Elementary Methods in Number Theory

Melvyn B. Nathanson

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(continued after index)

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To Paul Erdős,

1913–1996,

a friend and collaborator for 25 years, and a
master of elementary methods in number theory.

Preface

> Arithmetic is where numbers run across your mind looking for the answer.
> Arithmetic is like numbers spinning in your head faster and faster until you blow up with the answer.
> KABOOM!!!
> Then you sit back down and begin the next problem.
>
> Alexander Nathanson [99]

This book, *Elementary Methods in Number Theory*, is divided into three parts.

Part I, "A first course in number theory," is a basic introduction to elementary number theory for undergraduate and graduate students with no previous knowledge of the subject. The only prerequisites are a little calculus and algebra, and the imagination and perseverance to follow a mathematical argument. The main topics are divisibility and congruences. We prove Gauss's law of quadratic reciprocity, and we determine the moduli for which primitive roots exist. There is an introduction to Fourier analysis on finite abelian groups, with applications to Gauss sums. A chapter is devoted to the *abc conjecture*, a simply stated but profound assertion about the relationship between the additive and multiplicative properties of integers that is a major unsolved problem in number theory.

The "first course" contains all of the results in number theory that are needed to understand the author's graduate texts, *Additive Number Theory: The Classical Bases* [104] and *Additive Number Theory: Inverse Problems and the Geometry of Sumsets* [103].

The second and third parts of this book are more difficult than the "first course," and require an undergraduate course in advanced calculus or real analysis.

Part II is concerned with prime numbers, divisors, and other topics in multiplicative number theory. After deriving properties of the basic arithmetic functions, we obtain important results about divisor functions, and we prove the classical theorems of Chebyshev and Mertens on the distribution of prime numbers. Finally, we give elementary proofs of two of the most famous results in mathematics, the *prime number theorem*, which states that the number of primes up to x is asymptotically equal to $x/\log x$, and *Dirichlet's theorem* on the infinitude of primes in arithmetic progressions.

Part III, "Three problems in additive number theory," is an introduction to some classical problems about the additive structure of the integers. The first additive problem is *Waring's problem*, the statement that, for every integer $k \geq 2$, every nonnegative integer can be represented as the sum of a bounded number of kth powers. More generally, let $f(x) = a_k x^k + a_{k-1}x^{k-1} + \cdots + a_0$ be an integer-valued polynomial with $a_k > 0$ such that the integers in the set $A(f) = \{f(x) : x = 0, 1, 2, \ldots\}$ have no common divisor greater than one. Waring's problem for polynomials states that every sufficiently large integer can be represented as the sum of a bounded number of elements of $A(f)$.

The second additive problem is *sums of squares*. For every $s \geq 1$ we denote by $R_s(n)$ the number of representations of the integer n as a sum of s squares, that is, the number of solutions of the equation

$$n = x_1^2 + \cdots + x_s^2$$

in integers $x_1, \ldots, x_s$. The shape of the function $R_s(n)$ depends on the parity of s. In this book we derive formulae for $R_s(n)$ for certain even values of s, in particular, for $s = 2, 4, 6, 8$, and 10.

The third additive problem is the *asymptotics of partition functions*. A partition of a positive integer n is a representation of n in the form $n = a_1 + \cdots + a_k$, where the parts $a_1, \ldots, a_k$ are positive integers and $a_1 \geq \cdots \geq a_k$. The partition function $p(n)$ counts the number of partitions of n. More generally, if A is any nonempty set of positive integers, the partition function $p_A(n)$ counts the number of partitions of n with parts belonging to the set A. We shall determine the asymptotic growth of $p(n)$ and, more generally, of $p_A(n)$ for any set A of integers of positive density.

This book contains many examples and exercises. By design, some of the exercises require old-fashioned manipulations and computations with pencil and paper. A few exercises require a calculator. Number theory, after all, begins with the positive integers, and students should get to know and love them.

This book is also an introduction to the subject of "elementary methods in analytic number theory." The theorems in this book are simple statements about integers, but the standard proofs require contour integration,

modular functions, estimates of exponential sums, and other tools of complex analysis. This is not unfair. In mathematics, when we want to prove a theorem, we may use any method. The rule is "no holds barred." It is OK to use complex variables, algebraic geometry, cohomology theory, and the kitchen sink to obtain a proof. But once a theorem is proved, once we know that it is true, particularly if it is a simply stated and easily understood fact about the natural numbers, then we may want to find another proof, one that uses only "elementary arguments" from number theory. Elementary proofs are not better than other proofs, nor are they necessarily easy. Indeed, they are often technically difficult, but they do satisfy the aesthetic boundary condition that they use only arithmetic arguments.

