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The Perfect Number Theorem and Wilson's Theorem

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Summary. This article formalizes proofs of some elementary theorems of number theory (see [1, 26]): Wilson's theorem (that n is prime iff $n > 1$ and $(n-1)! \cong -1 \pmod{n}$), that all primes (1 mod 4) equal the sum of two squares, and two basic theorems of Euclid and Euler about perfect numbers. The article also formally defines Euler's sum of divisors function ϕ, proves that ϕ is multiplicative and that $\sum_{k|n} \phi(k) = n$.

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The articles [14], [38], [28], [32], [39], [11], [40], [13], [33], [12], [5], [4], [2], [6], [10], [37], [36], [25], [3], [15], [19], [35], [24], [30], [18], [34], [16], [9], [22], [21], [41], [17], [20], [7], [31], [29], [8], [23], and [27] provide the notation and terminology for this paper.

1. Preliminaries

We adopt the following convention: k, n, m, l, p denote natural numbers and n_0, m_0 denote non zero natural numbers.

We now state several propositions:

(1) $2^{n+1} < 2^{n+2} - 1$.

(2) If n_0 is even, then there exist k, m such that m is odd and $k > 0$ and $n_0 = 2^k \cdot m$.

(3) If $n = 2^k$ and m is odd, then n and m are relative prime.

(4) $\{n\}$ is a finite subset of $\mathbb{N}$.

(5) $\{n, m\}$ is a finite subset of $\mathbb{N}$.

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In the sequel f is a finite sequence and x, X, Y are sets.

The following four propositions are true:

(6) If f is one-to-one, then $f_{\restriction n}$ is one-to-one.

(7) If f is one-to-one and $n \in \operatorname{dom} f$, then $f(n) \notin \operatorname{rng}(f_{\restriction n})$.

(8) If $x \in \operatorname{rng} f$ and $x \notin \operatorname{rng}(f_{\restriction n})$, then $x = f(n)$.

(9) Let f_1 be a finite sequence of elements of $\mathbb{N}$ and f_2 be a finite sequence of elements of X. If $\operatorname{rng} f_1 \subseteq \operatorname{dom} f_2$, then $f_2 \cdot f_1$ is a finite sequence of elements of X.

In the sequel f_1, f_2, f_3 are finite sequences of elements of $\mathbb{R}$.

Next we state four propositions:

(10) If $X \cup Y = \operatorname{dom} f_1$ and X misses Y and $f_2 = f_1 \cdot \operatorname{Sgm} X$ and $f_3 = f_1 \cdot \operatorname{Sgm} Y$, then $\sum f_1 = \sum f_2 + \sum f_3$.

(11) If $f_2 = f_1 \cdot \operatorname{Sgm} X$ and $\operatorname{dom} f_1 \setminus f_1{}^{-1}(\{0\}) \subseteq X \subseteq \operatorname{dom} f_1$, then $\sum f_1 = \sum f_2$.

(12) $\sum f_1 = \sum (f_1 - \{0\})$.

(13) Every finite sequence of elements of $\mathbb{N}$ is a finite sequence of elements of $\mathbb{R}$.

In the sequel n_1, n_2, m_1, m_2 denote natural numbers.

We now state several propositions:

(14) If $n_1 \in \operatorname{NatDivisors} n$ and $m_1 \in \operatorname{NatDivisors} m$ and n and m are relative prime, then n_1 and m_1 are relative prime.

(15) If $n_1 \in \operatorname{NatDivisors} n$ and $m_1 \in \operatorname{NatDivisors} m$ and $n_2 \in \operatorname{NatDivisors} n$ and $m_2 \in \operatorname{NatDivisors} m$ and n and m are relative prime and $n_1 \cdot m_1 = n_2 \cdot m_2$, then $n_1 = n_2$ and $m_1 = m_2$.

(16) If $n_1 \in \operatorname{NatDivisors} n_0$ and $m_1 \in \operatorname{NatDivisors} m_0$, then $n_1 \cdot m_1 \in \operatorname{NatDivisors}(n_0 \cdot m_0)$.

(17) If n_0 and m_0 are relative prime, then $k \gcd n_0 {\cdot} m_0 = (k \gcd n_0) {\cdot} (k \gcd m_0)$.

(18) If n_0 and m_0 are relative prime and $k \in \operatorname{NatDivisors}(n_0 \cdot m_0)$, then there exist n_1, m_1 such that $n_1 \in \operatorname{NatDivisors} n_0$ and $m_1 \in \operatorname{NatDivisors} m_0$ and $k = n_1 \cdot m_1$.

(19) If p is prime, then $\operatorname{NatDivisors}(p^n) = \{p^k; k$ ranges over elements of $\mathbb{N}$: $k \leq n\}$.

(20) If $0 \neq l$ and $p > l$ and $p > n_1$ and $p > n_2$ and $l \cdot n_1 \bmod p = l \cdot n_2 \bmod p$ and p is prime, then $n_1 = n_2$.

(21) If p is prime, then $p\text{-count}(n_0 \gcd m_0) = \min(p\text{-count}(n_0), p\text{-count}(m_0))$.

2. Wilson's Theorem

One can prove the following proposition

(22) n is prime iff $((n -' 1)! + 1) \bmod n = 0$ and $n > 1$.

