

Fermat's little theorem. RSA.

# Computing large numbers modulo $n$

Fermat's little theorem

The Chinese remainder theorem

RSA

- (a) In modulo arithmetic, you can always reduce a large number to its remainder

$$a \equiv a \bmod n \pmod{n}.$$

- (b) Addition, subtraction, and multiplication preserve congruence:  
if  $a \equiv b \pmod{n}$  and  $c \equiv d \pmod{n}$ , then

$$a + c \equiv b + d \pmod{n},$$

$$a - c \equiv b - d \pmod{n}, \quad \text{and}$$

$$ac \equiv bd \pmod{n}.$$

- (c) Instead of a congruence relation, you can work with the equality of the remainders

$$a \equiv b \pmod{n} \quad \text{if and only if} \quad a \bmod n = b \bmod n$$

# Example

Fermat's little theorem

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Find  $x$  such that  $(25^8 + 13^2 + 15) \equiv x \pmod{21}$ .

In fact, we need to compute the remainder  $(25^8 + 13^2 + 15) \bmod 21$ :

$$25^2 \equiv 625 \equiv 16 \pmod{21}$$

$$25^4 \equiv (25^2)^2 \equiv 16^2 \equiv 256 \equiv 4 \pmod{21}$$

$$25^8 \equiv (25^4)^2 \equiv 4^2 \equiv 16 \pmod{21}$$

$$13^2 \equiv 169 \equiv 1 \pmod{21}$$

$$25^8 + 13^2 + 15 \equiv 16 + 1 + 15 \equiv 32 \equiv 11 \pmod{21}$$

Also we can say that

$$(25^8 + 13^2 + 15) \bmod 21 = 11.$$

# Example

Compute  $x = 12^{135} \bmod 137$ .

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# Example

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Compute  $x = 12^{135} \bmod 137$ .

$$12^2 \equiv 144 \equiv 7 \pmod{137}$$

$$12^4 \equiv (12^2)^2 \equiv 7^2 \equiv 49 \pmod{137}$$

$$12^8 \equiv (12^4)^2 \equiv 49^2 \equiv 2401 \equiv 72 \pmod{137}$$

$$12^{16} \equiv (12^8)^2 \equiv 72^2 \equiv 5184 \equiv 115 \pmod{137}$$

$$12^{32} \equiv (12^{16})^2 \equiv 115^2 \equiv 13225 \equiv 73 \pmod{137}$$

$$12^{64} \equiv (12^{32})^2 \equiv 73^2 \equiv 5329 \equiv 123 \pmod{137}$$

$$12^{128} \equiv (12^{64})^2 \equiv 123^2 \equiv 15129 \equiv 59 \pmod{137}$$

$$12^{135} \equiv 12^{128} \cdot 12^4 \cdot 12^2 \cdot 12 \equiv 59 \cdot 49 \cdot 7 \cdot 12 \equiv 242844 \equiv 80 \pmod{137}$$

# Lemma 1

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**Lemma.** Let  $p$  be a prime. If  $k$  is not a multiple of  $p$ , then if

$$ak \equiv bk \pmod{p}$$

then

$$a \equiv b \pmod{p}$$

Proof.

$$p \mid (ak - bk)$$

$$p \mid k(a - b)$$

By the lemma we proved in the previous lecture,  $p \mid k$  or  $p \mid (a - b)$ .  
Since  $p \nmid k$ , we conclude that  $p \mid (a - b)$ , or equivalently,

$$a \equiv b \pmod{p}.$$



# Observation

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| $x$         | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|-------------|---|---|---|---|---|----|----|----|----|----|----|----|
| $x \bmod 7$ | 5 | 6 | 0 | 1 | 2 | 3  | 4  | 5  | 6  | 0  | 1  | 2  |

When computing remainders of the division by  $p$  for a sequence of consecutive integers, we get all numbers from 0 to  $p - 1$ .

Can we come up with other ways for producing these numbers?

# Observation

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For example, we take every second integer: 2, 4, 6, 8, ...

| $x$         | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|-------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|
| $x \bmod 7$ |   | 2 |   | 4 |   | 6 |   | 1 |   | 3  |    | 5  |    | 0  |

We generate the same numbers, even though they are permuted.

Can we try another sequence: 3, 6, 9, 12, 15, ... right?

Yes, we can, but we can prove a more general result.



# Lemma 2

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**Lemma.** Let  $p$  be a prime. If  $k$  is not a multiple of  $p$ , the sequence

$$k \bmod p, \quad 2k \bmod p, \quad 3k \bmod p, \quad \dots \quad (p-1)k \bmod p$$

is a permutation of

$$1, 2, 3, \dots, p-1.$$

**Proof.** All remainders are in the interval between 1 and  $p-1$ .

Let's prove by contradiction that all of them are different.

