

# Solutions to Ireland, Rosen “A Classical Introduction to Modern Number Theory”

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September 25, 2019

## Chapter 4

**Ex. 4.1** Show that 2 is a primitive root modulo 29.

*Proof.* Let  $p = 29 : p - 1 = 2^2 \times 7$ .

$$2^4 = 16 \not\equiv 1 [29]$$

$$2^{14} = 4^7 = 4 \times 16^3 = 64 \times 256 \equiv 6 \times (-34) = -204 \equiv 86 = 3 \times 29 - 1 \equiv -1 [29]$$

$$2^{28} \equiv 1 [29] \text{ and } 2^d \not\equiv 1 \text{ if } d \mid 28, d < 28, \text{ hence 2 is a primitive element modulo 29. } \square$$

**Ex. 4.2** Compute all primitive roots for  $p = 11, 13, 17$ , and 19.

*Proof.* •  $p = 11$ . Then  $p - 1 = 10 = 2 \times 5$ .

$2^2 = 4 \not\equiv 1 \pmod{11}$ , and  $2^5 = 32 \equiv -1 \not\equiv 1 \pmod{11}$ , so 2 is a primitive element modulo 11.

The other primitive elements modulo 11 are congruent to the powers  $2^i, i \wedge 10 = 1, 1 \leq i < 10$ , namely  $2, 2^3, 2^7, 2^9$ .

$$2^7 \equiv 7 \pmod{11}, 2^9 \equiv 6 \pmod{11}, \text{ so}$$

$$\{\bar{2}, \bar{8}, \bar{7}, \bar{6}\} \text{ is the set of the generators of } U(\mathbb{Z}/11\mathbb{Z}).$$

Similarly :

$$\bullet p = 13 : \{2, 6, 11, 7\} \text{ is the set of the generators of } U(\mathbb{Z}/13\mathbb{Z}).$$

$$\bullet p = 17 : \{3, 10, 5, 11, 14, 7, 12, 6\} \text{ is the set of the generators of } U(\mathbb{Z}/17\mathbb{Z}).$$

$$\bullet p = 19 : \{2, 13, 14, 15, 3, 10\} \text{ is the set of the generators of } U(\mathbb{Z}/19\mathbb{Z}).$$

I obtain these results with the direct orders in S.A.G.E. :

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p = 19; Fp = GF(p); a = Fp.multiplicative_generator()
print([a^k for k in range(1,p) if gcd(k,p-1) == 1])
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□

**Ex. 4.3** Suppose that  $a$  is a primitive root modulo  $p^n$ ,  $p$  an odd prime. Show that  $a$  is a primitive root modulo  $p$ .

*Proof.* Suppose that  $a$  is a primitive root modulo  $p^n$  : then  $\bar{a}$  is a generator of  $U(\mathbb{Z}/p^n\mathbb{Z})$ .

If  $a$  was not a primitive root modulo  $p$ ,  $\bar{a}$  is not a generator of  $U(\mathbb{Z}/p\mathbb{Z})$ , so there exists  $b \in \mathbb{Z}, b \wedge p = 1$  such that  $a^k \not\equiv b \pmod{p}$  for all  $k \in \mathbb{Z}$ . A fortiori  $a^k \not\equiv b \pmod{p^n}$ , and  $b \wedge p^n = 1$ , so  $\bar{b} \in U(\mathbb{Z}/p^n\mathbb{Z})$  and  $\bar{b} \notin \langle \bar{a} \rangle$  in  $U(\mathbb{Z}/p^n\mathbb{Z})$ , in contradiction with the hypothesis. So  $a$  is a primitive root modulo  $p$ .

(the reasoning on the orders of  $a$ , modulo  $p$  and modulo  $p^n$ , is possible, but not so easy.) □

**Ex. 4.4** Consider a prime  $p$  of the form  $4t + 1$ . Show that  $a$  is a primitive root modulo  $p$  iff  $-a$  is a primitive root modulo  $p$ .

*Proof.* Solution 1.

As  $p - 1$  is even,  $(-a)^{p-1} = a^{p-1} \equiv 1 \pmod{p}$ .

If  $(-a)^n \equiv 1 \pmod{p}$ , with  $n \in \mathbb{N}$ , then  $a^n \equiv (-1)^n \pmod{p}$ .

If  $n$  is odd, then  $a^n \equiv -1, a^{2n} \equiv 1 \pmod{p}$ . As  $a$  is a primitive root modulo  $p$ ,  $p - 1 \mid 2n$ ,  $2t \mid n$ , so  $n$  is even : this is a contradiction.

Consequently,  $n$  is even, and  $a^n \equiv 1 \pmod{p}$ , so  $p - 1 \mid n$ , so the least  $n \in \mathbb{N}^*$  such that  $a^n \equiv 1 \pmod{p}$  is  $p - 1$  : the order of  $a$  modulo  $p$  is  $p - 1$ ,  $a$  is a primitive root modulo  $p$ .

Reciprocally, if  $-a$  is a primitive root modulo  $p$ , we apply the previous result at  $-a$  to obtain that  $-(-a) = a$  is a primitive root.

Solution 2.

Let  $p - 1 = 2^{a_0} p_1^{a_1} \cdots p_k^{a_k}$  the decomposition of  $p - 1$  in prime factors.

As  $p_i$  is odd for  $i = 1, 2, \dots, k$ ,  $(p - 1)/p_i$  is even, and  $a$  is primitive, so

$$\begin{aligned} (-a)^{(p-1)/p_i} &= a^{(p-1)/p_i} \not\equiv 1 \pmod{p}, \\ (-a)^{(p-1)/2} &= (-a)^{2k} = a^{2k} = a^{(p-1)/2} \not\equiv 1 \pmod{p}. \end{aligned}$$

So the order of  $a$  is  $p - 1$  modulo  $p$  (see Ex. 4.8) :  $a$  is a primitive element modulo  $p$ .  $\square$

**Ex. 4.5** Consider a prime  $p$  of the form  $4t + 3$ . Show that  $a$  is a primitive root modulo  $p$  iff  $-a$  has order  $(p - 1)/2$ .

*Proof.* Let  $a$  a primitive root modulo  $p$ .

As  $a^{p-1} \equiv 1 \pmod{p}$ ,  $p \mid (a^{(p-1)/2} - 1)(a^{(p-1)/2} + 1)$ , so  $p \mid a^{(p-1)/2} - 1$  or  $p \mid a^{(p-1)/2} + 1$ . As  $a$  is a primitive root modulo  $p$ ,  $a^{(p-1)/2} \not\equiv 1 \pmod{p}$ , so

$$a^{(p-1)/2} \equiv -1 \pmod{p}.$$

Hence  $(-a)^{(p-1)/2} = (-1)^{2t+1} a^{(p-1)/2} \equiv (-1) \times (-1) = 1 \pmod{p}$ .

Suppose that  $(-a)^n \equiv 1 \pmod{p}$ , with  $n \in \mathbb{N}$ .

Then  $a^{2n} = (-a)^{2n} \equiv 1 \pmod{p}$ , so  $p - 1 \mid 2n$ ,  $\frac{p-1}{2} \mid n$ .

So  $-a$  has order  $(p - 1)/2$  modulo  $p$ .

Reciprocally, suppose that  $-a$  has order  $(p - 1)/2 = 2t + 1$  modulo  $p$ . Let  $2, p_1, \dots, p_k$  the prime factors of  $p - 1$ , where  $p_i$  are odd.

$a^{(p-1)/2} = a^{2t+1} = -(-a)^{2t+1} = -(-a)^{(p-1)/2} \equiv -1$ , so  $a^{(p-1)/2} \not\equiv 1 \pmod{p}$ .

As  $p - 1$  is even,  $(p - 1)/p_i$  is even, so

$a^{(p-1)/p_i} = (-a)^{(p-1)/p_i} \not\equiv 1 \pmod{p}$  (since  $-a$  has order  $p - 1$ ).

So the order of  $a$  is  $p - 1$  (see Ex. 4.8) :  $a$  is a primitive root modulo  $p$ .  $\square$

**Ex. 4.6** If  $p = 2^{2^n} + 1$  is a Fermat prime, show that 3 is a primitive root modulo  $p$ .

*Proof.* Solution 1 (with quadratic reciprocity).

Write  $p = 2^k + 1$ , with  $k = 2^n$ .

We suppose that  $n > 0$ , so  $k \geq 2, p \geq 5$ . As  $p$  is prime,  $3^{p-1} \equiv 1 \pmod{p}$ .

In other words,  $3^{2^k} \equiv 1 \pmod{p}$  : the order of 3 is a divisor of  $2^k$ , a power of 2.

3 has order  $2^k$  modulo  $p$  iff  $3^{2^{k-1}} \not\equiv 1 \pmod{p}$ . As  $(3^{2^{k-1}})^2 \equiv 1 \pmod{p}$ , where  $p$  is prime, this is equivalent to  $3^{2^{k-1}} \equiv -1 \pmod{p}$ , which remains to prove.

$$3^{2^{k-1}} = 3^{(p-1)/2} \equiv \left(\frac{3}{p}\right) \pmod{p}.$$

As the result is true for  $p = 5$ , we can suppose  $n \geq 2$ . From the law of quadratic reciprocity :

$$\left(\frac{3}{p}\right)\left(\frac{p}{3}\right) = (-1)^{(p-1)/2} = (-1)^{2^{k-1}} = 1.$$

$$\text{So } \left(\frac{3}{p}\right) = \left(\frac{p}{3}\right)$$

$$\begin{aligned} p = 2^{2^n} + 1 &\equiv (-1)^{2^n} + 1 \pmod{3} \\ &\equiv 2 \equiv -1 \pmod{3}, \end{aligned}$$

so  $\left(\frac{3}{p}\right) = \left(\frac{p}{3}\right) = -1$ , that is to say

$$3^{2^{k-1}} \equiv -1 \pmod{p}.$$

The order of 3 modulo  $p = 2^{2^n} + 1$  is  $p - 1 = 2^{2^n} : 3$  is a primitive root modulo  $p$ .  
(On the other hand, if 3 is of order  $p - 1$  modulo  $p$ , then  $p$  is prime, so

$$F_n = 2^{2^n} + 1 \text{ is prime} \iff 3^{(F_n-1)/2} = 3^{2^{2^n}-1} \equiv -1 \pmod{F_n}.)$$

Solution 2 (without quadratic reciprocity, with the hint of chapter 4).

As above, if we suppose that 3 is not a primitive root modulo  $p$ , then  $3^{2^{n-1}} \equiv 1 \pmod{p}$ , so  $n \geq 2$ , and  $(-3)^{(p-1)/2} = 3^{2^{n-1}} \equiv 1 \pmod{p}$ , so  $-3$  is a square modulo  $p$  : there exists  $a \in \mathbb{Z}$  such that  $-3 \equiv a^2 \pmod{p}$ .

As  $2 \wedge p = 1$ , there exists  $u \in \mathbb{Z}$  such that  $2u \equiv -1 + a \pmod{p}$  ( $\bar{u}$  is similar to  $\omega = \frac{-1+i\sqrt{3}}{2} \in \mathbb{C}$ ). Then

$$\begin{aligned} 8u^3 &\equiv (-1 + a)^3 \\ &\equiv -1 + 3a - 3a^2 + a^3 \\ &\equiv -1 + 3a + 9 - 3a \\ &\equiv 8 \pmod{p} \end{aligned}$$

As  $p \wedge 2 = p \wedge 8 = 1$ ,  $u^3 \equiv 1 \pmod{p}$ . Moreover, if  $u \equiv 1 \pmod{3}$ , then  $a \equiv 3 \pmod{p}$ ,  $-3 \equiv 9 \pmod{p}$ ,  $p \mid 12$ , so  $p = 2$  or  $p = 3$ , in contradiction with  $p \geq 5$ . So the order of  $u$  modulo  $p$  is 3 :  $(\mathbb{Z}/p\mathbb{Z})^*$  contains an element  $\bar{u}$  of order 3. So  $3 \mid p - 1$ ,  $p \equiv 1 \pmod{3}$ , but  $p \equiv (-1)^{2^n} + 1 \equiv 2 \equiv -1 \pmod{3}$  : this is a contradiction, so 3 is a primitive root modulo  $p = 2^{2^n} + 1$ .  $\square$

**Ex. 4.7** Suppose that  $p$  is a prime of the form  $8t + 3$  and that  $q = (p - 1)/2$  is also a prime. Show that 2 is a primitive root modulo  $p$ .

*Proof.* The first examples of such couples  $(q, p)$  are  $(5, 11)$ ,  $(29, 59)$ ,  $(41, 83)$ ,  $(53, 107)$ ,  $(89, 179)$ .  
 $p = 2q + 1 = 8t + 3$  and  $p, q$  are prime numbers.

From Fermat's little theorem,  $2^{p-1} \equiv 1 \pmod{p}$ , so  $2^{2q} \equiv 1 \pmod{p}$ .

The order of 2 modulo  $p$  divides  $2q$  : to prove that the order of 2 is  $2q = p - 1$ , it is sufficient to prove

$$2^2 \not\equiv 1 \pmod{p}, \quad 2^q \not\equiv 1 \pmod{p}.$$

If  $2^2 \equiv 1 \pmod{p}$ , then  $p \mid 3$ ,  $p = 3$  and  $q = 1$  :  $q$  is not a prime, so  $2^2 \not\equiv 1 \pmod{p}$ .

If  $2^q = 2^{(p-1)/2} \equiv 1 \pmod{p}$ , then 2 is a square modulo  $p$  (prop. 4.2.1) : there exists  $a \in \mathbb{Z}$  such that  $2 \equiv a^2 \pmod{p}$ .

From the complementary case of law of quadratic reciprocity (see next chapter, prop. 5.1.3), 2 is a square modulo  $p$  iff

$$1 = \left(\frac{2}{p}\right) = (-1)^{(p^2-1)/8}.$$

Yet  $p \equiv 3 \pmod{8}$ , so  $p^2 \equiv 1 \pmod{16}$ ,  $\left(\frac{2}{p}\right) = (-1)^{(p^2-1)/8} = -1$ , so 2 is not a square modulo  $p$ . This is a contradiction, so  $2^q \not\equiv 1 \pmod{p}$  : 2 is a primitive root modulo  $p$ .  $\square$

**Ex. 4.8** Let  $p$  be an odd prime. Show that  $a$  is a primitive root modulo  $p$  iff  $a^{(p-1)/q} \not\equiv 1 \pmod{p}$  for all prime divisors  $q$  of  $p-1$ .

*Proof.* • If  $a$  is a primitive root, then  $a^k \not\equiv 1$  for all  $k$ ,  $1 \leq k < p-1$ , so  $a^{(p-1)/q} \not\equiv 1 \pmod{p}$  for all prime divisors  $q$  of  $p-1$ .

• In the other direction, suppose  $a^{(p-1)/q} \not\equiv 1 \pmod{p}$  for all prime divisors  $q$  of  $p-1$ .

Let  $\delta$  the order of  $a$ , and  $p-1 = q_1^{a_1} q_2^{a_2} \cdots q_k^{a_k}$  the decomposition of  $p-1$  in prime factors. As  $\delta \mid p-1$ ,  $\delta = q_1^{b_1} q_2^{b_2} \cdots q_k^{b_k}$ , with  $b_i \leq a_i$ ,  $i = 1, 2, \dots, k$ . If  $b_i < a_i$  for some index  $i$ , then  $\delta \mid (p-1)/q_i$ , so  $a^{(p-1)/q_i} \equiv 1 \pmod{p}$ , which is in contradiction with the hypothesis. Thus  $b_i = a_i$  for all  $i$ , and  $\delta = q-1$  :  $a$  is a primitive root modulo  $p$ .  $\square$

**Ex. 4.9** Show that the product of all the primitive roots modulo  $p$  is congruent to  $(-1)^{\phi(p-1)}$  modulo  $p$ .

*Proof.* Here we suppose  $p$  prime,  $p > 2$ . Let  $g$  a primitive root modulo  $p$ .  $U(\mathbb{Z}/p\mathbb{Z})$  is cyclic, generated by  $\bar{g}$ :

$$U(\mathbb{Z}/p\mathbb{Z}) = \{\bar{1}, \bar{g}, \bar{g}^2, \dots, \bar{g}^{p-2}\}, \quad \bar{g}^{p-1} = \bar{1}.$$

$\bar{g}^k$  is a primitive element iff  $k \wedge (p-1) = 1$ , so the product of primitive elements in  $U(\mathbb{Z}/p\mathbb{Z})$  is

$$\bar{P} = \prod_{\substack{k \wedge (p-1) = 1 \\ 1 \leq k < p-1}} \bar{g}^k.$$

so  $\bar{P} = \bar{g}^S$ , where  $S = \sum_{\substack{k \wedge (p-1) = 1 \\ 1 \leq k < p-1}} k$ .

From Ex. 2.22, we know that for  $n \geq 2$ ,

$$\sum_{\substack{k \wedge n = 1 \\ 1 \leq k < n}} k = \frac{1}{2} n \phi(n).$$

So  $S = \sum_{\substack{k \wedge (p-1) = 1 \\ 1 \leq k < p-1}} k = \frac{1}{2} (p-1) \phi(p-1)$ .

As  $p > 2$ ,  $p-1$  is even.  $(\bar{g}^{(p-1)/2})^2 = \bar{g}^{p-1} = \bar{1}$ , and  $\bar{g}^{(p-1)/2} \neq \bar{1}$ . As  $\mathbb{Z}/p\mathbb{Z}$  is a field,  $\bar{g}^{(p-1)/2} = -\bar{1}$ .

