardless numerous attempts to prove the statement, supported in our days by computer calculations up to $4 \times 10^{18}$, it remains unproven till now.

Let $\mathbb{N}$ be a set of natural numbers, and $\mathbb{P}$ a set of odd primes (all prime numbers excluding 2).

The Goldbach’s Conjecture (GC), as one of the oldest and notoriously known unsolved problems in Number theory, raises a question why it seems so difficult to decide whether the equation

$$p + p' = 2m,$$  \hspace{1cm} (*)

where $p$ and $p'$ are prime numbers, has at least one solution for each even number $2m \geq 6$. Indeed, occurrences of primes look very sporadic, so that it is hard to predict, that there exists a pair of primes $(p, p')$ related by the equation (*), especially for ‘big’ values of $m$. Notice that every solution $(n, n') = (p, p')$ in primes to the equation $p + p' = 2m$, must satisfy the condition: $(n, n') \in [3, 2m - 3]^2$. We call a prime number $p$ a $G_m$-prime (a Goldbach prime) if $p' = 2m - p$ is also a prime number. Then, denote $G_m \mathbb{P}$ as set of all $G_m$-primes, and call $G_m \mathbb{P}$ a Goldbach set.

Obviously, for all $m \geq 3$ we have $G_m \mathbb{P} \subset I_m = [3, 2m - 3]$. A set $G_m \mathbb{P}$ is empty if for some $m \geq 3$ $G_m$-primes do not exist. Goldbach function $G(2m)$ counts the number of solutions to the equation

$$n + n' = 2m, \quad (n, n') \in \mathbb{P}^2$$

(1)

where $n$ and $n'$ are prime numbers, $m$ is any integer $m \geq 3$.

Obviously, any pair $(p, p')$ of primes greater then 2 solves (1) for $2m = p + p'$. 
Due to infinity of \( p \), this implies that the Goldbach function has \( \limsup G(2m) = \infty \).

The Strong Goldbach Conjecture states that \( \min G(2m) = 1 \), so that every set \( G_m \) is a nonempty set for all \( m \geq 3 \). Calculations show that \( \max G(2m) \) increases with \( M \), though \( G(2m) \) is not a monotonically increasing function.

We observe that each pair \((n, n')\) which solves (1) must belong to a set \([3, 2m - 3]^2 = I_m^2\), where \( I_m = [3, 2m - 3] = \{3, 4, \ldots, 2m - 3\} \). Since 3 is prime, if \( n' = (2 \cdot m - 3) \in \mathbb{P} \), the pair \((3, 2 \cdot n - 3)\) solves (1), so that the prime \((2 \cdot m - 3) \in G_m \mathbb{P} \), and we need to consider the case \((2 \cdot m - 3) \notin \mathbb{P} \). In general, if \( p \) is a prime number such that \((2 \cdot m - p) \in \mathbb{P} \), then \((2 \cdot m - p) \in G_m \mathbb{P} \).

Consider a map \( \theta_m : I_m \rightarrow I_m \) given by the formula \( \theta_m(n) = 2m - n \).

Denote \( \mathcal{F}_m \) an algebra of all subsets of the interval \( I_m = [3, 2m - 3] \).

Obviously, \( \theta_m \) is one-to-one and has an inverse \( \theta_m^{-1} \), so that for all \( A \in \mathcal{F}_m \) we have \( \theta_m(A) \in \mathcal{F}_m, \theta_m^{-1}(A) \in \mathcal{F}_m \). Denote \( I_m = [3, m - 1], I_m^0 = \{m\}, I_m^+ = [m + 1, 2m - 3] \).

Obviously, \( \theta_m \) is idempotent: \( \theta_m^2 = id \) (an identical map), that is \( \theta_m^{-1} = \theta_m \).

Let \( S_m \) denote a set of prime numbers in the interval of integers \( I_m = [3, 2m - 3] \), that is \( S_m = I_m \cap \mathbb{P} \), and \( S_m^c = I_m \setminus S_m \) its complement in \( I_m \) so that

\[
I_m = S_m \cup S_m^c, \quad S_m \cap S_m^c = \emptyset.
\]

While \( S_m \) stands for the set of primes in \( I_m \),

\( S_m^c \) is the set of composite numbers in \( I_m \).

We denote \( \theta_m(S_m) = 2 \cdot m - S_m = \{n' \mid n' = 2 \cdot m - n, n \in S_m\} \).

The Strong Goldbach Conjecture asserts that for any \( m \geq 3 \) the set \( G_m \mathbb{P} \) is not empty:

\[
P_{\text{lm}}(2m) = \infty
\]
\[ G_m \mathbb{P} = \left\{ n, n' \mid n \in \mathbb{P}, n' = (2m - n) \in \mathbb{P} \right\} = (2m - S_m) \cap S_m = \theta_m(S_m) \cap S_m \neq \emptyset. \]

**Lemma 1.**

\( \theta_m \)-invariance of Goldbach sets: \( \theta_m(G_m \mathbb{P}) = G_m \mathbb{P} \).

**Proof.**

Notice that the sets \( I_m, \{ m \}, \{ 3, 2 \cdot m - 3 \} \) and \( \theta_m(S_m) \cap S_m \) are invariant sets of the map \( \theta_m : I_m \to I_m \) since for all \( n \in I_m \) we have \( \theta_m(\{ n, \theta_m(n) \}) = \{ \theta_m(n), \theta^2(n) \} = \{ \theta_m(n), n \} \), due to \( \theta^2 = id \). \( \theta_m \)-invariance of \( G_m \mathbb{P} \) also follows directly from the equalities

\[ \theta_m(G_m \mathbb{P}) = \theta_m(S_m \cap \theta_m(S_m)) = \theta_m(S_m) \cap \theta^2 S_m = \theta_m(S_m) \cap S_m = G_m \mathbb{P}. \]

Q.E.D.

In what follows we need several recursively derived formulas.