Assume that exist two distinct integers  $1 \leq i \neq j \leq p-1$  such that

$$ik \bmod p = jk \bmod p$$

$$ik \equiv jk \pmod{p}$$

By Lemma 1,  $i \equiv j \pmod{p}$ , and so  $i = j$ , because both are integers between 1 and  $p-1$ . Therefore, all remainders are different, and this proves the lemma.  $\square$

# Examples

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$k = 2$  and  $p = 5$ :

$$2 \bmod 5 = 2$$

$$4 \bmod 5 = 4$$

$$6 \bmod 5 = 1$$

$$8 \bmod 5 = 3$$

$k = 12$  and  $p = 7$ :

$$12 \bmod 7 = 5$$

$$24 \bmod 7 = 3$$

$$36 \bmod 7 = 1$$

$$48 \bmod 7 = 6$$

$$60 \bmod 7 = 4$$

$$72 \bmod 7 = 2$$

# Fermat's little theorem

Fermat's little  
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remainder theorem

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**Theorem.** Let  $p$  be a prime. If  $k$  is not a multiple of  $p$  (i.e.  $p \nmid k$ ) then

$$k^{p-1} \equiv 1 \pmod{p}$$

Proof.

$$1 \cdot 2 \cdot 3 \cdots (p-1) = \underbrace{(k \bmod p)}_{\equiv k \pmod{p}} \underbrace{(2k \bmod p)}_{\equiv 2k \pmod{p}} \underbrace{(3k \bmod p)}_{\dots} \cdots ((p-1)k \bmod p)$$

$$\begin{aligned} 1 \cdot 2 \cdot 3 \cdots (p-1) &\equiv k \cdot 2k \cdot 3k \cdots (p-1)k \pmod{p} \\ &\equiv 1 \cdot 2 \cdot 3 \cdots (p-1) \cdot k^{p-1} \pmod{p}. \end{aligned}$$

$$1 \equiv k^{p-1} \pmod{p}. \quad (\text{by Lemma 1})$$



# Fermat's little theorem

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**Theorem.** Let  $p$  be a prime. If  $k$  is not a multiple of  $p$  then

$$k^{p-1} \equiv 1 \pmod{p}$$

*Using this theorem, we can find an inverse,  $x$ ,*

$$kx \equiv 1 \pmod{p}.$$

How can we do that?

If  $k$  is not a multiple of  $p$  and  $p$  is a prime then  $k^{p-2}$  is an inverse!

$$k \cdot k^{p-2} = k^{p-1} \equiv 1 \pmod{p}$$

Because we need an inverse modulo  $p$ , the remainder  $(k^{p-2} \bmod p)$  is an inverse too.

Notice the difference with the Extended Euclid's algorithm that can be used for computing an inverse even when  $p$  is not a prime.

# Fermat's little theorem

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Compute an inverse of 12 modulo 137, that is find  $x$  such that

$$12x \equiv 1 \pmod{137}$$

137 is a prime, so we apply the theorem,

$$12 \cdot 12^{137-2} \equiv 1 \pmod{137}.$$

The inverse is

$$x = 12^{137-2} = 12^{135}.$$

Or, in fact, just the remainder  $12^{135} \bmod 137$  is also the inverse, and we have computed it already:  $12^{135} \bmod 137 = 80$ . Let's check:

$$12 \cdot 80 \equiv 960 \equiv 1 \pmod{137}$$

Thus 80 is a multiplicative inverse, indeed.

# Fermat's little theorem

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**Theorem.** Let  $p$  be a prime. If  $k$  is not a multiple of  $p$  then

$$k^{p-1} \equiv 1 \pmod{p}$$

Find  $x$  such that

$$12^{274} \equiv x \pmod{137}.$$

# Fermat's little theorem

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**Theorem.** Let  $p$  be a prime. If  $k$  is not a multiple of  $p$  then

$$k^{p-1} \equiv 1 \pmod{p}$$

Find  $x$  such that

$$12^{274} \equiv x \pmod{137}.$$

By Fermat's little theorem,  $12^{136} \equiv 1 \pmod{137}$ , so

$$12^{274} \equiv 12^{136} \cdot 12^{136} \cdot 12^2 \equiv 1 \cdot 1 \cdot 12^2 \equiv 144 \equiv 13 \pmod{137}$$

# Fermat's little theorem

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Find  $x$  such that

$$2015^{40321} \equiv x \pmod{2017}.$$



# Fermat's little theorem

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Find  $x$  such that

$$2015^{40321} \equiv x \pmod{2017}.$$

By Fermat's little theorem,  $2015^{2016} \equiv 1 \pmod{2017}$ , so

$$2015^{40321} \equiv 2015^{2016 \cdot 20} \cdot 2015 \equiv 1^{20} \cdot 2015 \equiv 2015 \equiv -2 \pmod{2017}$$

# The Chinese remainder theorem

Fermat's little theorem

The Chinese remainder theorem

RSA

**Theorem** (Chinese remainder). Let  $n_1, n_2, \dots, n_k$  be pairwise relatively prime positive integers greater than one and  $a_1, a_2, \dots, a_n$  arbitrary integers. Then the system

$$x \equiv a_1 \pmod{n_1},$$

$$x \equiv a_2 \pmod{n_2},$$

...

$$x \equiv a_k \pmod{n_k}$$

has a unique solution modulo  $n = n_1 \cdot n_2 \cdots n_k$ .