This book contains elementary proofs of some deep results in number theory. We give the Erdős-Selberg proof of the prime number theorem, Linnik's solution of Waring's problem, Liouville's still mysterious method to obtain explicit formulae for the number of representations of an integer as the sum of an even number of squares, and Erdős's method to obtain asymptotic estimates for partition functions. Some of these proofs have not previously appeared in a text. Indeed, many results in this book are new.

Number theory is an ancient subject, but we still cannot answer the simplest and most natural questions about the integers. Important, easily stated, but still unsolved problems appear throughout the book. You should think about them and try to solve them.

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Maplewood, New Jersey
November 1, 1999

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Notation and Conventions

We denote the set of positive integers (also called the natural numbers) by $\mathbf{N}$ and the set of nonnegative integers by $\mathbf{N}_0$. The integer, rational, real, and complex numbers are denoted by $\mathbf{Z}$, $\mathbf{Q}$, $\mathbf{R}$, and $\mathbf{C}$, respectively. The absolute value of $z \in \mathbf{C}$ is $|z|$. We denote by $\mathbf{Z}^n$ the group of lattice points in the n-dimensional Euclidean space $\mathbf{R}^n$.

The integer part of the real number x, denoted by $[x]$, is the largest integer that is less than or equal to x. The fractional part of x is denoted by $\{x\}$. Then $x = [x] + \{x\}$, where $[x] \in \mathbf{Z}$, $\{x\} \in \mathbf{R}$, and $0 \leq \{x\} < 1$. In computer science, the integer part of x is often called the *floor* of x, and denoted by $\lfloor x \rfloor$. The smallest integer that is greater than or equal to x is called the *ceiling* of x and denoted by $\lceil x \rceil$.

We adopt the standard convention that an empty sum of numbers is equal to 0 and an empty product is equal to 1. Similarly, an empty union of subsets of a set X is equal to the empty set, and an empty intersection is equal to X.

We denote the *cardinality* of the set X by $|X|$. The largest element in a finite set of numbers is denoted by $\max(X)$ and the smallest is denoted by $\min(X)$.

Let a and d be integers. We write $d|a$ if d divides a, that is, if there exists an integer q such that $a = dq$. The integers a and b are called *congruent* modulo m, denoted by $a \equiv b \pmod{m}$, if m divides $a - b$.

A *prime number* is an integer $p > 1$ whose only divisors are 1 and p. The set of prime numbers is denoted by $\mathbf{P}$, and p_k is the kth prime. Thus, $p_1 = 2, p_2 = 3, \ldots, p_{11} = 31, \ldots$. Let p be a prime number. We write $p^r \| n$

if p^r is the largest power of p that divides the integer n, that is, p^r divides n but p^{r+1} does not divide n.

The *greatest common divisor* and the *least common multiple* of the integers $a_1, \ldots, a_k$ are denoted by $(a_1, \ldots, a_k)$ and $[a_1, \ldots, a_k]$, respectively. If A is a nonempty set of integers, then $\gcd(A)$ denotes the greatest common divisor of the elements of A.

The *principle of mathematical induction* states that if $S(k)$ is some statement about integers $k \geq k_0$ such that $S(k_0)$ is true and such that the truth of $S(k-1)$ implies the truth of $S(k)$, then $S(k)$ holds for all integers $k \geq k_0$. This is equivalent to the *minimum principle*: A nonempty set of integers bounded below contains a smallest element.

