A Note on Fermat's Equation

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Abstract. Around 1637, Pierre de Fermat famously scribbled, and claimed to have a proof for, his statement that equation $a^n + b^n = c^n$ has no positive integer solutions for exponents $n > 2$. The theorem stood unproven for centuries until Andrew Wiles' groundbreaking work in 1994, with a notable caveat: Wiles' proof, while successful, relied on modern tools far beyond Fermat's claimed approach in terms of complexity. The present work potentially offers a solution which is closer in spirit to Fermat's original idea. The same tools designed to this effect are then used to prove the Beal conjecture, a well-known generalization of Fermat's Last Theorem.

1. Introduction

Fermat's Last Theorem, first stated by its namesake Pierre de Fermat in the 17^{th} century, it claims that there are no positive integer solutions to the equation $a^n + b^n = c^n$, whenever $n \in \mathbb{N}$ is greater than 2. In a margin note left on his copy of Diophantus' *Arithmetica*, Fermat claimed that he had a proof which the margin was too small to contain. [1]. Later mathematicians such Leonhard Euler and Sophie Germain made significant contributions to its study [2, 3], and 20^{th} contributions by Ernst Kummer proved the theorem for a specific class of numbers [4]. However, a complete solution remained out of reach.

Finally, in 1994, British mathematician Andrew Wiles announced a proof for Fermat's Last Theorem. His was a complex and multifaceted work, drawing on advanced areas of mathematics such as elliptic curves which were beyond the purview prevalent in Fermat's heyday. After some initial errors were addressed, Wiles' work was hailed as the long-awaited proof of the Theorem [5] and described as a "stunning advance" in the citation for Wiles's Abel Prize award in 2016. It also proved much of the Taniyama-Shimura conjecture, subsequently known as the modularity theorem, and opened up entire new approaches to numerous other problems and mathematically powerful modularity lifting techniques [6]. The techniques used by Wiles are ostensibly far from Fermat's claimed proof in terms of extension, complexity and novelty of tools used − many of which were only available during the 20^{th} century. In this article, we present what we contend is a a correct and short proof for Fermat's Last Theorem. The degree of actual closeness it might have with Fermat's own can only be speculated upon, but in our view simplicity was of paramount importance and we have deliberately eschewed techniques and results that were not available in the 17^{th} century.

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In 1993, Andrew Beal, an American amateur mathematician and banker, formulated a conjecture while exploring generalizations of Fermat's Last Theorem. Beal first publicly presented the conjecture, along with a $5000 prize for a proof or counterexample. This prize has since been raised several times and is currently held by the American Mathematical Society (AMS) at $1 million. Beal's conjecture states that if the equation $A^x + B^y = C^z$ holds, where A, B, C, x, y, and z are all positive integers with x, y, and z greater than 2, then A, B, and C must share a common prime factor $-$ in other words, there are no solutions to the aforementioned equation if A, B, and C are pairwise coprime [7]. The statement generalizes Fermat's, which arises as a special case whenever $x = y = z$.

Recent years have witnessed significant advancements in tackling the Beal conjecture, as evidenced by works such as [8, 9, 10]. For instance, Peter Norvig, a Google research director, performed a computational search for counterexamples and ruled out their existence for $x, y, z \leq 7$ and $A, B, C \leq 250000$, as well as for $x, y, z \leq 100$ and $A, B, C \leq 10000$ [11]. Our proposed proof of the Beal conjecture precludes any counterexamples from existing regardless of the range considered.

2. Background and ancillary results

Notation 2.1. As usual, $\binom{n}{k}$ stands for the binomial coefficient; $d \mid n$ stands for *integer d divides integer n*; and we denote by $\gcd(a, b)$, the *greatest common divisor* of a, b, i.e. the positive generator of the ideal $(a, b) \subset \mathbb{Z}$ or equivalently the common divisor of a, b that is divided by all common divisors thereof.