Thus  $\bar{P} = (-\bar{1})^{\phi(p-1)}$  : so the product  $P$  of all the primitive roots modulo  $p$  is such that

$$P \equiv (-1)^{\phi(p-1)} \pmod{p}.$$

$\square$

**Ex. 4.10** Show that the sum of all the primitive roots modulo  $p$  is congruent to  $\mu(p-1)$  modulo  $p$ .

*Proof.* Notation :  $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$  is the field with  $p$  elements,  $|x|$  the multiplicative order of an element  $x \in \mathbb{F}_p^*$ ,  $\mathbb{N}^* = \{1, 2, 3, \dots\}$ .

Let

$$\psi : \begin{cases} \mathbb{N}^* & \rightarrow \\ n & \mapsto \psi(n) = \sum_{d \in \mathbb{F}_p^*, |d|=n} d \end{cases}$$

$\psi(n)$  is the sum of the elements with order  $n$  in  $\mathbb{F}_p^*$ . So  $\psi(n) = 0$  if  $n \nmid p-1$ , and  $S = \psi(p-1)$  is the sought sum of all the primitive roots modulo  $p$ .

We compute for all  $n \in \mathbb{N}^*$

$$f(n) = \sum_{d|n} \psi(d).$$

$f(n)$  is the sum of elements whose order divides  $n$ , in other words the sum of the roots of  $x^n - 1$ . This sum is, up to the sign, the coefficient of  $x^{n-1}$ , so is null, except in the case  $n = 1$ , where the sum of the unique root 1 of  $x - 1$  is 1. So

$$f(1) = 1, \quad \forall n > 1, f(n) = 0,$$

( $f = \chi_{\{1\}}$  is the characteristic function of  $\{1\}$ ).

From the Möbius inversion formula, for all  $n \in \mathbb{N}^*$ ,  $\psi(n) = \sum_{d|n} \mu\left(\frac{n}{d}\right) f(d)$ , so

$$\psi(p-1) = \sum_{d|p-1} \mu\left(\frac{p-1}{d}\right) f(d) = \mu(p-1).$$

Conclusion :

$$S = \sum_{d \in \mathbb{F}_p^*, |d|=p-1} d = \mu(p-1) :$$

the sum of all the primitive roots modulo  $p$  is congruent to  $\mu(p-1)$  modulo  $p$ .  $\square$

**Ex. 4.11** Prove that  $1^k + 2^k + \dots + (p-1)^k \equiv 0 \pmod{p}$  if  $p-1 \nmid k$ , and  $-1 \pmod{p}$  if  $p-1 \mid k$ .

*Proof.* Let  $S_k = 1^k + 2^k + \dots + (p-1)^k$ .

Let  $g$  a primitive root modulo  $p$  :  $\bar{g}$  a generator of  $\mathbb{F}_p^*$ .

As  $(\bar{1}, \bar{g}, \bar{g}^2, \dots, \bar{g}^{p-2})$  is a permutation of  $(\bar{1}, \bar{2}, \dots, \overline{p-1})$ ,

$$\begin{aligned} \overline{S_k} &= \bar{1}^k + \bar{2}^k + \dots + \overline{p-1}^k \\ &= \sum_{i=0}^{p-2} \bar{g}^{ki} = \begin{cases} \overline{p-1} = -\bar{1} & \text{if } p-1 \mid k \\ \frac{\bar{g}^{(p-1)k} - 1}{\bar{g}^k - 1} = \bar{0} & \text{if } p-1 \nmid k \end{cases} \end{aligned}$$

since  $p-1 \mid k \iff \bar{g}^k = \bar{1}$ .

Conclusion :

$$\begin{aligned} 1^k + 2^k + \dots + (p-1)^k &\equiv 0 \pmod{p} \text{ if } p-1 \nmid k \\ 1^k + 2^k + \dots + (p-1)^k &\equiv -1 \pmod{p} \text{ if } p-1 \mid k \end{aligned}$$

$\square$

**Ex. 4.12** Use the existence of a primitive root to give another proof of Wilson's theorem  $(p-1)! \equiv -1 \pmod{p}$ .

*Proof.* As the result is trivial if  $p = 2$ , we suppose that  $p$  is an odd prime.

Let  $g$  a primitive root modulo  $p$  :  $\bar{g}$  a generator of  $\mathbb{F}_p^*$ .

As  $(\bar{g}^{(p-1)/2})^2 = \bar{g}^{p-1} = \bar{1}$ , and  $\bar{g}^{(p-1)/2} \neq 1$  in the field  $\mathbb{F}_p^*$ , then  $\bar{g}^{(p-1)/2} = -1$ , and  $(\bar{1}, \bar{g}, \bar{g}^2, \dots, \bar{g}^{p-2})$  is a permutation of  $(\bar{1}, \bar{2}, \dots, \overline{p-1})$ , so

$$\begin{aligned} \overline{(p-1)!} &= \prod_{k=0}^{p-2} \bar{g}^k \\ &= \bar{g}^{\sum_{k=0}^{p-2} k} \\ &= \bar{g}^{(p-2)(p-1)/2} \\ &= \left(\bar{g}^{(p-1)/2}\right)^{p-2} \\ &= (-\bar{1})^{p-2} \\ &= -1. \end{aligned}$$

Hence  $(p-1)! \equiv -1 \pmod{p}$  for each prime  $p$ . □

**Ex. 4.13** Let  $G$  be a finite cyclic group and  $g \in G$  a generator. Show that all the other generators are of the form  $g^k$ , where  $(k, n) = 1$ ,  $n$  being the order of  $G$ .

*Proof.* Suppose  $G = \langle g \rangle$ , with  $\text{Card } G = n$ , so the order of  $g$  is  $n$ .

Let  $x$  another generator of  $G$ , then  $x = g^k$ , and  $g = x^l$ ,  $k, l \in \mathbb{Z}$ , so  $g = g^{kl}$ ,  $g^{kl-1} = e$  :  $n \mid kl - 1$ , then  $kl - 1 = qn$ ,  $q \in \mathbb{Z}$ , so  $n \wedge k = 1$ .

Reciprocally, if  $u \wedge k = 1$ , there exist  $u, v \in \mathbb{Z}$  such that  $un + vk = 1$ , so  $g = g^{un+vk} = (g^n)^u (g^k)^v = x^v \in \langle x \rangle$ , so  $G \subset \langle x \rangle$ ,  $G = \langle x \rangle$  :  $x$  is a generator of  $G$ .

Conclusion : if  $g$  is a generator of  $G$ , all the other generators are the elements  $g^k$ , where  $k \wedge n = 1$ ,  $n = |G|$ . □

**Ex. 4.14** Let  $A$  be a finite abelian group and  $a, b \in A$  elements of order  $m$  and  $n$ , respectively. If  $(m, n) = 1$ , prove that  $ab$  has order  $mn$ .

*Proof.* Suppose  $|a| = m$ ,  $|b| = n$ ,  $m \wedge n = 1$ .

• If  $(ab)^k = e$ , then  $a^k = b^{-k}$ , so  $a^{kn} = b^{-kn} = (b^n)^{-k} = e$ , so  $m \mid kn$ , with  $m \wedge n = 1$ , so  $m \mid k$ .

Similarly,  $b^{km} = a^{-km} = (a^m)^{-k} = e$ , so  $n \mid km$ ,  $n \wedge m = 1$  :  $n \mid k$ .

As  $n \mid k$ ,  $m \mid k$ ,  $n \wedge m = 1$ ,  $nm \mid k$ .

• Reciprocally, if  $nm \mid k$ ,  $nm = qnm$ ,  $q \in \mathbb{Z}$ , so  $(ab)^k = a^k b^k = (a^m)^{qn} (b^n)^{qm} = e$ .

$$\forall k \in \mathbb{Z}, (ab)^k = e \iff nm \mid k.$$

So  $|ab| = nm$ . □

**Ex. 4.15** Let  $K$  be a field and  $G \subset K^*$  a finite subgroup of the multiplicative group of  $K$ . Extend the arguments used in the proof of Theorem 4.1 to show that  $G$  is cyclic.

**Solution 1.**

*Proof.* Let  $n = |G|$ . From Lagrange's theorem,  $a^n = 1$  for all  $a \in G$ , so the polynomial  $x^n - 1 \in K[x]$  has exactly  $n$  roots in  $G$ , and so

$$\forall x \in K, x \in G \iff x^n = 1.$$

If  $d \mid n$ , the polynomial  $x^d - 1 \in K[x]$  has exactly  $d$  roots in  $K$  otherwise  $x^n - 1 = (x^d - 1)g(x)$ ,  $g(x) \in K[x]$ , and  $\deg(g) = n - d$  has at most  $n - d$  roots, so  $x^n - 1$  would have less than  $n$  roots in  $K$ . As  $x_0^d = 1 \Rightarrow x_0^n = 1$ , all these roots are in  $G$ :  $x^d - 1$  has  $d$  roots in  $G$ .

Let  $\psi(d)$  the number of elements in  $G$  of order  $d$  ( $\psi(d) = 0$  if  $d \nmid n$ ). Then  $\sum_{c \mid d} \psi(c) = d$ . Applying the Möbius inversion theorem,  $\psi(d) = \sum_{c \mid d} \mu(c) d/c = \Phi(d)$  (Prop. 2.2.5), in particular,  $\psi(n) = \phi(n) > 1$  if  $n > 2$ . Since a group of order 2 is cyclic, we have shown in all cases the existence of an element of order  $n$  in  $G$ , so  $G$  is cyclic.

(variation :  $\psi(d) = 0$  if there exists no element of order  $d$ , and  $\psi(d) = \phi(d)$  otherwise : see Ex.4.13. So  $\psi(d) \leq \phi(d)$  for all  $d \mid n$ . As  $\sum_{d \mid n} \psi(d) = \sum_{d \mid n} \phi(d) = n$ ,  $\psi(d) = \phi(d)$  for all  $d \mid n$ . So there exists in  $G$  an element of order  $n$ , and  $G$  is cyclic.)  $\square$

### Solution 2.

*Proof.* Let  $n = |G| = p_1^{a_1} \cdots p_k^{a_k}$ . From Lagrange's theorem,  $y^n = 1$  for all  $y \in G$ .

$p(x) = x^{n/p_1} - 1 \in K[x]$  has at most  $n/p_1 < n$  roots in  $K^*$ , a fortiori in  $G$ , so there exists  $a \in G$  such that  $a^{n/p_1} \neq 1$ .

Let  $c_1 = a^{n/p_1^{a_1}} = a^{p_2^{a_2} \cdots p_k^{a_k}}$ . Then  $c_1^{p_1^{a_1}} = 1$  and  $c_1^{p_1^{a_1-1}} = a^{n/p_1} \neq 1$ , so  $|c_1| = p_1^{a_1}$ .

Similarly, there exist  $c_2, \dots, c_k$  with respective orders  $|c_i| = p_i^{a_i}$ .

From exercise 4.14, we obtain by induction that  $c = c_1 \cdots c_k$  has order  $p_1^{a_1} \cdots p_k^{a_k} = n$ , so  $G$  is cyclic.  $\square$

**Ex. 4.16** Calculate the solutions to  $x^3 \equiv 1 \pmod{19}$  and  $x^4 \equiv 1 \pmod{17}$ .

*Proof.* Here we note  $a$  the class of  $a$  in  $\mathbb{Z}/p\mathbb{Z}$ .

Let  $x \in \mathbb{F}_{19}$ .  $x^3 - 1 = 0 \iff x - 1 = 0$  or  $x^2 + x + 1 = 0$ .

$$\begin{aligned} x^2 + x + 1 = 0 &\iff (x + 10) - 99 = 0 \\ &\iff (x + 10)^2 - 4 = 0 \\ &\iff (x + 8)(x + 12) = 0 \end{aligned}$$

So, for all  $x \in \mathbb{Z}$ ,

$$x^3 \equiv 1 \pmod{19} \iff x \equiv 1, 7, 11 \pmod{19}.$$

Let  $x \in \mathbb{F}_{17}$ .

$$\begin{aligned} x^4 = 1 &\iff x^2 = 1 \text{ or } x^2 = -1 = 4^2 \\ &\iff x = \pm 1 \text{ or } x = \pm 4 \end{aligned}$$

So, for all  $x \in \mathbb{Z}$ ,

$$x^4 \equiv 1 \pmod{17} \iff x \equiv -1, 1, -4, 4 \pmod{17}.$$

Alternatively, we can take primitives roots modulo 19 and 17.

2 is a primitive root modulo 19, Let  $x = 2^k \in \mathbb{F}_{19}$ .

$$\begin{aligned} x^3 = 1 &\iff 2^{3k} = 1 \\ &\iff 18 \mid 3k \\ &\iff 6 \mid k \\ &\iff x = 1, 2^6 = 7, 2^{12} = 11 \end{aligned}$$

3 is a primitive root modulo 17. Let  $x = 3^k \in \mathbb{F}_{17}$ .

$$\begin{aligned} x^4 = 1 &\iff 3^{4k} = 1 \\ &\iff 16 \mid 4k \\ &\iff 4 \mid k \\ &\iff x = 1, 3^4 = -4, 3^8 = -1, 3^{12} = 4 \end{aligned}$$

□

**Ex. 4.17** Use the fact that 2 is a primitive root modulo 29 to find the seven solutions to  $x^7 \equiv 1 \pmod{29}$ .

*Proof.* Let  $x \in \mathbb{Z}$ , then  $x \equiv 2^k \pmod{29}, k \in \mathbb{N}$ .

$$\begin{aligned} x^7 \equiv 1 \pmod{29} &\iff 2^{7k} \equiv 1 \pmod{29} \\ &\iff 28 \mid 7k \\ &\iff 4 \mid k \end{aligned}$$

So the group cyclic  $S$  of the roots of  $x^7 - 1$  in  $\mathbb{F}_{29}$  are

$$\begin{aligned} S &= \{1, 2^4, 2^8, 2^{12}, 2^{16}, 2^{20}, 2^{24}\}, \\ S &= \{1, 16, 24, 7, 25, 23, 20\}. \end{aligned}$$

□

**Ex. 4.18** Solve the congruence  $1 + x + \cdots + x^6 \equiv 0 \pmod{29}$ .

*Proof.* As  $(1 + x + \cdots + x^6)(1 - x) = 1 - x^7$ ,

$$1 + x + \cdots + x^6 \equiv 0 \pmod{29} \iff \begin{cases} x^7 \equiv 1 \pmod{29} \\ x \not\equiv 1 \pmod{29} \end{cases}$$

From Ex. 4.17, the solutions are congruent to  $2^4, 2^8, 2^{12}, 2^{16}, 2^{20}, 2^{24}$  modulo 29. □

**Ex. 4.19** Determine the numbers  $a$  such that  $x^3 \equiv a \pmod{p}$  is solvable for  $p = 7, 11, 13$ .

*Proof.* (a) If  $p = 7$ , then  $3 \mid p - 1, d = 3 \wedge (p - 1) = 3$ . From Prop. 4.2.1,

$$\exists x \in \mathbb{Z}, a \equiv x^3 \pmod{7} \iff a \equiv 0 \pmod{7} \text{ or } a^{(p-1)/3} = a^2 \equiv 1 \pmod{7}.$$

So the numbers  $a$  such that  $x^3 \equiv a \pmod{7}$  is solvable are congruent at  $0, 1, -1$  modulo 7.



(b) If  $p = 11$ , then  $d = 3 \wedge (p - 1) = 1$ . With the same proposition,

$$\exists x \in \mathbb{Z}, a \equiv x^3 \pmod{11} \iff a \equiv 0 \pmod{11} \text{ or } a^{p-1} = a^6 \equiv 1 \pmod{11}.$$

So all integers  $a$  are cube modulo 11, in only one way.

For an alternative proof, the application

$$f : \begin{cases} \mathbb{F}_{11}^* & \rightarrow \mathbb{F}_{11}^* \\ x & \mapsto x^3 \end{cases}$$

$f$  is a bijection. Indeed,

- $f$  is a group homomorphism,
- $x^3 = 1 \Rightarrow (x^3)^7 = 1 \Rightarrow x = 1$  so  $\ker(f) = \{1\}$ ,
- $f : \mathbb{F}_{11}^* \rightarrow \mathbb{F}_{11}^*$  is injective and  $\mathbb{F}_{11}^*$  is finite, so  $f$  is bijective.

In  $\mathbb{F}_{11}$ ,  $0 = 0^3, 1 = 1^3, 2 = 7^3, 3 = 9^3, 4 = 5^3, 5 = 3^3, 6 = 8^3, 7 = 6^3, 8 = 2^3, 9 = 4^3, 10 = 10^3$ .

(c) If  $p = 13$ , then  $3 \mid p - 1, 3 \wedge (p - 1) = 3$ , so

$$\begin{aligned} \exists x \in \mathbb{Z}, a \equiv x^3 \pmod{13} &\iff a \equiv 0 \pmod{13} \text{ or } a^{(p-1)/3} = a^4 \equiv 1 \pmod{13} \\ &\iff a \equiv 0, 1, -1, 5, -5 \pmod{13} \end{aligned}$$

$$(5 \equiv 8^3 \pmod{13}).$$

□

**Ex. 4.20** Let  $p$  be a prime, and  $d$  a divisor of  $p - 1$ . Show that  $d$ th powers form a subgroup of  $U(\mathbb{Z}/p\mathbb{Z})$  of order  $(p - 1)/d$ . Calculate this subgroup for  $p = 11, d = 5$ , for  $p = 17, d = 4$ , and for  $p = 19, d = 6$ .