**Lemma 2.**

1. \( I_m = I_{m-1} \cup \{ 2m - 4, 2m - 3 \} \), where \( I_m = [3, 2m - 3] \) \hspace{1cm} (2)
2. \( S_m = S_{m-1} \cup (\mathbb{P} \cap \{ 2m - 3 \}) = \begin{cases} S_{m-1} \cup \{ 2m - 3 \} & \text{if } (2m - 3) \in \mathbb{P} \\ S_{m-1} & \text{if } (2m - 3) \notin \mathbb{P} \end{cases} \) \hspace{1cm} (3)
3. \( \theta_m(S_m) = \begin{cases} \theta_m(S_{m-1}) \cup \{ 3 \} & \text{if } \{ 2m - 3 \} \in \mathbb{P} \\ \theta_m(S_{m-1}) & \text{if } \{ 2m - 3 \} \notin \mathbb{P} \end{cases} \) \hspace{1cm} (4)
4. \( G_m \mathbb{P} = \begin{cases} \theta_m(S_m) \cap S_m = \theta_m(S_{m-1}) \cup \{ 3 \} & \text{if } (2m - 3) \in \mathbb{P} \\ \theta_m(S_m) \cap S_m = \theta_m(S_{m-1}) \cap S_{m-1} & \text{if } (2m - 1) \notin \mathbb{P} \end{cases} \) \hspace{1cm} (5)

**Proof.**

1. We observe that \( I_{m-1} = [3, 2 \cdot (m-1) - 3] = [3, 2 \cdot m - 5] \)

so that \( I_m = [3, 2m - 3] = I_{m-1} \cup \{ 2m - 4, 2m - 3 \}. \)
we have that

Thus, we need to concentrate on the case

Notice that (4) implies that if \( 2m-3 \in \mathbb{P} \) and \( S_m = S_{m-1} \) otherwise.

(3) \( \theta_m(S_m) = \theta_m(S_{m-1}) \cup \theta_m(\{2m-3\} \cap \mathbb{P}) = \begin{cases} \theta_m(S_{m-1}) \cup \{3\} & \text{if } \{2m-3\} \in \mathbb{P}, \\ \theta_m(S_{m-1}) & \text{if } \{2m-3\} \notin \mathbb{P} \end{cases} \)

since \( \theta_m(2m-3) = 2 \cdot m - (2m-3) = 3. \)

(4) \( G_m \mathbb{P} = \theta_m(S_m) \cap S_m = (\theta_m(S_{m-1}) \cup \{3\} \cap S_{m-1}) \cup \{3\} \)

if \( 2m-3 \in \mathbb{P} \), and \( G_m \mathbb{P} = \theta_m(S_{m-1}) \cap S_{m-1} \) if \( 2m-3 \notin \mathbb{P} \), that is

\[
G_m \mathbb{P} = \begin{cases} \theta_m(S_{m-1}) \cap S_{m-1} & \text{if } \{2m-3\} \notin \mathbb{P} \\ (\theta_m(S_{m-1}) \cap S_{m-1}) \cup \{3\} & \text{if } \{2m-3\} \in \mathbb{P} \end{cases}
\]

Q.E.D.

Notice that (4) implies that if \( \{2m-3\} \notin \mathbb{P} \), then \( S_m = S_{m-1} \) and \( G_m \mathbb{P} = \theta_m(S_{m-1}) \cap S_{m-1} \).

In the case when \( 2 \cdot m - 3 \in \mathbb{P} \), we have \( G_m \mathbb{P} \neq \emptyset \)

since \( 3 \in G_m \mathbb{P} \), \( 2m-3 \in \mathbb{P} \) and \( 3+(2m-3) = 2m \).

Thus, we need to concentrate on the case \( 2m-3 \notin \mathbb{P} \). We observe that \( \theta_m(S_{m-1}) = \theta_{m-1}(S_{m-1}) + 2 \),

due to Lemma 2 below. This implies \( G_m \mathbb{P} = (\theta_{m-1}(S_{m-1}) + 2) \cap S_{m-1} \). If \( p \in G_{m-1} \mathbb{P} \neq \emptyset \), then

\( p \in S_{m-1} \) and \( p \in \theta_{m-1}(S_{m-1}) \). Assuming now that \( p \) is a twin prime, that is \( (p+2) \in S_m = S_{m-1} \),

we have that \( G_{m-1} \mathbb{P} \neq \emptyset \) implies \( G_m \mathbb{P} = (\theta_{m-1}(S_{m-1}) + 2) \cap S_{m-1} \neq \emptyset \).

See in what follows the more detailed discussion and definitions of sets of twin primes \( T_i \mathbb{P} \) and \( i \)-primes \( T_i \mathbb{P} \) related to the Goldbach Conjecture.
Example 1.

Values of $I_m, S_m, \theta_m(S_m), G_m^P, G(2m)$ for $m = 19$:

$I_{19} = \{3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19\}

S_{19} = \{3, 5, 7, 11, 13, 17, 19, 23, 29, 31\}, \quad \theta_{19}(S_{19}) = \{7, 9, 15, 19, 21, 25, 27, 31, 33, 35\}

G_{19}^P = \{7, 19, 31\}, \quad G(38) = 3

Values of $I_m, S_m, \theta_m(S_m), G_m^P, G(2m)$ for $m = 20$:

$I_{20} = \{3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20\}

S_{20} = \{3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37\}, \quad \theta_{20}(S_{20}) = \{3, 9, 11, 17, 21, 23, 27, 29, 33, 35, 37\}

G_{20}^P = \{3, 11, 17, 23, 29, 37\}, \quad G(40) = 6

The next Lemma concerns some properties of the shift transformation $\theta_m$ ($m \geq 3$)

Lemma 3.

Define a transformation $\theta_m : \mathbb{Z} \rightarrow \mathbb{Z}$ such that $\theta_m(n) = 2 \cdot m - n, \quad n \in \mathbb{N}, \ m \in \mathbb{N} \ (m \geq 3)$.

