

01204211 Discrete Mathematics
Lecture 9a: Fermat's Little Theorem

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Fermat's
Last
Theorem

For all $n > 2$
 $a^n + b^n = c^n$

There is no solution
for $n > 2$

Quick recap

Number
theory
↳ gcd
↳ mod

- ① modular arithmetic — mod
— multiplicative inverse } gaussian elim / division
- ② polynomial
- ③ Fermat LT, Euler \rightarrow RSA

For any integer x and y , there exist a pair of integers a and b such that

$$a \cdot x + b \cdot y = \gcd(x, y).$$

→ Euclid alg

Thm: if $\gcd(x, y) = 1$ then
 $x^{-1} \pmod{y}$:

x^{-1}

exists

$$x \cdot x^{-1} \equiv 1 \pmod{y}$$

→ or multiplicative
inverse of $x \pmod{y}$ exists

Quick recap

For any integer x and y , there exist a pair of integers a and b such that

$$\text{If } \underline{\gcd(x, y) = 1} \quad \lceil \quad \underline{a \cdot x + b \cdot y = \gcd(x, y)} = 1 \quad \rfloor$$

$$\underline{a} \cdot x \equiv \underline{a} \cdot x + b \cdot y \equiv 1 \pmod{y}$$

$$\rightarrow \underline{a \text{ is } x^{-1} \pmod{y}}$$

Quick recap

For any integer x and y , there exist a pair of integers a and b such that

$$a \cdot x + b \cdot y = \gcd(x, y).$$

How to find a and b ? Use the extended GCD algorithm.

Finding a and b : Extended Euclid Algorithm

We will modify the Euclid algorithm so that it also returns a and b together with $\gcd(x, y)$.

```
Algorithm Euclid(x,y):  
  if x mod y == 0:  
  
    return y, 0, 1  
  else:  
    g, a', b' = Euclid(y, x mod y)  
  
    a = b'  
  
    b = a' - b'*floor(x / y)  
  
    return g, a, b
```

Recap: Congruences

Definition (congruences)

For an integer $m > 0$, if integers a and b are such that

$$\underline{a \bmod m} = \underline{b \bmod m},$$

we write

$$\underline{a \equiv b} \quad \boxed{(\bmod m)}.$$

We also have that

$$a \equiv b \pmod{m} \quad \Leftrightarrow \quad m \mid (a - b)$$

Recap: Multiplicative inverse modulo m

Definition

The multiplicative inverse modulo m of a , denoted by a^{-1} , is an integer such that

$$\underline{a \cdot a^{-1}} \equiv \underline{1} \pmod{\underline{m}}.$$

Theorem 1

An integer a has a multiplicative inverse modulo m iff $\gcd(a, m) = 1$.

How to test if an integer n is prime

$$\frac{\log n}{2} \text{ bit}$$

$$2^{\log n/2}$$

- Try to find factors of n . (Takes time \sqrt{n}) \times

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How to test if an integer n is prime

- ▶ Try to find factors of n . (Takes time \sqrt{n})
- ▶ If there is a property that holds **iff** n is prime, we can check that property. If we can check that quickly, we can test if n is prime.
- ▶ If there is a property that holds **if** n is prime, how can we make use of that property?

* Theorem 2 (Fermat's Little Theorem)

If p is prime and a is an integer such that $\gcd(a, p) = 1$,

$$\underline{a^{p-1}} \equiv \underline{1} \pmod{\underline{p}}.$$

↓


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

↑

Test(x):

for $a \in \{1, 2, \dots, x-1\}$

check $a^{x-1} \equiv 1 \pmod{x}$

→ yes: x prime?  Yes

→ no: x Not prime ✓

Theorem 2 (Fermat's Little Theorem)

If p is prime and a is an integer such that $\gcd(a, p) = 1$,

$$a^{p-1} \equiv 1 \pmod{p}.$$

How can we use Fermat's Little Theorem to check if integer n is prime?

Fermat test

$$a^{n-1} \equiv 1 \pmod{n}$$

composite



Algorithm CheckPrime(n):

pick integer a from $2, \dots, n-1$

if gcd(a,n) $\neq 1$:
return False

$O(\log^2 n)$

if power(a, $n-1$, n) $\neq 1$:
- - - -> return False ✓

// FLT

$O(\log^2 n)$

else:

return True

often false positive

$$\frac{1}{2^{10,000}}$$

How good is the Fermat test?

