Solutions to Ireland, Rosen "A Classical Introduction to Modern Number Theory"

Richard Ganaye

October 28, 2019

Chapter 7

Ex. 7.1 *Use the method of Theorem 1 to show that a finite subgroup of the multiplicative group of a field is cyclic.*

A solution is already given in Ex. 4.15

Ex. 7.2 *Find the finite subgroups of $\mathbb{R}^*$ and $\mathbb{C}^*$ and show directly that they are cyclic.*

Proof. If G is a finite subgroup of $\mathbb{R}$ or $\mathbb{C}$, and $n = |G|$, then from Lagrange's Theorem, $x^n = 1$ for all $x \in G$.

- If G is a finite subgroup of $\mathbb{R}^*$, then the solutions of $x^n = 1$ are in $\{-1, 1\}$, so $\{1\} \subset G \subset \{-1, 1\}$: $G = \{1\}$ or $G = \{-1, 1\}$, both cyclic.
- If G is a finite subgroup of $\mathbb{C}^*$, then $G \subset \mathbb{U}_n = \{e^{2ik\pi/n} \mid 0 \le k \le n-1\}$. As $|G| = |\mathbb{U}_n| = n$, then $G = \mathbb{U}_n \simeq \mathbb{Z}/n\mathbb{Z}$ is cyclic. □

Ex. 7.3 *Let F a field with q elements and suppose that $q \equiv 1 \pmod n$. Show that for $\alpha \in \mathbb{F}^*$, the equation $x^n = \alpha$ has either no solutions or n solutions.*

Proof. This is a particular case of Prop. 7.1.2., where $d = n \wedge (q-1) = n$: the equation $x^n = \alpha$ has solutions iff $\alpha^{(q-1)/n} = 1$. In this case, there are exactly $d = n$ solutions.

We give here a direct proof.

Let g a generator of F^*. Write $x = g^y, \alpha = g^a$. Then

$$x^n = \alpha \iff g^{ny} = g^a \iff q - 1 \mid ny - a.$$

Suppose that there exists $x \in F$ such that $x^n = \alpha$. Then there exists $y \in \mathbb{Z}$ such that $q - 1 \mid ny - a$. Since $n \mid q - 1$, then $n \mid a$.

$$q - 1 \mid ny - a \iff \frac{q-1}{n} \mid y - \frac{a}{n} \iff y = \frac{a}{n} + k\frac{q-1}{n}, k \in \mathbb{Z}.$$

As $\frac{a}{n} + (k+n)\frac{q-1}{n} = \frac{a}{n} + k\frac{q-1}{n}, k \in \mathbb{Z}$, the values $k = 0, 1 \cdots, n-1$ are sufficient :

$$x^n = \alpha \iff y = \frac{a}{n} + k\frac{q-1}{n}, k \in \{0, 1, \cdots, n-1\}.$$

Moreover, these solutions are all distinct : if $k, l \in \{0, 1, \cdots, n-1\}$,

$$\begin{aligned} g^{\frac{a}{n}+k\frac{q-1}{n}} = g^{\frac{a}{n}+l\frac{q-1}{n}} &\Rightarrow g^{(k-l)\frac{q-1}{n}} = 1 \\ &\Rightarrow q-1 \mid (k-l)\frac{q-1}{n} \\ &\Rightarrow n \mid k-l \\ &\Rightarrow k \equiv l\ [n] \Rightarrow k = l. \end{aligned}$$

Conclusion : if F is a field with q elements and $n \mid q-1$, the equation $x^n = \alpha$ has either no solutions or n solutions in F.

Remark :

$$\exists x \in F^*, x^n = \alpha \iff n \mid a \iff \alpha^{(q-1)/n} = 1.$$

Indeed, if $x^n = \alpha$ has a solution, we have proved that $n \mid a$, thus $\alpha^{(q-1)/n} = (g^{a/n})^{q-1} = 1$.

Reciprocally, if $\alpha^{(q-1)/n} = 1$, $g^{a.(q-1)/n} = 1$, thus $q-1 \mid a(q-1)/n$, so $n \mid a$: $\alpha = x^n$, with $x = g^{n/a}$. $\square$

Ex. 7.4 *(continuation) Show that the set of $\alpha \in F^*$ such that $x^n = \alpha$ is solvable is a subgroup with $(q-1)/n$ elements.*

Proof. Here $n \mid q-1$.

Let $\varphi = F^* \to F^*$ the application defined by $\varphi(x) = x^n$. φ is a morphism of groups, and $\ker \varphi$ is the set of solutions of $x^n = 1$. As $n \mid q-1$, $x^n = 1$ has exactly n solutions (Prop 7.1.1, Corollary2, or Ex 7.3 with $\alpha = 1$). So $|\ker \varphi| = n$.

Thus $\text{Im}\varphi \simeq F^*/\ker \varphi$ is a subgroup with cardinality $|F^*|/|\ker \varphi| = (q-1)/n$, and $\text{Im}\varphi$ is the set of α such that $x^n = \alpha$ is solvable.

Conclusion : the set of $\alpha \in F^*$ such that $x^n = \alpha$ is solvable is a subgroup with $(q-1)/n$ elements.

$\square$

Ex. 7.5 *(continuation) Let K be a field containing F such that $[K : F] = n$. For all $\alpha \in F^*$, show that the equation $x^n = \alpha$ has n solutions in K. [Hint: Show that $q^n - 1$ is divisible by $n(q-1)$ and use the fact that $\alpha^{q-1} = 1$.]*

Proof. As $q \equiv 1\ [n]$, $\frac{q^n-1}{q-1} = 1 + q + \cdots + q^{n-1} \equiv 0\ [n]$, then $n \mid \frac{q^n-1}{q-1}$:

$$q^n - 1 = kn(q-1), k \in \mathbb{N}.$$

Since $\alpha \in F^*$, $\alpha^{q-1} = 1$, so

$$\alpha^{(q^n-1)/n} = (\alpha^{q-1})^k = 1.$$

As $|K| = q^n$, Prop. 7.1.2 (or the final remark in Ex.7.3) show that there exists $x \in K^*$ such that $x^n = \alpha$. Then, from Ex.7.3, we know that there exist n solutions in K.

Conclusion : if $[K : F] = n$, the equation $x^n = \alpha$ has n solutions in K.

$\square$

Ex. 7.6 *Let $K \supset F$ be finite fields with $[K : F] = 3$. Show that if $\alpha \in F$ is not a square in F, it is not a square in K.*

Proof. Let $q = |F|$. Then $|K| = q^3$.

If the characteristic of F is 2, $q = 2^k$, and for all $x \in F$, $x = x^q = \left(x^{2^{k-1}}\right)^2$. So all elements in F or K are squares. We can now suppose that the characteristic of F is not 2, and consequently $1 \neq -1$ in F.

As α is not a square in F, $\alpha^{(q-1)/2} \neq 1$ (Prop. 7.1.2). From $0 = \alpha^{q-1} - 1 = (\alpha^{(q-1)/2} - 1)(\alpha^{(q-1)/2} + 1)$, we deduce $\alpha^{(q-1)/2} = -1$. Then

$$\alpha^{(q^3-1)/2} = (\alpha^{(q-1)/2})^{q^2+q+1} = (-1)^{q^2+q+1} = -1,$$

since $q^2 + q + 1$ is always odd.

$\alpha^{(q^3-1)/2} \neq 1$: this implies (Prop. 7.1.2) that α is not a square in K. □

Ex. 7.7 *Generalize Exercise 6 by showing that if α is not a square in F, it is not a square in any extension of odd degree and is a square in every extension of even degree.*

Proof. Write $q = [K : F]$, and $q = \text{Card } F$.

As α is not a square in F, the characteristic of F is not 2 (see Ex.7.6), and $\alpha^{(q-1)/2} \neq 1$. Since $\alpha^{q-1} = 1$, $\alpha^{(q-1)/2} = -1$.

$$\alpha^{(q^n-1)/2} = (\alpha^{(q-1)/2})^{1+q+\cdots+q^{n-1}} = (-1)^{1+q+\cdots+q^{n-1}}.$$

- If n is odd, $1+q+\cdots+q^{n-1} \equiv 1 \pmod 2$, thus $\alpha^{(q^n-1)/2} = -1 \neq 1$, and consequently α is not a square in K.
- If n is even, as q is odd ($\text{char}(F) \neq 2$), $1 + q + \cdots + q^{n-1} \equiv 0 \pmod 2$, thus $\alpha^{(q^n-1)/2} = 1$, so α is a square in K. □

Ex. 7.8 *In a field with 2^n elements, what is the subgroup of squares.*

Let F a field with $q = 2^n$ elements.

Proof 1

Proof. $d = (q-1) \wedge 2 = (2^n - 1) \wedge 2 = 1$, thus each $\alpha \in F^*$ verifies $\alpha^{(q-1)/d} = \alpha^{q-1} = 1$. Theorem 7.1.2 show that α is a square in F, of exactly one root. □

Proof 2

Proof. For all $x \in F$, $x = x^q = \left(x^{2^{n-1}}\right)^2$. So all elements in F or K are squares. □

Ex. 7.9 *If $K \supset F$ are finite fields, $|F| = q, \alpha \in F, q \equiv 1 \pmod n$, and $x^n = \alpha$ is not solvable in F, show that $x^n = \alpha$ is not solvable in K if $(n, [K : F]) = 1$.*

Proof. Let $k = [K : F]$. From hypothesis, $k \wedge n = 1$, so there exist integers u, v such that $uk + vn = 1$.

As $n \mid q - 1$, $n \wedge (q - 1) = n$, so the hypothesis "$x^n = \alpha$ is not solvable in F" implies that $\alpha^{(q-1)/n} \neq 1$ (Prop. 7.1.2).

Write $\omega = \alpha^{(q-1)/n}$, so $\omega \neq 1$ and $\omega^n = 1$.

As $n \mid q-1$, $n \mid q^k - 1$ and

$$\alpha^{(q^k-1)/n} = (\alpha^{(q-1)/n})^{1+q+q^2+\cdots+q^{k-1}} = \omega^{1+q+q^2+\cdots+q^{k-1}}.$$

Moreover $1+q+\cdots+q^{k-1} \equiv k \pmod n$, and $\omega^n = 1$, so $\alpha^{(q^k-1)/n} = \omega^k$.