*Proof.* Here  $p$  is a prime number, and  $d \mid p - 1$ . Let

$$f : \begin{cases} \mathbb{F}_p^* & \rightarrow \mathbb{F}_p^* \\ x & \rightarrow x^d \end{cases}$$

Then  $f$  is a group homomorphism, and  $\text{im}(f)$  is the set of  $d$ th powers, and consequently is a subgroup of  $U(\mathbb{F}_p) = \mathbb{F}_p^*$ .  $\ker(f)$  is the group of the roots of  $x^d - 1$ . As  $d \mid p - 1$ , the polynomial  $x^d - 1$  has exactly  $d$  roots (Prop. 4.1.2), so  $|\ker(f)| = d$ .

As  $\text{im}(f) \simeq \mathbb{F}_p^* / \ker(f)$ ,

$$|\text{im}(f)| = |\mathbb{F}_p^*| / |\ker(f)| = (p - 1)/d.$$

So there exist exactly  $(p - 1)/d$   $d$ th powers in  $(\mathbb{Z}/p\mathbb{Z})^*$ .

From Prop. 4.2.1, as  $d \mid p - 1, d \wedge p - 1$ , for all  $x \in \mathbb{F}_p^*$ ,

$$x \in \text{im}(f) \iff x^{(p-1)/d} = 1.$$

So the group of  $d$ th powers is the group of the roots of  $x^{(p-1)/d} - 1$ .

- If  $p = 11, d = 5$ ,  $\text{im}(f) = \{1, -1\}$ .
- If  $p = 17, d = 4$ ,  $x \in \text{im}(f) \iff x^4 = 1 : \text{im}(f) = \{1, -1, 4, -4\}$ .
- If  $p = 19, d = 6$ ,  $x \in \text{im}(f) \iff x^3 = 1 : \text{im}(f) = \{1, 7, 7^2 = 11\}$ , where  $7 \equiv 2^6 \pmod{19}$ .

□

**Ex. 4.21** If  $g$  is a primitive root modulo  $p$ , and  $d|p-1$ , show that  $g^{(p-1)/d}$  has order  $d$ . Show also that  $a$  is a  $d$ th power iff  $a \equiv g^{kd} \pmod{p}$  for some  $k$ . Do Exercises 16-20 making use of those observations.

*Proof.* Let  $x = \bar{g}^{(p-1)/d} \in \mathbb{F}_p^*$ , where  $g$  is a primitive root modulo  $p$ . For all  $k \in \mathbb{Z}$ ,

$$\begin{aligned} x^k = 1 &\iff g^{k \frac{p-1}{d}} = 1 \\ &\iff p-1 \mid k \frac{p-1}{d} \\ &\iff d \mid k \end{aligned}$$

So the order of  $\bar{g}^{(p-1)/d}$  is  $d$ .

- If  $\bar{a} = \bar{g}^{kd}$ , then  $\bar{a} = x^k$ , where  $x = \bar{g}^{(p-1)/d}$ , so  $\bar{a}$  is a  $d$ th power.
- If  $\bar{a} \neq \bar{0}$  is a  $d$ th power,  $\bar{a} = x^k, x \in \langle \bar{g} \rangle$ ,  $x = \bar{g}^k$ , so  $\bar{a} = \bar{g}^{kd}$ .

So, if  $a \not\equiv 0 \pmod{p}$ ,  $a$  is a  $d$ th power iff  $a \equiv g^{kd} \pmod{p}$  for some  $k$ .

By example (Ex. 4.20), 2 is a primitive root modulo 19, so the 6th powers modulo 19 are  $2^0 = 1, 2^6 = 7, 2^{12} = 11$ .  $\square$

**Ex. 4.22** If  $a$  has order 3 modulo  $p$ , show that  $1+a$  has order 6.

*Proof.* If  $a$  has order 3 modulo  $p$ , then  $0 \equiv a^3 - 1 = (a-1)(a^2 + a + 1) \pmod{p}$ , with  $a \not\equiv 1 \pmod{p}$ , so  $a^2 + a + 1 \equiv 0 \pmod{p}$ . Thus

$$\begin{aligned} (1+a)^3 &\equiv 1 + 3a + 3a^2 + a^3 \\ &\equiv 1 + 3a + 3(-1-a) + 1 \\ &\equiv -1 \pmod{p} \end{aligned}$$

So  $(1+a)^6 \equiv 1 \pmod{p}$ .

$$(1+a)^2 \equiv 1 + 2a + a^2 = 1 + 2a + (-1-a) \equiv a \not\equiv 1 \pmod{p}.$$

So  $(1+a)^6 \equiv 1, (1+a)^2 \not\equiv 1, (1+a)^3 \not\equiv 1 \pmod{p}$ , so the order of  $1+a$  divides 6, but doesn't divide 2 or 3, so  $1+a$  has order 6 modulo  $p$ .  $\square$

**Ex. 4.23** Show that  $x^2 \equiv -1 \pmod{p}$  has a solution iff  $p \equiv 1 \pmod{4}$ , and that  $x^4 \equiv -1 \pmod{p}$  has a solution iff  $p \equiv 1 \pmod{8}$ .

*Proof.* If  $x^2 \equiv -1 \pmod{p}$ , then  $\bar{x}$  has order 4 in  $\mathbb{F}_p^*$ , hence from Lagrange's theorem,  $4 \mid p-1$ .

Reciprocally, suppose  $4 \mid p-1$ , so  $p = 4k+1, k \in \mathbb{N}^*$ . From proposition 4.2.1, as  $2 \mid p-1$ ,  $-1$  is a square modulo  $p$  iff  $(-1)^{(p-1)/2} \equiv 1 \pmod{p}$ , which is true because  $(-1)^{(p-1)/2} = (-1)^{2k} = 1$ .

If  $x^4 \equiv -1 \pmod{p}$ , then  $\bar{x}^8 = 1 \in \mathbb{F}_p^*$ , and  $\bar{x}^4 \neq 1$ , so  $x$  has order 8 in  $\mathbb{F}_p^*$ , so  $8 \mid p-1$ .

Reciprocally, if  $p \equiv 1 \pmod{8}$ ,  $p = 8K+1, K \in \mathbb{N}^*$ . From Prop.4.2.1, as  $4 \mid p-1$ , there exists  $x \in \mathbb{Z}$  such that  $-1 = x^4$  iff  $(-1)^{(p-1)/4} \equiv 1 \pmod{8}$ , which is true because  $(-1)^{(p-1)/4} = (-1)^{2K} = 1$ .

Conclusion :

$$\exists x \in \mathbb{Z}, x^4 \equiv -1 \pmod{p} \iff p \equiv 1 \pmod{8}.$$

$\square$

**Ex. 4.24** Show that  $ax^m + by^n \equiv c \pmod{p}$  has the same number of solutions as  $ax^{m'} + by^{n'} \equiv c \pmod{p}$ , where  $m' = (m, p-1)$  and  $n' = (n, p-1)$ .

*Proof.* If  $a \wedge b \nmid c$ , the two equations have no solution. So we can suppose  $a \wedge b \mid c$ , and after division by  $\delta = a \wedge b$ , we obtain an equation  $a'x^m + b'y^n = c'$ ,  $a' = a/\delta, b' = b\delta, c' = c\delta$ , and  $a' \wedge b' = 1$ . So it remains to prove that  $ax^m + by^n \equiv c \pmod{p}$  has the same number of solutions as  $ax^{m'} + by^{n'} \equiv c \pmod{p}$  when  $a \wedge b = 1$ .

In this case the equation  $au + bv = c$  has solutions. Let  $N$  the number of solutions  $(\bar{x}, \bar{y})$  of the equation  $\bar{a}\bar{x}^m + \bar{b}\bar{y}^n = \bar{c}$ ,  $N'$  the number of solutions  $(\bar{x}, \bar{y})$  of the equation  $\bar{a}\bar{x}^{m'} + \bar{b}\bar{y}^{n'} = \bar{c}$ . Then

$$\begin{aligned} N &= \text{Card}\{(\bar{x}, \bar{y}) \in \mathbb{F}_p \times \mathbb{F}_p \mid \bar{a}\bar{x}^m + \bar{b}\bar{y}^n = \bar{c}\} \\ &= \sum_{\bar{a}\bar{u} + \bar{b}\bar{v} = \bar{c}} \text{Card}\{(\bar{x}, \bar{y}) \in \mathbb{F}_p \times \mathbb{F}_p \mid \bar{x}^m = \bar{u}, \bar{y}^n = \bar{v}\} \\ &= \sum_{\bar{a}\bar{u} + \bar{b}\bar{v} = \bar{c}} \text{Card}\{\bar{x} \in \mathbb{F}_p \mid \bar{x}^m = \bar{u}\} \times \text{Card}\{\bar{y} \in \mathbb{F}_p \mid \bar{y}^n = \bar{v}\}. \end{aligned}$$

The same is true for  $N'$ , so it is sufficient to prove that

$$\text{Card}\{\bar{x} \in \mathbb{F}_p \mid \bar{x}^m = \bar{u}\} = \text{Card}\{\bar{x} \in \mathbb{F}_p \mid \bar{x}^{m'} = \bar{u}\},$$

where  $m' = m \wedge (p-1)$ , and a similar equality for the equation  $\bar{y}^n = \bar{v}$ .

Let  $\bar{g}$  a generator of  $\mathbb{F}_p^*$ . Write  $\bar{u} = \bar{g}^r, r \in \mathbb{N}$ .

$$\begin{aligned} \exists \bar{x} \in \mathbb{F}_p, \bar{x}^m = \bar{u} &\iff \exists k \in \mathbb{Z}, \bar{g}^{mk} = \bar{g}^r \\ &\iff \exists k \in \mathbb{Z}, p-1 \mid mk - r \\ &\iff \exists k \in \mathbb{Z}, \exists l \in \mathbb{Z}, r = mk + l(p-1) \\ &\iff m \wedge (p-1) \mid r \end{aligned}$$

So

$$\{\bar{x} \in \mathbb{F}_p \mid \bar{x}^m = \bar{u}\} \neq \emptyset \iff m \wedge (p-1) \mid r,$$

and similarly

$$\{\bar{x} \in \mathbb{F}_p \mid \bar{x}^{m'} = \bar{u}\} \neq \emptyset \iff m' \wedge (p-1) \mid r.$$

Since  $m' \wedge (p-1) = (m \wedge (p-1)) \wedge (p-1) = m \wedge (p-1)$ , these two conditions are equivalent, so these two sets are empty for the same values of  $\bar{u}$ .

Let  $\bar{u}$  is such that  $\{\bar{x} \in \mathbb{F}_p \mid \bar{x}^m = \bar{u}\} \neq \emptyset$ , and  $x_0$  a fixed solution of  $\bar{x}^m = \bar{u}$ .

Write  $\bar{x} = \bar{g}^k, \bar{x}_0 = \bar{g}^{k_0}$ . Let  $d = m \wedge (p-1) (= m')$ .

$$\begin{aligned} \bar{x}^m = u &\iff \bar{x}^m = \bar{x}_0^m \\ &\iff \bar{g}^{mk} = \bar{g}^{mk_0} \\ &\iff p-1 \mid m(k - k_0) \\ &\iff \frac{p-1}{d} \mid \frac{m}{d}(k - k_0) \\ &\iff \frac{p-1}{d} \mid k - k_0 \\ &\iff \exists j \in \mathbb{Z}, k = k_0 + j \frac{p-1}{d} \end{aligned}$$

As  $g$  is a primitive root modulo  $p$ , the distinct solutions are  $x_0, x_0g^{\frac{p-1}{d}}, \dots, x_0g^{k\frac{p-1}{d}}, \dots, x_0g^{(d-1)\frac{p-1}{d}}$ , so in this case

$$\text{Card}\{\bar{x} \in \mathbb{F}_p \mid \bar{x}^m = \bar{u}\} = d = m \wedge (p-1).$$

As  $m' \wedge (p-1) = m \wedge (p-1)$ ,

$$\text{Card}\{\bar{x} \in \mathbb{F}_p \mid \bar{x}^m = \bar{u}\} = \text{Card}\{\bar{x} \in \mathbb{F}_p \mid \bar{x}^{m'} = \bar{u}\}.$$

So  $N = N' : ax^m + by^n \equiv c \pmod{p}$  has the same number of solutions as  $ax^{m'} + by^{n'} \equiv c \pmod{p}$ , where  $m' = (m, p-1)$  and  $n' = (n, p-1)$ .  $\square$

**Ex. 4.25** Prove Propositions 4.2.2 and 4.2.4.

**Proposition 4.2.2.** Suppose that  $a$  is odd,  $e \geq 3$ , and consider the congruence  $x^n \equiv a \pmod{2^e}$ . If  $n$  is odd, a solution always exists and it is unique.

If  $n$  is even, a solution exists iff  $a \equiv 1 \pmod{4}$ ,  $a^{2^{e-2}/d} \equiv 1 \pmod{2^e}$ , where  $d = (n, 2^{e-2})$ . When a solution exists there are exactly  $2d$  solutions.

*Proof.* We suppose that  $a$  is odd and  $e \geq 3$ .

From Theorem 2', we know that  $\{(-1)^a 5^b \mid 0 \leq a \leq 1, 0 \leq b \leq 2^{e-2}\}$  constitutes a reduced residue system modulo  $2^e$ , so we can write

$$\begin{aligned} a &\equiv (-1)^s 5^t \pmod{2^e}, 0 \leq s \leq 1, 0 \leq t \leq 2^{e-2}, \\ x &\equiv (-1)^y 5^z \pmod{2^e}, 0 \leq y \leq 1, 0 \leq z \leq 2^{e-2}. \end{aligned}$$

For all  $x \in \mathbb{Z}$ ,

$$x^n \equiv a \pmod{2^e} \iff (-1)^{ny} 5^{nz} \equiv (-1)^s 5^t \pmod{2^e}$$

Then  $(-1)^{ny} \equiv (-1)^s \pmod{4}$ ,  $ny \equiv s \pmod{2}$ ,  $(-1)^{ny} = (-1)^s$ , so  $5^{nz} \equiv 5^t \pmod{2^e}$ .

Reciprocally, if  $ny \equiv s \pmod{2}$  and  $5^{nz} \equiv 5^t \pmod{2^e}$ , then  $x^n \equiv a \pmod{2^e}$ , so

$$x^n \equiv a \pmod{2^e} \iff \begin{cases} ny \equiv s \pmod{2} \\ 5^{nz} \equiv 5^t \pmod{2^e} \end{cases} \iff \begin{cases} ny \equiv s \pmod{2} \\ nz \equiv t \pmod{2^{e-2}} \end{cases}$$

since the order of 5 modulo  $2^e$  is  $2^{e-2}$ .

• Suppose that  $n$  is an odd integer. Then

$$\begin{cases} ny \equiv s \pmod{2} \\ nz \equiv t \pmod{2^{e-2}} \end{cases} \iff \begin{cases} y \equiv s \pmod{2} \\ z \equiv n't \pmod{2^{e-2}} \end{cases}$$

where  $n'$  is an inverse of  $n$  modulo  $2^{e-2}$ :  $nn' \equiv 1 \pmod{2^{e-2}}$ .

So  $x^n \equiv a \pmod{2^e}$  has an unique solution modulo  $2^e$ .

• Suppose that  $n$  is an even integer.

Then  $\begin{cases} ny \equiv s \pmod{2} \\ nz \equiv t \pmod{2^{e-2}} \end{cases}$  implies  $s \equiv 0 \pmod{2}$  and  $d = n \wedge 2^{e-2} \mid t$ .

Then  $a \equiv (-1)^s 5^t \equiv 5^t \pmod{2^e}$ , so  $a \equiv 1 \pmod{4}$ .

Hence  $a^{\frac{2^{e-2}}{d}} \equiv \left(5^{2^{e-2}}\right)^{\frac{t}{d}} \equiv 1 \pmod{2^e}$ , since 5 has order  $2^{e-2}$ , and  $d \mid t$ .

So, if  $n$  is even, and  $d = n \wedge 2^{e-2}$ ,

$$\exists x \in \mathbb{Z}, x^n \equiv a \pmod{2^e} \Rightarrow \begin{cases} a \equiv 1 \pmod{4} \\ a^{\frac{2^{e-2}}{d}} \equiv 1 \pmod{2^e} \end{cases}$$

Reciprocally, suppose that  $\begin{cases} a \equiv 1 \pmod{4} \\ a^{\frac{2^{e-2}}{d}} \equiv 1 \pmod{2^e} \end{cases}$ . Then  $a \equiv (-1)^s 5^t \pmod{2^e}$  implies  $a \equiv (-1)^s \pmod{4}$ , so  $s$  is even, and  $a \equiv 5^t \pmod{2^e}$ .