When you call `CheckPrime(n)`:

- ▶ If n is prime,

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- ▶ If n is prime, `CheckPrime` always return `True`.
- ▶ If n is composite,

How good is the Fermat test?

When you call `CheckPrime(n)`:

- ▶ If n is prime, `CheckPrime` always return `True`.
- ▶ If n is composite, you want `CheckPrime` to return `False`, but **Fermat's Little Theorem does not guarantee that.**

Fermat test - when n is composite

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Algorithm CheckPrime(n):  
  pick integer  $a$  from  $2, \dots, n-1$   
  
  if  $\gcd(a, n) \neq 1$ :  
    return False  
  
  if  $\text{power}(a, n-1, n) \neq 1$ :  
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- ▶ $\gcd(a, n) \neq 1$, i.e., when you pick a with common factor with n .

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    if  $a^{n-1} \bmod n \neq 1$ :  
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```

If n is composite, the algorithm returns False when

- ✓ ▶ $\gcd(a, n) \neq 1$, i.e., when you pick a with common factor with n .
- ✓ ▶ $a^{n-1} \bmod n \neq 1$, i.e., when you find a that violates the property. We want to be in this case. How likely?

Proof of Fermat's Little Thm: Idea

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

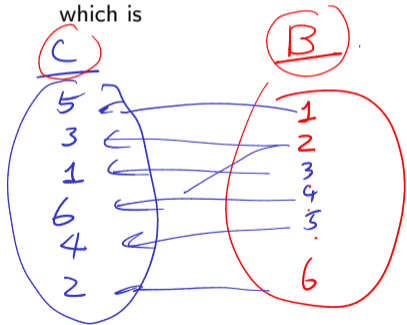
Let $p = 7$ and $a = 5$. Consider set

$$B = \{1, 2, 3, \dots, p-1\} = \{1, 2, 3, 4, 5, 6\}$$

Also consider set

$$C = \{1 \cdot 5 \bmod 7, 2 \cdot 5 \bmod 7, 3 \cdot 5 \bmod 7, \dots, 6 \cdot 5 \bmod 7\},$$

which is



$$a \cdot x \pmod{p}$$

$$\begin{aligned} &1 \cdot a \bmod p \\ &2 \cdot a \bmod p \\ &3 \cdot a \bmod p \\ &\vdots \\ &6 \cdot a \bmod p \end{aligned}$$

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Is this coincidental?

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which is

$$\underline{C} = \{5, 3, 1, 6, 4, 2\} = \underline{B.}$$

Is this coincidental? No. (We will prove that. But can you quickly tell why.)

Since $B = C$, the following terms are equal:

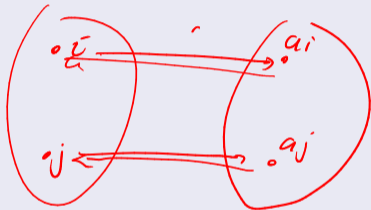
$$\left(\prod_{i \in B} i \right) \bmod 7 = \underline{1 \cdot 2 \cdot 3 \cdot 4 \cdot 5 \cdot 6 \bmod 7},$$

and

$$\begin{aligned} \left(\prod_{i \in C} i \right) \bmod 7 &= 5 \cdot 3 \cdot 1 \cdot 6 \cdot 4 \cdot 2 \bmod 7 \\ &= \underline{(1a)} \cdot \underline{(2a)} \cdot \underline{(3a)} \cdot \underline{(4a)} \cdot \underline{(5a)} \cdot \underline{(6a)} \bmod 7 \\ &= \underline{(1 \cdot 2 \cdot 3 \cdot 4 \cdot 5 \cdot 6)} \cdot \underline{a^6} \bmod 7. \end{aligned}$$

Proof of Fermat's Little Thm.

Recall that $\gcd(a, p) = 1$, i.e., there exists a multiplicative inverse a^{-1} of a modulo p . This implies that for $i \not\equiv j \pmod{p}$, $ai \not\equiv aj \pmod{p}$. Also note that $a \cdot 0 \equiv 0 \pmod{p}$.



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Let $B = \{1, 2, \dots, p-1\}$. Let

$$C = \{a \cdot i \bmod p \mid i \in B\}.$$

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Let $B = \{1, 2, \dots, p-1\}$. Let

$$C = \{a \cdot i \bmod p \mid i \in B\}.$$

Since for different $i, j \in B$, we have different $ai \bmod p$ and $aj \bmod p$, we know that $|C| = p - 1$. Also, $C \subseteq B$ because $0 \leq ai \bmod p \leq p - 1$ and $0 \notin C$. Thus, we can conclude that $C = B$.