Let f be a complex-valued function with domain D, and let g be a function on D such that $g(x) > 0$ for all $x \in D$. We write $f \ll g$ or $f = O(g)$ if there exists a constant $c > 0$ such that $|f(x)| \leq cg(x)$ for all $x \in D$. Similarly, we write $f \gg g$ if there exists a constant $c > 0$ such that $|f(x)| \geq cg(x)$ for all $x \in D$. For example, $f \gg 1$ means that $f(x)$ is uniformly bounded away from 0, that is, there exists a constant $c > 0$ such that $|f(x)| \geq c$ for all $x \in D$. We write $f \ll_{k,\ell,\ldots} g$ if there exists a positive constant c that depends on the variables $k, \ell, \ldots$ such that $|f(x)| \leq cg(x)$ for all $x \in D$. We define $f \gg_{k,\ell,\ldots} g$ similarly. The functions f and g are called *asymptotic* as x approaches a if $\lim_{x\to a} f(x)/g(x) = 1$. Positive-valued functions f and g with domain D have the same *order of magnitude* if $f \ll g \ll f$, or equivalently, if there exist positive constants c_1 and c_2 such that $c_1 \leq f(x)/g(x) \leq c_2$ for all $x \in D$. The *counting function* of a set A of integers counts the number of positive integers in A that do not exceed x, that is,

$$A(x) = \sum_{\substack{a \in A \\ 1 \leq a \leq x}} 1.$$

Using the counting function, we can associate various densities to the set A. The *Shnirel'man density* of A is

$$\sigma(A) = \inf_{n\to\infty} \frac{A(n)}{n}.$$

The *lower asymptotic density* of A is

$$d_L(A) = \liminf_{n\to\infty} \frac{A(n)}{n}.$$

The *upper asymptotic density* of A is

$$d_U(A) = \limsup_{n\to\infty} \frac{A(n)}{n}.$$

If $d_L(A) = d_U(A)$, then $d(A) = d_L(A)$ is called the *asymptotic density* of A, and

$$d(A) = \lim_{n\to\infty} \frac{A(n)}{n}.$$

Let A and B be nonempty sets of integers and $d \in \mathbf{Z}$. We define the *sumset*

$$A + B = \{a + b : a \in A, b \in B\},$$

the *difference set*

$$A - B = \{a - b : a \in A, b \in B\},$$

the *product set*

$$AB = \{ab : a \in A, b \in B\},$$

and the *dilation*

$$d * A = \{d\}A = \{da : a \in A\}.$$

The sets A and B *eventually coincide*, denoted by $A \sim B$, if there exists an integer n_0 such that $n \in A$ if and only if $n \in B$ for all $n \geq n_0$.

We use the following arithmetic functions:

$v_p(n)$	the exponent of the highest power of p that divides n
$\varphi(n)$	Euler phi function
$\mu(n)$	Möbius function
$d(n)$	the number of divisors of n
$\sigma(n)$	the sum of the divisors of n
$\pi(x)$	the number of primes not exceeding x
$\vartheta(x), \psi(x)$	Chebyshev's functions
$\ell(n)$	$\log n$ if n is prime and 0 otherwise
$\omega(n)$	the number of distinct prime divisors of n
$\Omega(n)$	the total number of prime divisors of n
$L(n)$	$\log n$, the natural logarithm of n
$\Lambda(n)$	von Mangoldt function
$\Lambda_2(n)$	generalized von Mangoldt function
$1(n)$	1 for all n
$\delta(n)$	1 if $n = 1$ and 0 if $n \geq 2$

A *ring* is always a ring with identity. We denote by $R^\times$ the multiplicative group of units of R. A commutative ring R is a field if and only if $R^\times = R \setminus \{0\}$. If $f(t)$ is a polynomial with coefficients in the ring R, then $N_0(f)$ denotes the number of distinct zeros of $f(t)$ in R. We denote by $M_n(R)$ the ring of $n \times n$ matrices with coefficients in R.

In the study of Liouville's method, we use the symbol

$$\{f(\ell)\}_{n=\ell^2} = \begin{cases} 0 & \text{if } n \text{ is not a square,} \\ f(\ell) & \text{if } n = \ell^2,\ \ell \geq 0. \end{cases}$$

Contents

Part I

A First Course in Number Theory

1
Divisibility and Primes

1.1 Division Algorithm

Divisibility is a fundamental concept in number theory. Let a and d be integers. We say that d is a *divisor* of a, and that a is a *multiple* of d, if there exists an integer q such that

$$a = dq.$$

If d divides a, we write

$$d|a.$$

For example, 1001 is divisible by 7 and 13. Divisibility is transitive: If a divides b and b divides c, then a divides c (Exercise 14).