Therefore  $5^{t\frac{2^{e-2}}{d}} \equiv 1 \pmod{2^e}$ , which implies  $2^{e-2} \mid t\frac{2^{e-2}}{d}$ , so  $d \mid t$ .

$$\begin{aligned} \exists x \in \mathbb{Z}, x^n \equiv a \pmod{2^e} &\iff \exists y \in \mathbb{Z}, \exists z \in \mathbb{Z}, \begin{cases} ny \equiv s \pmod{2} \\ nz \equiv t \pmod{2^{e-2}} \end{cases} \\ &\iff \exists z \in \mathbb{Z}, nz \equiv t \pmod{2^{e-2}} \quad (\text{since } n, s \text{ even}) \\ &\iff \exists z \in \mathbb{Z}, 2^{e-2} \mid nz - t \\ &\iff \exists z \in \mathbb{Z}, \frac{2^{e-2}}{d} \mid \frac{n}{d}z - \frac{t}{d} \\ &\iff \exists z \in \mathbb{Z}, \exists q \in \mathbb{Z}, q\frac{2^{e-2}}{d} + z\frac{n}{d} = \frac{t}{d} \end{aligned}$$

As  $\frac{2^{e-2}}{d} \wedge \frac{n}{d} = 1$ , there exists a solution  $(q, z_0)$  of this last equation, where  $0 \leq z_0 < \frac{2^{e-2}}{d}$ , and so  $x_0 = 5^{z_0}$  is a particular solution of  $x^n \equiv a \pmod{2^e}$ , therefore

$$\exists x \in \mathbb{Z}, x^n \equiv a \pmod{2^e} \iff \begin{cases} a \equiv 1 \pmod{4} \\ a^{\frac{2^{e-2}}{d}} \equiv 1 \pmod{2^e} \end{cases}$$

If there exists a particular solution  $x_0 \equiv (-1)^{y_0} 5^{z_0}$ , then

$$\begin{aligned} x^n \equiv a \pmod{2^e} &\iff x^n \equiv x_0^n \pmod{2^e} \\ &\iff \begin{cases} ny \equiv ny_0 \pmod{2} \\ nz \equiv nz_0 \pmod{2^{e-2}} \end{cases} \\ &\iff n(z - z_0) \equiv 0 \pmod{2^{e-2}} \quad (\text{since } n \text{ even}) \\ &\iff \frac{2^{e-2}}{d} \mid \frac{n}{d}(z - z_0) \\ &\iff \frac{2^{e-2}}{d} \mid z - z_0, \quad (\text{since } \frac{2^{e-2}}{d} \wedge \frac{n}{d} = 1) \\ &\iff \exists k \in \mathbb{Z}, z = z_0 + k\frac{2^{e-2}}{d} \end{aligned}$$

As the order of 5 modulo  $2^e$  is  $2^{e-2}$ , the solutions of  $x^n \equiv a \pmod{2^e}$  are

$$x_k = (-1)^{y_0} 5^{z_0 + k\frac{2^{e-2}}{d}}, \quad 0 \leq y < 2, \quad 0 \leq k < d,$$

so there are exactly  $2d$  solutions modulo  $2^e$ . □

**Proposition 4.2.4.** *Let  $2^l$  be the highest power of 2 dividing  $n$ . Suppose that  $a$  is odd and that  $x^n \equiv a \pmod{2^{2l+1}}$  is solvable. Then  $x^n \equiv a \pmod{2^e}$  is solvable for all  $e \geq 2l + 1$ , and consequently for all  $e \geq 1$ . Moreover, all these congruences have the same number of solutions.*

*Proof.* We suppose that  $a$  is odd, and that  $x^n \equiv a \pmod{2^{2l+1}}$  is solvable.  $l$  is such that  $n = 2^l n'$ , where  $n'$  is an odd integer.

Let the induction hypothesis be, for a fixed integer  $m \geq 2l + 1$ ,

$$\exists x_0 \in \mathbb{Z}, x_0^n \equiv a \pmod{2^m}.$$

Let  $x_1 = x_0 + b2^{m-l}$  : we show that for an appropriate choice of  $b \in \{0, 1\}$ ,  $x_1^n \equiv a \pmod{2^{m+1}}$ .

$$x_1^n = x_0^n + nb2^{m-l}x_0^{n-1} + 2^{2m-2l}A, \quad A \in \mathbb{Z}.$$

Since  $m \geq 2l + 1$ ,  $2m - 2l \geq m + 1$ , so

$$x_1^n \equiv x_0^n + nb2^{m-l}x_0^{n-1} \pmod{2^{m+1}}.$$

$$\begin{aligned} x_1^n \equiv a \pmod{2^{m+1}} &\iff (x_0^n - a) + n'bx_0^{n-1}2^m \equiv 0 \pmod{2^{n+1}} \\ &\iff \frac{x_0^n - a}{2^m} + n'bx_0^{n-1} \equiv 0 \pmod{2} \end{aligned}$$

As  $a$  is odd, and  $x_0^n \equiv a \pmod{2^m}$ ,  $m \geq 1$ ,  $x_0$  is odd, and  $n'$  is odd, so there exists a unique  $b \in \{0, 1\}$  such that  $\frac{x_0^n - a}{2^m} + n'bx_0^{n-1} \equiv 0 \pmod{2}$ . So there exists  $x_1 \in \mathbb{Z}$  such that  $x_1^n \equiv a \pmod{2^{m+1}}$ , and the induction is completed. Therefore,  $x^n \equiv a \pmod{2^e}$  is solvable for all  $e \geq 2l + 1$ , and consequently for all  $e \geq 1$ .

From the Proposition 4.2.2., with the hypothesis  $e \geq 3$ , we know that the number of solutions of the solvable equation  $x^n \equiv a \pmod{2^e}$ ,  $e \geq 2l + 1$ , is 1 if  $n$  is odd,  $2(n \wedge 2^{e-2})$  if  $n$  is even.

If  $n$  is even,  $l \geq 1$ ,  $e \geq 2l + 1 \geq 3$ . Since  $e \geq 2l + 1$ , and  $n = 2^l n'$  for an odd  $n'$ ,  $l \leq \frac{e-1}{2} \leq e - 2$ , so  $n \wedge 2^{e-2} = n'2^l \wedge 2^{e-2} = 2^l$ , and the number of solutions is  $2^{l+1}$ , independent of  $e \geq 2l + 1$ .

Conclusion : under the hypothesis  $x^n \equiv a \pmod{2^{2l+1}}$ , where  $l = \text{ord}_2(n)$ , then  $x^n \equiv a \pmod{2^e}$  is solvable for all  $e \geq 1$ , and all these congruences have the same number of solutions for  $e \geq 2l + 1$ ,  $e \geq 3$ .  $\square$

## Chapter 5

**Ex. 5.1** Use Gauss' lemma to determine  $\left(\frac{5}{7}\right)$ ,  $\left(\frac{3}{11}\right)$ ,  $\left(\frac{6}{13}\right)$ ,  $\left(\frac{-1}{p}\right)$ .

*Proof.* •  $a = 5, p = 7$ .

The array of values of the least residues modulo  $p = 7$ , for  $1 \leq k \leq (p-1)/2$ .

$k \pmod{7}$	1	2	3
$5k \pmod{7}$	-2	3	1

So the number of negative least residues is  $\mu = 1$ , and  $\left(\frac{5}{7}\right) = (-1)^\mu = -1$ .

•  $a = 3, p = 11$ .

$k \pmod{11}$	1	2	3	4	5
$3k \pmod{11}$	3	-5	-2	1	4

So  $\mu = 2$ ,  $\left(\frac{3}{11}\right) = (-1)^\mu = 1$ .

•  $a = 6, p = 13$ .

$k \pmod{13}$	1	2	3	4	5	6
$6k \pmod{13}$	6	-1	5	-2	4	-3

So  $\mu = 3$ ,  $\left(\frac{6}{13}\right) = (-1)^\mu = -1$ .

• If  $a = -1$ , and  $p$  an odd prime, the values of the least residues of  $-k$  modulo  $p$  for  $k = 1, 2, \dots, (p-1)/2$  are  $-k$ , all negative. So the number of negative least residues is  $\mu = (p-1)/2$ , and  $\left(\frac{-1}{p}\right) = (-1)^{(p-1)/2}$ .  $\square$

**Ex. 5.2** Show that the number of solutions to  $x^2 \equiv a \pmod{p}$  is equal to  $1 + (a/p)$ .

*Proof.* Let  $N$  the number of solutions of  $x^2 \equiv a \pmod{p}$ .

- If  $(\frac{a}{p}) = 0$ , then  $p \mid a$ ,  $a \equiv 0 \pmod{p}$ , so the unique solution of  $x^2 \equiv a = 0$  is  $x \equiv 0 \pmod{p}$ , so  $N = 1 = 1 + (\frac{a}{p})$ .
- If  $(\frac{a}{p}) = -1$ , then  $N = 0 = 1 + (\frac{a}{p})$ .
- If  $(\frac{a}{p}) = 1$ , then  $x^2 \equiv a \pmod{p}$  has a solution  $x_0$ , and  $x^2 \equiv a \pmod{p} \iff x^2 \equiv x_0^2 \pmod{p} \iff p \mid (x - x_0)(x + x_0) \iff x \equiv \pm x_0 \pmod{p}$ , so  $N = 2 = 1 + (\frac{a}{p})$ .  $\square$

**Ex. 5.3** Suppose  $p \nmid a$ . Show that the number of solutions to  $ax^2 + bx + c \equiv 0 \pmod{p}$  is equal to  $1 + ((b^2 - 4ac)/p)$ .

*Proof.* Here  $p$  is an odd prime number, and  $p \nmid a$ . Let  $N$  be the number of solutions of  $ax^2 + bx + c \equiv 0 \pmod{p}$

For  $\bar{x} \in \mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$ ,

$$\begin{aligned} \overline{a}\bar{x}^2 + \overline{b}\bar{x} + \overline{c} &= \overline{a} \left( \bar{x}^2 + \frac{\overline{b}}{\overline{a}} \bar{x} + \frac{\overline{c}}{\overline{a}} \right) \\ &= \overline{a} \left( \left( \bar{x} + \frac{\overline{b}}{2\overline{a}} \right)^2 - \frac{\overline{b}^2 - 4\overline{a}\overline{c}}{4\overline{a}^2} \right) \end{aligned}$$

Let  $\Delta = b^2 - 4ac$ . Then  $N$  is the number of solutions of  $\left( \bar{x} + \frac{\overline{b}}{2\overline{a}} \right)^2 - \frac{\overline{\Delta}}{4\overline{a}^2} = \overline{0}$  in  $\mathbb{F}_p$ . As in Ex.5.2,  $N = 1$  if  $\overline{\Delta} = \overline{0}$ ,  $N = 0$  if  $\overline{\Delta}$  is not a square in  $\mathbb{F}_p^*$ , otherwise  $\overline{\Delta} = \delta^2$ ,  $\delta \in \mathbb{F}_p^*$ , and the solutions are  $\bar{x} = (-\overline{b} \pm \delta)/2\overline{a}$ , so  $N = 2$ . In the three cases,  $N = 1 + (\frac{\Delta}{p})$ .  $\square$

**Ex. 5.4** Prove that  $\sum_{a=1}^{p-1} (a/p) = 0$ .

*Proof.* Here  $p$  is an odd prime (the result is false if  $p = 2$ ). In the interval  $[1, p-1]$ , there exist  $(p-1)/2$  residues, and  $(p-1)/2$  nonresidues (Prop. 5.1.2., Corollary 1), so  $\sum_{a=1}^{p-1} (a/p) = 0$ .  $\square$

*Proof.* As an alternative proof, let  $S = \sum_{a=1}^{p-1} (\frac{a}{p})$ , and  $b$  a nonresidue modulo  $p$  :  $(\frac{b}{p}) = -1$  (such a  $b$  exists if  $p \neq 2$ ). As  $a \mapsto ab$  is a bijection from  $\mathbb{F}_p^*$  to itself,

$$\left( \frac{b}{p} \right) S = \sum_{a=1}^{p-1} \left( \frac{ab}{p} \right) = \sum_{c=1}^{p-1} \left( \frac{c}{p} \right) = S,$$

so  $-S = S$ ,  $S = 0$ .  $\square$

**Ex. 5.5** Prove that  $\sum_{x=1}^{p-1} ((ax+b)/p) = 0$  provided that  $p \nmid a$ .

There is a mistake in the sentence : we must read

Prove that  $\sum_{x=0}^{p-1} ((ax+b)/p) = 0$  provided that  $p \nmid a$ .

By example,

$$\sum_{x=1}^{5-1} \left( \frac{x+1}{5} \right) = \left( \frac{2}{5} \right) + \left( \frac{3}{5} \right) + \left( \frac{4}{5} \right) = -1 \neq 0.$$

*Proof.* From exercise 5.3, as  $\left(\frac{0}{p}\right) = 0$ , we know that

$$\sum_{\bar{x} \in \mathbb{F}_p} \left(\frac{x}{p}\right) = \sum_{x=0}^{p-1} \left(\frac{x}{p}\right) = \sum_{x=1}^{p-1} \left(\frac{x}{p}\right) = 0.$$

(This sum is well defined, since  $\left(\frac{x}{p}\right)$  depends only of  $\bar{x} : x \equiv x' \pmod{p} \Rightarrow \left(\frac{x}{p}\right) = \left(\frac{x'}{p}\right)$ .)

As  $\bar{a} \neq \bar{0}$  in  $\mathbb{F}_p$ ,  $f : \begin{cases} \mathbb{F}_p & \rightarrow \mathbb{F}_p \\ x & \mapsto \bar{a}x + \bar{b} \end{cases}$  is a bijection. Thus

$$\begin{aligned} \sum_{x=0}^{p-1} \left(\frac{ax+b}{p}\right) &= \sum_{x \in \mathbb{F}_p} \left(\frac{f(x)}{p}\right) \\ &= \sum_{y \in \mathbb{F}_p} \left(\frac{y}{p}\right) \quad (y = f(x)) \\ &= 0 \end{aligned}$$

□

**Ex. 5.6** Show that the number of solutions to  $x^2 - y^2 \equiv a \pmod{p}$  is given by:

$$\sum_{y=0}^{p-1} \left(1 + \left(\frac{y^2 + a}{p}\right)\right).$$

*Proof.* Let  $S = \{(\bar{x}, \bar{y}) \in \mathbb{F}_p^2 \mid \bar{x}^2 - \bar{y}^2 = \bar{a}\}$ . From Ex.5.2,

$$\begin{aligned} |S| &= \sum_{\bar{y} \in \mathbb{F}_p} \text{Card} \{\bar{x} \in \mathbb{F}_p \mid \bar{x}^2 = \bar{y}^2 + \bar{a}\} \\ &= \sum_{y=0}^{p-1} \left(1 + \left(\frac{y^2 + a}{p}\right)\right). \end{aligned}$$

□

**Ex. 5.7** By calculating directly show that the number of solutions to  $x^2 - y^2 \equiv a \pmod{p}$  is  $p - 1$  if  $p \nmid a$ , and  $2p - 1$  if  $p \mid a$ . (Hint. Use the change of variables  $u = x + y, v = x - y$ .)

*Proof.* Let  $S = \{(\bar{x}, \bar{y}) \in \mathbb{F}_p^2 \mid \bar{x}^2 - \bar{y}^2 = \bar{a}\}$ , and  $T = \{(\bar{u}, \bar{v}) \in \mathbb{F}_p^2 \mid \bar{u}\bar{v} = \bar{a}\}$ . Then  $f : \begin{cases} S & \rightarrow T \\ (\bar{x}, \bar{y}) & \mapsto (\bar{x} + \bar{y}, \bar{x} - \bar{y}) \end{cases}$  is well defined (if  $(\bar{x}, \bar{y}) \in S$ ,  $(\bar{x} - \bar{y})(\bar{x} + \bar{y}) = a$ , so  $(\bar{x} + \bar{y}, \bar{x} - \bar{y}) \in T$ ). Moreover  $f$  is a bijection, with inverse  $(\bar{u}, \bar{v}) \mapsto ((\bar{u} + \bar{v})/2, (\bar{u} - \bar{v})/2)$ , so  $|S| = |T|$ .

We compute  $|T|$ .

- Suppose  $p \nmid a$ , so  $\bar{a} \neq \bar{0}$ . For  $\bar{v} \neq 0$ , there is no solution, and for each  $\bar{v} \neq 0$ , we obtain the unique solution  $(\bar{a}\bar{v}^{-1}, \bar{v})$ , so there exist  $p - 1$  solutions.

- Suppose  $p \mid a$ . The solutions of  $\bar{u}\bar{v} = \bar{0}$  are  $(\bar{0}, \bar{0})$ ,  $(\bar{0}, \bar{v})$  for each  $\bar{v} \neq \bar{0}$ ,  $(\bar{u}, \bar{0})$  for each  $\bar{u} \neq \bar{0}$ , that is to say  $N = 1 + (p - 1) + (p - 1) = 2p - 1$  solutions.



Conclusion :

$$\begin{aligned} \text{Card } \{(\bar{x}, \bar{y}) \in \mathbb{F}_p^2 \mid \bar{x}^2 - \bar{y}^2 = \bar{a}\} &= p - 1 \quad \text{if } p \nmid a \\ &= 2p - 1 \quad \text{if } p \mid a \end{aligned}$$

□

**Ex. 5.8** Combining the results of Ex. 5.6 and 5.7 show that:

$$\sum_{y=0}^{p-1} \left( \frac{y^2 + a}{p} \right) = \begin{cases} -1 & \text{if } p \nmid a \\ p - 1 & \text{if } p \mid a \end{cases}$$

*Proof.* Let  $S = \{(\bar{x}, \bar{y}) \in \mathbb{F}_p^2 \mid \bar{x}^2 - \bar{y}^2 = \bar{a}\}$ .

We obtain in Ex 5.6,  $|S| = \sum_{y=0}^{p-1} \left( 1 + \left( \frac{y^2 + a}{p} \right) \right)$ , and in Ex. 5.7. ,  $|S| = p - 1$  if  $p \nmid a$ ,  
 $|S| = 2p - 1$  if  $p \mid a$ .

So

$$S - p = \sum_{y=0}^{p-1} \left( \frac{y^2 + a}{p} \right) = \begin{cases} -1 & \text{if } p \nmid a \\ p - 1 & \text{if } p \mid a \end{cases}$$

□

**Ex. 5.9** Prove that  $1^2 3^2 \dots (p-2)^2 \equiv (-1)^{(p+1)/2} \pmod{p}$  using Wilson's theorem.

*Proof.* Here  $p$  is an odd prime.

