

Theorem 15.1 (Well-ordering principle). *Every non-empty subset A of \mathbb{N} has a smallest element.*

$\forall A \in \mathcal{P}(\mathbb{N}). A \neq \emptyset \implies A$ has a smallest element

where “has a smallest element” means $\exists a_0 \in A. \forall a \in A. a_0 \leq a$.

Proof. Theorem 3.5.1 in textbook. (induction)

16 Divisibility

Definition 16.1. For any $a, d \in \mathbb{N}$, write $d \mid a$ (d is a factor of/divides) a , a (is divisible by/a multiple of) d) iff $\exists k \in \mathbb{N}. d \cdot k = a$.

Examples. $\forall a, d \in \mathbb{N}$

- $a \mid a$ is true (because $a \cdot 1 = a$)
- $1 \mid a$ is true (because $1 \cdot a = a$)
- $d \mid 0$ is true (because $d \cdot 0 = 0$)
- $0 \mid a \implies a = 0$ (because only $0 \cdot 0 = 0$)

Lemma 16.2 (Divisibility implies ordering in \mathbb{N}). *For any $a, d \in \mathbb{N}$, with $a \neq 0$. If $d \mid a$, then $d \leq a$.*

Proof.

1. Suppose $d \mid a \implies \exists k \in \mathbb{N}. d \cdot k = a$
2. Since $a \neq 0$ by hypothesis, $d \neq 0, k \neq 0$. So $k \in \mathbb{N} \setminus \{0\} = S(\mathbb{N})$
3. so $\exists l \in \mathbb{N}. k = S(l)$
4. $a = d \cdot k = d \cdot (l + 1) = d \cdot l + d$
5. Since $d + d \cdot l = a$ and $d \cdot l \in \mathbb{N}$, $d \leq a$. □

Example. $\forall d \in \mathbb{N}. d \mid 1 \implies d = 1$.

Proof. $d \mid 1$, then by (division implies ordering) lemma, $d \leq 1$, so $d = 0 \vee d = 1$, but $0 \nmid 1$, so $d = 1$. □

Properties. Divisibility is reflexive, anti-symmetric and transitive. $\forall a, b, c \in \mathbb{N}$,

1. $\exists 1 \in \mathbb{N}. a \cdot 1 = a \implies a \mid a$
2. $a \mid b \wedge b \mid a \implies a \leq b \wedge b \leq a \implies a = b$ (by above lemma and anti-symmetry of ordering)
3. $a \mid b \wedge b \mid c \implies \exists l, m \in \mathbb{N}. a \cdot l = b, b \cdot m = c \implies a \cdot l \cdot m = c \implies a \mid c$

17 More Division

Theorem 17.1 (Division Algorithm). *Let $a, d \in \mathbb{N}$ with $d > 0$. Then there exists $q \in \mathbb{N}$ and $r \in \{0, \dots, d-1\}$ such that $a = qd + r$ in \mathbb{N} . Moreover, $q \in \mathbb{N}$ and $r \in \{0, \dots, d-1\}$ are uniquely determined by $a, d \in \mathbb{N}$.*

Theorem (Uniqueness of q, r). *Given $a, d \in \mathbb{N}, d > 0$, if $q, q' \in \mathbb{N}, r, r' \in \{0, \dots, d-1\}$ such that*

$$a = qd + r = q'd + r' \quad (17.1.1)$$

then $q = q', r = r'$. (uniqueness)

Proof.

1. Suppose for a contradiction that $r \neq r'$. By comparability of natural numbers, either $r > r'$ or $r' > r$.
2. Without loss of generality, assume $r > r'$, then

$$\exists s \in \mathbb{N}, s \neq 0. r = r' + s$$

3. Then by (17.1.1), $qd + r' + s = q'd + r'$, then by cancellation law for addition,

$$qd + s = q'd \quad (17.1.2)$$

4. Because $s \in \mathbb{N}, s \neq 0, q'd > qd$, then by cancellation law for multiplication, $q' > q$, so

$$\exists t \in \mathbb{N}, t \neq 0. q' = q + t$$

5. By (17.1.2),

$$\begin{aligned} qd + s &= (q + t) \cdot d \\ qd + s &= qd + td \\ s &= td && \text{(cancellation property of addition)} \\ d &\mid s && \text{(and } d > 0) \\ d &\leq s && \text{(division implies ordering)} \end{aligned}$$

6. which shows $d \leq s \leq r \implies d \leq r$, a contradiction with requirement that $r \in \{0, \dots, d-1\}$.

7. Hence $r = r'$, then by (17.1.1), $a = qd + r = q'd + r$.

8. $qd = q'd \implies q = q'$. (by cancellation law of $+, \times$)

9. $r = r'$ and $q = q'$, uniqueness of r, q shown. □

Theorem (Existence of q, r). Given $a, d \in \mathbb{N}, d > 0, \exists q, r \in \mathbb{N}$ with $r < d$ such that $a = qd + r$.

Proof.

