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Proof of Bunyakovsky's conjecture

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Abstract

In 1857, twenty years after Dirichlet's theorem on arithmetic progressions, the conjecture of the Ukrainian mathematician Victor Y. Bunyakovsky (1804-1889) is already a try to generalize this theorem to polynomial integer functions of degree m>1. This conjecture states that under three conditions a polynomial integer function of degree m>1 generates infinitely many primes.
The main contribution of this paper is to introduce a new approach to this conjecture. The key ideas of this new approach is to relate the conjecture to a general theory (here arithmetic progressions) and use the active constraint of this theory (Dirichlet's theorem) to achieve the proof.

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1. Introduction

In 1837 (Dirichlet, 1837)(Stephan, 2014), the German mathematician P. G. L. Dirichlet (1805-1859) proved that an arithmetic progression $a+bd$ of modulus d (a polynomial integer function of degree 1 in d where d, a and b are integers with $gcd(a, d)=1$), generates infinitely many primes.

In 1857, twenty years after Dirichlet's theorem, the conjecture of the Ukrainian mathematician Victor Y. Bunyakovsky (1804-1889) mentioned in (Bounyakowsky, 1857) is already a try to generalize this theorem to polynomial integer functions of degree m>1. This conjecture states that, under three conditions mentioned hereafter, a polynomial function of degree m>1 generates infinitely many primes. As of year 2020, this conjecture was still open.

2. Preliminary Notes

Definition 2.1 General functions are said to be polynomial integer functions if their expression is a polynomial of degree d=m:

$$f(n) = a_m n^m + a_{m-1} n^{m-1} + a_{m-2} n^{m-2} + ... + a_2 n^2 + a_1 n + a_0 \quad (1)$$

with the integers n, a_i in Z and m>0 so that all values f(n) are also in Z, Z being the infinite set of integers.

Bunyakovsky's conjecture states that, under three conditions mentioned hereafter, a polynomial integer function of degree m>1 generates infinitely many primes. The three conditions come from the fact that the considered polynomial moreover has to be irreducible, this word being taken with the sense given to it by Bunyakovsky's in its article:

A. the leading coefficient must be positive;
B. the polynomial coefficients have to verify $gcd(coefficients) = 1$;
C. the polynomial has to be irreducible, that is to say, not divisible by any other polynomial of degree d with $0 \leq d < m$.

Note. The integer function $f(n) = 5n^2 + 15n + 125$ is not irreducible because $gcd(a_i) = 5$; $f(n) = n^2 + n + 2$ is also not irreducible but for a different reason: an hidden constant factor 2 appears when $f(n)$ is written as

$$f(n) = n^2 + n + 2 = 2(n(n+1)/2 +1)$$

as $n(n+1)/2$ is always an integer and factor 2 is a polynomial of degree $d=0$.

3. Main Results

The proof will be given in two steps.

1. the polynomial integer function $f(n)$ will be related to a general theory from which it gets constraints;
2. the constraints will be applied to reach the proof.

3.1 Relating the Conjecture to the Theory of Arithmetic Progressions

Let's consider the infinitely many arithmetical progressions

$$A(n,k,\delta) = n + k\,\delta \tag{2}$$

where n and k are general integers and $\delta \neq 0$ is the integer common difference between numbers A. Let's add the relation

$$gcd(n,\delta) = 1 \tag{3}$$

so that not all combinations of n, k and δ are allowed but for the remaining ones Dirichlet's theorem applies. We thus can say that each of these remaining infinitely many arithmetic progressions contains infinitely many primes.