Then, for any subset $A \subseteq \mathbb{Z}$ and integer $t \in \mathbb{N}$ the following properties of $\theta_m$ hold true:

$$\theta_{m+t}(A) = \theta_m(A) + 2 \cdot t$$

$$\theta_m(A) = \theta_{m-t}(A) + 2 \cdot t$$

(6)

Proof.

$$\theta_{m+t}(A) = 2 \cdot (m+t) - A = 2 \cdot m - A + 2 \cdot t = \theta_m(A) + 2 \cdot t$$

$$\theta_m(A) = 2 \cdot m - A = 2 \cdot (m-t) - A + 2 \cdot t = \theta_{m-t}(A) + 2 \cdot t$$

Q.E.D.

Let $T_i^P = \{p \mid p \in \mathbb{P} \text{ and } (p+2) \in \mathbb{P}\}$ stand for a set of all twin primes and consider $G_k^P \cap T_i^P$

for each $k \ (3 \leq k \leq m)$. Thus, if for some $k \ (3 \leq k \leq m)$ $G_k^P \cap T_i^P \neq \emptyset$, then $G_{k+1}^P \neq \emptyset$.

Lemma 3 implies, in particular, that if a prime $p \in G_k^P$ has a twin prime $(p+2) \in \mathbb{P}$, then $(p+2) \in G_{k+1}^P$. This shows some connection between the Twin Prime Conjecture
and the Strong Goldbach Conjecture (SGC), and, moreover, between the $t$-Prime Conjecture (de Polignac Conjecture (1849)) and SGC as we see below. This also shows how nonempty Goldbach sets $G_k \mathbb{P}$ can propagate further with increasing values of $k$.

**Definition.**

Denote, in general, by $T_t \mathbb{P}$ ($t \in \mathbb{N}$) a set of $t$-primes for some $t \in \mathbb{N}$, that is

$$T_t \mathbb{P} = \{ p \mid p \in \mathbb{P} \text{ and } (p + 2 \cdot t) \in \mathbb{P} \}. \text{ Notice that } \bigcup_{t=0}^{\infty} T_t \mathbb{P} = T_0 \mathbb{P} = \mathbb{P}, \quad (7)$$

where $\mathbb{P}$ stands for the set of all odd prime numbers.

Consider examples below:

$$\{3,5,11,17,29,41\} \subset T_1 \mathbb{P}, \quad \{3,7,13,19,37,43\} \subset T_2 \mathbb{P}, \quad \{5,7,11,17,23,31,37,41\} \subset T_3 \mathbb{P}, \text{ and so on.}$$

Propagation of nonempty $G_k \mathbb{P}$ for all $k \geq 3$ is based on very simple observations.

**Lemma 4.**

Let $p \in G_k \mathbb{P} \neq \emptyset$ and $p \leq k$. There exist $q \in \mathbb{P}$ ($q > p$) and $t \in \mathbb{N}$ ($1 \leq t < k - 1$) such that $q = p + 2 \cdot t \in \mathbb{P}$, and $p \in T_t \mathbb{P}$. This implies that there exists $t \in \mathbb{N}$ ($1 \leq t < k - 1$) such that $p \in G_k \mathbb{P} \cap T_t \mathbb{P} \neq \emptyset$ and $q = (p + 2 \cdot t) \in G_{k+t} \mathbb{P} \neq \emptyset$.

**Proof.**

Let $p \in G_k \mathbb{P}$, $p \leq k$. Thanks to the Bertrand’s postulate [4], there exists a prime $q$ between integers $k$ and $2 \cdot k$ ($k > 3$). This implies that there exists $t \in \mathbb{N}$ such that this prime $q$ can be expressed in the form $q = (p + 2 \cdot t) \in \mathbb{P}$, where $1 \leq t < k - 1$.

Indeed, we can take $t = \frac{q - p}{2}$, so that $q = p + 2 \cdot t \in \mathbb{P}$. Then, $p \in G_k \mathbb{P}$ implies that $p + \theta_k(p) = 2 \cdot k$ and $(p + 2 \cdot t) + \theta_k(p) = 2 \cdot k + 2 \cdot t = 2 \cdot (k + t)$.

Since $q = p + 2 \cdot p \in \mathbb{P}$ and $\theta_k(p) \in G_k \mathbb{P}$, we have $p \in G_k \mathbb{P} \cap T_t \mathbb{P} \neq \emptyset$.
and \( q = (p + 2 \cdot t) \in G_{k+1} \neq \emptyset \). 

Q.E.D.

Lemma 5.

1. For \( k > 3 \) and \( p < k \) each \( p \in G_k \) is a \( t \)-prime for an appropriate value of \( t > 0 \).
2. For any \( p \in G_k \) there exist \( p' = \theta_k(p) \in G_k \), \( q \in \mathbb{P} \), \( q > p \), and \( t \geq 1 \), such that \( q = p + 2 \cdot t \), and both \( p' \) and \( q \) belong to \( G_{k+1} \neq \emptyset \).
3. Let \( G_k = \{ p_{k,1}, p_{k,2}, \ldots, p_{k,n(k)-1}, p_{k,n(k)} \} \) were \( p_{k,i} < p_{k,i+1} \)
   for all \( i = 1, 2, \ldots, n(k) - 1 = G(2k) - 1 \). Denote \( t_{ki} = \frac{p_{k+1,i} - p_{k,i}}{2} \).
   Then, \( G_k \cap T_{j^u} \neq \emptyset \) and \( G_{k+1} \neq \emptyset \) for all \( i = 1, 2, \ldots, n(k) - 1 = G(2k) - 1 \).
4. Let for each \( j \) \( (3 < j \leq k) \) there exist \( t \geq 1 \) such that \( G_{j} \cap T_{j^u} \neq \emptyset \).
   Then \( G_j \neq \emptyset \) for all \( j \) \( (3 < j \leq k) \).
5. Let \( G_j \neq \emptyset \) \( (j \geq 3) \) and there exists \( k > j \) such that \( G_j \cap T_{k^u} \neq \emptyset \). Then \( G_k \neq \emptyset \)
6. If for \( m > 3 \) there exist \( k \) \( (3 \leq k < m) \) and \( t = m - k \) such that \( G_k \cap T_t \neq \emptyset \),
   then \( G_m \neq \emptyset \).