The following results are immediate. Firstly we have the Binomial Theorem [12], which for every $n \in \mathbb{Z}_{\geq 0}$ describes the distributive expansion of the n^{th} power of the binomial $x + y$ in any commutative ring $(R, +, \cdot)$:

$$(x+y)^n = \binom{n}{0} \cdot x^n \cdot y^0 + \binom{n}{1} \cdot x^{n-1} \cdot y^1 + \ldots + \binom{n}{n} \cdot x^0 \cdot y^n. \tag{1}$$

Proposition 2.2 ([13]). *$p \in \mathbb{N}$ is prime if and only if $p \mid \binom{p}{k}$ for all integers $0 < k < p$.*

Proposition 2.3. *If n is a positive integer,*

$$x^n - y^n = (x - y) \cdot \sum_{k=0}^{n-1} x^k \cdot y^{n-1-k}.$$

$\mathbb{Z}$ is trivially an integral domain (e.g. [14, Ch. II §1]) hence:

Proposition 2.4 (Cancellation property on $\mathbb{Z}$). *For any $a, b, c \in \mathbb{Z}$, $a \neq 0$ and $a \cdot b = a \cdot c$ imply $b = c$.*

Proposition 2.5 ([15]). *Let $a, b, c \in \mathbb{N}$ greater than 1. If a, b are coprime (i.e. $\gcd(a, b) = 1$) and $a = b \cdot c$, then $a \mid c$.*

Lemma 2.6. *The solutions (x, y) for the Diophantine equation*

$$a \cdot x + b \cdot y = c \cdot x + d \cdot y, \tag{2}$$

where the integer coefficients satisfy $d \neq b$, $a \neq c$ and $a \cdot b \cdot c \cdot d \neq 0$, are

$$(x, y) = \left(k \cdot \frac{d - b}{\gcd(d - b, a - c)}, k \cdot \frac{a - c}{\gcd(d - b, a - c)}\right), \qquad k \in \mathbb{Z}.$$

Proof. It is well known and very easily proven [16, Theorem 2.1.1] that if (x_0, y_0) is a particular solution to Diophantine equation $Ax + Bx = C$, then the general solution of this equation is

$$x = x_0 + k \cdot \frac{B}{\gcd(A, B)}, \quad y = y_0 - k \cdot \frac{A}{\gcd(A, B)}, \qquad k \in \mathbb{Z}.$$

In the equation resulting from (2), we have $A = a - c$, $B = b - d$, $C = 0$ and particular solution $(x_0, y_0) = (0, 0)$, and the Lemma follows immediately. $\square$

3. Main Result

Lemma 3.1. *Let a, b, c be pairwise distinct integers such that*

$$\{\pm 1, 0\} \cap \{a, b, c, a - b, a - c, c - b, a + b\} = \varnothing$$

and p, q and r be three prime integers, not necessarily distinct. If

$$p \mid \gcd(a + b, c), \quad q \mid \gcd(c - b, a), \quad r \mid \gcd(c - a, b),$$

then $c = a + b$ or $\max\{\gcd(a, b), \gcd(a, c), \gcd(b, c)\} > 1$.

Proof. Our hypotheses can be written as

$$a + b = p \cdot u, \tag{3}$$
$$c - b = q \cdot v, \tag{4}$$
$$c - a = r \cdot w, \tag{5}$$
$$c = p \cdot U, \tag{6}$$
$$a = q \cdot V, \tag{7}$$
$$b = r \cdot W, \tag{8}$$

with $u, v, w, U, V, W \in \mathbb{N}$. Two immediate conditions linking these numbers arise. Firstly, (7) combined with (3) (resp. (6) combined with (4)) yield

$$q \cdot V + b = p \cdot u, \qquad p \cdot U - b = q \cdot v,$$

which added together become

$$p \cdot U + q \cdot V = p \cdot u + q \cdot v \Rightarrow p(u - U) + q(v - V) = 0. \tag{9}$$

Secondly, and similarly, (8) combined with (3) (resp. (6) combined with (5)) yield

$$a + r \cdot W = p \cdot u, \qquad p \cdot U - a = r \cdot w,$$

thus

$$p \cdot U + r \cdot W = p \cdot u + r \cdot w \Rightarrow p(u - U) + r(w - W) = 0. \tag{10}$$

Subtracting (10) from (9) entails

$$q \cdot |v - V| = r \cdot |w - W| = p \cdot |u - U|, \tag{11}$$

which will come handy later on.

Let $G = \{\gcd(a, b), \gcd(a, c), \gcd(b, c)\}$. At this juncture, we make the following claims:

(i) $0 \in \{u - U, v - V, w - W\}$ if and only if $\{u - U, v - V, w - W\} = \{0\}$;
(ii) $u = U$, $v = V$ and $w = W$ if and only if $c = a + b$;
(iii) $(u - U) \cdot (v - V) \cdot (w - W) \neq 0$ implies $\max G > 1$.