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Since $B = C$, we have that $\prod_{i \in B} i \equiv \prod_{i \in C} i \pmod{p}$, i.e.

$$\begin{aligned} \cancel{1 \cdot 2 \cdots (p-1)} &\equiv (a1) \cdot (a2) \cdot (a3) \cdots (a(p-1)) \pmod{p} \\ &\equiv \cancel{(1 \cdot 2 \cdots (p-1))} \cdot a^{p-1} \pmod{p}. \end{aligned}$$

Since each of $1, 2, \dots, p-1$ has an inverse modulo p , we can multiply both sides with $1^{-1}, 2^{-1}, \dots, (p-1)^{-1}$ to obtain

$$1 \equiv a^{p-1} \pmod{p},$$

as required.



Exercise

Prove that for any integer a and prime p ,

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

How good is the Fermat test when n is composite?

To answer correctly, we want a to be such that $\gcd(a, n) \neq 1$ or

$$\underline{a^{n-1} \not\equiv 1 \pmod{n}}.$$

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We refer to $a \in \{1, 2, \dots, p-1\}$ such that $\gcd(a, n) = 1$ and $a^{n-1} \not\equiv 1 \pmod{n}$ as a **witness**. The other element b such that $b^{n-1} \equiv 1 \pmod{n}$ is called a **non-witness**. How likely that we randomly choose an element and get a witness?

Number of witnesses

Suppose that there exists a witness a ; we know that $a^{n-1} \not\equiv 1 \pmod{n}$. How can we find other witnesses?

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Suppose that there exists a witness a ; we know that $a^{n-1} \not\equiv 1 \pmod{n}$. How can we find other witnesses?

Consider a non-witness b such that $b^{n-1} \equiv 1 \pmod{n}$.

Carmichael Number

A Carmicheal number is a composite number n where

$$b^{n-1} \equiv 1 \pmod{n},$$

for every b which are relatively prime to n .

Carmicheal numbers are rare. The smallest is $561 = 3 \cdot 11 \cdot 17$. The next ones are 1105, 1729, and 2465. There are 20,138,200 Carmicheal numbers between 1 and 10^{21} .

So, if we ignore Carmicheal numbers, the Fermat test is very good. There are other probabilistic tests (e.g, Miller-Rabin test) that uses other properties that works for all numbers and there are deterministic algorithms for testing primes.

Lemma 3

If n is not a Carmicheal number, the Fermat test returns that n is a composite with probability at least $1/2$.

Note that if you repeat the test for k times, the probability that it gives the wrong answer is at most $1/2^k$.

Running time

```
Algorithm CheckPrime(n):  
  pick integer a from 2,...,n-1  
  
  if gcd(a,n) != 1:  
    return False  
  
  if power(a,n-1,n) != 1:  
    return False  
  else:  
    return True
```

Special case of Euler's theorem

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

$$a^{(p-1)(q-1)} \equiv 1 \pmod{pq}$$

Theorem 4 (Euler's theorem)

If p and q are different primes, for a such that $\gcd(a, \underline{p}\underline{q}) = 1$, we have

$$a^{(p-1)(q-1)} \equiv 1 \pmod{pq}.$$

↪ used RSA

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Is this useful?

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Is this useful? Yes! In the RSA algorithm.

RSA

- ▶ Private key: (d, n) , Public key: (e, n)
- ▶ Encryption $E(m) = m^e \bmod n$, Decryption: $D(w) = w^d \bmod n$.
- ▶ Goal: Select e, d, n such that $D(E(m)) = m^{ed} \bmod n = m$.

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- ▶ Pick two primes p and q . Let $n = pq$.
- ▶ Pick e (usually a small number)
- ▶ Pick d such that $d = e^{-1} \pmod{(p-1)(q-1)}$, i.e., $ed \equiv 1 \pmod{(p-1)(q-1)}$, or $ed = k \cdot (p-1)(q-1) + 1$, for some integer k .
- ▶ What is $m^{ed} \bmod n$?

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$$\begin{aligned} m^{ed} &\equiv m^{k(p-1)(q-1)+1} \pmod{n} \\ &\equiv (m^{(p-1)(q-1)})^k \cdot m \pmod{n} \\ &\equiv 1^k \cdot m \pmod{n} \\ &\equiv m \pmod{n} \end{aligned}$$

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What is the requirement for m ? $\gcd(m, n) = 1$, otherwise you can use the message to factor n .