Proof.

1. Indeed, for \( p \in G_k \) we have \( p' = \theta_k(p) = 2 \cdot k - p \in G_k \) and \( p' = p + 2t \),
   where \( t = \frac{p' - p}{2} \), so that \( p \in T_t \).
2. In general, for any \( p \in G_k \) there exist \( q \in \mathbb{P} \), \( q > p \), and \( t = \frac{q - p}{2} \geq 1 \), so that
   \( q = p + 2 \cdot t \) and \( p + \theta_j(p) + 2 \cdot t = p' + q = 2 \cdot k + 2 \cdot t = 2 \cdot (k + t) \), which means that
   \( p' \in G_{k+1} \) and \( q \in G_{k+1} \).
3. This statement follows directly from the above statement 2.
4. Due to Lemma 4, since $G_{j\cdot t} \cap T_{j} \neq \emptyset$ for an appropriate $t \geq 1$, we have $G_{j} \neq \emptyset$ for each $j \leq k$.

5. $G_{j} \cap T_{k-j} \neq \emptyset$ implies that there exists $p \in G_{j}$ and $t = k - j$ such that $q = (p + 2 \cdot (k - j)) \in \mathbb{P}$.

Then, $p + \theta_{j}(p) + 2 \cdot (k - j) = \theta_{j}(p) + 2 \cdot j + 2 \cdot (k - j) = 2 \cdot k$ and both $\theta_{j}(p)$ and $q$ are primes that belong to $G_{k} \neq \emptyset$.

6. Due to Lemma 4, $G_{k} \cap T_{j} \neq \emptyset$ and $t = m - k$ imply $G_{k} \cap T_{j} = G_{k+(m-k)} \neq \emptyset$.

Q.E.D.

This shows how nonempty Goldbach sets $G_{3}, G_{4}, G_{5}, \ldots, G_{12}, \ldots$ have been generated:

$G_{1} = \{ 3 \}, G_{3} = \{ 3, 3 + 2 \}, G_{4} = \{ 3, 5, 5 + 2 \}, G_{5} = \{ 5, 5 + 2 \},$

$G_{7} = \{ 3, 7, 7 + 4 \}, G_{8} = \{ 3, 5, 11, 11 + 2 \}, G_{9} = \{ 5, 7, 11, 11 + 2 \},$

$G_{10} = \{ 3, 7, 13, 13 + 4 \}, G_{11} = \{ 3, 11, 17, 17 + 2 \}, G_{12} = \{ 5, 7, 11, 13, 17 + 2 \}, \ldots$

Let $p \in G_{k}$, $p' = \theta_{k}(p) \in G_{k}$, where $p' = \theta_{k}(p) = 2 \cdot k - p$. Let $q$ be prime and $q > p$ such that $q = p + 2 \cdot t$, where $t = \frac{q - p}{2}$. $G_{k} \neq \emptyset$.

This implies that $q + \theta_{k}(p) = (p + 2 \cdot t) + \theta_{k}(p) = (p + \theta_{k}(p)) + 2 \cdot t = 2 \cdot (k + t)$.

Since both $q$ and $\theta_{k}(p)$ are primes and $q + \theta_{k}(p) = 2 \cdot (k + t)$, we have $q$ and $\theta_{k}(p)$ belong to $G_{k+m} \neq \emptyset$. For instance, if for some $k$ ($3 \leq k \leq m$) we have $G_{k-1} \cap T_{j} \neq \emptyset$, then, due to Lemma 3, $G_{k+1} \neq \emptyset$.

Consider $p = 3$ and $q = 5$, that is we start from $G_{3} = \{ 3 \}$.

Then, $t = \frac{5 - 3}{2} = 1$ and $\theta_{3}(3) = 3$. Thus, we have $q + \theta_{3}(p) = 5 + 3 = 2 \cdot (3 + 1) = 8$ where
Then, due to Lemma 4, for each $G_k \mathbb{P} \neq \emptyset$ there exists $t \in \mathbb{N}$ such that $G_k \mathbb{P} \cap T^t \mathbb{P} \neq \emptyset$, which implies $G_{k+t} \mathbb{P} \neq \emptyset$. This means that the occurrence of a $t$-prime in a non-empty set $G_k \mathbb{P}$ implies that $G_{k+t} \mathbb{P}$ is necessarily non-empty. This provides proliferation of non-empty sets $G_k \mathbb{P}$ $t$ steps forward, so that $G_{k+t} \mathbb{P}$ is not empty for any $k$.

Starting from $k = 3$ and $t = 1$ the ‘wave’ of $G_k$-primes propagates forward recursively as $k \to \infty$ without gaps, supported by the existence of $t$-primes, as we demonstrate below.

Observe that each pair of primes $(p,q)$ such that $p \in G_k \mathbb{P}$, $q > p$ and $q \in S_m = I_m \cap \mathbb{P}$, generates a nonempty set $G_{k+t} \mathbb{P}$, where $t = \frac{q-p}{2}$ and $p$ is a $t$-prime in $G_k \mathbb{P}$.

Notice that there are infinitely many $t$-prime numbers in $\mathbb{N}$ and at least $G(2m) - 1$ $t$-primes in each $G_m \mathbb{P}$ for $m \geq 3$. The goal of Lemma 5 is to demonstrate that we can build a nonempty Goldbach set $G_m \mathbb{P}$ for each $m \geq 3$, given a sequence of nonempty Goldbach sets $\{G_k \mathbb{P}\}_{3 \leq k \leq m-1}$, due to the assumption of mathematical induction.

We need the following simple Lemmas.

**Lemma 6.**

Let $S_m = I_m \cap \mathbb{P}$, where $I_m = [3,2 \cdot m - 3]$.