3. All Primes Congruent to 1 Modulo 4 are the Sum of Two Squares

Next we state the proposition

(23) If p is prime and $p \bmod 4 = 1$, then there exist n, m such that $p = n^{\mathbf{2}} + m^{\mathbf{2}}$.

4. The Sum of Divisors Function

Let I be a set, let f be a function from I into $\mathbb{N}$, and let J be a finite subset of I. Then $f \restriction J$ is a bag of J.

Let I be a set, let f be a function from I into $\mathbb{N}$, and let J be a finite subset of I. Observe that $\sum (f \restriction J)$ is natural.

We now state two propositions:

(24) Let f be a function from $\mathbb{N}$ into $\mathbb{N}$, F be a function from $\mathbb{N}$ into $\mathbb{R}$, and J be a finite subset of $\mathbb{N}$. If $f = F$ and there exists k such that $J \subseteq \operatorname{Seg} k$, then $\sum (f \restriction J) = \sum \operatorname{FuncSeq}(F, \operatorname{Sgm} J)$.

(25) Let I be a non empty set, F be a partial function from I to $\mathbb{R}$, f be a function from I into $\mathbb{N}$, and J be a finite subset of I. If $f = F$, then $\sum (f \restriction J) = \sum_{\kappa=0}^{J} F(\kappa)$.

We follow the rules: I, j denote sets, f, g denote functions from I into $\mathbb{N}$, and J, K denote finite subsets of I.

We now state three propositions:

(26) If J misses K, then $\sum (f \restriction (J \cup K)) = \sum (f \restriction J) + \sum (f \restriction K)$.

(27) $\sum (f \restriction (\{j\})) = f(j)$.

(28) $\sum ((\cdot_{\mathbb{N}} \cdot (f \times g)) \restriction (J \times K)) = \sum (f \restriction J) \cdot \sum (g \restriction K)$.

Let k be a natural number. The functor $\operatorname{EXP} k$ yielding a function from $\mathbb{N}$ into $\mathbb{N}$ is defined by:

(Def. 1) For every natural number n holds $(\operatorname{EXP} k)(n) = n^k$.

Let k, n be natural numbers. The functor $\sigma_k(n)$ yields an element of $\mathbb{N}$ and is defined as follows:

(Def. 2)(i) For every non zero natural number m such that $n = m$ holds $\sigma_k(n) = \sum (\operatorname{EXP} k \restriction \operatorname{NatDivisors} m)$ if $n \neq 0$,

(ii) $\sigma_k(n) = 0$, otherwise.

Let k be a natural number. The functor Σk yields a function from $\mathbb{N}$ into $\mathbb{N}$ and is defined by:

(Def. 3) For every natural number n holds $(\Sigma k)(n) = \sigma_k(n)$.

Let n be a natural number. The functor $\sigma(n)$ yields an element of $\mathbb{N}$ and is defined as follows:

(Def. 4) $\sigma(n) = \sigma_1(n)$.

The following propositions are true:

(29) $\sigma_k(1) = 1$.

(30) If p is prime, then $\sigma(p^n) = \frac{p^{n+1}-1}{p-1}$.

(31) If $m \mid n_0$ and $n_0 \neq m \neq 1$, then $1 + m + n_0 \leq \sigma(n_0)$.

(32) If $m \mid n_0$ and $k \mid n_0$ and $n_0 \neq m$ and $n_0 \neq k$ and $m \neq 1$ and $k \neq 1$ and $m \neq k$, then $1 + m + k + n_0 \leq \sigma(n_0)$.

(33) If $\sigma(n_0) = n_0 + m$ and $m \mid n_0$ and $n_0 \neq m$, then $m = 1$ and n_0 is prime.

Let f be a function from $\mathbb{N}$ into $\mathbb{N}$. We say that f is multiplicative if and only if:

(Def. 5) For all non zero natural numbers n_0, m_0 such that n_0 and m_0 are relative prime holds $f(n_0 \cdot m_0) = f(n_0) \cdot f(m_0)$.

One can prove the following propositions:

(34) Let f, F be functions from $\mathbb{N}$ into $\mathbb{N}$. Suppose f is multiplicative and for every n_0 holds $F(n_0) = \sum(f \restriction \mathrm{NatDivisors}\, n_0)$. Then F is multiplicative.

(35) $\mathrm{EXP}\, k$ is multiplicative.

(36) Σk is multiplicative.

(37) If n_0 and m_0 are relative prime, then $\sigma(n_0 \cdot m_0) = \sigma(n_0) \cdot \sigma(m_0)$.

5. Two Basic Theorems on Perfect Numbers

Let n_0 be a non zero natural number. We say that n_0 is perfect if and only if:

(Def. 6) $\sigma(n_0) = 2 \cdot n_0$.

We now state two propositions:

(38) If $2^p -' 1$ is prime and $n_0 = 2^{p -' 1} \cdot (2^p -' 1)$, then n_0 is perfect.

(39) If n_0 is even and perfect, then there exists a natural number p such that $2^p -' 1$ is prime and $n_0 = 2^{p -' 1} \cdot (2^p -' 1)$.

6. A Formula Involving Euler's ϕ Function

The function ϕ from $\mathbb{N}$ into $\mathbb{N}$ is defined by:

(Def. 7) For every element k of $\mathbb{N}$ holds $\phi(k) = \mathrm{Euler}\, k$.

The following proposition is true

(40) $\sum(\phi \restriction \mathrm{NatDivisors}\, n_0) = n_0$.

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