If $\omega^k = 1$, then $\omega = \omega^{uk+vn} = (\omega^k)^u(\omega^n)^v = 1$, which is in contradiction with $\omega = \alpha^{(q-1)/n} \neq 1$.

So $\alpha^{(q^k-1)/n} = \omega^k \neq 1$, and consequently the equation $x^n = \alpha$ has no solution in K. □

Ex. 7.10 *If $K \supset F$ be finite fields and $[K : F] = 2$. For $\beta \in K$, show that $\beta^{1+q} \in F$ and moreover that every element in F is of the form β^{1+q} for some $\beta \in K$.*

Proof. If $\beta = 0$, $\beta^{1+q} = 0 \in F$, and if $\beta \in K^*$, $\beta^{q^2-1} = 1$, so $\left(\beta^{1+q}\right)^{q-1} = 1$, thus $\beta^{1+q} \in F$ (Prop. 7.1.1, Corollary 1).

Let g a generator of $K^* : K^* = \{1, g, g^2, \cdots, g^{q^2-2}\}$.

For every in integer $k \in \mathbb{Z}$,

$$g^k \in F^* \iff (g^k)^{q-1} = 1 \iff g^{k(q-1)} = 1 \iff q^2 - 1 \mid k(q-1) \iff q+1 \mid k.$$

Thus $F^* = \{1, g^{q+1}, g^{2(q+1)}, \cdots, g^{(q-2)(q+1)}\}$. I $\alpha \in F^*$, there exists $i, 0 \le i \le q-1$ such that $\alpha = g^{i(q+1)}$. If we write $\beta = g^i$, then $\alpha = \beta^{1+q}$ (and for $\alpha = 0$, we take $\beta = 0$).

Conclusion : if K is a quadratic extension of F (F, K finite fields), every element in F is of the form β^{1+q} for some $\beta \in K$. □

Ex. 7.11 *With the situation being that of Exercise 10 suppose that $\alpha \in F$ has order $q-1$. Show that there is a $\beta \in K$ with order q^2-1 such that $\beta^{1+q} = \alpha$.*

Write $|a|$ the order of an element a in a group G. We recall the following lemma :

Lemma If $|a| = d$, then for all $i \in \mathbb{Z}$, $|a^i| = \frac{d}{d \wedge i}$.

Proof. Indeed, for all $k \in \mathbb{Z}$,

$$(a^i)^k = e \iff a^{ik} = e \iff d \mid ik \iff \frac{d}{d \wedge i} \mid \frac{i}{d \wedge i} k \iff \frac{d}{d \wedge i} \mid k.$$

□

Proof. (Ex. 7.11)

Let $\alpha \in F^*$ with $|a| = q-1$, and g a generator of K^*, so $|g| = q^2 - 1$. We know from exercise 7.10 that there exists an integer i such that $\alpha = g^{i(q+1)}$.

Let $h = g^{q+1}$. As $h^{q-1} = 1$, then $h \in F^*$, and since $|g| = q^2-1$, $|h| = q-1$, so h is a generator of F^*.

Note that for all $s \in \mathbb{Z}$, $\alpha = g^{(i+s(q-1))(q+1)}$, since $g^{q^2-1} = 1$.

We will show that we can choose s such that $j = i + s(q-1)$ is relatively prime with $q+1$. Then j is such that $\alpha = g^{j(q+1)} = h^j$.

i is odd : if not α is an element of the subgroup of squares in F^*, so its order divides $(q-1)/2$, in contradiction with $|\alpha| = q-1$.

$(q-1) \wedge (q+1) \mid 2$. Since $i-1$ is even, there exist integers s, t verifying the Bézout's equation

$$i - 1 = t(q+1) - s(q-1).$$

Then $j = i + s(q-1) = 1 + t(q+1)$ is relatively prime with $q+1$: $j \wedge (q+1) = 1$.

Moreover, as $\alpha = h^j$, with $|\alpha| = |h| = q-1$, the lemme implies that

$$q - 1 = |\alpha| = \frac{q-1}{(q-1) \wedge j},$$

so $(q-1) \wedge j = 1$. As $(q+1) \wedge j = 1$ and $(q-1) \wedge j = 1$, then $(q^2-1) \wedge j = 1$.

Let $\beta = g^j$: then $\alpha = \beta^{1+q}$, and using the lemma :

$$|\beta| = |g^j| = \frac{q^2-1}{(q^2-1) \wedge j} = q^2 - 1.$$

Conclusion : there exists a $\beta \in K^*$ with order $q^2 - 1$ such that $\beta^{1+q} = \alpha$. $\square$

Ex. 7.12 *Use Proposition 7.2.1 to show that given a field k and a polynomial $f(x) \in k[x]$ there is a field $K \supset k$ such that $[K : k]$ is finite and $f(x) = a(x-\alpha_1)(x-\alpha_2)\cdots(x-\alpha_n)$ in $K[x]$.*

Proof. We show by induction on the degree n of f that for all polynomials $f \in k[x]$ with $\deg(f) = n \geq 1$, there exists a field extension K such that $[K : k]$ is finite, and $f(x)$ splits in linear factors on K.

If $n = 1$, $f(x) = ax + b = a(x - \alpha_0)$, where $\alpha_0 = -b/a$: $K = k$ is suitable.

Suppose that the property is true for all polynomials of degree less than n on an arbitrary field k.

Let $f(x) \in k[x], \deg(f) = n$. From propoistion 7.2.1. applied to an irreducible factor of f, there exists a field $L, [L : K] < \infty$ and $\alpha \in L$ such that $f(\alpha_1) = 0$. Then $f(x) = (x - \alpha_1)g(x), g(x) \in L[x]$.

Applying the induction hypothesis in the field L on the polynomial $g \in L[x]$ with $\deg(g) = n-1$, we obtain a field $K, [K : L] < \infty$ such that $g(x) = a(x-\alpha_2)\cdots(x-\alpha_n)$ with $\alpha_i \in K$. So $f(x) = a(x-\alpha_1)(x-\alpha_2)\cdots(x-\alpha_n)$ splits in linear factors in K. The induction is achieved. $\square$

Ex. 7.13 *Apply Exercise 7.12 to $k = \mathbb{Z}/p\mathbb{Z}$ and $f(x) = x^{p^n} - x$ to obtain another proof of Theorem 2.*

Proof. Let $f(x) = x^{p^n} - x$. We know from Ex. 7.12 that there exists a finite extension K of $\mathbb{F}_p$ such that f splits in linear factors on K :

$$f(x) = \prod_{k=1}^{p^n} (x - \alpha_k), \qquad \alpha_1, \ldots, \alpha_{p^n} \in K.$$

The set $k = \{\alpha_1, \cdots, \alpha_{p_n}\} \subset K$ of the roots of $x^{p^n} - x$ is a subfield of K : indeed, if $\alpha, \beta \in k$,

(a) $f(1) = 0$, so $1 \in k$

(b) $(\alpha - \beta)^{p^n} = \alpha^{p^n} - \beta^{p^n} = \alpha - \beta$, so $\alpha - \beta \in k$.

(c) $(\alpha\beta)^{p^n} = \alpha^{p^n}\beta^{p^n} = \alpha\beta$, so $\alpha\beta \in k$.

(d) $(\alpha^{-1})^{p^n} = (\alpha^{p^n})^{-1} = \alpha^{-1}$, so $\alpha^{-1} \in k$ if $\alpha \neq 0$.

As $f'(x) = -1$, $f(x) \wedge f'(x) = 1$, so f has no multiple root, so the cardinality of k is p^n.

Let $g(x) \in \mathbb{F}_p[x]$ a factor of $f(x)$, irreducible in $\mathbb{F}_p[x]$, with $d = \deg(g)$. As $g \mid f$, g splits in linear factors in $k[x]$. Let α a root of $g(x)$ in k. As g is irreducible on $\mathbb{F}_p$, $d = \deg(g) = [\mathbb{F}_p[\alpha] : \mathbb{F}_p]$. Moreover $n = [k : \mathbb{F}_p] = [k : \mathbb{F}_p[\alpha]]\, [\mathbb{F}_p[\alpha] : \mathbb{F}_p]$, so $d \mid n$.

Reciprocally, suppose that g is any irreducible polynomial in $\mathbb{F}_p[x]$, with $d = \deg(g) \mid n$. Then $K_0 = \mathbb{F}_p[x]/\langle g \rangle$ contains a root α of g, and $[K_0 : \mathbb{F}_p] = \deg(g) = d$, so $\alpha^{p^d} = \alpha$.

As $d \mid n$, then $p^d - 1 \mid p^n - 1$ and $x^{p^d} - 1 \mid x^{p^n} - 1$ (Lemma 2,3 in section 1), so

$$x^{p^d} - x \mid x^{p^n} - x.$$

$f(\alpha) = \alpha^{p^n} - \alpha = 0$ and g is the minimal polynomial of α, so $g \mid f$.

Conclusion :

$$x^{p^n} - x = \prod_{d \mid n} F_d(x),$$

where $F_d(x)$ is the product of the monic irreducible polynomial of degree d. ☐

Ex. 7.14 *Let F be a field with q elements and n a positive integer. Show that there exist irreducible polynomials in $F[x]$ of degree n.*

Proof. Leq $F = \mathbb{F}_q$ a field with $q = p^m$ elements, and n a positive integer.

From Theorem 2 Corollary 3, there exists an irreducible polynomial $f(x) \in \mathbb{F}_p[x]$ of degree nm. Let g an irreducible factor of f in $\mathbb{F}_q[x]$, and α a root of g in an extension of $\mathbb{F}_q$.

We show that $\mathbb{F}_q \subset \mathbb{F}_p[\alpha]$.

$\mathbb{F}_q$ and $\mathbb{F}_p[\alpha]$ are two subfield of the same finite field $\mathbb{F}_q[\alpha]$. Moreover, $|\mathbb{F}_q| = p^m$, and $|\mathbb{F}_p[\alpha]| = p^{nm}$. As $m \mid n$, $\mathbb{F}_q \subset \mathbb{F}_p[\alpha]$.

Indeed, for all $\gamma \in \mathbb{F}_q[\alpha]$,

$$\gamma \in \mathbb{F}_q \Rightarrow \gamma^{p^m} = \gamma \Rightarrow \gamma^{p^{mn}} = \gamma \Rightarrow \gamma \in \mathbb{F}_p[\alpha].$$

So $\mathbb{F}_q \subset \mathbb{F}_p[\alpha]$.