(That is, there is a solution  $x$  with  $0 \leq x < n$ , and all other solutions are congruent modulo  $n$  to this solution.)

# RSA cryptosystem

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RSA is a public key cryptosystem introduced by Ronald Rivest, Adi Shamir, and Leonard Adleman.

## *Constructing a public key:*

1. You pick two large primes  $p$  and  $q$ . (How large? In practice, if their decimal representations are more than 200 digits long, they are large enough).
2. Let  $n = pq$ .
3. You pick an integer  $e$  such that  $\gcd(e, (p-1)(q-1)) = 1$ .

The public key is a pair  $(n, e)$ .

# RSA encryption

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You are given the *public key*  $(n, e)$ , such that  $n = pq$ , and  $\gcd(e, (p-1)(q-1)) = 1$ . Where  $p$  and  $q$  are unknown primes.

1. You break the message (a long string of digits) into blocks so that each is less than  $n$

$$\text{Message} = \underbrace{17519273}_{M_1 < n} \underbrace{40137520}_{M_2 < n} \underbrace{43028230}_{M_3 < n} \underbrace{14459489}_{M_4 < n}$$

2. Each block is encrypted separately:

$$C_i = M_i^e \bmod n$$

3. The encrypted blocks can be transmitted to the receiver.

# RSA decryption

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The *decryption key* is an integer  $d$  such that

$$ed \equiv 1 \pmod{(p-1)(q-1)}$$

So,  $d$  is the multiplicative inverse of  $e$  modulo  $(p-1)(q-1)$ .

If  $p$  and  $q$  are unknown, it's hard to compute  $d$ .

To decrypt each encrypted block  $C_i$ , you compute  $C_i^d \bmod n$ .

Turns out that the original message

$$M_i = C_i^d \bmod n.$$

Let's show that this is the case.

# RSA decryption

Fermat's little theorem

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The decryption key  $d$  is such that  $ed \equiv 1 \pmod{(p-1)(q-1)}$

$$ed = 1 + k(p-1)(q-1)$$

$$C_i \equiv M_i^e \pmod{pq}$$

$$\begin{aligned} C_i^d &\equiv (M_i^e)^d \equiv M_i^{1+k(p-1)(q-1)} \pmod{pq} \\ &\equiv M_i \cdot M_i^{k(p-1)(q-1)} \pmod{pq} \end{aligned}$$

If  $a \equiv b \pmod{pq}$ , there exists  $t$  s.t.  $a - b = tpq$ , and so

$$a \equiv b \pmod{q} \quad \text{and} \quad a \equiv b \pmod{p}.$$

Therefore,

$$C_i^d \equiv M_i \cdot M_i^{k(p-1)(q-1)} \pmod{p}$$

$$C_i^d \equiv M_i \cdot M_i^{k(p-1)(q-1)} \pmod{q}$$

# RSA decryption

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Take the first:

$$C_i^d \equiv M_i \cdot (M_i^{p-1})^{k(q-1)} \pmod{p}$$

If  $p \mid M_i$ , then  $M_i \equiv 0 \pmod{p}$ . This means  $C_i^d \equiv 0 \pmod{p}$ .  
Hence,

$$C_i^d \equiv 0 \equiv M_i \pmod{p}$$

If  $p \nmid M_i$ , then  $M_i^{p-1} \equiv 1 \pmod{p}$  by Fermat's little theorem, hence

$$C_i^d \equiv M_i \cdot 1^{k(q-1)} \equiv M_i \pmod{p}$$

Therefore in any case,

$$C_i^d \equiv M_i \pmod{p}$$

Similarly,

$$C_i^d \equiv M_i \pmod{q}$$

# RSA decryption

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We have shown that

$$C_i^d \equiv M_i \pmod{p}$$

$$C_i^d \equiv M_i \pmod{q}$$

Recall that we want to prove that

$$C_i^d \equiv M_i \pmod{pq}$$

If this is the case, then we can decrypt  $C_i$  by taking the remainder  $C_i^d \bmod pq$ .



# RSA decryption

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We have shown that

$$C_i^d \equiv M_i \pmod{p}$$

$$C_i^d \equiv M_i \pmod{q}$$

Recall that we want to prove that

$$C_i^d \equiv M_i \pmod{pq}$$

If this is the case, then we can decrypt  $C_i$  by taking the remainder  $C_i^d \bmod pq$ .

$C_i^d - M_i$  is a multiple of  $p$  and a multiple of  $q$ , which are primes. But because the prime factorization is unique, the difference  $C_i^d - M_i$  should be also a multiple of  $pq$ . Thus

$$C_i^d \equiv M_i \pmod{pq}$$

This is why RSA decryption works!