From Wilson's theorem, as  $k(p-k) \equiv -k^2 \pmod{p}$  for  $k = 1, 2, \dots, p-1$ ,

$$\begin{aligned} -1 &\equiv (p-1)! \\ &\equiv \left[ 1 \times 2 \times \dots \times k \times \dots \times \left( \frac{p-1}{2} \right) \right] \times \left[ \left( \frac{p+1}{2} \right) \times \dots \times (p-k) \dots \times (p-2) \times (p-1) \right] \\ &\equiv \prod_{k=1}^{(p-1)/2} k(p-k) \\ &\equiv (-1)^{(p-1)/2} \prod_{k=1}^{(p-1)/2} k^2 \\ &\equiv (-1)^{(p-1)/2} \left[ \left( \frac{p-1}{2} \right)! \right]^2 \pmod{p} \end{aligned}$$

So

$$\left[ \left( \frac{p-1}{2} \right)! \right]^2 \equiv (-1)^{(p+1)/2} \pmod{p}.$$

Moreover, from Wilson' theorem and Fermat's little theorem,

$$\begin{aligned} 1^2 2^2 3^2 \dots (p-1)^2 &= [(p-1)!]^2 \equiv 1 \pmod{p} \\ 2^2 4^2 \dots (p-1)^2 &= (2^{p-1})^2 \left[ \left( \frac{p-1}{2} \right)! \right]^2 \equiv \left[ \left( \frac{p-1}{2} \right)! \right]^2 \pmod{p} \end{aligned}$$

Thus

$$1^2 3^2 \dots (p-2)^2 \left[ \left( \frac{p-1}{2} \right)! \right]^2 \equiv 1 \pmod{p}.$$

which gives

$$1^2 3^2 \dots (p-2)^2 \equiv (-1)^{(p+1)/2} \pmod{p}.$$

□

**Ex. 5.10** Let  $r_1, r_2, \dots, r_{(p-1)/2}$  be the quadratic residues between 1 and  $p$ . Show that their product is congruent to 1 (mod  $p$ ) if  $p \equiv 3 \pmod{4}$ , and to  $-1$  if  $p \equiv 1 \pmod{4}$ .

*Proof.* We proved in Ex. 5.9 that

$$\left[ \left( \frac{p-1}{2} \right)! \right]^2 \equiv (-1)^{(p+1)/2} \pmod{p}.$$

The application  $f : \left\{ \begin{array}{ccc} \{\bar{1}, \bar{2}, \dots, \overline{(p-1)/2}\} & \mapsto & \{\bar{r}_1, \bar{r}_2, \dots, \overline{r_{(p-1)/2}}\} \\ x & \mapsto & x^2 \end{array} \right\}$  is a bijection, so

$$\prod_{i=1}^{(p-1)/2} r_i \equiv \left[ \left( \frac{p-1}{2} \right)! \right]^2 \pmod{p},$$

so

$$\prod_{i=1}^{(p-1)/2} r_i \equiv (-1)^{(p+1)/2} \pmod{p}.$$

That is to say, the product of the quadratic residues between 1 and  $p$  is congruent to 1 (mod  $p$ ) if  $p \equiv 3 \pmod{4}$ , and to  $-1$  if  $p \equiv 1 \pmod{4}$ . □

**Ex. 5.11** Suppose that  $p \equiv 3 \pmod{4}$ , and that  $q = 2p + 1$  is also prime. Prove that  $2^p - 1$  is not prime. (Hint : Use the quadratic character of 2 to show that  $q \mid 2^p - 1$ ) One must assume that  $p > 3$ .

*Proof.* The result is false if  $p = 3$ , so we must suppose  $p > 3$ .

$p = 4k + 3$  for an integer  $k$ , so  $q = 2p + 1 = 8k + 7 \equiv -1 \pmod{8}$ . Thus

$$\left( \frac{2}{q} \right) = (-1)^{(q^2-1)/8} = 1.$$

So  $2^{(q-1)/2} \equiv 1 \pmod{q}$ ,  $2^p \equiv 1 \pmod{q}$ , so  $q \mid 2^p - 1$ .

Moreover, as  $p > 3$ ,  $q = 2p + 1 < 2^p - 1$

$$(2p + 1 < 2^p - 1 \iff 2p < 2^p - 2 \iff p + 1 < 2^{p-1}.$$

$4 + 1 < 2^{4-1}$  and for all  $k \geq 4$ ,  $k + 1 < 2^{k-1}$  implies  $k + 2 < 2^{k-1} + 1 \leq 2^k$ , and  $4 + 1 < 2^{4-1}$ , so by induction  $k + 1 < 2^{k-1}$  for all  $k > 3$ .

So  $q \mid 2^p - 1$  with  $1 < q < 2^p - 1$  :  $2^p - 1$  is composite.

Conclusion : if  $p \equiv 3 \pmod{4}$ ,  $p > 3$  is prime, and  $q = 2p + 1$  is also prime, then  $2^p - 1$  is not a prime.

For instance, le Mersenne's number  $2^{11} - 1 = 2047$  is not a prime :  $2047 = 23 \times 89$ . □

**Ex. 5.12** Let  $f(x) \in \mathbb{Z}[x]$ . We say that a prime  $p$  divides  $f(x)$  if there's an integer  $n$  such that  $p \mid f(n)$ . Describe the prime divisors of  $x^2 + 1$  and  $x^2 - 2$ .

*Proof.*  $p$  divides  $x^2 + 1$  iff there exists  $a \in \mathbb{Z}$  such that  $-1 \equiv a^2 \pmod{p}$ , iff  $p = 2$  or  $\left(\frac{-1}{p}\right) = 1$  iff  $p = 2$  or  $p \equiv 1 \pmod{4}$ .

$p$  divides  $x^2 - 2$  iff there exists  $a \in \mathbb{Z}$  such that  $2 \equiv a^2 \pmod{p}$ , iff  $p = 2$  or  $\left(\frac{2}{p}\right) = 1$  iff  $p = 2$  or  $p \equiv \pm 1 \pmod{8}$ .  $\square$

**Ex. 5.13** Show that any prime divisor of  $x^4 - x^2 + 1$  is congruent to 1 modulo 12.

*Proof.* • As  $a^6 + 1 = (a^2 + 1)(a^4 - a^2 + 1)$ ,  $p \mid a^4 - a^2 + 1$  implies  $p \mid a^6 + 1$ , so  $\left(\frac{-1}{p}\right) = 1$  and  $p \equiv 1 \pmod{4}$ .

•  $p \mid 4a^4 - 4a^2 + 4 = (2a - 1)^2 + 3$ , so  $\left(\frac{-3}{p}\right) = 1$ .

As  $-3 \equiv 1 \pmod{4}$ ,  $\left(\frac{-3}{p}\right) = \left(\frac{p}{3}\right)$ , so  $\left(\frac{p}{3}\right) = 1$ , thus  $p \equiv 1 \pmod{3}$ .

$4 \mid p - 1$  and  $3 \mid p - 1$ , thus  $12 \mid p - 1$ :

$$p \equiv 1 \pmod{12}.$$

$\square$

**Ex. 5.14** Use the fact that  $U(\mathbb{Z}/p\mathbb{Z})$  is cyclic to give a direct proof that  $(-3/p) = 1$  when  $p \equiv 1 \pmod{3}$ . [Hint : There is a  $\rho$  in  $U(\mathbb{Z}/p\mathbb{Z})$  of order 3. Show that  $(2\rho + 1)^2 = -3$ .]

*Proof.* Suppose that  $p \equiv 1 \pmod{3}$ . Let  $g$  a generator of  $\mathbb{F}_p^*$ . Then  $g$  has order  $p - 1$ , thus  $\rho = g^{(p-1)/3}$  has order 3. As  $\rho^3 = 1, \rho \neq 1$ , then  $\rho^2 + \rho + 1 = 0$ .

$$\begin{aligned} (2\rho + 1)^2 &= 4\rho^2 + 4\rho + 1 \\ &= 4(\rho^2 + \rho + 1) - 3 \\ &= -3. \end{aligned}$$

Thus  $\left(\frac{-3}{p}\right) = 1$ .  $\square$

The inverse form of this proposition is also true for an odd prime  $p$  : if  $\left(\frac{-3}{p}\right) = 1$ , then there exists  $a \in \mathbb{F}_p^*$  such that  $-\bar{3} = a^2$ .  $\rho = \frac{-1+a}{2}$  has order 3. Indeed  $\rho^2 = \frac{1+a^2-2a}{4} = \frac{-2-2a}{4} = \frac{-1-a}{2}$ , so

$$\begin{aligned} 1 + \rho + \rho^2 &= 1 + \frac{-1+a}{2} + \frac{-1-a}{2} \\ &= 0 \end{aligned}$$

so  $\rho \neq 1, \rho^3 = 1$ . The group  $\mathbb{F}_p^*$  contains an element of order 3, thus from Lagrange's theorem  $3 \mid p - 1$  :  $p \equiv 1 \pmod{3}$ .

**Ex. 5.15** If  $p \equiv 1 \pmod{5}$ , show directly that  $(5/p) = 1$  by the method of Ex. 5.14. [Hint : Let  $\rho$  be an element of  $U(\mathbb{Z}/p\mathbb{Z})$  of order 5. Show that  $(\rho + \rho^4)^2 + (\rho + \rho^4) - \bar{1} = \bar{0}$ , etc.]

*Proof.* Let  $g$  a generator of  $\mathbb{F}_p^*$ .  $g$  has order  $p-1$ , thus  $\rho = g^{(p-1)/5}$  has order 5.

Let

$$\begin{cases} \alpha &= \rho + \rho^4 \\ \beta &= \rho^2 + \rho^3 \end{cases}$$

As  $0 = \rho^5 - 1 = (\rho - 1)(1 + \rho + \rho^2 + \rho^3 + \rho^4)$  and  $\rho \neq 1$ , then  $1 + \rho + \rho^2 + \rho^3 + \rho^4 = 0$ , thus

$$\begin{aligned} \alpha + \beta &= -1 \\ \alpha\beta &= \rho^3 + \rho^4 + \rho + \rho^2 = -1 \end{aligned}$$

So  $\alpha, \beta$  are the roots in  $\mathbb{F}_p$  of  $x^2 + x - 1 : \alpha^2 + \alpha - 1 = 0$ .

Thus  $4\alpha^2 + 4\alpha - 4 = (2\alpha + 1)^2 - 5 = 0 : 5$  is a square in  $\mathbb{F}_p^*$  and  $\left(\frac{5}{p}\right) = 1$ .  $\square$

**Ex. 5.16** Using quadratic reciprocity find the primes for which 7 is quadratic residue. Do the same for 15.

*Proof.* 7 is a quadratic residue for 2 and for the odd primes such that  $\left(\frac{7}{p}\right) = 1$ .

From the law of quadratic reciprocity,

$$\left(\frac{7}{p}\right) = 1 \iff (-1)^{(p-1)/2} \left(\frac{p}{7}\right) = 1$$

iff either  $p \equiv 1 \pmod{4}$  and  $\left(\frac{p}{7}\right) = 1$ , or  $p \equiv -1 \pmod{4}$  and  $\left(\frac{p}{7}\right) = -1$ .

In the first case,  $p \equiv 1 \pmod{4}, p \equiv 1, 4, 2 \pmod{7}$ , which gives  $p \equiv 1, -3, 9 \pmod{28}$ .

In the second case,  $p \equiv -1 \pmod{4}, p \equiv -1, -4, -2 \pmod{7}$ , which gives  $p \equiv -1, 3, -9 \pmod{28}$ .

Conclusion : the primes for which 7 is a quadratic residue are 2 and the odd primes  $p$  such that

$$\left(\frac{7}{p}\right) = 1 \iff p \equiv \pm 1, \pm 3, \pm 9 \pmod{28}.$$

$\square$

15 is a quadratic residue for 2 and for the odd primes such that  $\left(\frac{15}{p}\right) = 1$ .

$$\left(\frac{15}{p}\right) = 1 \iff \left(\frac{3}{p}\right) = \left(\frac{5}{p}\right) = 1 \text{ or } \left(\frac{3}{p}\right) = \left(\frac{5}{p}\right) = -1$$

From the examples of theorem 2, we know that

$$\left(\frac{3}{p}\right) = 1 \iff p \equiv 1, -1 \pmod{12}, \quad \left(\frac{3}{p}\right) = -1 \iff p \equiv 5, -5 \pmod{12},$$

$$\left(\frac{5}{p}\right) = 1 \iff p \equiv 1, -1 \pmod{5}, \quad \left(\frac{5}{p}\right) = -1 \iff p \equiv 2, -2 \pmod{5}.$$

As  $5 \wedge 12 = 1$ , there exist 8 cases, all possible, which give

$$\left(\frac{15}{p}\right) = 1 \iff p \equiv \pm 1, \pm 7, \pm 11, \pm 17 \pmod{60}.$$

For instance, the primes 2, 7, 11, 17, 43, 53, 59, 61, 67, 137, ... are suitable.

**Ex. 5.17** Supply the details to the proof of Proposition 5.2.1 and to the corollary to the lemma following it.

**Proposition 5.2.1**

(a)  $(a_1/b) = (a_2/b)$  if  $a_1 \equiv a_2 \pmod{b}$ .

(b)  $(a_1 a_2/b) = (a_1/b)(a_2/b)$ .

(c)  $(a/b_1 b_2) = (a/b_1)(a/b_2)$ .

*Proof.* (a) Let  $b = p_1 p_2 \cdots p_m$ , where the  $p_i$  are not necessarily distinct primes. For each prime  $p_i$ ,  $(a_1, p_i) = (a_2, p_i)$  (Prop. 5.1.2 (c)), so  $\prod_i (a_1, p_i) = \prod_i (a_2, p_i)$ , thus  $(a_1/b) = (a_2/b)$ .

(b) From Prop. 5.1.2(b),

$$(a_1 a_2/b) = \prod_i (a_1 a_2/p_i) = \prod_i (a_1/p_i)(a_2/p_i) = \prod_i (a_1/p_i) \prod_i (a_2/p_i) = (a_1/b)(a_2/b).$$

(c) Let  $b_1 = p_1 p_2 \cdots p_m$ ,  $b_2 = q_1 q_2 \cdots q_l$ . Then  $b_1 b_2 = p_1 p_2 \cdots p_m q_1 q_2 \cdots q_l = \prod_{i=1}^{m+l} r_i$ , where  $r_i = p_i$  for  $i = 1, \dots, m$ ,  $r_i = q_{i-m}$  for  $i = m+1, \dots, m+l$ . Then

$$(a/b_1 b_2) = \prod_{i=1}^{m+l} (a/r_i) = \prod_{i=1}^m (a/p_i) \prod_{j=1}^l (a/q_j) = (a/b_1)(a/b_2).$$

□

**Lemma.** Let  $r$  and  $s$  be odd integers. Then

(a)  $(rs - 1)/2 \equiv ((r - 1)/2) + ((s - 1)/2) \pmod{2}$ .

(b)  $(r^2 s^2 - 1)/8 \equiv ((r^2 - 1)/8) + ((s^2 - 1)/8) \pmod{2}$ .

(Proof in the book.)

**Corollary.** Let  $r_1, r_2, \dots, r_m$  be odd integers. Then

(a)  $\sum_{i=1}^m (r_i - 1)/2 \equiv (r_1 r_2 \cdots r_m - 1)/2 \pmod{2}$ .

(b)  $\sum_{i=1}^m (r_i^2 - 1)/8 \equiv (r_1^2 r_2^2 \cdots r_m^2 - 1)/8 \pmod{2}$ .

*Proof.* Let  $\mathcal{P}(m)$  the proposition defined by

$$\mathcal{P}(m) \iff \sum_{i=1}^m (r_i - 1)/2 \equiv (r_1 r_2 \cdots r_m - 1)/2 \pmod{2}.$$

Then  $\mathcal{P}(1) \iff (r_1 - 1)/2 \equiv (r_1 - 1)/2 \pmod{2}$  is true, and  $\mathcal{P}(2)$  is part (a) of the lemma. If we make the induction hypothesis  $\mathcal{P}(m)$ , then

$$\begin{aligned} \sum_{i=1}^{m+1} (r_i - 1)/2 &= \sum_{i=1}^m (r_i - 1)/2 + (r_{m+1} - 1)/2 \\ &\equiv (r_1 r_2 \cdots r_m - 1)/2 + (r_{m+1} - 1)/2 \pmod{2} \\ &\equiv (r_1 r_2 \cdots r_m r_{m+1} - 1)/2 \pmod{2}, \end{aligned}$$

where the last congruence is a consequence of the part (a) of the Lemma : the induction is completed, and  $\mathcal{P}(m)$  is true for all  $m \geq 1$ .

The proof of part (b) is similar. □

**Ex. 5.18** Let  $D$  be a square-free integer that is also odd and positive. Show that there's an integer  $b$  prime to  $D$  such that  $(b/D) = -1$ .

*Proof.* Let  $D = p_1 p_2 \cdots p_k$ , where the  $p_i$  are distinct odd primes.