For every prime $p \in S_m$ there is $k \leq m$ such that $p \in G_k \mathbb{P}$.

**Proof.**

Indeed, we can take $k = p$. Then, $p \in G_p \mathbb{P}$ since $p + p = 2 \cdot p \leq 2 \cdot m$. 

3 and 5 both belong to $G_3 \mathbb{P} = G_4 = \{3,5\}$. 

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Another possibility is to consider \( k = \frac{3+p}{2} \), since \( 3+p \leq 2m \).

Q.E.D.

Lemma 7.

For all \( m \geq 3 \) we have

\[
S_m = \bigcup_{k=3}^{m} G_k^P = G^{(m)}P. \tag{8}
\]

Proof.

For any \( p \in S_m \), due to Lemma 1, there exists \( k \leq m \) such that \( p \in G_k^P \).

And vice versa, if \( p \in G^{(m)}P \), that is \( S_{m-1} = \bigcup_{k=3}^{m-1} G_k^P \) \( p \in G_k^P \) for some \( k \leq m \), then \( p \in S_m \).

Q.E.D.

Lemma 8.

Let \( G_k^P \neq \emptyset \) for all \( 3 \leq k \leq m-1 \). Assuming that \( 2m-3 \in \mathbb{P} \), we have \( 2m-3 \in G_k^P \neq \emptyset \).

Otherwise, if \( 2m-3 \notin G_m^P \), we have \( S_m = S_{m-1} \). Then, for any \( m \geq 3 \) the equality

\[
\bigcup_{k=3}^{m-1} \left[ (G_k^P + 2 \cdot (m-k)) \cap S_m \right] = G_m^P = \emptyset \tag{9}
\]

holds true.

Proof.

Denote \( A_{k,m} = (G_k^P + 2 \cdot (m-k)) \).

Then,

\[
\bigcup_{k=3}^{m-1} \left[ (G_k^P + 2 \cdot (m-k)) \cap S_m \right] = \bigcup_{k=3}^{m-1} \left[ A_{k,m} \cap S_m \right] = \left( \bigcup_{k=3}^{m-1} A_{k,m} \right) \cap S_m.
\]

Consider \( \theta_m(A_{k,m}) = 2m - A_{k,m} = 2m - G_k^P - 2 \cdot (m-k) = 2k - G_k^P = \theta_k(G_k^P) \).

Due to Lemma 1, we have \( \theta_k(G_k^P) = G_k^P \).
This implies that \( \theta_m \left( \bigcup_{k=3}^{m-1} A_{k,m} \right) \cap S_m \bigg) = \left( \bigcup_{k=3}^{m-1} A_{k,m} \right) \cap \left( \bigcup_{k=3}^{m-1} G_k \bigg) \cap \theta_m \left( S_m \bigg) .

According to Lemma 7, \( S_{m-1} = \left( \bigcup_{k=3}^{m-1} G_k \bigg) \). Since \( S_m = S_{m-1} \) if \( 2 \cdot m - 3 \neq G_m \),
we have \( \theta_m \left( \bigcup_{k=3}^{m-1} A_{k,m} \right) \cap S_m \bigg) = S_m \cap \theta_m \left( S_m \bigg) = G_m \bigg \neq \emptyset \), since \( \left( \bigcup_{k=3}^{m-1} A_{k,m} \right) \cap S_m \neq \emptyset \), due to the assumption of mathematical induction.

Q.E.D.

The proof of Lemmas 5 and 8 show a definite connection between the number of solutions to the Goldbach equation \( p + p' = 2 \cdot m \) in the intervals \( I_m = [3, 2 \cdot m - 3] \) and the number of \( t \)-primes in sets \( G_k \bigg \) for \( k : 3 \leq k < m \).

**Recursive Algorithm generating the infinite sequence**

**of nonempty Goldbach sets** \( G_m \bigg \neq \emptyset \) **for all natural** \( m \geq 3 \).

Given integer \( m \geq 3 \), this algorithm will find all pairs \( (p, p') \) of prime numbers such that \( p + p' = 2 \cdot m \). The algorithm works recursively and generates \( G_m \bigg \), starting from \( G_3 \bigg = \{3\} \), by using the sequence \( G_3 \bigg, G_4 \bigg, G_5 \bigg, \ldots, G_k \bigg \) up to \( k = m - 1 \).

1. Since \( G_m \bigg \) belongs to the interval of integers \( I_m = [3, 2 \cdot m - 3] \), we verify first whether \( (2 \cdot m - 3) \in \mathbb{P} \).

If \( (2 \cdot m - 3) \in \mathbb{P} \), then \( \{3, 2 \cdot m - 3\} \subseteq G_m \bigg \) and we set \( G_3 = \{3\} \). Otherwise, \( G_3 \bigg = \emptyset \).

2. Then we assign \( t = m - k \), \( tG_k = G_k + 2 \cdot t \) and calculate the subsets of primes \( pr \_ tG_k = tG_k \cap \mathbb{P} \) (all \( t \)-primes in \( tG_k \)) to form the set \( G_{k+1} = G_k \cup pr \_ tG_k \), by repeating these calculations in the cycle for \( k = 3, 4, \ldots, m - 1 \).
3. Finally, we obtain $G_m = G_m \mathbb{P}$ as a union $\bigcup_{k=3}^{m-1} \left[(G_k \mathbb{P} + 2 \cdot (m-k) \cap S_m)\right]$. 

See in APPENDIX the text of R-script and data lists of the calculated $G_k \mathbb{P}$ for $k:3 \leq k \leq m$.

A sequence of Goldbach sets $\{G_k \mathbb{P} \mid 3 \leq k \leq m\}$ represents solutions to the system of Goldbach equations $\{x + y = 2 \cdot k \mid 3 \leq k \leq m\}$ in the intervals $I_k = [3,2 \cdot k - 3]$.