The *minimum principle* states that every nonempty set of integers bounded below contains a smallest element. For example, a nonempty set of nonnegative integers must contain a smallest element. We can see the necessity of the condition that the nonempty set be bounded below by considering the example of the set $\mathbf{Z}$ of all integers, positive, negative, and zero.

The minimum principle is all we need to prove the following important result.

Theorem 1.1 (Division algorithm) *Let a and d be integers with $d \geq 1$. There exist unique integers q and r such that*

$$a = dq + r \tag{1.1}$$

and

$$0 \leq r \leq d - 1. \tag{1.2}$$

The integer q is called the *quotient* and the integer r is called the *remainder* in the division of a by d.

Proof. Consider the set S of nonnegative integers of the form

$$a - dx$$

with $x \in \mathbf{Z}$. If $a \geq 0$, then $a = a - d \cdot 0 \in S$. If $a < 0$, let $x = -y$, where y is a positive integer. Since d is positive, we have $a - dx = a + dy \in S$ if y is sufficiently large. Therefore, S is a nonempty set of nonnegative integers. By the minimum principle, S contains a smallest element r, and $r = a - dq \geq 0$ for some $q \in \mathbf{Z}$. If $r \geq d$, then

$$0 \leq r - d = a - d(q + 1) < r$$

and $r - d \in S$, which contradicts the minimality of r. Therefore, q and r satisfy conditions (1.1) and (1.2).

Let q_1, r_1, q_2, r_2 be integers such that

$$a = dq_1 + r_1 = dq_2 + r_2 \qquad \text{and} \qquad 0 \leq r_1, r_2 \leq d - 1.$$

Then

$$|r_1 - r_2| \leq d - 1$$

and

$$d(q_1 - q_2) = r_2 - r_1.$$

If $q_1 \neq q_2$, then

$$|q_1 - q_2| \geq 1$$

and

$$d \leq d|q_1 - q_2| = |r_2 - r_1| \leq d - 1,$$

which is impossible. Therefore, $q_1 = q_2$ and $r_1 = r_2$. This proves that the quotient and remainder are unique. □

For example, division of 16 by 7 gives the quotient 2 and the remainder 2, that is,

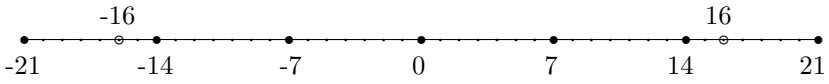
$$16 = 7 \cdot 2 + 2.$$

Division of -16 by 7 gives the quotient -3 and the remainder 5, that is,

$$-16 = 7(-3) + 5.$$

A simple geometric way to picture the division algorithm is to imagine the real number line with dots at the positive integers. Let q be a positive integer, and put a large dot on each multiple of q. The integer a either lies on one of these large dots, in which case a is a multiple of q, or a lies on a dot strictly between two large dots, that is, between two successive

multiples of q, and the distance r between a and the largest multiple of q that is less than a is a positive integer no greater than $q-1$. For example, if $q=7$ and $a=\pm 16$, we have the following picture.



The *principle of mathematical induction* states that if $S(k)$ is some statement about integers $k \geq k_0$ such that $S(k_0)$ is true and such that the truth of $S(k-1)$ implies the truth of $S(k)$, then $S(k)$ holds for all integers $k \geq k_0$. Another form of the principle of mathematical induction states that if $S(k_0)$ is true and if the truth of $S(k_0), S(k_0+1), \ldots, S(k-1)$ implies the truth of $S(k)$, then $S(k)$ holds for all integers $k \geq k_0$. Mathematical induction is equivalent to the minimum principle (Exercise 18).

Using mathematical induction and the division algorithm, we can prove the existence and uniqueness of m-adic representations of integers.

Theorem 1.2 *Let m be an integer, $m \geq 2$. Every positive integer n can be represented uniquely in the form*

$$n = a_0 + a_1 m + a_2 m^2 + \cdots + a_k m^k, \tag{1.3}$$

where k is the nonnegative integer such that

$$m^k \leq n < m^{k+1}$$

and $a_0, a_1, \ldots, a_k$ are integers such that

$$1 \leq a_k \leq m-1$$

and

$$0 \leq a_i \leq m-1 \qquad \text{for } i = 0, 1, 2, \ldots, k-1.$$

This is called the *m-adic representation* of n. The integers a_i are called the *digits* of n to *base m*. Equivalently, we can write

$$n = \sum_{i=0}^{\infty} a_i m^i,$$

where $0 \leq a_i \leq m-1$ for all i, and $a_i = 0$ for all sufficiently large integers i.