1. Consider the following subset of \mathbb{N} :

$$S := \{ n \in \mathbb{N} : \exists q \in \mathbb{N}. a = qd + n \}$$

[(S consists of all natural numbers of form $a - q \cdot d$ for various choices of q)]

2. Then $a = 0 \cdot d + a$, shows $a \in S$, in particular $S \neq \emptyset$, then by well-ordering principle,

$$\exists r \in S. \forall n \in S. r \leq n$$

3. This means $\exists q \in \mathbb{N}. a = qd + r$.

Claim. $r < d$

- Suppose for contradiction $r \geq d, \exists k \in \mathbb{N}. d + k = r$ ($k = r - d$)
 - Then $a = qd + d + k = (q + 1) \cdot d + k$
 - This shows that $k \in S$, then by fact that $r \in S$ is smallest, we must have $r \leq k$.
 - But $d + k = r \implies k \leq r$, so $r = k$ (*by anti-symmetry of ordering*)
 - then we have $d + r = r$, cancelling $+$, $d = 0$, a contradiction with $d > 0$.
4. So given any number a and factor d , there exists quotient q and remainder $r < d$ such that $a = qd + r$ \square

Corollary 17.2. Let $n \in \mathbb{N}$. Then $\neg(n \text{ is even}) \iff (\exists l \in \mathbb{N}. n = 2l + 1)$

Proof.

1. Apply division algorithm to n with $d = 2$,

$$\exists q \in \mathbb{N}, r \in \{0, 1\}. n = 2q + r$$

and q, r above are uniquely defined by n . Either $r = 0$ exclusive or $r = 1$.

2. Case $r = 0$, then $n = 2q$ is even (*by definition*)
3. If n is odd, then $\exists l \in \mathbb{N}. n = 2l + 1$, then

$$2q + 0 = n = 2l + 1$$

with $q, l \in \mathbb{N}$ and $0, 1 \in \{0, 1\}$ a contradiction with uniqueness of remainder

4. Case $r = 1$, then $n = 2q + 1$ is odd
5. if n is even, then $\exists k \in \mathbb{N}. n = 2k$, again

$$2k + 0 = n = 2q + 1$$

a contradiction with uniqueness of remainder. \square

Prime numbers and factorisation

Definition 17.3. A prime number is a natural number, $p \in \mathbb{N}$ such that

- $p > 1$ (ie. $p \neq 0 \wedge p \neq 1$)
- $\forall d \in \mathbb{N}. d \mid p. d = 1 \vee d = p.$

equivalently: $\forall r, s \in \mathbb{N}. p = r \cdot s$, one has $r = 1 \vee s = 1$.

Definition 17.4. A composite number is a natural number $n \in \mathbb{N}$ such that

- $n > 1$ (ie. $n \neq 0 \wedge n \neq 1$)
- n is not prime

equivalently: $\exists d \in \mathbb{N}. d \mid n \wedge d \neq 1 \wedge d \neq n$

Theorem 17.5 (Existence of prime factors). *Let $a \in \mathbb{N}$ with $a > 1$. Then $\exists p. p \mid a$ where p is a prime number.*

Proof.

1. Consider the subset

$$S := \{ d \in \mathbb{N} : d > 1 \wedge d \mid a \}$$

ie. S is set of all divisors of a which are > 1 .

2. Then since $a > 1$ by given hypothesis, and $a \mid a$, we get $a \in S$, $S \neq \emptyset$. then by well-ordering principle

$$\exists p \in S. \forall d \in S. p \leq d$$

3. so we know $p \in \mathbb{N}, p > 1, p \mid a$.

Claim. p is prime.

- If not, $\exists r, s \in \mathbb{N}. (p = r \cdot s) \wedge (r \neq 1) \wedge (s \neq 1)$. (defn of composite numbers)
- Then because $s \mid p$ and $p \mid a$, $s \mid a$.
- because $p \in S \implies p > 1 \implies p \neq 0$, so $s \neq 0$, then $s > 1$, hence $s \in S$.

$$\begin{aligned} s &= 1 \cdot s < 2 \cdot s \\ 2 &\leq r \\ s &< 2 \cdot s \leq r \cdot s = p \\ s &< p \end{aligned}$$

- because $2 \leq r$ and $1 < s \implies s \neq 0$.
- $s < p$ contradicts with p being smallest in S .

4. So every natural number $a \in \mathbb{N}$ has prime factor(s) $p \in \mathbb{N}$ where $p \mid a$. □

Theorem 17.6 (Fundamental Theorem of Arithmetic or Unique Prime Factorisation property of \mathbb{N}).

For any natural number $a \in \mathbb{N}$ with $a > 1$, there exists a (finitely many) sequence of prime numbers p_1, \dots, p_r such that $a = \prod_{i=1}^r p_i$.

Moreover, the primes p_1, \dots, p_r are unique up to reordering. ie if q_1, \dots, q_s is another sequence of primes such that $a = \prod_{i=1}^s q_i$, then $r = s$ (same number) and q_1, \dots, q_r , up to re-ordering, matches p_1, \dots, p_r .