We show that $\mathbb{F}_q[\alpha] = \mathbb{F}_p[\alpha]$.

As $\mathbb{F}_p \subset \mathbb{F}_q$, $\mathbb{F}_p[\alpha] \subset \mathbb{F}_q[\alpha]$.

Let $\beta \in \mathbb{F}_q[\alpha]$: $\beta = \sum_{i=1}^{k} a_i \alpha^i$, where $a_i \in \mathbb{F}[q] \subset \mathbb{F}_p[\alpha]$, so $a_i = p_i(\alpha), p_i \in \mathbb{F}_p[\alpha]$. Consequently

$$\beta = \sum_{i=1}^{k} p_i(\alpha)\alpha^i \in \mathbb{F}_p[\alpha],$$

so $\mathbb{F}_q[\alpha] = \mathbb{F}_p[\alpha]$.

$$nm = [\mathbb{F}_p[\alpha] : \mathbb{F}_p] = [\mathbb{F}_q[\alpha] : \mathbb{F}_p] = [\mathbb{F}_q[\alpha] : \mathbb{F}_q] \times [\mathbb{F}_q : \mathbb{F}_p] = [\mathbb{F}_q[\alpha] : \mathbb{F}_q] \times m.$$

Thus $[\mathbb{F}_q[\alpha] : \mathbb{F}_q] = n$, and g is the minimal polynomial of α on $\mathbb{F}_q$, so $\deg(g) = n$.

Conclusion : if F is a field with $q = p^m$ elements, there exist irreducible polynomials in $F[x]$ of degree n for all positive integers n. ☐

Ex. 7.15 *Let $x^n - 1 \in F[x]$, where F is a finite field with q elements. Suppose that $(q, n) = 1$. Show that $x^n - 1$ splits into linear factors in some extension field and that the least degree of such a field is the smallest integer f such that $q^f \equiv 1 \pmod{n}$.*

Proof. From exercise 7.12, we know that $x^n - 1$ splits into linear factors in some extension field K, with $[K : F] < \infty$:

$$u(x) = x^n - 1 = (x - \zeta_0)(x - \zeta_1) \cdots (x - \zeta_{n-1}), \qquad \zeta_i \in K.$$

$u'(x) \wedge u(x) = nx^{n-1} \wedge (x^n - 1) = 1$, since $x(nx^{n-1}) - n(x^n - 1) = n$, and $n \neq 0$ in the field F, since we know from the hypothesis $q \wedge n = 1$ that the characteristic p doesn't divide n. So the n roots of $x^n - 1$ are distinct.

The set $G = \{x \in K \mid x^n = 1\}$ is a subgroup of K^*, thus G is cyclic of order n. Let ζ a generator of G. Then

$$x^n - 1 = (x - 1)(x - \zeta)(x - \zeta^2) \cdots (x - \zeta^{n-1}).$$

Let $p(x)$ the minimal polynomial of ζ on F, and f the degree of p :

$$f = \deg(p) = [F[\zeta] : F].$$

So $\operatorname{Card} F[\zeta] = q^f$, and since $\zeta \in F[\zeta]^*$, $\zeta^{q^f - 1} - 1 = 0$. As the order of ζ in the group G is n, $n \mid q^f - 1$, namely $q^f \equiv 1 \pmod{n}$.

Let k any positive integer such that $q^k \equiv 1 \pmod{n}$.

Then $n \mid q^k - 1$, so $\zeta^{q^k - 1} - 1 = 0$, $\zeta^{q^k} - \zeta = 0$. Let L an extension of K such that $x^{q^k} - x$ splits in linear factors in L. As $\zeta^{q^k} - \zeta = 0$, ζ belongs to the subfield M of L with cardinality q^k, such that $[M : F] = k$. Thus $\mathbb{F}[\zeta] \subset M$, so $f = [F[\zeta] : F] \leq k = [M : F]$.

$f = [F[\zeta] : F]$ is the smallest $k \in \mathbb{N}^*$ such that $q^k \equiv 1 \pmod{n}$.

If K is any extension of F containing the roots of $x^n - 1$, then $K \supset F[\zeta]$, where ζ is a primitive root of unity, so $[K : F] \geq [F[\zeta] : F] = f$.

Conclusion : the minimal degree of a extension $K \supset F$ containing the roots of $x^n - 1$, with $n \wedge q = 1$, is the smallest positive integer f such that $q^f \equiv 1 \pmod{n}$, the order of q modulo n. □

Ex. 7.16 *Calculate the monic irreducible polynomials of degree 4 in $\mathbb{Z}/2\mathbb{Z}[x]$.*

Proof. Write F_d the product of irreducible monic polynomials in $\mathbb{F}_2[x]$.

Theorem 2 gives

$$x^{16} - x = x^{2^4} - x = \prod_{d \mid 4} F_d(x) = F_1(x)F_2(x)F_4(x)$$

and

$$x^4 - x = x^{2^2} - x = \prod_{d \mid 2} F_d(x) = F_1(x)F_2(x)$$

so $F_4(x) = \frac{x^{16} - x}{x^4 - x} = \frac{x^{15} - 1}{x^3 - 1} = x^{12} + x^9 + x^6 + x^3 + 1$

$F_4(x) = (x^4 + x^3 + x^2 + x + 1)(x^4 + x + 1)(x^4 + x^3 + 1)$

Among the 16 monic polynomials of degree 4 in $\mathbb{F}_2[x]$, 3 are irreducible :

$$\begin{aligned} P_1(x) &= x^4 + x^3 + x^2 + x + 1, \\ P_2(x) &= x^4 + x + 1 \\ P_3(x) &= x^4 + x^3 + 1 \end{aligned}$$

With sage :

```
sage: A = PolynomialRing(GF(2),'x')
sage: x = A.gen()
sage: f = (x^16-x)/(x^4-x)
sage: factor(f)
(x^4 + x + 1) * (x^4 + x^3 + 1) * (x^4 + x^3 + x^2 + x + 1)
```

□

Ex. 7.17 *Let q and p be distinct odd primes. Show that the number of monic irreducibles of degree q in $\mathbb{Z}/p\mathbb{Z}$ is $q^{-1}(p^q - p)$.*

Proof. From Theorem 2 Corllary 2, we know that the number of irreducible polynomials on $\mathbb{F}_p$ of degree q is given by

$$N_q = \frac{1}{q} \sum_{d \mid q} \mu\left(\frac{q}{d}\right) p^d.$$

As q is prime, d takes the values $1, q$, with $\mu(1) = 1, \mu(q) = -1$, so

$$N_q = \frac{p^q - p}{q}.$$

□

Ex. 7.18 *Let p be a prime with $p \equiv 3 \pmod 4$. Show that the residue classes modulo p in $\mathbb{Z}[i]$ form a field with p^2 elements.*

Proof. If p is a prime rational integer, with $p \equiv 3 \pmod 4$, then p is a prime in $\mathbb{Z}[i]$.

Indeed, p is irreducibel : if $p = uv,\ u, v \in \mathbb{Z}[i]$, where $u = c + di, v$ are not units, then $p^2 = N(u)N(v),\ N(u) > 1, N(v) > 1$, so $p = N(u) = u\overline{u} = c^2 + d^2$.

As $c^2 \equiv 0, 1 \pmod 4, d^2 \equiv 0, 1 \pmod 4$, so $p \equiv 1 \pmod 4$, which is in contradiction with the hypothesis.

So p is irreducible in $\mathbb{Z}[i]$, and since $\mathbb{Z}[i]$ is a principal ideal domain, p is prime in $\mathbb{Z}[i]$, thus $\mathbb{Z}[i]/(p)$ is a field.

Let $z = a + bi \in \mathbb{Z}[i]$. The Euclidean division of a, b by q gives

$$a = qp + r,\ 0 \le r < p, \qquad b = q'p + s,\ 0 \le s < p,$$

so

$$z \equiv r + is \pmod p,\ 0 \le r < p, 0 \le s < p.$$

Let's verify that these p^2 elements are in differnet classes of congruences modulo p.

If $r + is \equiv r' + is' \pmod p$, then $(r - r')/p + i(s - s')/p \in \mathbb{Z}[i]$, so $r \equiv r', s \equiv s' \pmod p$.

As r, r', s, s' are between 0 and $p - 1$, $r = r', s = s'$.

So the cardinality of the field $\mathbb{Z}[i]/(p)$ is p^2. □

Ex. 7.19 *Let F be a finite field with q elements . If $f(x) \in F[x]$ has degree t, put $|f| = q^t$. Verify the formal identity $\sum_f |f|^{-s} = (1-q^{1-s})^{-1}$. The sum is over all monic polynomials.*

Proof. Let U the set of monic polynomials in $\mathbb{F}_q[x]$, and U_t the set of monic polynomials of degree t, and $s \in \mathbb{C}$. Then $U = \coprod_{t\in\mathbb{N}} U_t$, so

$$\begin{aligned}\sum_{f\in U} |f|^{-s} &= \sum_{t=0}^{\infty} \sum_{f\in U_t} |f|^{-s}\\ &= \sum_{t=0}^{\infty} \frac{1}{q^{ts}} \sum_{f\in U_t} 1\end{aligned}$$

As $\sum_{f\in U_t} 1 = \mathrm{Card}\,(U_t) = q^t$, then, for $\mathrm{Re}(s) > 1$

$$\begin{aligned}\sum_{f\in U} |f|^{-s} &= \sum_{t=0}^{\infty} \frac{1}{q^{t(s-1)}}\\ &= \frac{1}{1-\frac{1}{q^{s-1}}}\\ &= (1-q^{1-s})^{-1}\end{aligned}$$

As $\left|\frac{1}{q^{t(s-1)}}\right| = \frac{1}{q^{t(\mathrm{Re}(s)-1)}}$, the serie is absolutely convergent for $\mathrm{Re}(s) > 1$. This justifies the grouping of terms in this sum.