Proof. For $k \geq 0$, let $S(k)$ be the statement that every integer in the interval $m^k \leq n < m^{k+1}$ has a unique m-adic representation. We use induction on k. The statement $S(0)$ is true because if $1 \leq n < m$, then $n = a_0$ is the unique m-adic representation.

Let $k \geq 1$, and assume that the statements $S(0), S(1), \ldots, S(k-1)$ are true. We shall prove $S(k)$. Let $m^k \leq n < m^{k+1}$. By the division algorithm, we can divide n by m^k and obtain

$$n = a_k m^k + r, \quad \text{where } 0 \leq r < m^k.$$

Then

$$0 < m^k - r \leq n - r = a_k m^k \leq n < m^{k+1}.$$

Dividing this inequality by m^k, we obtain $0 < a_k < m$. Since m and a_k are integers, it follows that

$$1 \leq a_k \leq m - 1.$$

If $r = 0$, then $n = a_k m^k$ is an m-adic representation. If $r \geq 1$, then $m^{k'} \leq r < m^{k'+1}$ for some nonnegative integer $k' \leq k-1$. By the induction assumption, $S(k')$ is true and r has a unique m-adic representation of the form

$$r = a_0 + a_1 m + \cdots + a_{k-1} m^{k-1}$$

with $0 \leq a_i \leq m-1$ for $i = 0, 1, \ldots, k-1$. It follows that n has the m-adic representation

$$n = a_0 + a_1 m + \cdots + a_{k-1} m^{k-1} + a_k m^k.$$

We shall show that this representation is unique. Let

$$n = b_0 + b_1 m + \cdots + b_\ell m^\ell$$

be another m-adic representation of n, where $0 \leq b_j \leq m-1$ for all $j = 0, 1, \ldots, \ell$ and $b_\ell \geq 1$. If $\ell \geq k+1$, then

$$n < m^{k+1} \leq b_\ell m^\ell \leq n,$$

which is impossible. If $\ell \leq k-1$, then the inequalities $b_j \leq m-1$ imply that

$$\begin{aligned} n &= b_0 + b_1 m + \cdots + b_\ell m^\ell \\ &\leq (m-1) + (m-1)m + \cdots + (m-1)m^\ell \\ &= m^{\ell+1} - 1 \\ &< m^k \\ &\leq n, \end{aligned}$$

which is also impossible. Therefore, $k = \ell$. If $a_k < b_k$, then

$$\begin{aligned} n &= a_0 + a_1 m + \cdots + a_{k-1} m^{k-1} + a_k m^k \\ &\leq (m-1) + (m-1)m + \cdots + (m-1)m^{k-1} + a_k m^k \\ &= (m^k - 1) + a_k m^k \\ &< (a_k + 1) m^k \\ &\leq b_k m^k \\ &\leq n, \end{aligned}$$

which again is impossible. Therefore, $b_k \leq a_k$. By symmetry, we have $a_k \leq b_k$ and so $a_k = b_k$. Then

$$\begin{aligned} n - a_k m^k &= a_0 + a_1 m + a_2 m^2 + \cdots + a_{k-1} m^{k-1} \\ &= b_0 + b_1 m + b_2 m^2 + \cdots + b_{k-1} m^{k-1} \\ &< m^k. \end{aligned}$$

By the induction assumption, $a_i = b_i$ for $i = 0, 1, \ldots, k-1$. Thus, the m-adic representation of n exists and is unique, and $S(k)$ is true. By mathematical induction, $S(k)$ holds for all $k \geq 0$. □

For example, the 2-adic representation of 100 is

$$100 = 1 \cdot 2^2 + 1 \cdot 2^5 + 1 \cdot 2^6,$$

and the 3-adic representation of 100 is

$$100 = 1 + 2 \cdot 3^2 + 1 \cdot 3^4.$$

The 10-adic representation of 217 is

$$217 = 7 + 1 \cdot 10^1 + 2 \cdot 10^2.$$

Exercises

1. Find all divisors of 20.
2. Find all divisors of 29,601.
3. Find all divisors of 1.
4. Find the quotient and remainder for a divided by d when
   (a) $a = 281$ and $d = 23$.
   (b) $a = 281$ and $d = 12$.
   (c) $a = 291$ and $d = 23$.
   (d) $a = 291$ and $d = 12$.
5. Find the quotient and remainder for $10^k + 1$ divided by 11 for $k = 1, 2, 3, 4, 5$.
6. Compute the m-adic representation of 526 for $m = 2, 3, 7$, and 9.
7. Compute the 100-adic representation of 783,614,955.
8. Prove that n is even, then n^2 is divisible by 4.