Existence.

Proof.

1. Given $a \in \mathbb{N}$, $a > 1$, show: \exists primes p_1, \dots, p_r such that $a = \prod_{i=1}^r p_i$.
2. For $a \in \mathbb{N}$, $a > 1$, let

$$Q(a) := \exists \text{ primes } p_1, \dots, p_r. a = \prod_{i=1}^r p_i$$

3. Base case: $Q(2)$ is true because 2 is prime, so $a = 2$, can take $r = 1, p_1 = 2$.
4. Induction step: Assume $a > 1$ and $Q(2), \dots, Q(a)$ true. then $Q(a+1)$ true because
5. $a+1$ is either prime xor not prime
6. Case $a+1$ is prime, then $Q(a+1)$ is true (take $r = 1, p_1 = a+1$)
7. Case $a+1$ is not prime, then $a+1 > 1$,

$$\exists r, s \in \mathbb{N}. a+1 = r \cdot s, r \neq 1, s \neq 1.$$

(clear that $r \neq 0, s \neq 0$ either)

8. $r \mid (a+1) \implies r \leq a+1$ and $s \neq 1 \implies r < a+1 \implies r \leq a$
9. Symmetrically, $s \leq a$.
10. Then $r, s \in \{2, 3, \dots, a\}$, so $Q(r), Q(s)$ are true by induction hypothesis.

11. Hence \exists primes $p_1, \dots, p_l. r = \prod_{i=1}^l p_i$.
and \exists primes $p_{l+1}, \dots, p_{l+m}. s = \prod_{i=l+1}^{l+m} p_i$.

12. Then $a+1 = r \cdot s = \prod_{i=1}^l p_i \cdot \prod_{i=l+1}^{l+m} p_i$ is a product of primes.

13. by strong induction, $Q(a)$ true for all $a \geq 2$. □

Uniqueness. (ad-hoc proof using wop, not (easily) generalisable to other context.)

Proof.

1. Suppose on contrary that uniqueness of factorisation fails, consider the set

$$S := \{ a \in \mathbb{N} : a > 1, a \text{ has non-unique prime factors} \}$$

ie. assuming $S \neq \emptyset$.

2. By well-ordering principle, S has smallest element $a \in S$

3. So $a \in \mathbb{N}, a > 1, \exists$ primes $p_1, \dots, p_r, q_1, \dots, q_s$ such that $a = \prod_{i=1}^r p_i = \prod_{i=1}^s q_i$ and p_1, \dots, p_r and q_1, \dots, q_s are distinct even allowing permutation.

Claim. None of p 's appear among the q 's.

$$\forall i \in \{1, \dots, r\}. \forall j \in \{1, \dots, s\}. p_i \neq q_j$$

- i. Suppose $\exists i \in \{1, \dots, r\}. \exists j \in \{1, \dots, s\}. p_i = q_j$, then

$$p_1 \cdots p_{i-1} \cdot p_{i+1} \cdots p_r = \frac{a}{p_i} = \frac{a}{q_j} = q_1 \cdots q_{j-1} \cdot q_{j+1} \cdots q_s$$

- ii. Take a' as above expression, we have $a' < a$, and having non-unique prime factors, so $a' \in S$, a contradiction with smallest $a \in S$.

4. Without loss of generality, assume $p_1 < q_1$, so $\exists t \in \mathbb{N}. t \neq 0, p_1 + t = q_1$.

5. consider $b := t \cdot q_2 \cdots q_s$, t nonzero, so $b \geq 1$.

6. Also, $a = q_1 \cdot q_2 \cdots q_s$, so $b < a$, so $b \notin S$, ie b has the unique prime factorisation property

7. If $t = 1$, then $b = q_2 \cdots q_s$ must be the unique prime factorisation of b . Then by above claim, p_1 does not appear among q_2, \dots, q_s . Yet,

$$\begin{aligned} b &= (q_1 - p_1) \cdot q_2 \cdots q_s \\ &= q_1 q_2 \cdots q_s - p_1 q_2 \cdots q_s \\ &= p_1 p_2 \cdots p_r - p_1 q_2 \cdots q_s \\ &= p_1 (p_2 \cdots p_r - q_2 \cdots q_s) \end{aligned}$$

8. So $p_1 \mid b$, which should appear in the prime factorisation of b , a contradiction, so $t \neq 1$.

9. So $t = q_1 - p_1 > 1$. Now $q_1 - p_1 \leq b \leq a$, so $q_1 - p_1 \notin S$. So $q_1 - p_1$ has unique prime factorisation, say

$$q_1 - p_1 = l_1 \cdots l_u$$

where l_1, \dots, l_u are primes.

10. By examination of $b = (q_1 - p_1) \cdot q_2 \cdots q_s = p_1 (p_2 \cdots p_r - q_2 \cdots q_s)$, p_1 must appear in prime factor of b .

11. But $b = l_1 \cdots l_u \cdot q_1 \cdots q_s$ is also a prime factorisation of b , but

12. *I give up, this is useless.*

□