Conclusion : if $\mathrm{Re}(s) > 1$,

$$\sum_{f\in U} |f|^{-s} = (1-q^{1-s})^{-1},$$

where U is the set of monic polynomials in $\mathbb{F}_q[x]$. □

Ex. 7.20 *With the notation of Exercise 19 let $d(f)$ be the number of monic divisors of f and $\sigma(f) = \sum_{g|f} |g|$, where the sum is over the monic divisors of f. Verify the following identities :*

(a) $\sum_f d(f)|f|^{-s} = (1-q^{1-s})^{-2}$

(b) $\sum \sigma(f)|f|^{-s} = (1-q^{1-s})^{-1}(1-q^{2-s})^{-1}$

Proof. (a) With the notation of 7.19, for $s \in \mathbb{C}, \mathrm{Re}(s) > 1$, $\sum_{f\in U} |f|^{-s}$ is absolutely convergent and

$$(1-q^{1-s})^{-1} = \sum_{f\in U} |f|^{-s}$$

Then

$$\begin{aligned}(1-q^{1-s})^{-2} &= \sum_{f\in U} |f|^{-s} \sum_{g\in U} |g|^{-s}\\ &= \sum_{(f,g)\in U^2} |fg|^{-s}\\ &= \sum_{h\in U} \sum_{g\in U,\, g|h} |h|^{-s},\end{aligned}$$

indeed, the application

$$\varphi : \left\{ \begin{array}{ccc} U \times U & \to & \{(h,g) \in U \times U, g \mid h\} \\ (f,g) & \mapsto & (fg, g) \end{array} \right.$$

is a bijection.

So

$$\begin{aligned} (1-q^{1-s})^{-2} &= \sum_{h \in U} |h|^{-s} \mathrm{Card}\{g \in U, g \mid h\} \\ &= \sum_{h \in U} |h|^{-s} d(h) \\ &= \sum_{f \in U} d(f) |f|^{-s} \end{aligned}$$

(b) Similarly,

$$\begin{aligned} (1-q^{1-s})^{-1}(1-q^{2-s})^{-1} &= \sum_{f \in U} |f|^{-s} \sum_{g \in U} |g|^{-s+1} \\ &= \sum_{(f,g) \in U^2} |g| \, |fg|^{-s} \\ &= \sum_{h \in U} \sum_{g \in U,\, g | h} |g| \, |h|^{-s} \\ &= \sum_{h \in U} |h|^{-s} \sum_{g \in U,\, g | h} |g| \\ &= \sum_{h \in U} \sigma(h) |h|^{-s} \\ &= \sum_{f \in U} \sigma(f) |f|^{-s} \end{aligned}$$

□

Ex. 7.21 *Let F be a field with $q = p^n$ elements. For $\alpha \in F$ set $f(x) = (x-\alpha)(x-\alpha^p)(x-\alpha^{p^2}) \cdots (x-\alpha^{p^{n-1}})$. Show that $f(x) \in \mathbb{Z}/p\mathbb{Z}[x]$. In particular, $\alpha + \alpha^p + \cdots + \alpha^{p^{n-1}}$ and $\alpha\alpha^p\alpha^{p^2} \cdots \alpha^{p^{n-1}}$ are in $Z/p\mathbb{Z}$.*

Proof. Let $F : \left\{ \begin{array}{ccc} \mathbb{F}_q & \to & \mathbb{F}_q \\ x & \mapsto & x^p \end{array} \right.$.

As the characteristic of $\mathbb{F}_q$ is p, $(x+y)^p = x^p + y^p$ et $(xy)^p = x^p y^p$, and each homomorphism of field is injective, F is a field automorphism (Frobenius automorphism).

For every automorphism H in $\mathbb{F}_q$, and every polynomial $p(x) = \sum a_i x^i \in \mathbb{F}_q[x]$, write $(H.p)(x) = \sum_i H(a_i) x^i$. Then for all $(p,q) \in \mathbb{F}_q[x]^2$, $H.(pq) = (H.p)(H.q)$.

With this notation,

$$f(x) = (x-\alpha)(x-F\alpha)(x-F^2\alpha) \cdots (x-F^{n-1}\alpha),$$

$$(H.f)(x) = (x-F\alpha)(x-F^2\alpha)(x-F^3\alpha) \cdots (x-F^n\alpha).$$

Since $\alpha \in \mathbb{F}_{p^n}$, $F^n\alpha = \alpha^{p^n} = \alpha$, thus

$$H.f = f.$$

In other words, if $f(x) = \sum_i a_i x^i$, then for all i, $H(a_i) = a_i$, so $a_i^p = a_i$, thus $a_i \in \mathbb{F}_p$, and $f \in \mathbb{F}_p[x]$. In particular, the coefficients $a_{n-1} = \alpha+\alpha^p+\cdots+\alpha^{p^{n-1}}, a_0 = \alpha\alpha^p\alpha^{p^2}\cdots\alpha^{p^{n-1}}$ are in $\mathbb{F}_p$. $\square$

Ex. 7.22 *(continuation) Set* $\mathrm{tr}(\alpha) = \alpha + \alpha^p + \cdots + \alpha^{p^{n-1}}$. *Prove that*

(a) $\mathrm{tr}(\alpha) + \mathrm{tr}(\beta) = \mathrm{tr}(\alpha + \beta)$.

(b) $\mathrm{tr}(a\alpha) = a\,\mathrm{tr}(\alpha)$ *for* $a \in \mathbb{Z}/p\mathbb{Z}$.

(c) There is an $\alpha \in F$ *such that* $\mathrm{tr}(\alpha) \neq 0$.

Proof. Let F the Frobenius automorphism of $\mathbb{F}_q$ introduced in Ex.7.21.

(a),(b) : If $x, y \in \mathbb{F}_q$, and $a \in \mathbb{F}_p$, then $a^p = a$, so $F(x + y) = (x + y)^p = x^p + y^p = F(x) + F(y)$, and $F(ax) = a^p x^p = ax^p = aF(x)$, so F is $\mathbb{F}_p$-linear, and also $tr = I + F + F^2 + \cdots + F^{n-1}$.

(c) The polynomial $p(x) = x + x^p + x^{p^2} + \cdots + x^{p^{n-1}}$ has degree p^{n-1}, so $p(x)$ has at most p^{n-1} roots in $\mathbb{F}_q$, and $|\mathbb{F}_q| = p^n > deg(p) = p^{n-1}$. Therefore there exist in $\mathbb{F}_q$ some element α which is not a root of $p(x)$, and so $\mathrm{tr}(\alpha) = p(\alpha) \neq 0$. $\square$

Ex. 7.23 *(continuation) For* $\alpha \in F$ *consider the polynomial* $x^p - x - \alpha \in F[x]$. *Show that this polynomial is either irreducible or the product of linear factors. Prove that the latter alternative holds iff* $\mathrm{tr}(\alpha) = 0$.

Proof. Let $f(x) = x^p - x - \alpha \in F[x]$. There exists an extension $K \supset F$ with finite degree on F which contains a root γ of f.

As $\gamma^p - \gamma - \alpha = 0$, then for all $i \in \mathbb{F}_p$,

$$(\gamma + i)^p - (\gamma + i) - \alpha = (\gamma^p - \gamma - \alpha) + i^p - i = 0.$$

So f has n distinct roots in K : $\gamma, \gamma + 1, \ldots, \gamma + p - 1$, and so

$$f(x) = (x - \gamma)(x - \gamma - 1)\cdots(x - \gamma - (p - 1)).$$

$F[\gamma]$ contains all roots of f.

• If $\gamma \in F$, $f(x)$ splits in linear factors in F. $f(x)$ is not irreducible, since $\deg(f) = p > 1$.

• If $\gamma \notin F$, we will show that f is irreducible in $F[x]$.

If not, then $f(x) = g(x)h(x)$ is the product of two polynomials $g, h \in F[x]$ such that $1 \leq \deg(g) \leq p - 1$.

The unicity of the decomposition in irreducible factors in $F[\gamma][x]$ shows that

$$g(x) = \prod_{i\in A}(x - \gamma - i),$$

where A is a subset of $\mathbb{F}_p$, with $A \neq \emptyset, A \neq \mathbb{F}_p$. As $g(x) \in F[x]$, $\sum\limits_{i\in A}(\gamma + i) = k\gamma + l \in \mathbb{F}_p$, where $1 \leq k = |A| \leq p - 1$ and $l = \sum\limits_{i\in A} i \in \mathbb{F}_p$.

So $k\gamma \in \mathbb{F}_p$. Since $\gamma \notin \mathbb{F}_p$, k is not invertible in $\mathbb{F}_p$, in contradiction with $1 \le k \le p-1$. Consequently, $f(x)$ is irreducible.

We conclude that $x^p - x - \alpha \in F[x]$ is irreducible iff $\gamma \notin F$.

Let F the Frobenius automorphism of K (cf. Ex. 7.21).

$$\alpha = F(\gamma) - \gamma, F(\alpha) = F^2(\gamma) - F(\gamma), \ldots, F^{n-1}(\alpha) = F^n(\gamma) - F^{n-1}(\gamma).$$

The sum of these equalities gives

$$\mathrm{tr}(\alpha) = \alpha + F(\alpha) + \cdots + F^{n-1}(\alpha) = F^n(\gamma) - \gamma = \gamma^{p^n} - \gamma.$$

As the cardinality of F is $q = p^n$,

$$\gamma \in F \iff \gamma^{p^n} - \gamma = 0 \iff \mathrm{tr}(\alpha) = 0.$$

Conclusion : $x^p - x - \alpha$ is irreducible iff $\mathrm{tr}(\alpha) \ne 0$. If $\mathrm{tr}(\alpha) = 0$, $x^p - x - \alpha$ splits in linear factors in $F[x]$. □

Ex. 7.24 *Suppose that $f(x) \in \mathbb{Z}/p\mathbb{Z}[x]$ has the property that $f(x+y) = f(x) + f(y) \in \mathbb{Z}/p\mathbb{Z}[x,y]$. Show that $f(x)$ must be of the form $a_0x + a_1x^p + a_2x^{p^2} + \cdots + a_mx^{p^m}$.*

Lemma *If the prime number p divides all binomial coefficients $\binom{n}{1}, \binom{n}{2}, \ldots, \binom{n}{n-1}$, then n is a power of p.*

Proof. Let $u(x) = (x+1)^n - x^n - 1 \in \mathbb{F}_p[x]$. Then $f(x) = \sum_{k=1}^{n-1} \binom{n}{i} x^i = 0$.

Write $n = p^a q$, with $p \wedge q = 1$. With a reductio as absurdum, suppose that $q > 1$. Then

$$f(x) = 0 = (x+1)^{p^\alpha q} - x^{p^\alpha q} - 1 = (x^{p^\alpha} + 1)^q - x^{p^\alpha q} - 1 = \sum_{k=1}^{q-1} \binom{q}{k} x^{kp^a}.$$

Consequently, the coefficient of x^{p^a} is null, so $p \mid q$: this is absurd. Therefore $q = 1$ and $n = p^a$. □

Proof. (Ex. 7.24)

Suppose that $f \in \mathbb{F}_p[x]$ verify in $\mathbb{F}_p[x,y]$ the equality $f(x+y) = f(x) + f(y)$.