This system is an algebraic variety given by linear equations $x + y = 2 \cdot k \ (3 \leq k \leq m)$, which solutions (if exist) are pairs of prime numbers $(p,p') \in \mathbb{P}^2$.

Each Goldbach set $G_k \mathbb{P}$ geometrically is a sequence of points with coordinates $(p,p') \in \mathbb{P}^2$ on the segment of a straight line given by $x + y = 2 \cdot k$, $(x,y) \in [0,2 \cdot k]$, symmetrically located on the line with respect to a point $(k,k)$, due to invariance $\theta_k(G_k \mathbb{P}) = G_k \mathbb{P}$, where $\theta_k(x) = 2k - x = y$. See below Fig. 1 and 2 representing Diophantine geometry of Goldbach sets, where dots are points with coordinates $(p,p') \in \mathbb{P}^2$ on the corresponding lines.

These dots are solutions to the Goldbach equations $x + y = 2 \cdot k \ (3 \leq k \leq m)$.

The theorem below answers the question how many solutions are in each Goldbach set.

**Theorem 1.**

A set $G_m \mathbb{P}$ of solutions to the Goldbach equation $p + p' = 2 \cdot m$ in primes $(p,p') \in \mathbb{P}^2$ in each interval $I_m = [3,2 \cdot m - 3]$ includes a prime $p < m$ such that both $p$ and $p' = \theta_m(p)$ are co-primes with $m$, that is $gcd(m,p) = (m,p) = 1$, $gcd(m,\theta_m(p)) = (m,\theta_m(p)) = 1$.

The number of solutions to the Goldbach equation $p + p' = 2 \cdot m$ in primes $(p,p') \in \mathbb{P}^2$ in each interval $I_m = [3,2 \cdot m - 3]$ is equal to the number of $t$-primes in the set $G_m \mathbb{P}$.
such that \( t = \frac{p' - p}{2} \).

**Proof.**

Consider a quadratic polynomial \( P_m(x) = x^2 + 2 \cdot m \cdot x + c \) for integer valued \( m, c \) and \( x \in \mathbb{Z} \).

Let a pair of primes \((p, p')\) be a solution to the Goldbach equation \( p + p' = 2 \cdot m \) in the interval \( I_m = [3, 2 \cdot m - 3] \). Obviously, for \( c = p \cdot p' \), the pair of prime numbers \((p, p') \in \mathbb{P}^2\) are roots of the polynomial \( P_m(x) = x^2 - 2 \cdot m \cdot x + p \cdot p' = (x - p) \cdot (x - p') \).

Discriminant of \( P_m(x) \) is \( D = 4 \cdot (m^2 - p \cdot p') = 4 \cdot t^2 \), where \( t \) is a nonnegative integer.

Observe that \((m^2 - p \cdot p') = t^2 \) follows \((m - t) \cdot (m + t) = p \cdot p' \).

Since \( p \) and \( p' \) are not equal prime numbers, the equation \((m - t) \cdot (m + t) = p \cdot p' \) for an integer \( t \) and \( p \leq p' \) implies: \( m - t = p \) and \( m + t = p' \),

so that \( t = \frac{p' - p}{2} \) and \( p' = p + 2 \cdot t \). This means that \( p \in G_m \mathbb{P} \) is a \( t \)-prime in \( G_m \mathbb{P} \),

where \( t = \frac{p' - p}{2} \). Therefore, we have as many solutions to the equation \( P_m(x) = x^2 + 2 \cdot m \cdot x + p \cdot p' \) as there are \( t \)-primes, \( t = \frac{p' - p}{2} \), in the set \( G_m \mathbb{P} \).

Assume now that \( 2 \cdot m = p + q, \ c = p \cdot q \), where \( p \in \mathbb{P} \) and \( q = 2 \cdot m - p \) is an unknown integer.

Then the polynomial \( P_m(x) \) takes a form: \( P_m(x) = x^2 + 2 \cdot m \cdot x + p \cdot (2 \cdot m - p) \).

Its discriminant is \( D_m = 4 \cdot (m^2 - p \cdot (2 \cdot m - p)) = 4 \cdot (m^2 - 2 \cdot m \cdot p + p^2) = 4 \cdot (m - p)^2 \).

The solutions to the equation \( P_m(x) = 0 \) are \( x_{1,2} = m \pm (m - p) \), where \( x_1 = p, x_2 = 2 \cdot m - p \).

For instance, let \( m = 9, \ c = 45 \). Then, \( P_9(x) = x^2 - 18x + 45 \) has 2 roots:

\( x_1 = 3 \in \mathbb{P}, x_2 = 2 \cdot 9 - 3 = 15 \notin \mathbb{P} \), and they are not included in \( G_9 \mathbb{P} \). Meanwhile, for \( m = 9 \)
and $c = 65$ we have $P_g(x) = x^2 - 18x + 65$ with roots $x_1 = 5 \in \mathbb{P}$, $x_2 = 2 \cdot 9 - 5 = 13 \in \mathbb{P}$, so that $5 \in G_g\mathbb{P}$ and $13 \in G_g\mathbb{P}$. Notice that $3, \theta_g(3) = 15$ and $2 \cdot 9 = 18$ are not coprime numbers, while $5, \theta_g(5) = 13$ and $2 \cdot 9 = 18$ are coprime. Denote $[x]_p = \text{mod}(x, p)$.

Then, $[P_m(x)]_p = [x]^2 - [2 \cdot m]_p \cdot [x]_p$.

The equation $[P_m(x)]_p = [x]^2 - [2 \cdot m]_p \cdot [x]_p = [x]_p \cdot ([x]_p - [2 \cdot m]_p) = 0$

has the following different sets of solutions: $[x]_p = 0$ and $([x]_p - [2 \cdot m - p]_p) = 0$.

Since we are solving equation $P_m(x) = 0$ in primes within an interval $I_m = [3, 2 \cdot m - 3]$, the solutions are: $x_1 = p \in S_m = I_m \cap \mathbb{P}$, $x_2 = \theta_m(p) = 2 \cdot m - p \in S_m$, assuming that the numbers $(m, p)$ and $(m, \theta_m(p))$ are coprime in each pair, that is, $\gcd(m, p) = (m, p) = 1$

and $\gcd(m, \theta_m(p)) = (m, \theta_m(p)) = 1$.

