

A special case of Dirichlet's theorem

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23 September, 2017 (at 15:49)

Entrance. An *arithmetic progression* (A.P.) means a set $T + M\mathbb{Z}$ of integers,^{♥1} where the *gap* (or *modulus*) M is a posint and *translation* (or *target*) T is an integer. I'll also use *comb* for "arithmetic progression".

An A.P. $\mathcal{C} := T + M\mathbb{Z}$ is *coprime* if $T \perp M$.

1: Dirichlet's Theorem. *Each coprime arithmetic progression contains infinitely many prime numbers.* ♦

While this is difficult to prove in general, there are three easy special^{♥2} cases, the combs

$$-1 + 3\mathbb{Z} \quad -1 + 4\mathbb{Z} \quad \text{and} \quad -1 + 6\mathbb{Z}.$$

We will establish this last case.

Henceforth, let \equiv mean \equiv_6 and let "congruent" mean "mod-6 congruent".

2a: Lemma. *Suppose a product $q_1 \cdot q_2 \cdot \dots \cdot q_L$ of integers^{♥3} is coprime to 6. Then each multiplicand q_ℓ is coprime to 6.* ♦

Proof. **Exer:** ; prove the contrapositive. Where does your argument use that each q_ℓ is an *integer*?

Does the lemma generalize to "6" being replaced by N , an arbitrary posint? ♦

Henceforth, symbols r and q , with or without appendages, range over the integers.

2b: Corollary. *Suppose product $r := q_1 \cdot q_2 \cdot \dots \cdot q_L$ is congruent to -1 . For oddly-many indices ℓ in $[1..L]$, then, $q_\ell \equiv -1$.*

In particular, there exists an index $k \in [1..L]$ such that $q_k \equiv -1$. ♦

Proof. Since $r \perp 6$ (i.e., $-1 \perp 6$), our Lemma tells us that each q_ℓ is coprime to 6. But of the six residue classes $0, \pm 1, \pm 2, 3$, only^{♥2} $+1$ and -1 are coprime to 6. So each q_ℓ is congruent to either $+1$ or -1 .

Let D denote the number of indices ℓ st. $q_\ell \equiv -1$. Then

$$r \equiv [-1]^D \cdot [+1]^{L-D} \stackrel{\text{note}}{=} [-1]^D.$$

Consequently, D is odd. ♦

^{♥1}This is the set $\{T + Mk \mid k \in \mathbb{Z}\}$. Equivalently, it is the set of integers n such that $n \equiv_M T$.

^{♥2}No mystery here: The three moduli $M=3,4,6$ are those with $\varphi(M)=2$. (Euler phi.) The two coprime residue-classes are ± 1 .

^{♥3}If we allow the $\{q_\ell\}_\ell$ to be general real numbers then the result is either false or broken, depending on how you interpret "coprime" for real numbers.

3: Six Theorem. *Comb $\mathcal{C} := -1 + 6\mathbb{Z}$ owns infinitely many primes.* ♦

Remark. We could start our argument by "FTSOContradiction, suppose $p_1 < p_2 < \dots < p_J$ is the complete list of primes in \mathcal{C} ." But instead, let's use the idea for a *constructive argument* that produces new primes from old. To this end, as an alternative to saying "in \mathcal{C} ", we define an ADJECTIVE: An integer n is **6NEG** if $n \equiv_6 -1$, and is **6POS** if $n \equiv_6 +1$. □

4: The Six Algorithm. *Suppose $p_1 \leq p_2 \leq \dots \leq p_J$ is a list of 6NEG primes. Let $N := \prod_{j=1}^J p_j$. Define*

$$4a: \quad K := \begin{cases} N + 4, & \text{if } J \text{ is even (i.e } N \equiv +1) \\ N + 6, & \text{if } J \text{ is odd (i.e } N \equiv -1) \end{cases}.$$

Then oddly-many of the prime factors of K are 6NEG, and none of them is in the given list. Have the algorithm return the least 6NEG prime factor. ♦

Pf that (4) works. The minimum value of N is 1; this, when the list is empty. Thus $K \geq 4$, hence is a posint, so we can factor it into a product of primes,

$$*: \quad K = q_1 \cdot q_2 \cdot \dots \cdot q_L.$$

By its defn, K is 6NEG. Hence Coro. (2b) applies to tell us that oddly many of $\text{Rhs}(*)$ are 6NEG primes.

The last step is to show that the primes of $\text{Rhs}(*)$ are new. FTSOC, suppose some q is in $(p_j)_{j=1}^J$. Then this q divides both K and N , hence $q \mid [K - N]$. Thus q divides either 4 or 6, so $q \in \{2, 3\}$. But 2 is neither 6NEG nor 6POS, and ditto for 3; so this contradicts Corollary (2b). Thus no q is in our p -list. ♦

Application. Let \mathcal{P} be $(p_j)_{j=1}^J$. When \mathcal{P} is the empty tuple, then $N = 1$ so $K = 1 + 4 = 5$. Oddly many of the prime factors of 5 are 6NEG; our alg produces the least such, which is 5.

Now set $\mathcal{P} := (5)$. So $N = 5$ and $K = 5 + 6 = 11$; this produces 11.

Let $\mathcal{P} := (5, 5)$. So $N=25$ and $K=29$, yielding 29.

Let $\mathcal{P} := (5, 11)$; so $N=55$ and $K=59$, yielding 59.

Let $\mathcal{P} := (5, 11, 11)$; so $N=605$, $J = 3$ and $K=611$. Now $611 = 13 \cdot 47$, a 6POS times a 6NEG (so oddly many 6NEG, as predicted). Hence the algorithm produces 47.

Lastly, let $\mathcal{P} := (5, 7)$; so $N=35$, $J = 2$ and $K=39$. Now $39 = 3 \cdot 13$ and ~~–whoa Nellie!~~ *neither* of this primes is 6NEG! *What went wrong?* Oh!, *are we a Dufus!* We forgot to check the hypotheses! Each prime in \mathcal{P} is supposed to be 6NEG, but 7 is *not* 6NEG. \square

Variant. Notice that we can replace (4a) by

$$4b: \quad K := \begin{cases} N - 2, & \text{if } J \text{ is even (i.e } N \equiv +1) \\ N - 6, & \text{if } J \text{ is odd (i.e } N \equiv -1) \end{cases}$$

as long as K is positive. Indeed, the 2 can be replaced by any $\alpha \equiv 2$ as long as none of the primes in \mathcal{P} divides α , and K ends up positive. And 6 can be replaced by any $\beta \equiv 0$ with the same restrictions.

Let $\mathcal{P} := (5, 11, 17)$; so $N=935$ and $J = 3$, so we need a $\beta \equiv 0$ coprime to N . Well, $\beta:=36$ is acceptable, yielding $935-36=899$, which factors as $29 \cdot 31$. And indeed, oddly many are 6NEG; our routine returns 29, a new 6NEG prime. \square

4c: Variant. Given a list \mathcal{P}' of 6NEG primes, here is a different replacement for (4a), . To make a new list \mathcal{P} with evenly many members, adjoin to \mathcal{P}' , if necessary, a copy of 5. Now set $K := N - 2$. Etc. \square

Efficient? The routine would be reasonable *except* for the factor- K -into-primes step. As of Sept2009, no one knows how to factor efficiently. \square

Filename: Problems/NumberTheory/dirichlet-thm.6neg-case.
latex

As of: Friday 02Oct2009. Typeset: 23Sep2017 at 15:49.