Let us prove these statements. (i) is the easiest to address: an identity between any of u, v, w and its upper-case counterpart yields trivial cancellations of terms in (9) and (10) and thus the remaining two required identities, on account of the fact that $\mathbb{Z}$ is an integral domain. The other implication is trivial.

Let us prove (ii). Necessity is obvious: $a+b=c$ and (3), (6) imply $p \cdot U = p \cdot u$ and the remaining identities $v = V, w = W$ follow from (i). Sufficiency holds because $v = V$ implies $a = q \cdot V = q \cdot v = c - b$, thus $c = a + b$.

Let us prove (iii). Assume that $u - U, v - V, w - W \neq 0$. Lemma 2.6 and (9), (10) imply the existence of $k, k' \in \mathbb{Z}$ such that

$$p = k \cdot \frac{v - V}{\gcd(v - V, U - u)} = k' \cdot \frac{w - W}{\gcd(w - W, U - u)}, \tag{12}$$

$$q = -k \cdot \frac{u - U}{\gcd(v - V, U - u)}, \tag{13}$$

$$r = -k' \cdot \frac{u - U}{\gcd(w - W, U - u)}, \tag{14}$$

Primality and (12) imply $|k|, |k'| \in \{1, p\}$ which leads to four cases.

CASE 1: $|k| = |k'| = p$. This implies p divides, hence equals, q, r.
CASE 2: $|k| = 1$, $|k'| = p$. This implies $p \mid r$, thus $p = r$.
CASE 3: $|k| = p$, $|k'| = 1$. Implies $p \mid q$, thus $p = q$.
CASE 4: $|k| = |k'| = 1$. Then (12), (13), (14) become

$$|v - V| \cdot \gcd(w - W, u - U) = |w - W| \cdot \gcd(v - V, u - U) \tag{15}$$

$$p \cdot |u - U| \cdot \gcd(v - V, U - u) = q \cdot |v - V| \cdot \gcd(v - V, U - u), \tag{16}$$

$$p \cdot |u - U| \cdot \gcd(w - W, U - u) = r \cdot |w - W| \cdot \gcd(w - W, U - u) \tag{17}$$

based on the following equations:

$$p = \frac{|v - V|}{\gcd(v - V, U - u)} = \frac{|w - W|}{\gcd(w - W, U - u)}$$

$$|k| = p \cdot \frac{\gcd(v - V, U - u)}{|v - V|} = q \cdot \frac{\gcd(v - V, U - u)}{|u - U|}$$

$$|k'| = p \cdot \frac{\gcd(w - W, U - u)}{|w - W|} = r \cdot \frac{\gcd(w - W, U - u)}{|u - U|}.$$

(16) $-$ (17) and (11) imply the following:

$$\gcd(v - V, U - u) = \gcd(w - W, U - u). \tag{18}$$

Domain cancellation Proposition 2.4 and our hypothesis $u - U, v - V, w - W \neq 0$ imply that (15) and (18) result in

$$|v - V| = |w - W| \tag{19}$$

(11) and (19) implies $q \mid r$, thus $q = r$.

Condition (ii) and the hypothesis in (iii) are all-encompassing and mutually exclusive on account of (i). $\square$

Theorem 3.2. *The statement of Fermat's Last Theorem is true.*

Proof. We will proceed by contradiction. Aside from the fact that case $n = 4$ was proven to have no solutions by Fermat himself, further simplifying assumptions at our disposal are:

- the consideration of an odd prime p as the selected exponent;
- the coprimality of a, b, c;
- and the condition $a, b, c > 1$ on account of Catalan's conjecture, proven by Mihăilescu in [17].

Therefore, the Diophantine equation whose positive integer solvability constitutes our hypothesis is, for a given fixed prime $p > 2$,

$$a^p + b^p = c^p, \qquad \text{where } a, b, c > 1 \text{ and } a, b, c \in \mathbb{N} \text{ are pairwise coprime.} \tag{20}$$

Assume such a, b, c exist. Substituting $x = a$, $y = -b$ and using that p is odd,

$$a^p + b^p = (a+b) \cdot \sum_{k=0}^{p-1} a^k \cdot (-b)^{p-1-k} = c^p \tag{21}$$

by Proposition 2.3. Next, we notice that binomial formula (1) implies

$$(a+b)^p > a^p + b^p = c^p \quad \text{thus} \quad a + b > c. \tag{22}$$

Suppose that c and $(a+b)$ are coprime. That means their difference $r = (a+b) - c$ is a number coprime with both c and $a+b$. Next, (21) and the Binomial Theorem yield

$$(a+b) \cdot \sum_{k=0}^{p-1} a^k \cdot (-b)^{p-1-k} = ((a+b) - r)^p = (a+b) \cdot m - r^p$$

for a certain integer m. That is the same as

$$r^p = (a+b) \cdot m - (a+b) \cdot \sum_{k=0}^{p-1} a^k \cdot (-b)^{p-1-k} = (a+b) \cdot m', \quad m' \in \mathbb{Z}.$$

