

# Modular arithmetic

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## 1 Residue Classes

Let  $n$  be a nonzero integer. For integers  $a$  and  $b$ , we say that

$$a \equiv b \pmod{n} \iff n \mid b - a.$$

Notice that for fixed values of  $a$  and  $n$ , infinitely many values of  $b$  satisfy  $a \equiv b \pmod{n}$ .

- Prove that  $a \equiv a \pmod{n}$ .
- Prove that if  $a \equiv b \pmod{n}$  then  $b \equiv a \pmod{n}$ .
- Prove that if  $a \equiv b \pmod{n}$  and  $b \equiv c \pmod{n}$  then  $a \equiv c \pmod{n}$ .

We may divide the integers into  $n$  sets (the *residue classes mod  $n$* ), such that two integers are in the same residue class if and only if they are congruent mod  $n$ . The sets are as follows:

$$\begin{aligned} [0]_n &= \{\dots, -2n, -n, 0, n, 2n, \dots\} \\ [1]_n &= \{\dots, 1 - 2n, 1 - n, 1, 1 + n, 1 + 2n, \dots\} \\ [2]_n &= \{\dots, 2 - 2n, 2 - n, 2, 2 + n, 2 + 2n, \dots\} \\ &\vdots \\ [n-1]_n &= \{\dots, -1 - n, -1, n-1, 2n-1, 3n-1, \dots\} \end{aligned}$$

The numbers  $0, 1, \dots, n-1$  are called the *least residues mod  $n$* . The set of least residues mod  $n$  is called the *integers mod  $n$* , denoted  $\mathbb{Z}_n$ .

- Find the least residue of  $-1 \bmod 2022$ .

## 2 Operations

- Prove that addition, subtraction, multiplication and exponentiation are consistently defined: that is, if  $a, b, c, d$  are integers with  $a \equiv b \pmod{n}$  and  $c \equiv d \pmod{n}$  then

$$a + c \equiv b + d \pmod{n}, \quad a - c \equiv b - d \pmod{n}, \quad ac \equiv bd \pmod{n}, \quad a^m \equiv b^m \pmod{n}.$$

Therefore, it makes sense to define addition, subtraction and multiplication in  $\mathbb{Z}_n$ . For each of these operations (we use  $\circ$  to denote any of them), we let  $a \circ b$  in  $\mathbb{Z}_n$  be the least residue of  $a \circ b$  in  $\mathbb{Z}$ .

- What are  $3 + 2$  and  $3 \times 2$  in  $\mathbb{Z}_4$ ?

Assume that for some integer  $a$  there is a least residue  $b$  such that  $ab \equiv 1 \pmod{n}$ . We call  $b$  the *inverse* of  $a \pmod{n}$ .

We define  $\frac{c}{a} \equiv cb \pmod{n}$ , for each positive integer  $c$ .

- Prove that if  $c$  has an inverse mod  $n$ , and  $cx \equiv cy \pmod{n}$ , then  $x \equiv y \pmod{n}$ .
- Prove that each integer has at most one inverse mod  $n$ .
- Prove that if  $b$  and  $d$  both have inverses mod  $n$ , then so does  $bd$ .
- Prove that

$$\begin{aligned} \frac{a}{b} + \frac{c}{d} &\equiv \frac{ad + bc}{bd} \pmod{n}, & \frac{a}{b} - \frac{c}{d} &\equiv \frac{ad - bc}{bd} \pmod{n}, \\ \frac{a}{b} \cdot \frac{c}{d} &\equiv \frac{ac}{bd} \pmod{n}, & \frac{a}{b} \div \frac{c}{d} &\equiv \frac{ad}{bc} \pmod{n} \end{aligned}$$

assuming all of the denominators have inverses.

## 3 The integers modulo a prime

Let  $p$  be a prime.

- Let  $a$  be an integer. Prove that  $a$  has an inverse mod  $p$  if and only if  $p \nmid a$ .
- Prove that  $(p - 1)! \equiv -1 \pmod{p}$ .
- Let  $\mathbb{Z}_p^*$  be the set of nonzero residues mod  $p$ , and let  $a$  be an element of  $\mathbb{Z}_p^*$ .
  - Prove that the function  $f(x) = ax$  is a bijection from  $\mathbb{Z}_p^*$  to  $\mathbb{Z}_p^*$ .
  - Deduce that  $p \mid a^{p-1} - 1$ .

## 4 The integers modulo an integer

Let  $n$  be an integer.