Write $f(x) = \sum_{k=1}^{d} c_i x^i$.

$$\begin{aligned} 0 = f(x+y) - f(x) - f(y) &= \sum_{n=0}^{d} c_n[(x+y)^n - x^n - y^n] \\ &= \sum_{n=0}^{d} \sum_{k=1}^{n-1} c_n \binom{n}{k} x^k y^{n-k} \end{aligned}$$

So for all n, for all k, $1 \le k \le n-1$, $c_n \binom{n}{k} = 0$ in $\mathbb{F}_p$.

From the lemma, if n is not a power of p, there exists a k, $1 \le k \le n-1$ such that $\binom{n}{k} \not\equiv 0 \pmod{p}$, so $c_n = 0$. If we write $a_k = c_{p^k}$, then $f(x)$ is of the form

$$f(x) = a_0x + a_1x^p + a_2x^{p^2} + \cdots + a_mx^{p^m}.$$

□

Chapter 8

Ex. 8.1 *Let p be a prime and $d = (m, p-1)$. Prove that $N(x^m = a) = \sum \chi(a)$, the sum being over all χ such that $\chi^d = \varepsilon$.*

Proof. Let $d = m \wedge (p-1)$. we prove that $N(x^m = a) = N(x^d = a)$ for all $d \in \mathbb{F}_p$.

• If $a = 0$, 0 is the only root of $x^m - a$ or $x^d - a$, so $N(x^m = a) = N(x^d = a) = 1$.

• If $a \in \mathbb{F}_p^*$ and $x^n = a$ has a solution, then we know from the demonstration of Proposition 4.2.1 that $N(x^n - a) = d = N(x^d - a)$.

• If If $a \in \mathbb{F}_p^*$ and $x^n = a$ has no solution, then (Prop. 4.2.1) $a^{(p-1)/d} \neq 1$, so $x^d = a$ has no solution : $N(x^n - a) = 0 = N(x^d - a)$.

Using Prop. 8.1.5, as $d \mid n$, we obtain

$$N(x^n = a) = N(x^d = a) = \sum_{\chi^d = \varepsilon} \chi(a).$$

□

Ex. 8.2, false sentence. *With the notation of Exercise 1 show that $N(x^m = a) = N(x^d = a)$ and conclude that if $d_i = (m_i, p-1)$, then $\sum_i a_i x^{m_i} = b$ and $\sum_i a_i x^{d_i} = b$ have the same number of solutions.*

This result is false. I give a counterexample with $p = 5$: $x + x^3 = 0 \in \mathbb{F}_5[x]$ has 3 solutions $0, 2, -2$. As $3 \wedge (p-1) = 3 \wedge 4 = 1$, the reduced equation is $x + x = 0$, which has an unique solution 0. The true sentence is :

Ex. 8.2 *With the notation of Exercise 1 show that $N(x^m = a) = N(x^d = a)$ and conclude that if $d_i = (m_i, p-1)$, then $\sum_i a_i x_i^{m_i} = b$ and $\sum_i a_i x_i^{d_i} = b$ have the same number of solutions.*

Proof. From Ex. 8.1, we know that

$$N(x^m = a) = \sum_{\chi^d = \varepsilon} \chi(a) = N(x^d = a).$$

Using this result, we obtain

$$\begin{aligned}
N\left(\sum_{i=1}^{l} a_i x_i^{m_i} = b\right) &= \sum_{a_1 u_1 + \cdots + a_l u_l = b} \prod_{i=1}^{l} N(x^{m_i} = u_i) \\
&= \sum_{a_1 u_1 + \cdots + a_l u_l = b} \prod_{i=1}^{l} N(x^{d_i} = u_i) \\
&= N\left(\sum_{i=1}^{l} a_i x_i^{d_i} = b\right)
\end{aligned}$$

□

Ex. 8.3 *Let χ be a non trivial multiplicative character of $\mathbb{F}_p$ and ρ be the character of order 2. Show that $\sum_t \chi(1-t^2) = J(\chi,\rho)$.[Hint: Evaluate $J(\chi,\rho)$ using the relation $N(x^2 = a) = 1 + \rho(a)$.]*

Proof.

$$\begin{aligned}
J(\chi,\rho) &= \sum_{a+b=1} \chi(a)\rho(b)\\
&= \sum_{a+b=1} \chi(a)(N(x^2=b)-1)\\
&= \sum_{a+b=1} \chi(a)N(x^2=b) - \sum_{a+b=1} \chi(a)
\end{aligned}$$

As $\chi \neq \varepsilon$,

$$\sum_{a+b=1} \chi(a) = \sum_{a\in\mathbb{F}_p} \chi(a) = 0.$$

Let $C = \{x^2 \mid x \in \mathbb{F}^*\}$ the set of squares in $\mathbb{F}_p^*$, $\overline{C}$ its complementary in $\mathbb{F}_p^*$:

$$\mathbb{F}_p = \{0\} \cup C \cup \overline{C}.$$

Then

$$\begin{aligned}
J(\chi,\rho) &= \sum_{a+b=1} \chi(a)N(x^2=b)\\
&= \sum_{a+b=1,b=0} \chi(a)N(x^2=b) + \sum_{a+b=1,b\in C} \chi(a)N(x^2=b) + \sum_{a+b=1,b\in\overline{C}} \chi(a)N(x^2=b)\\
&= \chi(1) + 2\sum_{b\in C}\chi(1-b)
\end{aligned}$$

(because $N(x^2=b) = 0$ if $x \in \overline{C}$, and $N(x^2=b) = 2$ if $x \in C$). As each $b \in C$ has two roots, and as the set of roots of two distinct b are disjointed,

$$J(\chi,\rho) = \chi(1) + \sum_{t\in\mathbb{F}_p^*} \chi(1-t^2) = \sum_{t\in\mathbb{F}_p} \chi(1-t^2).$$

Conclusion : if χ is a non trivial multiplicative character of $\mathbb{F}_p$ and ρ the character of order 2,

$$J(\chi,\rho) = \sum_{t\in\mathbb{F}_p} \chi(1-t^2).$$

□

Ex. 8.4 *Show, if $k \in \mathbb{F}_p, k \neq 0$, that $\sum_t \chi(t(k-t)) = \chi(k^2/2^2)J(\chi,\rho)$.*

Proof. We know from Ex. 8.3 that $J(\chi,\rho) = \sum_t \chi(1-t^2)$, so

$$
\begin{aligned}
\leq J(\chi,\rho) &= \sum_{t\in\mathbb{F}_p} \chi(1-t)\chi(1+t)\\
&= \sum_{u\in\mathbb{F}_p} \chi(u)\chi(2-u) \qquad (u = 1-t)\\
&= \chi(2^2) \sum_{u\in\mathbb{F}_p} \chi\left(\frac{u}{2}\right)\chi\left(1-\frac{u}{2}\right)\\
&= \chi(2^2) \sum_{v\in\mathbb{F}_p} \chi(v)\chi(1-v) \qquad (u = 2v)\\
&= \chi(2^2)\chi(k^{-2}) \sum_{w\in\mathbb{F}_p} \chi(kv)\chi(k-kv)\\
&= \chi(2^2/k^2) \sum_{t\in\mathbb{F}_p} \chi(t)\chi(k-t) \qquad (t = kv).
\end{aligned}
$$

Conclusion : if $k \in \mathbb{F}^*$, and χ is a non trivial character, ρ the character of order 2,

$$\sum_{t\in\mathbb{F}_p} \chi(t(k-t)) = \chi(k^2/2^2)J(\chi,\rho).$$

□

Ex. 8.5 *If $\chi^2 \neq \varepsilon$, show that $g(\chi)^2 = \chi(2)^{-2}J(\chi,\rho)g(\chi^2)$. [Hint: Write out $g(\chi)^2$ explicitly and use Exercise 4.]*

Proof. Let $\zeta = e^{2i\pi/p}$. Using the result of Ex. 8.4, we obtain

$$
\begin{aligned}
g(\chi)^2 &= \left(\sum_t \chi(t)\zeta^t\right)\left(\sum_s \chi(s)\zeta^s\right)\\
&= \sum_{s,t} \chi(t)\chi(s)\zeta^{t+s}\\
&= \sum_k \left(\sum_{s+t=k} \chi(t)\chi(s)\right)\zeta^k\\
&= \sum_k \left(\sum_t \chi(t(k-t)\right)\zeta^k\\
&= \chi(-1)\sum_t \chi(t^2) + \sum_{k\neq 0} \chi(k^2/2^2)J(\chi,\rho)\zeta^k\\
&= \chi(-1)\sum_t \chi^2(t) + \chi(2)^{-2}J(\chi,\rho)\sum_{k\neq 0} \chi^2(k)\zeta^k
\end{aligned}
$$

If $\chi^2 \neq \varepsilon, \sum_t \chi^2(t) = 0$, so

$$g(\chi)^2 = \chi(2)^{-2}J(\chi,\rho)g(\chi^2).$$

□

Ex. 8.6 *(continuation) Show that $J(\chi,\chi) = \chi(2)^{-2}J(\chi,\rho)$.*

Proof. As $\chi^2 \ne \rho$, Theorem 1 Chapter 8 gives $J(\chi,\chi) = g(\chi)^2/g(\chi^2)$, and Exercise 8.5 gives $g(\chi)^2/g(\chi^2) = \chi(2)^{-2}J(\chi,\rho)$, so

$$J(\chi,\chi) = \chi(2)^{-2}J(\chi,\rho).$$

$\square$

Ex. 8.7 *Suppose that $p \equiv 1 \pmod 4$ and that χ is a character of order 4. Then $\chi^2 = \rho$ and $J(\chi,\chi) = \chi(-1)J(\chi,\rho)$. [Hint: Evaluate $g(\chi)^4$ in two ways.]*

Proof. As χ is a character of order 4, χ^2 is a character of order 2, and ρ (Legendre's character) is the unique character of order 2, so $\chi^2 = \rho$.