Let  $s$  a nonresidue modulo  $p_k$ . From Chinese remainder theorem, as  $p_i \wedge p_j = 1$  if  $i \neq j$ , there exists an integer  $b$  such that

$$b \equiv 1 \pmod{p_1}, b \equiv 1 \pmod{p_2}, \dots, b \equiv 1 \pmod{p_{k-1}}, b \equiv s \pmod{p_k}.$$

Then  $(b/p_i) = 1$ ,  $i = 1, 2, \dots, k-1$ ,  $(b/p_k) = -1$ , so  $b \wedge p_i = 1$  for all  $i = 1, 2, \dots, k$ . Then  $b \wedge D = b \wedge p_1 \cdots p_k = 1$ , and

$$\left(\frac{b}{D}\right) = \prod_{i=1}^k \left(\frac{b}{p_i}\right) = \left(\frac{b}{p_k}\right) = -1.$$

□

**Ex. 5.19** Let  $D$  be as in Exercise 18. Show that  $\sum(a/D) = 0$ , where the sum is over a reduced residue system modulo  $D$ . Conclude that exactly one half of the elements in  $U(\mathbb{Z}/D\mathbb{Z})$  satisfy  $(a/D) = 1$ .

*Proof.* Let  $b$  such that  $(b/D) = -1$ : the existence of  $b$  comes from Ex 5.18.

Let  $S = \sum_{a \in A} (a/D)$ , where  $A$  is reduced residue system modulo  $D$ . As two reduced system modulo  $D$  represent the same elements in  $U(\mathbb{Z}/D\mathbb{Z})$ , the sum is independent of the reduced residue system  $A$ : we can write

$$S = \sum_{\bar{a} \in U(\mathbb{Z}/D\mathbb{Z})} (a/D).$$

As  $b \wedge D = 1$ , we know from Ex. 3.6 that  $B = bA = \{ba \mid a \in A\}$  is also a reduced system modulo  $D$ . In other words, the application  $U(\mathbb{Z}/D\mathbb{Z}) \rightarrow U(\mathbb{Z}/D\mathbb{Z}), \bar{a} \mapsto \bar{a}\bar{b}$  is a bijection, so

$$\left(\frac{b}{D}\right) S = \sum_{\bar{a} \in U(\mathbb{Z}/D\mathbb{Z})} \left(\frac{b}{D}\right) \left(\frac{a}{D}\right) = \sum_{\bar{a} \in U(\mathbb{Z}/D\mathbb{Z})} \left(\frac{ba}{D}\right) = \sum_{\bar{c} \in U(\mathbb{Z}/D\mathbb{Z})} \left(\frac{c}{D}\right) = S \quad (\bar{c} = \bar{a}\bar{b}).$$

As  $(b/D) = -1$ ,  $-S = S$ , so  $S = 0$ .

Since  $(a/D) = \pm 1$ , one half of the elements in  $U(\mathbb{Z}/D\mathbb{Z})$  satisfy  $(a/D) = 1$ , and one half of the elements in  $U(\mathbb{Z}/D\mathbb{Z})$  satisfy  $(a/D) = -1$ . □

**Ex. 5.20** (continuation) Let  $a_1, a_2, \dots, a_{\phi(D)/2}$  be integers between 1 and  $D$  such that  $(a_i, D) = 1$  and  $(a_i/D) = 1$ . Prove that  $D$  is a quadratic residue modulo a prime  $p \nmid D$ ,  $p \equiv 1 \pmod{4}$  iff  $p \equiv a_i \pmod{D}$  for some  $i$ .

*Proof.* From Ex. 5.19 we know that there exist exactly  $\phi(D)/2$  integers  $a_i$  between 1 and  $D$  such that  $a_i \wedge D = 1$  and  $(a_i/D) = 1$ . So  $\{\bar{a}_1, \dots, \bar{a}_{\phi(D)/2}\}$  is the set of all  $\bar{a} \in U(\mathbb{Z}/D\mathbb{Z})$  such that  $(a/D) = 1$ .

Let  $D = p_1 p_2 \cdots p_k$ , with distinct  $p_i$ , and  $p$  a prime number,  $p \equiv 1 \pmod{4}$ ,  $p \notin \{p_1, \dots, p_k\}$  (so  $p = 4k + 1, k \in \mathbb{N}$ ).

( $\Leftarrow$ ) Suppose that  $p \equiv a_i$  for some  $i$ ,  $1 \leq i \leq \phi(D)/2$ , then  $(p/D) = (a_i/D) = 1$ , so (Prop. 5.2.2)

$$\left(\frac{D}{p}\right) = (-1)^{\frac{p-1}{2} \frac{D-1}{2}} \left(\frac{p}{D}\right) = (-1)^{2k(\frac{D-1}{2})} \left(\frac{p}{D}\right) = \left(\frac{p}{D}\right) = 1.$$

( $\Rightarrow$ ) Suppose that  $D$  is a quadratic residue modulo  $p$ . Then  $(D/p) = 1$ , so

$$\left(\frac{p}{D}\right) = (-1)^{\frac{p-1}{2} \frac{D-1}{2}} \left(\frac{D}{p}\right) = 1.$$

Thus  $\bar{p} \in \{\bar{a}_1, \dots, \bar{a}_{\phi(D)/2}\}$  since  $\{\bar{a}_1, \dots, \bar{a}_{\phi(D)/2}\}$  is the set of all  $\bar{a} \in U(\mathbb{Z}/D\mathbb{Z})$  such that  $(a/D) = 1$ . Consequently  $p \equiv a_i \pmod{D}$  for some  $i$ .  $\square$

**Ex. 5.21** Apply the method of Ex. 5.19 and 5.20 to find those primes for which 21 is a quadratic residue.

*Proof.* Let  $D = 21 = 3 \times 7$  ( $D$  is positive, odd and square-free). We first search the  $\phi(D)/2 = 6$  integers  $a$ ,  $1 \leq a \leq 21$ , such that  $(a/D) = 1$ .

$$\left(\frac{a}{21}\right) = 1 \iff \left(\frac{a}{3}\right) = \left(\frac{a}{7}\right) = 1 \text{ or } \left(\frac{a}{3}\right) = \left(\frac{a}{7}\right) = -1.$$

The first case is equivalent to  $a \equiv 1 \pmod{3}$ ,  $a \equiv 1, 2, 4 \pmod{7}$ , that is  $a \equiv 1, 16, 4 \pmod{21}$ .

The second case gives  $a \equiv -1 \pmod{3}$ ,  $a \equiv -1, -2, -4 \pmod{7}$ , that is  $a \equiv -1, -16, -4 \pmod{21}$ , or equivalently  $a \equiv 20, 5, 17 \pmod{21}$ .

So  $A = \{1, 4, 5, 16, 17, 20\}$  is the set of the integers  $a$  such that  $1 \leq a \leq 21$ ,  $(a/D) = 1$ .

As  $(21/3) = (21/7) = 0$ , 21 is not a quadratic residue modulo 3 or 7.

•  $p \equiv 1 \pmod{4}$ .

From Ex.5.20, we know that  $D = 21$  is a quadratic residue modulo an odd prime  $p$ ,  $p \neq 3, p \neq 7$ ,  $p \equiv 1 \pmod{4}$ , iff  $p \equiv a \pmod{D}$  for some  $a \in A$ .

•  $p \equiv -1 \pmod{4}$ .

As  $D = 21 \equiv 1 \pmod{4}$ ,  $\left(\frac{D}{p}\right) \left(\frac{p}{D}\right) = (-1)^{\frac{p-1}{2} \frac{D-1}{2}} = 1$ , so the same reasoning as in Ex. 5.20 show that  $D$  is a quadratic residue modulo 21 iff  $p \equiv a, a \in A$ .

Conclusion : 21 is a quadratic residue for 2, and for the primes  $p$  such that

$$p \equiv 1, 4, 5, 16, 17, 20 \pmod{21}.$$

$\square$

**Ex. 5.22** Use the Jacobi symbol to determine  $(113/997)$ ,  $(215/761)$ ,  $(514/1093)$ , and  $(401/757)$ .

*Proof.*  $(113/997) = (997/113) = (93/11) = (113/93) = (20/93) = (2^2/93)(5/93) = (5/93) = (93/5) = (3/5) = (5/3) = (2/3) = -1$ .

$(215/761) = (761/215) = (116/215) = (2^2/215)(29/215) = (29/215) = (215/29) = (12/29) = (2^2/29)(3/29) = (3/29) = (29/3) = (2/3) = -1$ .

$(514/1093) = (2/1093)(257/1093) = -(257/1093) = -(1093/57) = -(65/257) = -(257/65) = -(62/65) = -(2/65)(31/65) = -(31/65) = -(65/31) = -(3/31) = (31/3) = (1/3) = 1$ .

$(401/757) = (757/401) = (356/401) = (401/89) = (45/89) = (89/45) = (44/45) = (2^2/45)(11/45) = (11/45) = (45/11) = (1/11) = 1$ .  $\square$

**Ex. 5.23** Suppose that  $p \equiv 1 \pmod{4}$ . Show that there exist integers  $s$  and  $t$  such that  $pt = 1 + s^2$ . Conclude that  $p$  is not a prime in  $\mathbb{Z}[i]$ . Remember that  $\mathbb{Z}[i]$  has unique factorization.

*Proof.* As  $p \equiv 1 \pmod{4}$ , then  $\left(\frac{-1}{p}\right) = (-1)^{\frac{p-1}{2}} = 1$  :  $-1$  is a square modulo  $p$ .

So  $-1 \equiv s^2 \pmod{p}$ ,  $s \in \mathbb{Z}$  : there exist  $s \in \mathbb{Z}, t \in \mathbb{Z}$  such that  $pt = 1 + s^2$ .

In  $\mathbb{Z}[i]$ ,  $p \mid (s+i)(s-i)$ .

If  $p$  was a prime in  $\mathbb{Z}[i]$ , then  $p \mid s+i$  ou  $p \mid s-i$ .

This implies  $s \pm i = (a+bi)p$ ,  $(a,b) \in \mathbb{Z}^2$ , thus  $\pm 1 = bp$ ,  $p \mid 1$  : it's impossible.

Conclusion : if  $p \equiv 1 \pmod{4}$ ,  $p$  is not a prime in  $\mathbb{Z}[i]$ .  $\square$

**Ex. 5.24** If  $p \equiv 1 \pmod{4}$ , show that  $p$  is a sum of two squares, i.e.  $p = a^2 + b^2$  with  $a, b \in \mathbb{Z}$ . (Hint :  $p = \alpha\beta$ , with  $\alpha$  and  $\beta$  being non units in  $\mathbb{Z}[i]$ . Remember that  $\mathbb{Z}[i]$  has unique factorisation.)

*Proof.*  $\mathbb{Z}[i]$  is a principal ideal domain, thus  $p$  prime is in  $\mathbb{Z}[i]$  iff  $p$  is irreducible in  $\mathbb{Z}[i]$ .

If  $p \equiv 1 \pmod{4}$ ,  $p$  is not a prime from Ex.5.23, so it is not irreducible :

$p = \alpha\beta$ ,  $\alpha, \beta \in \mathbb{Z}[i]$ ,  $N(\alpha) > 1$ ,  $N(\beta) > 1$  (where  $N(a+bi) = a^2 + b^2$  is the complex norm).

$N(p) = p^2 = N(u)N(v)$ ,  $1 < N(u) < p^2$

Thus  $N(u) = p$ , that is  $p = a^2 + b^2$ , where  $u = a+bi$ .

Conclusion : if  $p$  is prime in  $\mathbb{N}$ ,  $p \equiv 1 \pmod{4}$ , then  $p = a^2 + b^2$ ,  $a, b \in \mathbb{Z}$ ,  $p$  is a sum of two squares.  $\square$

**Ex. 5.25** An integer is called a biquadratic residue modulo  $p$  if it is congruent to a fourth power. Using the identity  $x^4 + 4 = ((x+1)^2 + 1)((x-1)^2 + 1)$  show that  $-4$  is a biquadratic residue modulo  $p$  iff  $p \equiv 1 \pmod{4}$ .

*Proof.*  $x^4 + 4 = (x^4 + 4x^2 + 4) - 4x^2 = (x^2 + 2)^2 - 4x^2 = (x^2 + 2 - 2x)(x^2 + 2 + 2x)$ , so

$$x^4 + 4 = ((x-1)^2 + 1)((x+1)^2 + 1).$$

If  $-4 \equiv x^4 \pmod{p}$ , then  $p \mid (x+1)^2 + 1$  or  $p \mid (x-1)^2 + 1$

In the two cases,  $-1$  is a quadratic residue modulo  $p$ , thus  $\left(\frac{-1}{p}\right) = 1$  :  $p \equiv 1 \pmod{4}$ .

Reciprocally, if  $p \equiv 1 \pmod{4}$ ,  $\left(\frac{-1}{p}\right) = 1$ , then it exists an integer  $a$  such that  $-1 \equiv a^2 \pmod{p}$ .

Let  $x = a - 1$ . Then  $p \mid (x+1)^2 + 1$ , thus  $p \mid x^4 + 4$  :  $-4$  is a biquadratic residue modulo  $p$ .

Conclusion :

$$\exists x \in \mathbb{Z}, x^4 \equiv -4 \pmod{p} \iff p \equiv 1 \pmod{4}.$$

$\square$

**Ex. 5.26** This exercise and Ex. 5.27 and 5.28 give Dirichlet's beautiful proof that 2 is a biquadratic residue modulo  $p$  iff  $p$  can be written in the form  $A^2 + 64B^2$ , where  $A, B \in \mathbb{Z}$ . Suppose that  $p \equiv 1 \pmod{4}$ . Then  $p = a^2 + b^2$  by Ex. 5.24. Take  $a$  to be odd. Prove the following statements:

(a)  $(a/p) = 1$ .

(b)  $((a+b)/p) = (-1)^{((a+b)^2-1)/8}$ .



$$(c) \ (a+b)^2 \equiv 2ab \pmod{p}$$

$$(d) \ (a+b)^{(p-1)/2} \equiv (2ab)^{(p-1)/4} \pmod{p}.$$

*Proof.* Let  $p$  a prime number,  $p \equiv 1 \pmod{4}$  :  $p = 4k + 1, k \in \mathbb{N}^*$ .

Then  $p = a^2 + b^2$  (Ex. 5.24).

As  $a, b$  are not of the same parity, up to exchange  $a$  and  $b$ , we will suppose that  $a$  is odd (then  $b$  is even).

(a)

$$\left(\frac{a}{p}\right) \equiv a^{\frac{p-1}{2}} = a^{2k} \pmod{p}.$$

Using the law of quadratic reciprocity for Jacobi's symbol (Proposition 5.2.2), where  $a, p$  are odd numbers :

$$\left(\frac{a}{p}\right) = \left(\frac{p}{a}\right) (-1)^{\frac{p-1}{2} \frac{a-1}{2}} = \left(\frac{p}{a}\right),$$

since  $p \equiv 1 \pmod{4}$ .

If  $a = p_1 p_2 \cdots p_l$  is the decomposition of  $a$  in prime factors, with not necessarily distinct primes, then

$$\left(\frac{p}{a}\right) = \left(\frac{p}{p_1}\right) \left(\frac{p}{p_2}\right) \cdots \left(\frac{p}{p_l}\right).$$

Since  $p = a^2 + b^2$ ,  $p \equiv b^2 \pmod{p_i}$ , thus  $\left(\frac{p}{p_i}\right) = 1$  for all  $i$ .

$$\left(\frac{a}{p}\right) = \left(\frac{p}{a}\right) = 1.$$

(b)  $a + b$  is odd, and  $p \equiv 1 \pmod{4}$ , thus

$$\left(\frac{a+b}{p}\right) = \left(\frac{p}{a+b}\right) = \left(\frac{2^2 p}{a+b}\right) = \left(\frac{2}{a+b}\right) \left(\frac{2p}{a+b}\right).$$

If  $a + b = q_1 q_2 \cdots q_l$ , as  $2p = (a+b)^2 + (a-b)^2$ ,  $2p \equiv (a-b)^2 \pmod{q_i}$ , thus  $\left(\frac{2p}{q_i}\right) = 1$ .

$$\left(\frac{2p}{a+b}\right) = \left(\frac{2p}{q_1}\right) \cdots \left(\frac{2p}{q_l}\right) = 1.$$

Moreover  $\left(\frac{2}{a+b}\right) = (-1)^{\frac{(a+b)^2-1}{8}}$ , so

$$\left(\frac{a+b}{p}\right) = (-1)^{\frac{(a+b)^2-1}{8}}.$$

$$(c) \ (a+b)^2 = a^2 + b^2 + 2ab = p + 2ab \equiv 2ab \pmod{p}$$

$$(d) [(a+b)^2]^{\frac{p-1}{4}} \equiv (2ab)^{\frac{p-1}{4}} \pmod{p}, \text{ thus}$$

$$(a+b)^{\frac{p-1}{2}} \equiv (2ab)^{\frac{p-1}{4}} \pmod{p}.$$

□

**Ex. 5.27** Suppose that  $f$  is such that  $b \equiv af \pmod{p}$ . Show that  $f^2 \equiv -1 \pmod{p}$ , and that  $2^{(p-1)/4} \equiv f^{ab/2} \pmod{p}$ .

*Proof.* Let  $f$  such as  $b \equiv af \pmod{p}$ .

This is equivalent to  $\bar{f} = \bar{b}\bar{a}^{-1}$  dans  $\mathbb{F}_p^*$ .

As  $\bar{a}^2 = -\bar{b}^2$ ,  $\bar{f}^2 = -1$  :  $f^2 \equiv -1 \pmod{p}$ .