- Let  $a$  be an integer. Prove that  $a$  has an inverse mod  $n$  if and only if  $\gcd(n, a) = 1$ .
- Say  $ax \equiv ay \pmod{n}$ , but  $\gcd(n, a) \neq 1$ . What can we say about  $x$  and  $y$ ?
- Let  $\mathbb{Z}_n^*$  be the set of least residues mod  $n$  which are coprime to  $n$ , and let  $a$  be an element of  $\mathbb{Z}_n^*$ .
  - Prove that the function  $f(x) = ax$  is a bijection from  $\mathbb{Z}_n^*$  to  $\mathbb{Z}_n^*$ .
  - Deduce that  $n \mid a^{\varphi(n)} - 1$ .

## 5 Chinese Remainder Theorem

- Let  $a$  and  $b$  be coprime positive integers, and let  $c$  and  $d$  be integers. Prove that there is exactly one least residue  $x \pmod{ab}$  such that

$$c \equiv x \pmod{a}, \quad d \equiv x \pmod{b}.$$

- Let  $a_1, a_2, \dots, a_k$  be coprime positive integers, and let  $b_1, b_2, \dots, b_k$  be integers. Prove that there is exactly one least residue  $x \pmod{a_1 a_2 \cdots a_k}$  such that for each  $i$ ,

$$b_i \equiv x \pmod{a_i}.$$

- Recall that  $\varphi(n)$  is the number of positive integers which are at most  $n$  and coprime to  $n$ . Prove that  $\varphi$  is multiplicative.

## 6 Choosing good mods

Prove that:

- Squares are 0, 1 or 4 mod each of  $\{5, 8\}$ , and 0 or 1 mod 3.
- Cubes are 0, 1 or  $-1$  mod each of  $\{7, 9\}$ .

Often a problem will be solved by considering it under an appropriate mod. In general, for  $n$ th powers, try looking mod  $m$  where  $\varphi(m)$  is a small multiple of  $n$ .

Also, of course, try choosing a mod which divides a bunch of terms.

- Find all positive integers  $a, b$  such that

$$a^4 + b^4 = 10a^2b^2 - 2022.$$

However, remember that if you find a single solution to an equation, then that solution is still a solution in every mod so you won't be able to find a contradiction.

- Find all positive integers  $a, b$  such that

$$a^4 + b^4 = 97.$$

## 7 Problems

1. Prove that if  $a^m \equiv 1 \pmod{p}$  and  $a^n \equiv 1 \pmod{p}$  then  $a^{\gcd(m,n)} \equiv 1 \pmod{p}$ .
2. We define

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

For each prime  $p$  and positive integer  $k$ , find the least residues of

$$\binom{p-1}{k} \quad \text{and} \quad \frac{1}{p} \binom{p}{k}$$

in mod  $p$ .

3. Find all primes  $p$  such that  $29^p + 1$  is a multiple of  $p$ .
4. Define the sequence  $a_n = 2^n + 3^n + 6^n - 1$ ,  $n \in \mathbb{N}$ . Find all primes which do not divide  $a_n$  for any  $n$ .
5. Let  $p = 3k - 1$  be a prime. Prove that

$$1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \cdots - \frac{1}{2k-2} + \frac{1}{2k-1} \equiv 0 \pmod{p}.$$

6. Find all positive integers  $n$  such that  $2^n + 7^n$  is a perfect square.
7. Show that for any fixed integers  $n$  and  $a$ , the sequence  $a, a^a, a^{a^a}, \dots$  is eventually constant mod  $n$ .
8. Prove that for each positive integer  $n$  there exist  $n$  consecutive positive integers, none of which is a prime power.
9. Prove that every positive integer has at least as many divisors which are  $1 \pmod{4}$  as divisors which are  $3 \pmod{4}$ .
10. Let  $d$  be a positive integer. Prove that at least one of  $2d - 1$ ,  $5d - 1$ ,  $13d - 1$  is not a perfect square.
11. Find all pairs of positive integers  $x, y$  such that  $x! + 5 = y^3$ .
12. Prove that if  $m$  and  $n$  are natural numbers, then  $3^m + 3^n + 1$  is not a perfect square.
13. Find all primes  $p$  and  $q$  such that  $p + q = (p - q)^3$ .
14. Find all pairs of positive integers  $x, y$  such that  $1 + 2^x + 2^{2x+1} = y^2$ .
15. Find all integers  $a, b$  such that

$$a^3 + (a+1)^3 + \cdots + (a+1)^3 = b^4 + 1.$$

16. Find all positive integers  $a$  for which  $1! + 2! + \cdots + a!$  is a perfect cube.
17. What is the least residue mod  $n$  of the product of the elements of  $\mathbb{Z}_n^*$ ?