From Prop. 8.3.3 we have

$$g(\chi)^4 = \chi(-1)pJ(\chi,\chi)J(\chi,\chi^2) = \chi(-1)pJ(\chi,\chi)J(\chi,\rho).$$

Squaring the result of Ex. 8.5, we obtain

$$g(\chi)^4 = \chi(2)^{-4}J(\chi,\rho)^2\left[g(\chi^2)\right]^2.$$

Moreover $\chi(2^4) = \chi^4(2) = \varepsilon(2) = 1$, and $g(\chi^2) = g(\rho) = g$, so $\left[g(\chi^2)\right]^2 = g^2 = (-1)^{(p-1)/2}p = p$ (From Prop. 6.3.2 and $p \equiv 1 \pmod 4$).

Equating these two result, we obtain

$$\chi(-1)pJ(\chi,\chi)J(\chi,\rho) = J(\chi,\rho)^2 p.$$

As $g(\chi)^4 \ne 0$ since $|g(\chi)|^2 = p$, we have $J(\chi,\rho) \ne 0$, so

$$\chi(-1)J(\chi,\chi) = J(\chi,\rho).$$

$[\chi(-1)]^2 = \chi((-1)^2) = \chi(1) = 1$, so $\chi(-1) = \pm 1$, and $\chi(-1)^{-1} = \chi(-1)$, thus

$$J(\chi,\chi) = \chi(-1)J(\chi,\rho).$$

$\square$

Ex. 8.8 *Generalize Exercise 3 in the following way. Suppose that p is a prime, $\sum_t \chi(1-t^m) = \sum_\lambda J(\chi,\lambda)$, where λ varies over all characters such that $\lambda^m = \varepsilon$. Conclude that $|\sum_t \chi(1-t^m)| \le (m-1)p^{1/2}$.*

Proof. For all $y \in \mathbb{F}_p$, write $A_y = \{x \in \mathbb{F}_p \mid x^m = y\}$. Then $|A_y| = N(x^m = y)$.

$\mathbb{F}_p = \coprod_{y\in\mathbb{F}_p} A_y$ is the disjoint union of the A_y, so

$$\sum_{t\in\mathbb{F}_p}\chi(1-t^m) = \sum_{y\in\mathbb{F}_p}\sum_{t\in A_y}\chi(1-t^m) = \sum_{y\in\mathbb{F}_p}|A_y|\chi(1-y) = \sum_{y\in\mathbb{F}_p}N(x^m = y)\chi(1-y).$$

Moreover, $N(x^m = y) = \sum\limits_{\lambda^m=\varepsilon} \lambda(y)$ (Prop. 8.1.5), so

$$\begin{aligned}\sum_{t\in\mathbb{F}_p} \chi(1-t^m) &= \sum_{y\in\mathbb{F}_p}\sum_{\lambda^m=\varepsilon} \lambda(y)\chi(1-y)\\ &= \sum_{\lambda^m=\varepsilon}\sum_{x+y=1} \chi(x)\lambda(y)\\ &= \sum_{\lambda^m=\varepsilon} J(\chi,\lambda)\end{aligned}$$

Conclusion :

$$\sum_{t\in\mathbb{F}_p} \chi(1-t^m) = \sum_{\lambda^m=\varepsilon} J(\chi,\lambda).$$

We know that there exist m character whose order divides m. As $\chi \neq \varepsilon$, $J(\chi,\varepsilon) = 0$, and $|J(\chi,\lambda)| = \sqrt{p}$ for every $\lambda \neq \varepsilon$,

$$\left|\sum_{t\in\mathbb{F}_p} \chi(1-t^m)\right| \leq \sum_{\lambda^m=\varepsilon,\lambda\neq\varepsilon} |J(\chi,\lambda)| = (m-1)\sqrt{p}.$$

□

Ex. 8.9 *Suppose that* $p \equiv 1 \pmod 3$ *and that* χ *is a character of order 3. Prove (using Exercise 5) that* $g(\chi)^3 = p\pi$*, where* $\pi = \chi(2)J(\chi,\rho)$*.*

Proof. As χ is o character of order 3, $\chi^2 \neq \varepsilon$. From Exercise 5, we know that

$$g(\chi)^2 = \chi(2)^{-2} J(\chi,\rho) g(\chi^2).$$

So

$$g(\chi)^3 = \chi(2)^{-2} J(\chi,\rho) g(\chi^2) g(\chi).$$

Recall (§8.2) that

$$\overline{g(\chi)} = \sum_t \overline{\chi(t)}\zeta^{-t} = \chi(-1)\sum_t \overline{\chi(-t)}\zeta(-t) = \chi(-1) g(\chi),$$

Here $\chi(-1) = 1$, because $\chi(-1) = \chi((-1)^3) = \chi^3(-1) = \varepsilon(-1) = 1$. Hence

$$g(\chi^2)g(\chi) = g(\bar{\chi})g(\chi) = \overline{g(\chi)}g(\chi) = |g(\chi)|^2 = p.$$

Moreover $\chi(2)^3 = \chi^3(2) = 1$, so $\chi(2)^{-2} = \chi(2)$.

Conclusion : if χ is a character of order 3,

$$g(\chi)^3 = p\pi, \text{ where } \pi = \chi(2)J(\chi,\rho).$$

□

Ex. 8.10 *(continuation) Show that $\chi\rho$ is a character of order 6 and that*

$$g(\chi\rho)^6 = (-1)^{(p-1)/2} p \bar{\pi}^4$$

.

Proof. $(\chi\rho)^6 = \chi^6\rho^6 = \varepsilon, (\chi\rho)^2 = \chi^2 \neq \varepsilon, (\chi\rho)^3 = \rho^3 = \rho \neq \varepsilon$, so $\chi\rho$ is of order 6.

$J(\chi,\rho)g(\chi\rho) = g(\chi)g(\rho)$ since $\chi, \rho, \chi\rho$ are non trivial characters. So

$$g(\chi\rho)^6 = \frac{g(\chi)^6 g(\rho)^6}{J(\chi,\rho)^6}.$$

From Exercise 8.9, $g(\chi)^6 = p^2\pi^2$. Proposition 6.3.2 gives $g(\rho)^2 = (-1)^{(p-1)/2}p$, so $g(\rho)^6 = (-1)^{(p-1)/2}p^3$. As $\pi = \chi(2)J(\chi,\rho)$, $J(\chi,\rho)^6 = \chi(2)^{-6}\pi^6 = \pi^6$, since $\chi(2)^3 = 1$. Therefore

$$g(\chi\rho)^6 = \frac{p^2\pi^2(-1)^{(p-1)/2}p^3}{\pi^6} = (-1)^{(p-1)/2}p^5\pi^{-4}.$$

Moreover, $\pi\bar{\pi} = \chi(2)\overline{\chi(2)}J(\chi,\rho)\overline{J(\chi,\rho)} = |J(\chi,\rho)|^2 = p$ (Theorem 8.1, Corollary), so $\pi^{-1} = \bar{\pi}/p$. In conclusion,

$$g(\chi\rho)^6 = (-1)^{(p-1)/2}p\bar{\pi}^4.$$

□

Ex. 8.11 *Use Gauss' theorem to find the number of solutions to $x^3 + y^3 = 1$ in $\mathbb{F}_p$ for $p = 13, 19, 37,$ and 97.*

Proof. • $p = 13$.

$4 \times 13 = 52 = (-5)^2 + 27 \times 1^2$, where $-5 \equiv 1 \pmod 3$, so $A = -5$.

If $p = 13$, $N(x^3 + y^3 = 1) = p - 2 + A = 13 - 2 - 5 = 6$: the solutions are only the trivial solutions.

• $p = 19$.

$4 \times 19 = 76 = 7^2 + 27 \times 1^2$, where $7 \equiv 1 \pmod 3$, so $A = 7$.

If $p = 19$, $N(x^3 + y^3 = 1) = 19 - 2 + 7 = 24$.

• $p = 37$.

$4 \times 37 = 148 = (-11)^2 + 27 \times 1^2$, where $-11 \equiv 1 \pmod 3$, so $A = -11$.

If $p = 37$, $N(x^3 + y^3 = 1) = 37 - 2 - 11 = 24$.

• $p = 97$.

$4 \times 97 = 388 = 19^2 + 27 \times 1^2$, where $19 \equiv 1 \pmod 3$, so $A = 19$.

If $p = 97$, $N(x^3 + y^3 = 1) = 97 - 2 + 19 = 114$.

(These results were verified on pari/gp).) □

Ex. 8.12 *If $p \equiv 1 \pmod 4$, then we have seen that $p = a^2 + b^2$ with $a, b \in \mathbb{Z}$. If we require that a and b are positive, that a be odd, and that b is even, show that a and b are uniquely determined. (Hint: Use the fact that unique factorization holds in $\mathbb{Z}[i]$ and that if $p = a^2 + b^2$ then $a + bi$ is a prime in $\mathbb{Z}[i]$.)*

Proof. Suppose that p is prime, $p \equiv 1 \pmod 4$, and $p = a^2 + b^2 = c^2 + d^2$, where a, b, c, d are positive integers, a, c odd, b, d even. We will show that $a = c, b = d$.

As $p = N(a + bi)$, $\pi = a + bi$ is irreducible in $\mathbb{Z}[i]$: indeed $\pi = uv$ implies that $p = N(\pi) = N(u)N(v)$, so $N(u) = 1$ or $N(v) = 1$, and u or v is an unit.

Since $\mathbb{Z}[i]$ is a principal ideal domain, π is a prime in $\mathbb{Z}[i]$.

$(a+bi)(a-bi) = (c+di)(c-di)$, so the prime π divides $c+di$, or it divides $c-di$.

As $N(\pi) = N(c+di) = N(c-di)$, the quotient is an unit. Therefore π is an associate of $c+di$ or $c-di$. Since the units in $\mathbb{Z}[i]$ are $1, -1, i, -i$,

$$a+bi = \pm(c+di), \text{ or } a+bi = \pm i(c+di), \text{ or } a+bi = \pm(c-di), \text{ or } a+bi = \pm i(c-di).$$

In all cases, $a = \pm c, b = \pm d$, or $a = \pm d, b = \pm c$. Since a, b, c, d are positive, $a = c, b = d$, or $a = d, b = c$. As ac are odds, and b, d even, $a = c, b = d$: the unicity of the decomposition is proved. $\square$

Ex. 8.13 *If $p \equiv 1 \pmod 3$, we have seen that $4p = A^2 + 27B^2$, with $A, B \in \mathbb{Z}$. If we require that $A \equiv 1 \pmod 3$, show that A is uniquely determined. (Hint: Use the fact that unique factorization holds in $\mathbb{Z}[\omega]$. This proof is a little trickier than that for Exercise 12.)*

Proof. Suppose that $4p = A^2 + 27B^2 = C^2 + 27D^2$, where $A \equiv C \equiv 1 \pmod 3$. We will show that $A = C$.