9. Prove that n is odd, then $n^2 - 1$ is divisible by 8.

10. Prove that $n^3 - n$ is divisible by 6 for every integer n.

11. Prove that if d divides a, then d^k divides a^k for every positive integer k.

12. Prove that if d divides a and d divides b, then d divides $ax + by$ for all integers x and y.

13. Prove that if a and d are integers such that d divides a and $|a| < d$, then $a = 0$.

14. Prove that divisibility is transitive, that is, if a divides b and b divides c, then a divides c.

15. Prove by induction that $n \leq 2^{n-1}$ for all positive integers n.

16. Prove by induction that

$$1 + 2 + \cdots + n = \frac{n(n+1)}{2}$$

for all positive integers n.

17. Prove by induction that

$$1^3 + 2^3 + \cdots + n^3 = (1 + 2 + \cdots + n)^2$$

for all positive integers n, that is, the sum of the cubes of the first n integers is equal to the square of the sum of the first n integers.

18. Prove that the principle of mathematical induction is equivalent to the minimum principle.

19. Let a and d be integers with $d \geq 1$. Prove that there exist unique integers q' and r' such that

$$a = dq' + r'$$

and

$$-\frac{d}{2} < r' \leq \frac{d}{2}.$$

20. For integers n and k with $n \geq 1$ and $0 \leq k \leq n$, we define the *binomial coefficient*

$$\binom{n}{k} = \frac{n(n-1)\cdots(n-k+1)}{k!}.$$

Define $\binom{0}{0} = 1$. Prove that for all $n \geq 1$,

$$\binom{n}{0} = \binom{n}{n} = 1$$

and

$$\binom{n}{k} = \binom{n-1}{k} + \binom{n-1}{k-1}$$

for $1 \leq k \leq n-1$.

21. Prove that the product of any k consecutive integers is always divisible by $k!$.

    Hint: Use induction on n to show that $\binom{n}{k}$ is an integer.

22. Let $m_0, m_1, m_2, \ldots$ be a strictly increasing sequence of positive integers such that $m_0 = 1$ and m_i divides m_{i+1} for all $i \geq 0$. Prove that every positive integer n can be represented uniquely in the form

$$n = \sum_{i=0}^{\infty} a_i m_i,$$

    where

$$0 \leq a_i \leq \frac{m_{i+1}}{m_i} - 1 \qquad \text{for all } i \geq 0$$

    and $m_i = 0$ for all but finitely many integers i.

23. Prove that every positive integer n can be represented uniquely in the form

$$n = \sum_{k=0}^{\infty} a_k k!,$$

    where

$$0 \leq a_k \leq k.$$

24. Prove that every positive integer n can be uniquely represented in the form

$$n = b_0 + b_1 3 + b_2 3^2 + \cdots + b_{k-1} 3^{k-1} + 3^k,$$

    where $b_i \in \{0, 1, -1\}$ for $i = 0, 1, 2, \ldots, k-1$.

25. Let $\mathbf{N}^k$ denote the set of all k-tuples of positive integers. We define the *lexicographic order* on $\mathbf{N}^k$ as follows. For $(a_1, \ldots, a_k), (b_1, \ldots, b_k) \in \mathbf{N}^k$, we write

$$(a_1, \ldots, a_k) \preceq (b_1, \ldots, b_k)$$

    if either $a_i = b_i$ for all $i = 1, \ldots, k$, or there exists an integer j such that $a_i = b_i$ for $i < j$ and $a_j < b_j$. Prove that

    (a) The relation $\preceq$ is *reflexive* in the sense that if $(a_1, \ldots, a_k) \preceq (b_1, \ldots, b_k)$ and $(b_1, \ldots, b_k) \preceq (a_1, \ldots, a_k)$, then $(a_1, \ldots, a_k) = (b_1, \ldots, b_k)$.