Let's now discover the key feature of the proof. Let's build a new polynomial function $X(A)$ by applying the polynomial integer function $f(n) = polynomial(n)$ to these infinitely many arithmetic progressions, $polynomial(n)$ being any irreducible polynomial. We get the polynomial integer function

$$X(A) = polynomial(A) \tag{4}$$

From (2) we then have

$$\begin{aligned} X(A) &= polynomial(n+k\delta) \\ &= polynomial(n) + (polynomial(n+k\delta\,)\text{-}polynomial(n)) \\ &= \Sigma_{d=0,m}\, a_d\, n^d + (\,(\,\Sigma_{d=0,m}\, a_d\, (n+k\delta)^d\,) - (\,\Sigma_{d=0,m}\, a_d\, n^d\,)\,) \end{aligned}$$

and, noticing that all terms of $polynomial(n)$ disappear in

$$(polynomial(n+k\delta\,)\text{-}polynomial(n))$$

we get

$$X(A) = X(n,k,\delta) = polynomial(n) + k.\delta\,.h(n,k,\delta) \tag{5}$$

where $h(n,k,\delta)$ is a polynomial.

Let's illustrate this result with the irreducible polynomial

$$polynomial(n) = 5n^2+3n+7$$

This gives

$$
\begin{aligned}
X(A) &= polynomial(n+k\delta\,) \\
&= polynomial(n) + (polynomial(n+k\delta\,)\text{-}polynomial(n)) \\
&= (5n^2+3n+7)+(5(n+k\delta\,)^2+3(n+k\delta\,)+7) - (\,5n^2+3n+7) \\
&= (5n^2+3n+7) +((5(2nk\delta + k^2\delta^2)+3k\delta)) \\
&= (5n^2+3n+7) + k\delta(5(2n+k\delta\,)+3)
\end{aligned}
$$

This result allows us to look at function $X(A)$ as if it were an infinite set of arithmetic progressions $X(n,k,\delta)$ of miscellaneous common differences or moduli. As its second term $k.\delta.h(n,k,\delta)$ is made of three factors, we have several ways to choose a modulus μ from it but only $\mu = \delta.h(n,k,\delta)$ leads simply to the proof of Bunyakovsky's conjecture. We thus choose to write

$$X(A) = X(n,k,\delta) = polynomial(n) + k\,[\delta.h(n,k,\delta)] \tag{6}$$

which settles the equivalence between the function $X(A)$ with the infinite set of arithmetic progressions $X(n,k,\delta)$.

3.2 Proof of Bunyakovsky's Conjecture

According to Dirichlet's theorem, each of the arithmetic progressions of (6) contains infinitely many primes when the following condition is verified.

$$gcd(polynomial(n),\, \delta.h(n,k,\delta)) = 1 \tag{7}$$

As the second term $\delta.h(n,k,\delta)$ of this *gcd* is composite, this condition is *almost always* verified when its first term *polynomial(n)* is prime. The word *almost* is justified by the two exceptions that can create constant divisors $\neq 1$ by

$divisor = gcd(polynomial(n),\, \delta) \neq 1$

or $divisor = gcd(polynomial(n),\, h(n,k,\delta)) \neq 1$)

Finally, disregarding these two exceptions that do not verify Dirichlet's *gcd* condition, we have to consider two facts:

1. The second term of $gcd(polynomial(n),\, \delta.h(n,k,\delta))$ is never prime;
2. Dirichlet's theorem *always implies* by its *gcd* condition (7) that each of the infinitely many arithmetic progressions $X(n,k,\delta)$ contains infinitely many primes.

These two facts *imply* that the first term of the *gcd* in (7) (any irreducible *polynomial(n)*) *has to be infinitely often coprime* with the second term $\delta.h(n,k,\delta)$ in order to be in accordance with the infinitely many primes that have to be present in each of the infinitely many arithmetic progressions $X(n,k,\delta)$ and particularly those primes present in the arithmetic progressions $X(n,0,\delta)$ that define primes in *polynomial(n)* by (6) with $k=0$. As infinitely many coprimes of $\delta.h(n,k,\delta)$ include infinitely many primes it solves Bunyakovsky's conjecture.

4. Conclusion

Bunyakovsky's conjecture has been solved and only arithmetic progressions and Dirichlet's theorem are necessary to prove it.

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