Let $\omega = e^{2i\pi/3} = -1/2 + i\sqrt{3}/2$. Then $i\sqrt{3} = 2\omega + 1$, and for all x, y, $x^3 + 3y^2 = (x + i\sqrt{3}y)(x - i\sqrt{3}y) = (x + (2\omega+1)y)(x - (2\omega+1)y)$,

$$x^2 + 3y^2 = (x + y + 2jy)(x - y - 2jy).$$

With $x = A, y = 3B$, we obtain

$$4p = A^2 + 27B^2 = (A + 3B + 6\omega B)(A - 3B - 6\omega B).$$

Note that A, B are of same parity, since $4p = A^2 + 27B^2$.

So we can write $p = ((A+3B)/2 + 3\omega B)((A-3B)/2 - 6\omega B)$:

$$p = \pi\overline{\pi}, \text{ where } \pi = \frac{A+3B}{2} + 3\omega B \in \mathbb{Z}[\omega].$$

π is a prime in $\mathbb{Z}[\omega]$: indeed $\pi = uv$, $u, v \in \mathbb{Z}[\omega]$ implies $p = N(\pi) = N(u)N(v)$, then $N(u) = 1$ or $N(v) = 1$, u or v is an unit, so π is irreducible in the principal ideal domain $\mathbb{Z}[\omega]$, thus π is a prime in $\mathbb{Z}[\omega]$.

$$\pi\overline{\pi} = \left(\frac{A+3B}{2} + 3\omega B\right)\left(\frac{A-3B}{2} - 3\omega B\right) = \left(\frac{C+3D}{2} + 3\omega D\right)\left(\frac{C-3D}{2} - 3\omega D\right).$$

As π is a prime, it divides $\frac{C+3D}{2} + 3\omega D$ or its conjugate. Since they have the same norm

p, they are associated. The units of $\mathbb{Z}[\omega]$ are $\pm 1, \pm j, \pm j^2$, so there exists 12 cases :

$$\frac{A+3B}{2} + 3\omega B = \pm\left(\frac{C+3D}{2} + 3\omega D\right)$$
$$\frac{A+3B}{2} + 3\omega B = \pm\omega\left(\frac{C+3D}{2} + 3\omega D\right)$$
$$\frac{A+3B}{2} + 3\omega B = \pm\omega^2\left(\frac{C+3D}{2} + 3\omega D\right)$$
$$\frac{A+3B}{2} + 3\omega B = \pm\left(\frac{C-3D}{2} - 3\omega D\right)$$
$$\frac{A+3B}{2} + 3\omega B = \pm\omega\left(\frac{C-3D}{2} - 3\omega D\right)$$
$$\frac{A+3B}{2} + 3\omega B = \pm\omega^2\left(\frac{C-3D}{2} - 3\omega D\right)$$

If we replace D by $-D$, we obtain the 6 last cases from the 6 first cases, so it is sufficient to examine the first 6 cases. Recall that $(1,\omega)$ is a $\mathbb{Z}$-base of $\mathbb{Z}[\omega]$.

1) $A + 3B + 6\omega B = C + 3D + 6\omega D$.

   Then $B = D$ and $A + 3B = C + 3D$, so $A = C$, which is the expected result. The five other cases are impossible :

2) $A + 3B + 6\omega B = -C - 3D - 6\omega D$.

   Then $B = -D, A = -C$. As $A \equiv C \equiv 1 \pmod 3$, this is impossible.

3) $A+3B+6\omega B = \omega(C+3D+6\omega D) = \omega(C+3D)+(-1-\omega)6D = -6D+\omega(C-3D)$.

   Then $A + 3B = -6D$, $A \equiv 0 \pmod 3$, this is impossible.

4) $A+3B+6\omega B = -\omega(C+3D+6\omega D) = -\omega(C+3D)+(1+\omega)6D = 6D+\omega(-C+3D)$.

   Then $A + 3B = -6D$, $A \equiv 0 \pmod 3$, this is impossible.

5) $A + 3B + 6\omega B = \omega^2(C + D + 6\omega D) = (-1 - \omega)(C + 3D) + 6D = -C + 3D + \omega(-C - 3D)$. Then $A + 3B = -C + 3D$, $A \equiv -C \pmod 3$, this is impossible.

6) $A+3B+6\omega B = -\omega^2(C+3D+6\omega D) = (1+\omega)(C+3D)-6D = (C-3D)+\omega(C+3D)$.

   Then $6B = C + 3D$, $C \equiv 0 \pmod 3$, this is impossible.

In conclusion $A = C$. □

Ex. 8.14 *Suppose that* $p \equiv 1 \pmod n$ *and that* χ *is a character of order* n. *Show that* $g(\chi^n) \in \mathbb{Z}[\zeta]$, *where* $\zeta = e^{2\pi i/n}$.

Proof. From Proposition 8.3.3 we know that

$$g(\chi)^n = \chi(-1)pJ(\chi,\chi)J(\chi,\chi^2)\cdots J(\chi,\chi^{n-2}).$$

Let $\mathbb{U}_n = \{x \in \mathbb{C} \mid x^n = 1\} = \{1, \zeta, \ldots, \zeta^{n-1}\}$, with $\zeta = e^{2\pi i/n}$, the group of n-th roots of unity. As the order of χ is n, for all $x \in \mathbb{F}_p^*$, $(\chi(x))^n = \chi^n(x) = \varepsilon(x) = 1$, so $\chi(x) \in \mathbb{U}_n$, and also $\chi^k(x) = (\chi(x))^k$.

Therefore $J(\chi,\chi^k) = \sum_{x+y=1} \chi(x)\chi^k(x) \in \mathbb{Z}[\zeta]$. Moreover $\chi(-1) = \pm 1$, so $\chi(-1)$ and p are in $\mathbb{Z}[\zeta]$. In conclusion $g(\chi^n) \in \mathbb{Z}[\zeta]$. □

Ex. 8.15 *Suppose that $p \equiv 1 \pmod 6$ and let χ and ρ be characters of order 3 and 2, respectively. Show that the number of solutions to $y^2 = x^3 + D$ in $\mathbb{F}_p$ is $p + \pi + \overline{\pi}$, where $\pi = \chi\rho(D)J(\chi\rho)$. If $\chi(2) = 1$, show that the number of solutions to $y^2 = x^3 + 1$ is $p + A$, where $4p = A^2 + 27B^2$ and $A \equiv 1 \pmod 3$. Verify this result numerically when $p = 31$.*

Proof. $x \mapsto -x$ is a bijection between the set of roots of $x^3 = b$ and the set of roots of $(-x)^3 = b$, so $N(x^3 = b) = N((-x)^3 = b) = N(x^3 = -b)$.

As χ is a character of order 3, the characters whose order divides 3 are $\varepsilon, \chi, \chi^2$. Using Prop. 8.1.5, we obtain

$$\begin{aligned}
N(y^2 = x^3 + D) &= \sum_{a+b=D} N(y^2 = a)N((-x)^3 = b)\\
&= \sum_{a+b=D} N(y^2 = a)N(x^3 = b)\\
&= \sum_{a+b=D} (1 + \rho(a))(1 + \chi(b) + \chi^2(b))\\
&= \sum_{i=0}^{1}\sum_{j=0}^{2}\sum_{a+b=D} \rho^i(a)\chi^j(b)\\
&= \sum_{i=0}^{1}\sum_{j=0}^{2} \rho(D)^i\chi(D)^j \sum_{a'+b'=1} \rho^i(a')\chi^j(b') \qquad (a = Da', b = Db')\\
&= \sum_{i=0}^{1}\sum_{j=0}^{2} \rho(D)^i\chi(D)^j J(\chi^j, \rho^i)
\end{aligned}$$

We know (Theorem 1) that $J(\chi, \varepsilon) = J(\chi^2, \varepsilon) = J(\varepsilon, \rho) = 0, J(\varepsilon, \varepsilon) = p$, so

$$N(y^2 = x^3 + D) = p + \rho(D)\chi(D)J(\chi, \rho) + \rho(D)\chi^2(D)J(\chi^2, \rho).$$

As $\chi^2(D) = \chi^{-1}(D) = \overline{\chi(D)}$, and as $\overline{\rho(D)} = \rho(D)$, then $J(\chi^2, \rho) = J(\overline{\chi}, \overline{\rho}) = \overline{J(\chi, \rho)}$, and

$$N(y^2 = x^3 + D) = p + \pi + \bar{\pi}, \text{ where } \pi = (\rho\chi)(D)J(\chi, \rho).$$

If $\chi(2) = 1$, then from Exercise 8.6 we have

$$J(\chi, \chi) = \chi(2)^{-2}J(\chi, \rho) = J(\chi, \rho).$$

With $D = 1$ (if $\chi(2) = 1$), we obtain

$$N(y^2 = x^3 + 1) = p + \pi + \bar{\pi}, \pi = J(\chi, \rho) = J(\chi, \chi).$$

From Prop. 8.3.4 we know that $J(\chi, \chi) = a + b\omega, b \equiv 0 \pmod 3), a \equiv -1 \pmod 3$.

$\pi + \overline{\pi} = 2\,\mathrm{Re}\,J(\chi, \chi) = 2a - b \equiv 1 \pmod 3$, and $p = N(J(\chi, \rho)) = a^2 - ab + b^2$, so $4p = (2a - b)^2 + 3b^2$.

Writing $A = 2a - b, B = b/3$, we obtain $4p = A^2 + 27B^2, A \equiv 1 \pmod 3$ (the unicity of A if proved in Exercise 8.13).

Conclusion : $N(y^2 = x^3 + 1) = p + A$, where $4p = A^2 + 27B^2, A \equiv 1 \pmod 3$.