However, the resulting statement $r^p = (a+b) \cdot m'$ means $a+b$ divides r^p. Since that implies the natural numbers $r, a+b$ cannot be coprime, we reach a contradiction. Therefore, c and $(a+b)$ share a factor greater than 1. Let us now apply the same method to prove a and $c-b$ are not coprime. First we start with an equivalent expression of (20)

$$a^p = c^p - b^p.$$

Substituting $x = c$, $y = b$ and using that p is odd,

$$c^p - b^p = (c-b) \cdot \sum_{k=0}^{p-1} c^k \cdot b^{p-1-k} = a^p$$

by Proposition 2.3.

Next, we notice that $a > c - b$ on account of (22). Suppose that a and $(c-b)$ are coprime. Then similarly to the above situation, their difference $a - (c-b)$ (which is the same r as above) is coprime with both a and $c-b$. Next, we obtain that

$$(c-b) \cdot \sum_{k=0}^{p-1} c^k \cdot b^{p-1-k} = ((c-b) + r)^p$$

and

$$(c-b) \cdot \sum_{k=0}^{p-1} c^k \cdot b^{p-1-k} = (c-b) \cdot m'' + r^p$$

after applying the Binomial Theorem where m'' is an integer. That is the same as

$$r^p = (c-b) \cdot \sum_{k=0}^{p-1} c^k \cdot b^{p-1-k} - (c-b) \cdot m''$$

which is equal to $r^p = (c-b) \cdot m'''$ for some $m''' \in \mathbb{Z}$. However, the expression

$$r^p = (c-b) \cdot m'''$$

means the number $(c-b)$ divides r^p. Since that implies the natural numbers r and $(c-b)$ cannot be coprime, we reach a contradiction. In this way, we prove that a and $(c-b)$ share a factor greater than 1. Following the same steps as the above two cases *mutatis mutandis*, and exploiting the symmetry of the left-hand side of (20) with respect to a and b, we conclude that b and $(c-a)$ share a factor greater than 1.

Finally, we arrive at the following:

- Natural numbers c and $(a+b)$ share a common prime factor p'.
- Natural numbers a and $(c-b)$ share a common prime factor q'.
- Natural numbers b and $(c-a)$ share a common prime factor r'.

Pairwise different natural numbers $a, b, c > 1$, and the above prime numbers p', q', r', satisfy the hypotheses of Lemma 3.1. Given that we know $c \neq (a+b)$ due to (22), said Lemma implies $\max\{\gcd(a,b), \gcd(a,c), \gcd(b,c)\} > 1$ but this poses a contradiction with the pairwise coprimality of $a, b, c \in \mathbb{N}$ assumed from the outset in (20). Thus our original assumption that (20) had positive integer solutions for prime $p > 2$ has led to a final contradiction. □

Theorem 3.3. *Beal's conjecture is true.*

Proof. Assume otherwise, i.e. identity $A^x + B^y = C^z$ holds for some $A, B, C, x, y, z \in \mathbb{N}$ such that $x, y, z > 2$ and A, B, C are pairwise coprime. We can assume that $A, B, C > 1$ in virtue of the already-proven Catalan conjecture [17]. Let p, q, r be different prime numbers such that $p \mid C$, $q \mid A$ and $r \mid B$