We deduce from Ex. 5.26 (d) and (b) that

$$\begin{aligned} (2ab)^{\frac{p-1}{4}} &\equiv (a+b)^{\frac{p-1}{2}} = \left(\frac{a+b}{p}\right) \\ &\equiv (-1)^{\frac{(a+b)^2-1}{8}} \\ &\equiv (f^2)^{\frac{(a+b)^2-1}{8}} \\ &\equiv f^{\frac{(a+b)^2-1}{4}} = f^{\frac{a^2+b^2-1+2ab}{4}} \\ &\equiv f^{\frac{p-1}{4}} f^{\frac{ab}{2}} \pmod{p} \end{aligned}$$

Since  $a^{\frac{p-1}{2}} = \left(\frac{a}{p}\right) = 1$  from Ex. 5.26(a)), then

$$(ab)^{\frac{p-1}{4}} \equiv (a^2 f)^{\frac{p-1}{4}} \equiv a^{\frac{p-1}{2}} f^{\frac{p-1}{4}} \equiv f^{\frac{p-1}{4}} \pmod{p},$$

so

$$2^{\frac{p-1}{4}} f^{\frac{p-1}{4}} \equiv f^{\frac{ab}{2}} f^{\frac{p-1}{4}} \pmod{p}.$$

As  $f^{\frac{p-1}{4}} \not\equiv 0 \pmod{p}$ ,

$$2^{\frac{p-1}{4}} \equiv f^{\frac{ab}{2}} \pmod{p}.$$

□

**Ex. 5.28** Show that  $x^4 \equiv 2 \pmod{p}$  has a solution for  $p \equiv 1 \pmod{4}$  iff  $p$  is of the form  $A^2 + 64B^2$ .

*Proof.* If  $p \equiv 1 \pmod{4}$  and if there exists  $x \in \mathbb{Z}$  such that  $x^4 \equiv 2 \pmod{p}$ , then

$$2^{\frac{p-1}{4}} \equiv x^{p-1} \equiv 1 \pmod{p}.$$

From Ex. 5.27, where  $p = a^2 + b^2$ ,  $a$  odd, we know that

$$f^{\frac{ab}{2}} \equiv 2^{\frac{p-1}{4}} \equiv 1 \pmod{p}.$$

Since  $f^2 \equiv -1 \pmod{p}$ , the order of  $f$  modulo  $p$  is 4, thus  $4 \mid \frac{ab}{2}$ , so  $8 \mid ab$ .

As  $a$  is odd,  $8 \mid b$ , then  $p = A^2 + 64B^2$  (with  $A = a$ ,  $B = b/8$ ).

Reciprocally, if  $p = A^2 + 64B^2$ , then  $p \equiv 1 \pmod{4}$ .

Let  $a = A$ ,  $b = 8B$ . Then

$$2^{\frac{p-1}{4}} \equiv f^{\frac{ab}{2}} \equiv f^{4AB} \equiv (-1)^{2AB} \equiv 1 \pmod{p}.$$

As  $2^{\frac{p-1}{4}} \equiv 1 \pmod{p}$ ,  $x^4 \equiv 2 \pmod{p}$  has a solution in  $\mathbb{Z}$  (Prop. 4.2.1) : 2 is a biquadratic residue modulo  $p$ .

Conclusion :

$$\exists A \in \mathbb{Z}, \exists B \in \mathbb{Z}, p = A^2 + 64B^2 \iff (p \equiv 1 \pmod{4} \text{ and } \exists x \in \mathbb{Z}, x^4 \equiv 2 \pmod{p}).$$

Remark : the equation  $x^4 \equiv 2 \pmod{p}$  has also solutions if  $p \equiv -1 \pmod{8}$ .

Indeed, the equation  $x^4 \equiv 2 \pmod{p}$  has a solution in  $\mathbb{Z}$  iff  $2^{\frac{p-1}{d}} \equiv 1$ , where  $d = 4 \wedge (p-1) = 2$ , thus iff  $2^{\frac{p-1}{2}} \equiv 1 \pmod{p}$ , which is true as  $\left(\frac{2}{p}\right) = 1$ .

For instance,  $8^4 \equiv 2 \pmod{23}$ , with  $23 \equiv -1 \pmod{8}$ . □

**Ex. 5.29** Let  $(RR)$  be the number of pairs  $(n, n+1)$  in the set  $1, 2, 3, \dots, p-1$  such that  $n$  and  $n+1$  are both quadratic residues modulo  $p$ . Let  $(NR)$  be the number of pairs  $(n, n+1)$  in the set  $1, 2, 3, \dots, p-1$  such that  $n$  is a quadratic nonresidue and  $n+1$  is a quadratic residue. Similarly, define  $(RN)$  and  $(NN)$ . Determine the sums  $(RR) + (RN)$ ,  $(NR) + (NN)$ ,  $(RR) + (NR)$ , and  $(RN) + (NN)$ .

*Proof.* Let  $E$  the set of pairs  $(n, n+1) \in \mathbb{N}^2, 1 \leq n \leq p-2 : |E| = p-2$ .

Write  $RR$  the set of pairs  $(n, n+1)$  such that  $n$  and  $n+1$  are both a quadratic residues, and  $(RR) = |RR|$  its cardinality, and similar definitions for  $RN, NR, NN$ .

As  $E = RR \cup RN \cup NR \cup NN$  (disjoint union),

$$(RR) + (RN) + (NR) + (NN) = |E| = p-2.$$

•  $RR \cup RN$  is the set of pairs  $(n, n+1)$  in  $E$  such that  $n$  is a residue. Its cardinality is the number of residues in  $[1, p-2]$ , so the number of residues in  $[1, p-1]$ , minus  $s$ , where  $s = 1$  if  $p-1$  is a residue,  $s = 0$  otherwise. In both cases  $p \equiv 1, 3 \pmod{4}$ ,  $s = \frac{1+(-1)^{\frac{p-1}{2}}}{2}$ , and the total number of residues is  $(p-1)/2$ , so

$$(RR) + (RN) = \frac{p-1}{2} - s = \frac{p-1}{2} - \frac{1+(-1)^{\frac{p-1}{2}}}{2} = \frac{1}{2}(p-2 - (-1)^{\frac{p-1}{2}}).$$

• Similarly,  $(NR) + (NN)$  is the number of nonresidues in  $[1, p-1]$ , minus  $t$ , where  $t = 1$  if  $p-1$  is a nonresidue,  $t = 0$  otherwise :  $t = \frac{1-(-1)^{\frac{p-1}{2}}}{2}$ , so

$$(NR) + (NN) = \frac{1}{2}(p-2 + (-1)^{\frac{p-1}{2}})$$

(the sum of these two results is indeed  $p-2 = |E|$ ).

• As 1 is a residue,  $(RR) + (NR)$  is the number of residues in  $[1, p-1]$ , minus 1 :

$$(RR) + (NR) = \frac{p-1}{2} - 1.$$

•  $(RN) + (NN)$  is the number of nonresidues in  $[2, p-1]$ , equal to the number of residues in  $[1, p-1]$  :

$$(RN) + (NN) = \frac{p-1}{2}.$$

□

**Ex. 5.30** Show that  $(RR) + (NN) - (RN) - (NR) = \sum_{n=1}^{p-1} (n(n+1)/p)$ . Evaluate this sum and show that it is equal to  $-1$ . (Hint : The result of Exercise 8 is useful.)

*Proof.* Let  $\chi$  be the characteristic function of  $RR \cup NN$  : if  $1 \leq n \leq p-1$ ,  $\chi(n) = 1$  if  $n, n+1$  are both residues, or if  $n, n+1$  are both non residues. Then

$$\chi(n) = \frac{1}{2} \left( 1 + \left( \frac{n}{p} \right) \left( \frac{n+1}{p} \right) \right)$$

(if  $\chi(n) = 1$ ,  $\left( \frac{n}{p} \right) \left( \frac{n+1}{p} \right) = 1$ , and  $\left( \frac{n}{p} \right) \left( \frac{n+1}{p} \right) = -1$  otherwise.)

Similarly, let  $\chi'$  the characteristic function of  $RN \cup NR$  :  $\chi(n) = 1$  if exactly one of the integer  $n, n+1$  is a residue, 0 otherwise. Then

$$\chi'(n) = \frac{1}{2} \left( 1 - \left( \frac{n}{p} \right) \left( \frac{n+1}{p} \right) \right).$$

As each integer  $n$  between 1 and  $p-1$  brings the contribution 1 if  $n \in RR \cup NN$ , and  $-1$  if  $n \in RN \cup NR$ , then

$$\begin{aligned} (RR) + (NN) - (RN) - (NR) &= \sum_{n=1}^{p-1} (\chi(n) - \chi'(n)) \\ &= \frac{1}{2} \sum_{n=1}^{p-1} \left( 1 + \left( \frac{n(n+1)}{p} \right) \right) - \left( 1 - \left( \frac{n(n+1)}{p} \right) \right) \\ &= \sum_{n=1}^{p-1} \left( \frac{n(n+1)}{p} \right) \end{aligned}$$

To evaluate this sum  $S$ , note that  $4n(n+1) = (2n+1)^2 - 1$ , so

$$S = \sum_{n=1}^{p-1} \left( \frac{n(n+1)}{p} \right) = \sum_{n=1}^{p-1} \left( \frac{4n(n+1)}{4p} \right) = \sum_{n=1}^{p-1} \left( \frac{(2n+1)^2 - 1}{4p} \right).$$

This sum can be written  $S = \sum_{\bar{n} \in \mathbb{F}_p^*} ((2\bar{n}+1)^2 - 1)/p = \sum_{\bar{n} \in \mathbb{F}_p} ((2\bar{n}+1)^2 - 1)/p$ , since  $(0/p) = 0$ . As  $f : \mathbb{F}_p \rightarrow \mathbb{F}_p, \bar{n} \mapsto (2\bar{n}+1)$  is a bijection (2 is invertible in  $\mathbb{F}_p^*$ ),

$$\sum_{\bar{n} \in \mathbb{F}_p} \left( \frac{(2\bar{n}+1)^2 - 1}{p} \right) = \sum_{\bar{y} \in \mathbb{F}_p} \left( \frac{y^2 - 1}{p} \right) \quad (y = 2\bar{n}+1).$$

As  $p \nmid 1$ , the evaluation of this last sum is given in Exercise 5.8 :  $S = -1$ , so

$$(RR) + (NN) - (RN) - (NR) = \sum_{n=1}^{p-1} \left( \frac{n(n+1)}{p} \right) = -1.$$

□

**Ex. 5.31** Use the results of Exercises 29 and 30 to show that  $(RR) = \frac{1}{4}(p-4-\varepsilon)$ , where  $\varepsilon = (-1)^{(p-1)/2}$

*Proof.* To summarize the results of the Ex. 5.29 and 5.30,

$$\begin{aligned}(a)(RR) + (RN) + (NR) + (NN) &= p - 2 \\ (b)(RR) + (NN) - (RN) - (NR) &= -1\end{aligned}$$

and

$$\begin{aligned}(c)(RR) + (RN) &= \frac{1}{2} \left( p - 2 - (-1)^{\frac{p-1}{2}} \right) \\ (d)(RR) + (NR) &= \frac{p-1}{2} - 1\end{aligned}$$

The sum of (a) and (b) gives

$$(e)(RR) + (NN) = \frac{p-3}{2}.$$

The sum of (c),(d),(e) gives (using (a))

$$2(RR) + p - 2 = \frac{p-2}{2} + \frac{p-1}{2} + \frac{p-3}{2} - 1 - \frac{(-1)^{\frac{p-1}{2}}}{2},$$

so

$$\begin{aligned}2(RR) &= \frac{p-1}{2} + \frac{p-3}{2} - \frac{p-2}{2} - 1 - \frac{(-1)^{\frac{p-1}{2}}}{2} = \frac{p}{2} - 2 - \frac{(-1)^{\frac{p-1}{2}}}{2}, \\ (RR) &= \frac{1}{4}(p - 4 - \varepsilon), \text{ where } \varepsilon = (-1)^{\frac{p-1}{2}}.\end{aligned}$$

□

**Ex. 5.32** If  $p$  is an odd prime, show that  $(2/p) = \prod_{j=1}^{(p-1)/2} 2 \cos(2\pi j/p)$ . Use this to give another proof to Proposition 5.1.3.

*Proof.* Let  $p$  an odd prime number, and  $\zeta = e^{2i\pi/p}$  : then  $\zeta^p = 1$ .

Let

$$P = \prod_{j=0}^{p-1} (\zeta^j + \zeta^{-j}) = \prod_{j=0}^{p-1} 2 \cos(2\pi j/p).$$

$$\begin{aligned}P &= \zeta^0 \zeta^{-1} \dots \zeta^{-(p-1)} \prod_{j=0}^{p-1} (\zeta^{2j} + 1) \\ &= (\zeta^p)^{-(p-1)/2} \prod_{j=0}^{p-1} (\zeta^{2j} + 1) \\ &= \prod_{j=0}^{p-1} (\zeta^{2j} + 1)\end{aligned}$$

As  $\zeta^j$  depends only of the class  $\bar{j} \in \mathbb{F}_p$ , this product can be written

$$P = \prod_{\bar{j} \in \mathbb{F}_p} (\zeta^{2j} + 1) = \prod_{\bar{k} \in \mathbb{F}_p} (\zeta^k + 1) \quad (k = 2j),$$

since  $f : \mathbb{F}_p \rightarrow \mathbb{F}_p, x \mapsto 2x$  is a bijection. So

$$P = \prod_{k=0}^{p-1} (\zeta^k + 1).$$

Since  $\zeta^0 = 1, \zeta, \dots, \zeta^{p-1}$  are the roots of the polynomial  $f(x) = x^p - 1$ , then  $1 + \zeta^0, \dots, 1 + \zeta^{p-1}$  are the roots of  $g(x) = (x - 1)^p - 1 = f(x - 1)$ , so  $g(x) = \prod_{k=0}^{p-1} (x - (1 + \zeta^k))$ .

As  $g(0) = (-1)^p - 1 = -2 = (-1 - \zeta^0) \cdots (-1 - \zeta^{p-1}) = -\prod_{k=0}^{p-1} (\zeta^k + 1)$ , we obtain

$$P = \prod_{j=0}^{p-1} 2 \cos(2\pi j/p) = \prod_{k=0}^{p-1} (\zeta^k + 1) = 2,$$

so

$$\prod_{j=1}^{p-1} 2 \cos(2\pi j/p) = 1.$$

$$\begin{aligned} 1 &= \prod_{j=1}^{p-1} 2 \cos(2\pi j/p) \\ &= \prod_{j=1}^{(p-1)/2} 2 \cos(2\pi j/p) \prod_{j=(p+1)/2}^{p-1} 2 \cos(2\pi j/p) \\ &= \prod_{j=1}^{(p-1)/2} 2 \cos(2\pi j/p) \prod_{k=1}^{(p-1)/2} 2 \cos(2\pi - 2\pi k/p) \quad (k = p - j) \end{aligned}$$

As  $\cos(2\pi - \alpha) = \cos(\alpha)$ ,

$$1 = \left( \prod_{j=1}^{(p-1)/2} 2 \cos(2\pi j/p) \right)^2, \text{ so } \prod_{j=1}^{(p-1)/2} 2 \cos(2\pi j/p) = \pm 1$$

Case 1 : if  $1 \leq j \leq p/4, 0 \leq 2\pi j/p < \pi/2$ , so  $\cos(2\pi j/p) > 0$ ,

case 2 : if  $p/4 < j \leq (p-1)/2, \pi/2 < 2\pi j/p < \pi$ , so  $\cos(2\pi j/p) < 0$ .

In the first case,  $2 \leq 2j \leq (p-1)/2$  : the least residue of  $2j$  is positive. In the second case  $p/2 < 2j \leq p-1$  : the least residue of  $2j$  is negative.

Let  $\mu$  the number of negative least residues of the integer  $2j$ ,  $1 \leq j \leq (p-1)/2$  : we know from Gauss' Lemma that  $(2/p) = (-1)^\mu$ . As  $\mu$  is also the number of  $j$ ,  $1 \leq j \leq (p-1)/2$  such that  $\cos(2\pi j/p) > 0$ ,

$$\prod_{j=1}^{(p-1)/2} 2 \cos(2\pi j/p) = (-1)^\mu = \left(\frac{2}{p}\right).$$

If  $p \equiv 1 \pmod{8}$ ,  $p = 8q + 1, q \in \mathbb{N}$ . For  $1 \leq j \leq (p-1)/2$ ,

$$\cos(2\pi j/p) < 0 \iff p/4 \leq j \leq (p-1)/2 \iff 2q + 1 \leq j \leq 4q,$$

so  $\mu = 2q$  and  $(2/p) = (-1)^\mu = 1$ .

If  $p \equiv -1 \pmod{8}$ ,  $p = 8q - 1$ ,  $q \in \mathbb{N}^*$ .

$$\cos(2\pi j/p) < 0 \iff p/4 \leq j \leq (p-1)/2 \iff 2q \leq j \leq 4q-1,$$

so  $\mu = 2q$  and  $(2/p) = (-1)^\mu = 1$ .

If  $p \equiv 3 \pmod{8}$ ,  $p = 8q + 3$ ,  $q \in \mathbb{N}$ .

$$\cos(2\pi j/p) < 0 \iff p/4 \leq j \leq (p-1)/2 \iff 2q+1 \leq j \leq 4q+1,$$

so  $\mu = 2q+1$  and  $(2/p) = (-1)^\mu = 1$ .