Q.E.D.

Diophantine Geometry of Goldbach Sets

$G_k\mathbb{P}$ $(k = 3, 4, \ldots, 50)$ (Fig.1)
Every dot in the above figure denotes a point with coordinates \((p, p')\) such that 
\[p + p' = 2 \cdot k\] on the line \(x + y = 2 \cdot k\), where \(3 \leq k \leq m\).

We apply now one of the most fundamental and simple proof techniques in mathematics known as **mathematical induction** [3]. Let \(\text{Prop}(m)\) denote a statement about a natural number \(m\), and let \(m_0\) be a fixed number. A proof that \(\text{Prop}(m)\) is true for all \(m \geq m_0\) by induction requires two steps:

* **Basis step:** Verify that \(\text{Prop}(m_0)\) is true.

* **Induction step:** Assuming that \(\text{Prop}(k)\) is true for all \(k\) such that \(m_0 \leq k \leq m\), verify that \(\text{Prop}(m+1)\) is true.

**Theorem 2.**

\(\text{Prop}(m)\): For all integer \(m \geq 3\), the set \(G_{m} \mathbb{P}\) of solutions to the equation \(n + n' = 2m\), \((n, n') \in \mathbb{P}^2\), in prime numbers is not empty.
The Prop(m) can be equivalently stated as: \( G_m \subseteq \emptyset \) for all integers \( m \geq 3 \).

**Proof.**

(1) Basic step.

As we know, \( m \leq 4 \cdot 10^3 \).

Let \( m_0 = 3 \). Then \( 2 \cdot 3 = 3 + 3 \).

(2) Induction step.

Assume that \( G_k \subseteq \emptyset \) for all integers \( k : m_0 \leq k \leq m \).

Let \( k = m + 1 \). In Lemma 2 we proved (3) that \( S_m = \begin{cases} S_{m-1} \cup \{2m-3\} & \text{if } (2m-3) \in \mathbb{P} \\ S_{m-1} & \text{if } (2m-3) \not\in \mathbb{P} \end{cases} \).

Then, we have:

\[ I_{m+1} = [3, 2 \cdot (m+1) - 3] = [3, 2 \cdot m - 1] \quad \text{and} \quad S_{m+1} = \begin{cases} S_m \cup \{2m-1\} & \text{if } (2m-1) \in \mathbb{P} \\ S_m & \text{if } (2m-1) \not\in \mathbb{P} \end{cases} \]

In the case \( (2m-1) \in \mathbb{P} \), the formula (5) implies \( G_{m+1} \subseteq \emptyset \) if \( (2m-1) \in \mathbb{P} \), so that \( G_{m+1} \neq \emptyset \).

We can also confirm the last equality directly, because \( 3 + (2m-1) = 2(m+1) \)

implies that \( 3 \in G_{m+1} \) and \( (2m-1) \in G_{m+1} \) if \( (2m-1) \in \mathbb{P} \), so that \( G_{m+1} \neq \emptyset \).

Consider now a general situation which includes the case \( (2m-1) \not\in \mathbb{P} \). If \( (2m-1) \not\in \mathbb{P} \),

then we have \( S_{m+1} = S_m \), and due to Lemma 8, \( G_{m+1} \subseteq S_{m+1} = S_m = \bigcup_{k=3}^{m} G_k = G^{(m)} \),

and we have \( G_{m+1} \cap G^{(m)} \neq \emptyset \). This means that there exists \( k \leq m \) such that \( G_{m+1} \cap G_k \neq \emptyset \).

Therefore, \( G_{m+1} \neq \emptyset \). Thus, assuming by the induction assumption, that \( G_k \neq \emptyset \)

for all \( k (3 \leq k < m) \), we have \( G_{m+1} \neq \emptyset \). Moreover, due to Lemma 8, we have a recursive formula (9) for Goldbach sets, which implies
Thus, we have

\[ \bigcup_{k=3}^{m} \left( G_k^m \mathbb{P} + 2 \cdot (m+1-k) \cap S_m \right) = G_{m+1}^m \mathbb{P} \neq \emptyset. \] (10)

Q.E.D.

An example below illustrates the above statement with some computer calculations.

In this example we consider sets \( G_m^\mathbb{P} = \theta_m(S_m) \cap S_m \) for \( m \) from 105 to 110.

Notice that many of those sets can be calculated based on the rule that if a prime \( p \in G_k^\mathbb{P} \) has a twin prime \( (p+2) \in \mathbb{P} \), that is \( t = 1 \) and \( p \in T_1^\mathbb{P} \), then \( (p+2) \in G_{k+1}^\mathbb{P} \).

For example, terms in \( G_{105}^\mathbb{P} \) are calculated by this rule by using terms in \( G_{105}^\mathbb{P} \).

Meanwhile, terms in \( G_{110}^\mathbb{P} \) are calculated by using terms in \( G_{108}^\mathbb{P} \) for \( t = 2 \) based on the general rule: if \( p < k \) and \( p \in G_k^\mathbb{P} \cap T_1^\mathbb{P} \), then \( p \in \mathbb{P} \) and \( p + 2 \cdot t \in \mathbb{P} \) implies \( (p + 2 \cdot t) \in G_{k+t}^\mathbb{P} \).

(Lemma 3): \( 23 + 197 = (19 + 2 \cdot 2) + 197 = 220 = 2 \cdot 110 \), since \( 19 + 197 = 216 = 2 \cdot 108 \).