CASE 1: p is odd. Binomial formula (1) and Proposition 2.2 allow us to rewrite the equation $A^x + B^y = C^z$ as

$$(A^x + B^y)^p = C^{pz} \quad \Rightarrow \quad a + b + p \cdot A^x \cdot B^y \cdot k = c, \tag{23}$$

$$(C^z - B^y)^p = A^{px} \quad \Rightarrow \quad a = c - b + p \cdot C^z \cdot B^y \cdot n, \tag{24}$$

$$(C^z - A^x)^p = B^{py} \quad \Rightarrow \quad b = c - a + p \cdot C^z \cdot A^x \cdot m, \tag{25}$$

where $a = A^{x \cdot p}$, $b = B^{y \cdot p}$ and $c = C^{z \cdot p}$ and $k, m, n \in \mathbb{Z}$. This implies that $k > 0$ because all the binomial summands that it arises from are strictly positive; this in turn entails $n, m \neq 0$. Thus $a + b - c$ is divisible by p on account of (23). We have $p \mid a + b$ (due to (23) and $p \mid c$) and (24), (25) and Proposition 2.5 imply

$$a + b - c = p \cdot C^z \cdot B^y \cdot n = p \cdot C^z \cdot A^x \cdot m \quad \text{hence } A^x \mid n \text{ and } B^y \mid m, \tag{26}$$

which in turn implies $q \mid c - b$ from (24) (because $q \mid n$ from (26) and $q \mid a$) and $r \mid c - a$ from (25) (because $r \mid b$ and $r \mid m$ due to (26)). Natural numbers a, b, c, p, q, r thus fulfill the hypotheses of Lemma 3.1. The number c cannot be equal to $a + b$ because that would imply $n = m = k = 0$ in (23), (24), (25) which we know is not true as seen in the previous paragraph. Thus by elimination Lemma 3.1 implies $\max\{\gcd(a,b), \gcd(a,c), \gcd(b,c)\} > 1$, but this contradicts our hypothesis that A, B, C, hence a, b, c, are pairwise coprime.

CASE 2: $p = 2$. Then q, r are odd, and (23)–(25) can be replaced by

$$(A^x + B^y)^q = C^{qz} \quad \Rightarrow \quad -a' = -c' + b' + q \cdot A^x \cdot B^y \cdot k', \tag{27}$$

$$(B^y - C^z)^q = -A^{zq} \quad \Rightarrow \quad c' = a' + b' + q \cdot B^y \cdot C^z \cdot n', \tag{28}$$

$$(C^z - A^x)^q = B^{qy} \quad \Rightarrow \quad b' = -a' + c' + q \cdot C^z \cdot A^x \cdot m', \tag{29}$$

for $a' = -C^{z \cdot q}$, $b' = B^{y \cdot q}$ and $c' = -A^{x \cdot q}$. The rest of the proof is similar to that of CASE 1. Again, $k' > 0$ because it arises from a binomial sum with positive summands, hence $n', m' \neq 0$ as well. Thus $a' + b' - c' \neq 0$ and is divisible by q on account of (27). $q \mid a' + b'$ due to (28) and $q \mid c'$, and (27) and (29) imply

$$a' + b' - c' = -q \cdot A^x \cdot B^y \cdot k' = q \cdot C^z \cdot A^x \cdot m' \quad \text{hence } C^z \mid k' \text{ and } B^y \mid m', \tag{30}$$

which in turns imply $p \mid k'$ and $r \mid m'$, hence $p \mid c' - b'$ (because of (27) and $p \mid a'$) and $r \mid c' - a'$ (because of (29) and $r \mid b'$). All in all, a', b', c', p', q', r' (i.e. $p' = q$, $q' = p$ and $r' = r$) once again fulfill the hypotheses of Lemma 3.1 and the exact same argument used in CASE 2 ensues.

In conclusion, assuming the given natural numbers A, B, and C are pairwise coprime leads to a contradiction. □

4. Conclusion

This paper presents a new and concise proof of Fermat's Last Theorem. We have shown that the equation:

$$a^n + b^n = c^n,$$

has no positive integer solutions for any natural numbers a, b, c and any integer exponent n greater than 2. This accomplishment contributes to resolves a long-standing problem in Number Theory, first posed by Pierre de Fermat nearly 387 years ago. Our proof leverages the vast history of mathematical attempts to tackle this Theorem, offering a simpler and shorter approach compared to previous methods.

This is the bona fide confirmation that the wealth of tools available in Fermat's days was indeed enough to prove his seminal result, and it opens exciting avenues for further exploration. The techniques developed here show promise for application to similar Diophantine equations and other problems in Number Theory and, by extension, Abstract Algebra.

A case in point is the definitive proof of the Beal conjecture that we also present here. We have shown that if equation

$$A^x + B^y = C^z,$$

holds with integer exponents $x, y, z > 2$, then A, B, C must share a nontrivial common factor. This had remained an open problem ever since it was first proposed by Andrew Beal in 1993. This successful proof of his eponymous conjecture vindicates the aforementioned potential of simple tools as applied to difficult problems.

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