If  $p \equiv -3 \pmod{8}$ ,  $p = 8q - 3$ ,  $q \in \mathbb{N}^*$ ,

$$\cos(2\pi j/p) < 0 \iff p/4 \leq j \leq (p-1)/2 \iff 2q \leq j \leq 4q-2,$$

so  $\mu = 2q-1$  and  $(2/p) = (-1)^\mu = 1$ . □

**Ex. 5.33** Use Proposition 5.3.2 to derive the quadratic character of  $-1$ .

*Proof.* Let  $f(z) = e^{2\pi iz} - e^{-2\pi iz}$ . If  $p$  is an odd prime,  $a \in \mathbb{Z}$ , and  $p \nmid a$ , we know from Prop. 5.3.2 that

$$\prod_{l=1}^{(p-1)/2} f\left(\frac{la}{p}\right) = \left(\frac{a}{p}\right) \prod_{l=1}^{(p-1)/2} f\left(\frac{l}{p}\right).$$

For  $a = -1$ , as  $f(-z) = -f(z)$ ,

$$\begin{aligned} \left(\frac{-1}{p}\right) \prod_{l=1}^{(p-1)/2} f\left(\frac{l}{p}\right) &= \prod_{l=1}^{(p-1)/2} f\left(\frac{-l}{p}\right) \\ &= (-1)^{(p-1)/2} \prod_{l=1}^{(p-1)/2} f\left(\frac{l}{p}\right) \end{aligned}$$

Moreover  $f(z) = 0 \iff e^{4\pi iz} = 1 \iff 4\pi iz = 2ki\pi, k \in \mathbb{Z} \iff z = k/2, k \in \mathbb{Z}$ , so, if  $l \in \mathbb{Z}$ ,  $f\left(\frac{l}{p}\right) = 0 \iff l/p = k/2, k \in \mathbb{Z} \iff p \mid 2l \iff p \mid l$ . For  $1 \leq l < p$ , this is impossible, so  $\prod_{l=1}^{(p-1)/2} f\left(\frac{l}{p}\right) \neq 0$ . Consequently,

$$\left(\frac{-1}{p}\right) = (-1)^{(p-1)/2}.$$

□

**Ex. 5.34** If  $p$  is an odd prime distinct from 3, show that

$$\left(\frac{3}{p}\right) = \prod_{j=1}^{(p-1)/2} \left(3 - 4\sin^2\left(\frac{2\pi j}{p}\right)\right).$$

*Proof.* Let  $p$  an odd prime number,  $p \neq 3$  and  $\zeta = e^{2i\pi/p}$ .

$$\begin{aligned} 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) &= 3 - 4 \left( \frac{\zeta^j - \zeta^{-j}}{2i} \right)^2 \\ &= 3 + \zeta^{2j} + \zeta^{-2j} - 21 \\ &= 1 + \zeta^{2j} + \zeta^{-2j} \\ &= 1 + 2 \cos \left( \frac{4\pi j}{p} \right) \end{aligned}$$

(Or  $\cos(2\alpha) = 1 - 2 \sin^2 \alpha$ , so  $3 - 4 \sin^2 \alpha = 1 + 2 \cos \alpha$ .)

Let

$$P = \prod_{j=1}^{p-1} \left( 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) \right) = \prod_{\bar{j} \in \mathbb{F}_p^*} \left( 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) \right).$$

Then

$$\begin{aligned} P &= \prod_{\bar{j} \in \mathbb{F}_p^*} (1 + \zeta^{2j} + \zeta^{-2j}) \\ &= \prod_{\bar{k} \in \mathbb{F}_p^*} (1 + \zeta^k + \zeta^{-k}) \quad (k = 2j) \end{aligned}$$

since  $f : \mathbb{F}_p \rightarrow \mathbb{F}_p, \bar{j} \mapsto 2\bar{j}$  is a bijection. So

$$\begin{aligned} P &= \prod_{k=0}^{p-1} \zeta^{-k} (1 + \zeta^k + \zeta^{2k}) \\ &= 3 \prod_{k=1}^{p-1} \zeta^{-k} (1 + \zeta^k + \zeta^{2k}) \\ &= 3 \prod_{k=0}^{p-1} \zeta^{-k} \frac{\prod_{k=1}^{p-1} (1 - \zeta^{3k})}{\prod_{k=1}^{p-1} (1 - \zeta^k)} \end{aligned}$$

$\prod_{k=0}^{p-1} \zeta^{-k} = (\zeta^p)^{-(p-1)/2} = 1$ . Moreover,  $\prod_{k=1}^{p-1} (1 - \zeta^{3k}) = \prod_{k=1}^{p-1} (1 - \zeta^k)$ , since  $\bar{k} \mapsto 3\bar{k}$  is a bijection in  $\mathbb{F}_p^*$ , so  $P = 3$ , and consequently

$$\begin{aligned} 1 &= \prod_{j=1}^{p-1} \left( 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) \right) \\ &= \prod_{j=1}^{(p-1)/2} \left( 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) \right) \prod_{j=(p+1)/2}^{p-1} \left( 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) \right) \\ &= \prod_{j=1}^{(p-1)/2} \left( 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) \right) \prod_{k=1}^{(p-1)/2} \left( 3 - 4 \sin^2 \left( \frac{2\pi(k-j)}{p} \right) \right) \quad (k = p-j) \\ &= \left[ \prod_{j=1}^{(p-1)/2} \left( 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) \right) \right]^2 \end{aligned}$$

So  $\prod_{j=1}^{(p-1)/2} \left( 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) \right) = \pm 1$ .



Let  $\nu$  the number of negative factors in this product.

If  $1 \leq j \leq (p-1)/2$ , then  $0 < 4\pi j/p < 2\pi$ .

$$\begin{aligned}
1 + 2 \cos \frac{4\pi j}{p} < 0 &\iff \cos \frac{4\pi j}{p} < \cos \frac{2\pi}{3} \\
&\iff \frac{2\pi}{3} < \frac{4\pi j}{p} < \frac{4\pi}{3} \\
&\iff \frac{p}{6} < j < \frac{p}{3} \\
&\iff \frac{p}{2} < 3j < p
\end{aligned}$$

Let  $\mu$  the number of integers  $j, 1 \leq j \leq (p-1)/2$  such their least remainder is negative. Since  $3 \leq 3j \leq 3(p-1)/2$  and  $3j \neq p/2$ , these  $j$  are such that  $\frac{p}{2} < 3j < p$ , so  $\mu = \nu$ . Therefore

$$\prod_{j=1}^{(p-1)/2} \left( 3 - 4 \sin^2 \left( \frac{2\pi j}{p} \right) \right) = (-1)^\nu = (-1)^\mu = \left( \frac{3}{p} \right).$$

□

**Ex. 5.35** Use the preceding exercise to show that 3 is a square modulo  $p$  iff  $p$  is congruent to 1 or  $-1$  modulo 12.

*Proof.* We know from Ex. 5.34 that  $\nu = \text{Card} \{j \in [1, (p-1)/2] \mid p/2 \leq 3j < p\} = \mu$ .  $\nu$  is the number of  $j$  such that  $p/6 \leq j < p/3$ , so  $\nu = \lfloor p/3 \rfloor - \lfloor p/6 \rfloor$ .

If  $p = 12k + 1$ ,  $\nu = \lfloor p/3 \rfloor - \lfloor p/6 \rfloor = 4k - 2k = 2k : (3/p) = (-1)^\nu = 1$

If  $p = 12k + 5$ ,  $\nu = \lfloor p/3 \rfloor - \lfloor p/6 \rfloor = 4k + 1 - 2k = 2k + 1 : (3/p) = (-1)^\nu = -1$

If  $p = 12k - 5$ ,  $\nu = \lfloor p/3 \rfloor - \lfloor p/6 \rfloor = 4k - 2 - (2k - 1) = 2k - 1 : (3/p) = (-1)^\nu = -1$

If  $p = 12k - 1$ ,  $\nu = \lfloor p/3 \rfloor - \lfloor p/6 \rfloor = 4k - 1 - (2k - 1) = 2k : (3/p) = (-1)^\nu = 1$

3 is a square modulo  $p$  ( $p \neq 2, p \neq 3$ ) iff  $p$  is congruent to 1 or  $-1$  modulo 12. □

**Ex. 5.36** Show that part (c) of Proposition 5.2.2 is true if  $a$  is negative and  $b$  is positive (both still odd).

As said by Adam Michalik, the Jacobi symbol  $\left(\frac{a}{b}\right)$  only defined for positive  $b$ , so the question, which concerns  $\left(\frac{a}{b}\right)\left(\frac{b}{a}\right)$ ,  $a < 0$  makes no sense.

To give sense to this question, we must substitute the Kronecker symbol to the Jacobi symbol. The Kronecker symbol (not defined in Ireland-Rosen) is the usual extension of Jacobi symbol (see for instance [Henri Cohen] A course in computational algebraic number theory, [Henri Cohen] Number theory (vol. 1), or [Harvey Cohn] Advanced number theory).

We define Kronecker (or Kronecker-Jacobi) symbol  $\left(\frac{a}{b}\right)$  for any  $a$  and  $b$  in  $\mathbb{Z}$  in the following way.

(1) If  $b = 0$ , then  $\left(\frac{a}{0}\right) = 1$  if  $a = \pm 1$ , and is equal to 0 otherwise.

(2) For  $b \neq 0$ , write  $b = \prod p$ , where the  $p$  are not necessarily distinct primes (including 2), or  $p = -1$  to take care of the sign. Then we set

$$\left(\frac{a}{b}\right) = \prod \left(\frac{a}{p}\right),$$

where  $\left(\frac{a}{p}\right)$  is the Legendre symbol defined above for  $p > 2$ , and where we define

$$\left(\frac{a}{2}\right) = \begin{cases} 0 & \text{if } a \text{ is even} \\ (-1)^{(a^2-1)/8} & \text{if } a \text{ is odd,} \end{cases}$$

and also

$$\left(\frac{a}{-1}\right) = \begin{cases} 1 & \text{if } a \geq 0 \\ -1 & \text{if } a < 0 \end{cases}$$

*Proof.* Suppose  $a < 0, b > 0$ , both odd. Let  $a = -A, A > 0, A = p_1 p_2 \cdots p_k$ , where the  $p_i$  are not necessarily distinct primes. Then

$$\begin{aligned} \left(\frac{a}{b}\right) \left(\frac{b}{a}\right) &= \left(\frac{-A}{b}\right) \left(\frac{b}{-A}\right) \\ \left(\frac{-A}{b}\right) &= \left(\frac{-1}{b}\right) \left(\frac{A}{b}\right) = (-1)^{(b-1)/2} \left(\frac{A}{b}\right) \\ \left(\frac{b}{-A}\right) &= \left(\frac{b}{-1}\right) \left(\frac{b}{p_1}\right) \cdots \left(\frac{b}{p_k}\right) = \left(\frac{b}{A}\right) \end{aligned}$$

so, from Prop. 5.2.2, as  $A, b$  are odd and positive,

$$\begin{aligned} \left(\frac{a}{b}\right) \left(\frac{b}{a}\right) &= (-1)^{\frac{b-1}{2}} \left(\frac{A}{b}\right) \left(\frac{b}{A}\right) \\ &= (-1)^{\frac{b-1}{2}} (-1)^{\frac{A-1}{2} \frac{b-1}{2}} \\ &= (-1)^{\frac{b-1}{2} [1 + \frac{A-1}{2}]} \\ &= (-1)^{\frac{b-1}{2} \frac{1+A}{2}} \\ &= (-1)^{\frac{b-1}{2} \frac{a-1}{2}} \end{aligned}$$

So the law of quadratic reciprocity remains valid for the Kronecker symbol when  $a$  is negative ( $b > 0, a, b$  both odd).  $\square$

**Ex. 5.37** Show that if  $a$  is negative, then  $p \equiv q \pmod{4a}$ ,  $p \nmid a$  implies  $(a/p) = (a/q)$ .

*Proof.* Write  $a = -A, A > 0$ . As  $p \equiv q \pmod{4a}$ , we know from Prop. 5.3.3. (b) that  $(A/p) = (A/q)$ .

Moreover,

$$\begin{aligned} \left(\frac{a}{p}\right) &= \left(\frac{-A}{p}\right) = (-1)^{(p-1)/2} \left(\frac{A}{p}\right) \\ \left(\frac{a}{q}\right) &= \left(\frac{-A}{q}\right) = (-1)^{(q-1)/2} \left(\frac{A}{q}\right) \end{aligned}$$

As  $p \equiv q \pmod{4a}$ ,  $p = q + 4ak, k \in \mathbb{Z}$ , so

$$(-1)^{(p-1)/2} = (-1)^{(q+4ak-1)/2} = (-1)^{(q-1)/2},$$

so  $(a/p) = (a/q)$ .  $\square$

**Ex. 5.38** Let  $p$  be an odd prime. Derive the quadratic character of 2 modulo  $p$  by verifying the following steps, involving the Jacobi symbol:

$$\left(\frac{2}{p}\right) = \left(\frac{8-p}{p}\right) = \left(\frac{p}{p-8}\right) = \left(\frac{8}{p-8}\right) = \left(\frac{2}{p-8}\right).$$

Generalize the argument to show that

$$\left(\frac{a}{p}\right) = \left(\frac{a}{p-4a}\right), \quad a > 0, p \nmid a.$$

(As in Ex. 5.36, since  $8-p$  or  $p-8$  is negative, we interpret  $(a/b)$  as the Kronecker symbol : see definition in Ex. 5.36.)

*Proof.* As  $(2^2/p) = 1$  and  $8-p \equiv 8 \pmod{p}$ ,

$$\left(\frac{2}{p}\right) = \left(\frac{2^2}{p}\right) \left(\frac{2}{p}\right) = \left(\frac{8}{p}\right) = \left(\frac{8-p}{p}\right).$$

As  $p$  and  $8-p$  are odd numbers and  $p > 0$ , from the extension of the law of quadratic reciprocity to  $a < 0$  proved in Ex. 5.36, we obtain

$$\left(\frac{8-p}{p}\right) = (-1)^{\frac{7-p}{2} \frac{p-1}{2}} \left(\frac{p}{8-p}\right).$$

Moreover

$$(7-p)(p-1) \equiv (-1-p)(p-1) = 1-p^2 \pmod{8}$$

As  $p = 2k+1$  is odd,  $p^2 = 4k^2 + 4k + 1 = 8\frac{k(k+1)}{2} + 1 \equiv 1 \pmod{8}$ , so  $(7-p)(p-1) \equiv 0 \pmod{8}$  and  $\frac{7-p}{2} \frac{p-1}{2}$  is even, so

$$\left(\frac{8-p}{p}\right) = \left(\frac{p}{8-p}\right).$$

As  $p > 0$ ,  $\left(\frac{p}{-1}\right) = 1$ , thus  $\left(\frac{p}{8-p}\right) = \left(\frac{p}{-1}\right) \left(\frac{p}{p-8}\right) = \left(\frac{p}{p-8}\right)$  (with the same argument, this is also true for the 3 odd primes such that  $8-p > 0$ ), so

$$\left(\frac{8-p}{p}\right) = \left(\frac{p}{p-8}\right).$$

□

As  $p \equiv 8 \pmod{p-8}$ ,  $\left(\frac{p}{p-8}\right) = \left(\frac{8}{p-8}\right)$ , and since  $8 = 2^2 \times 2$ ,  $\left(\frac{8}{p-8}\right) = \left(\frac{2}{p-8}\right)$ . We have proved for all odd primes  $p$  that

$$\left(\frac{2}{p}\right) = \left(\frac{8-p}{p}\right) = \left(\frac{p}{p-8}\right) = \left(\frac{8}{p-8}\right) = \left(\frac{2}{p-8}\right).$$

The preceding arguments remain valid if we replace the odd prime  $p$  by any odd positive integer. So with an immediate induction, we see that for all  $k \in \mathbb{N}$ ,

$$\left(\frac{2}{p}\right) = \left(\frac{2}{p-8k}\right).$$

So the quadratic character of 2 modulo  $p$  depends only of the class of  $p$  modulo 8.

If  $p \equiv 1 \pmod{8}$ ,  $\left(\frac{2}{p}\right) = \left(\frac{2}{1}\right) = 1$ .

If  $p \equiv -1 \pmod{8}$ ,  $\left(\frac{2}{p}\right) = \left(\frac{2}{-1}\right) = 1$ .

If  $p \equiv \pm 3 \pmod{8}$ ,  $\left(\frac{2}{p}\right) = \left(\frac{2}{\pm 3}\right) = -1$ .

Generalization : let  $a > 0$  and  $p$  an odd positive integer such that  $p \wedge a = 1$  (not necessarily prime).

$$\left(\frac{a}{p}\right) = \left(\frac{4ap}{p}\right) = \left(\frac{4a-p}{p}\right) = (-1)^{\frac{4a-p-1}{2} \frac{p-1}{2}} \left(\frac{p}{4a-p}\right).$$

$(4a-p-1)(p-1) = 4a(p-1) + 1 - p^2 \equiv 0 \pmod{8}$ , so

$$\left(\frac{a}{p}\right) = \left(\frac{p}{4a-p}\right).$$

As  $\left(\frac{p}{-1}\right) = 1$ ,

$$\left(\frac{p}{4a-p}\right) = \left(\frac{p}{p-4a}\right).$$

Since  $p \equiv 4a \pmod{p} - 4a$ , and 4 is a square,

$$\left(\frac{p}{p-4a}\right) \equiv \left(\frac{4a}{p-4a}\right) = \left(\frac{a}{p-4a}\right).$$

We have proved

$$\left(\frac{a}{p}\right) = \left(\frac{4a-p}{p}\right) = \left(\frac{p}{p-4a}\right) = \left(\frac{4a}{p-4a}\right) = \left(\frac{a}{p-4a}\right).$$

By induction, for all  $k \geq 0$ ,  $\left(\frac{a}{p}\right) = \left(\frac{a}{p-4a}\right)$ , so  $\left(\frac{a}{p}\right)$  depends only of the class of  $p$  modulo  $4a$ .