The calculations below illustrate the conclusion of the Theorem

(see the data referred in Example 2). We would like to verify that \( G_{110}^\mathbb{P} \neq \emptyset \), by using that

\( G_k^\mathbb{P} \neq \emptyset \) for all \( k \leq 110 \). Consider \( G_{110}^\mathbb{P} \) \((m = 110, 2 \cdot m = 220)\). If we choose \( t = 1 \) it would not work with \( G_{109}^\mathbb{P} \), because \( G_{109}^\mathbb{P} \cap T_1^\mathbb{P} = \emptyset \). We try then \( G_{108}^\mathbb{P} \) and \( t = 2 \).

We have \( G_{108}^\mathbb{P} \cap T_2^\mathbb{P} \neq \emptyset \) and \( p = 19 \in G_{108}^\mathbb{P} \cap T_2^\mathbb{P} \). Then, \( p + 2 \cdot t = 19 + 2 \cdot 2 = 23 \) should belong (due to Lemma 3) to \( G_{110}^\mathbb{P} \). Therefore, \( 2 \cdot 110 - 23 = 197 \in G_{110}^\mathbb{P} \).

Thus, we have \( 23 + 197 = 2 \cdot 110 \), which means that \( G_{110}^\mathbb{P} \neq \emptyset \). Notice that in this instance \( k = 109, k + 1 \cdot t = 109 + 1 \cdot 2 = 108 \) and \( (k+1) + t = 108 + 2 = 110 \) and we established that \( G_{(k+1)+t}^\mathbb{P} = G_{110}^\mathbb{P} \neq \emptyset \) by using the fact that \( G_{108}^\mathbb{P} \cap T_2^\mathbb{P} \neq \emptyset \).
Example 2.

Sets \( G_m \cap = \theta_m (S_m) \cap S_m \) for \( m \) from 105 to 110

\[
G_{105} = \{11, 13, 17, 19, 29, 31, 37, 43, 47, 53, 59, 61, 71, 73\}
\]

\[
G_{106} = \{13, 19, 31, 61, 73, 103, 109, 139, 151, 181, 193, 197, 199\}
\]

\[
G_{107} = \{3, 17, 23, 41, 47, 83, 101, 107, 113, 131, 167, 173, 191, 197, 211\}
\]

\[
G_{108} = \{5, 17, 19, 23, 37, 43, 53, 59, 67, 79, 89, 103, 107, 109\}
\]

\[
G_{109} = \{7, 19, 37, 61, 67, 79, 109, 139, 151, 157, 181, 199, 211\}
\]

\[
G_{110} = \{23, 29, 41, 47, 53, 71, 83, 89, 107, 113\}
\]

Thus, we can predict that \( G_{110} \neq \emptyset \) without explicit calculation of this set, just by using the previously calculated sets \( G_{109}, G_{108}, G_{107}, \ldots \) By using the algorithm described in Lemma 5, we find that \( G_{109} \cap T_2 = \emptyset \), but \( G_{108} \cap T_2 \neq \emptyset \), since, for instance, \( 19 \in G_{108} \cap T_2 \), and \( 19 + 2 \cdot 2 = 23 \in G_{110} \).
Conclusion

I tried to follow the ‘natural logic’ of the problem, by being more exploratory rather than artificially creative and used a computer as my permanent companion and an advisor.

As to simplicity of the used methods, I recall to the point the well-known Poincaré Recurrence Theorem [7], which proof takes only a few lines of the text and is based mainly on elementary set-theoretical operations. Meanwhile the significance of the Poincaré Recurrence Theorem can be hardly overestimated.

Notice that the proof in Lemma 5 that there exists \( t \geq 1 \) such that \( G_{k+t} \cap T^t \neq \emptyset \), which immediately implies that \( G_{k+1} \neq \emptyset \) for all \( 3 \leq k \leq m \) is not constructive, since it does not provide a formula but outlines an algorithm for finding the number \( t \).

This is a typical “existence” theorem. Notice, by the way, that the proof of the famous Poincaré recurrence theorem is not constructive as well, since it does not provide a number \( n \) of iterations, after which the recurrence occurs. The Poincaré theorem states only that such number \( n \) exists. Meanwhile the proof in Lemma 8 is quite constructive since it is based on the recursive formula (10) given above (see the calculated examples of Goldbach set sequences in the Appendix).

I would like to express here my acknowledgement to the peer-reviewer Dr. Dmitry Kleinbock for his critical and thoughtful reading of many versions of this paper, valuable advice and support. The spirit of friendly interaction in our numerous discussions was very crucial for me.
APPENDIX

The text of R-script for computer realization of Recursive Algorithm

generating sequences of Goldbach sets \( G_k \) for \( k = 3, 4, 5, \ldots, m \)

```r
# Function GenG(m) generates sets G(m) of Goldbach primes such that p + p' = 2m (3 <= m <= 2m-3)
# for each natural m (3 <= m <= 2m-3). This function is based on Lemma3 algorithm:
# G(m) includes each p + 2t if p is a t-prime in the Goldbach set G(k) (3 <= k <= m-1) for t = m-k.
# Thus, G(m) is a union of subsets tG(k) of t-primes in G(k) such that
# tG(k) = \{p + 2t | p is in G(k), p + 2t is prime for each t = m - k\}.
# Notice that G(m) is recurrently generated from the Goldbach sets G(k), where
# 3 <= k <= m-1,
# starting from G(3) = \{3\} (3+3=6). This confirms by the principle of
# mathematical induction
# non-emptiness of Goldbach sets G(m) for all natural m = 3,4,5,... (the
# Goldbach Conjecture).

# Needed packages: 'numbers' and 'sets'. Needed function: GmR.
# Created by GMS
# Date: 06.30.21.

GenG <- function(m) {
  Gm <- NULL
  for (k in (3: m-1)) {
    Gk <- Gm(k)
    t <- m - k
    tGk <- Gk + 2*t
    pr_tGk <- tGk[isPrime(tGk)]
    Gm <- union(Gm, pr_tGk)
  }
  return(sort(Gm))
}
```

#source '~/Documents/R/Number Theory/GenG.R')

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Data lists of calculated $G_k\mathbb{P}$ for $k = 3, 4, 5, \ldots, m$

<table>
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