If $p = 31$, 3 is a primitive element, and $2 = 3^{24} = (3^8)^3$ in $\mathbb{F}_{31}$, therefore $\chi(2) = 1$.
$31 = 4 + 27$, $4 \times 31 = 124 = 4^2 + 27 \times 2^2$, and $4 \equiv 1 \pmod 3$, so
if $p = 31$, $N(y^2 = x^3 + 1) = 35$. ☐

Ex. 8.16 *Suppose that $p \equiv 1 \pmod 4$ and that χ is a character of order 4. Let N be the number of solutions to $x^4 + y^4 = 1$ in $\mathbb{F}_p$. Show that $N = p + 1 - \delta_4(-1)4 + 2\,\mathrm{Re}\,J(\chi,\chi) + 4\,\mathrm{Re}\,J(\chi,\rho)$.*

Proof. Let χ a character of order 4 : such a character exists since $p \equiv 1 \pmod 4$. Then

$$\begin{aligned}
N(x^4 + y^4 = 1) &= \sum_{a+b=1} N(x^4 = a)N(y^4 = b) \\
&= \sum_{a+b=1} \sum_{i=0}^{3} \chi^i(a) \sum_{j=0}^{3} \chi^j(b) \\
&= \sum_{i=0}^{3} \sum_{j=0}^{3} \sum_{a+b=1} \chi^i(a)\chi^j(b) \\
&= \sum_{i=0}^{3} \sum_{j=0}^{3} J(\chi^i, \chi^j) \\
&= p - \chi(-1) - \chi^2(-1) - \chi^3(-1) \\
&+ J(\chi,\chi) + J(\chi,\chi^2) + J(\chi^2,\chi) \\
&+ J(\chi^2,\chi^3) + J(\chi^3,\chi^2) + J(\chi^3,\chi^3),
\end{aligned}$$

since from Theorem 1, we have $J(\varepsilon,\varepsilon) = p$, $J(\varepsilon,\chi^j) = 0$ for $j = 1,2,3$, and $J(\chi^i,\chi^{4-i}) = -\chi^i(-1)$.

Moreover

$$-[\chi(-1) + \chi^2(-1) + \chi^3(-1)] = 1 - [1 + \chi(-1) + \chi^2(-1) + \chi^3(-1)],$$

and

$$\left\{ \begin{array}{lll} 1 + \chi(-1) + \chi^2(-1) + \chi^3(-1) = \frac{1-\chi^4(-1)}{1-\chi(-1)} & = 0 & \text{if } \chi(-1) \neq 1 \\ & = 4 & \text{if } \chi(-1) = 1. \end{array} \right.$$

Let g a generator of $\mathbb{F}_p^*$. Recall that $\chi(g) = e^{qi\pi/2}$ with q odd, so $\chi : a = g^k \mapsto e^{iqk\pi k/2} = i^{qk}$, thus

$$\chi(a) = 1 \iff \chi(g^k) = 1 \iff i^{qk} = 1 \iff 4 \mid k \iff a = b^4, b \in \mathbb{F}^*.$$

δ_4 is defined by $\delta_4(a) = 1$ if a is a fourth power, 0 if not. Then

$$-[\chi(-1) + \chi^2(-1) + \chi^3(-1)] = 1 - \delta_4(-1)4.$$

Moreover $J(\chi,\chi) + J(\chi^3,\chi^3) = 2\,\mathrm{Re}\,(J(\chi,\chi))$, and

$$J(\chi,\chi^2) + J(\chi^3,\chi^2) + J(\chi^2,\chi) + J(\chi^2,\chi^3) = 2\,\mathrm{Re}\,(J(\chi,\chi^2) + 2\,\mathrm{Re}\,(J(\chi^2,\chi) = 4\,\mathrm{Re}\,(J(\chi,\chi^2)).$$

χ is of order 4, so $\rho = \chi^2$ is the unique character of order 2, the Legendre's character.

In conclusion,

$$N(x^4 + y^4 = 1) = p + 1 - \delta_4(-1)4 + 2\,\mathrm{Re}\,(J(\chi,\chi)) + 4\,\mathrm{Re}\,(J(\chi,\rho)).$$

$\square$

Ex. 8.17 *(continuation) By Exercise 8.7, $J(\chi,\chi) = \chi(-1)J(\chi,\rho)$. Let $\pi = -J(\chi,\rho)$. Show that*

(a) $N = p - 3 - 6\,\mathrm{Re}\,\pi$ *if* $p \equiv 1 \pmod 8$.

(b) $N = p + 1 - 2\,\mathrm{Re}\,\pi$ *if* $p \equiv 5 \pmod 8$.

Proof. Let g a generator in $\mathbb{F}_p^*$. As $(g^{(p-1)/2})^2 = 1$ and $g^{(p-1)/2} \neq 1$, then $g^{(p-1)/2} = -1$. As in Exercise 8.16, write $\chi(g) = e^{qi\pi/2}$, with q odd.

Then -1 is a fourth power in $\mathbb{F}_p^*$ iff (see Exercice 8.16)

$$\begin{aligned}
\delta_4(-1) = 1 &\iff \chi(-1) = 1\\
&\iff \chi(g^{(p-1)/2}) = 1\\
&\iff e^{q((p-1)/2)i\pi/2} = 1\\
&\iff 4 \mid q(p-1)/2\\
&\iff 4 \mid (p-1)/2\\
&\iff p \equiv 1 \pmod 8.
\end{aligned}$$

By Exercise 8.7, as χ is a character of order 4,

$$J(\chi,\chi) = \chi(-1)J(\chi,\rho).$$

- If $p \equiv 1[8]$,
  $\chi(-1) = 1$, so $J(\chi,\chi) = J(\chi,\rho)$, and $\delta_4(-1) = 1$.

$$\begin{aligned}
N &= p + 1 - \delta_4(-1)4 + 2\,\mathrm{Re}\,J(\chi,\chi) + 4\,\mathrm{Re}\,J(\chi,\rho)\\
&= p - 3 + 6\,\mathrm{Re}\,J(\chi,\rho)\\
&= p - 3 - 6\,\mathrm{Re}\,\pi, \qquad \text{where } \pi = -J(\chi,\rho).
\end{aligned}$$

- If $p \equiv 5[8]$,
  $\chi(-1) = -1$, donc $J(\chi,\chi) = -J(\chi,\rho)$, et $\delta_4(-1) = 0$

$$\begin{aligned}
N &= p + 1 - \delta_4(-1)4 + 2\,\mathrm{Re}\,J(\chi,\chi) + 4\,\mathrm{Re}\,J(\chi,\rho)\\
&= p + 1 + 2\,\mathrm{Re}\,J(\chi,\rho)\\
&= p + 1 - 2\,\mathrm{Re}\,\pi.
\end{aligned}$$

□

Ex. 8.18 *(continuation) Let $\pi = a + bi$. One can show (see Chapter 11, Section 5) that a is odd, b is even, and $a \equiv 1 \pmod 4$ if $4 \mid b$ and $a \equiv -1 \pmod 4$ if $4 \nmid b$. Let $p = A^2 + B^2$ and fix A by requiring that $A \equiv 1 \pmod 4$. Then show that*

(a) $N = p - 3 - 6A$ *if* $p \equiv 1 \pmod 8$,

(b) $N = p + 1 + 2A$ *if* $p \equiv 5 \pmod 8$.

Proof. Recall that $\pi = -J(\chi,\rho) \in \mathbb{Z}[i]$, so $\pi = a + bi,\ a, b \in \mathbb{Z}$.

1) We begin by proving that $\pi \equiv 1 \pmod{2+2i}$ (see Chapter 11, Section 5).
   For all $t \in \mathbb{F}_p^*$, $\rho(t) = \pm 1$, so $\rho(t) - 1 \equiv 0 \pmod 2$.

Let's verify that $\chi(t) - 1 \equiv 0 \pmod{1+i}$. $\chi(t) \in \{1, -1, i, -i\}$, so $\chi(t) - 1 \in \{0, -2, i-1, -i-1\}$. As $2 = (1-i)(1+i)$ and $i - 1 = i(1+i)$, we obtain

$$\forall t \in \mathbb{F}_p^*,\ 1+i \mid \chi(t) - 1.$$

Thus

$$\forall s \in \mathbb{F}_p^*, \forall t \in \mathbb{F}_p^*,\ (\rho(s)-1)(\chi(t)-1) \equiv 0 \pmod{2+2i}.$$

Moreover, if $s = 0, t = 1$, then $\chi(b) = 1$, and if $s = 1, t = 0$, then $\rho(s) = 1$, so

$$\sum_{s+t=1} (\rho(s)-1)(\chi(b)-1) \equiv 0 \pmod{2+2i}.$$

This gives, when developing this expression, :

$$-\pi - \sum_{b \in \mathbb{F}_p} \chi(b) - \sum_{a \in \mathbb{F}_p} \rho(a) + p \equiv 0 \pmod{2+2i}.$$

As $\sum_b \chi(b) = \sum_a \rho(a) = 0$, we obtain

$$\pi \equiv p \pmod{2+2i}.$$

Finally, $p \equiv 1 \pmod 4$, and $2+2i \mid 4$ since $4 = (1-i)(2+2i)$, so $p \equiv 1 \mod 2+2i$, so

$$\pi \equiv 1 \pmod{2+2i}.$$

2) By Corollary of Theorem 1, $N(\pi) = N(J(\chi, \rho) = p = a^2 + b^2$.

We know that $p \equiv 1 \pmod 4$, $p = a^2 + b^2$ and $a + ib \equiv 1 \pmod{2+2i}$. Then we prove that a is odd, b is even, and $a \equiv 1 \pmod 4$ if $4 \mid b$ and $a \equiv -1 \pmod 4$ if $4 \nmid b$.

$a + bi \equiv 1 \pmod{2+2i}$, so $a + bi \equiv 1 \pmod 2$, so a is odd, and b is even.

- If $4 \mid b$, then $2 + 2i \mid b$.

$a \equiv 1 \pmod{2+2i}$, and by complex conjugation, $a \equiv 1 \pmod{2-2i}$, so $52 + 2i)(2-2i) = 8 \mid (a-1)^2$, thus $4 \mid a - 1$.

- If $4 \nmid b$, then $b = 4k + 2, k \in \mathbb{Z}$.

Therefore, $1 \equiv a + bi \equiv a + 2i \pmod{2+2i}$. As $2i \equiv -2 \pmod{2+2i}$, $a \equiv 3 \equiv -1 \pmod{2+2i}$. By conjugation, $a \equiv -1 \pmod{2-2i}$. Multiplying these congruences, we obtain $8 \mid (a+1)^2$, so $a \equiv -1 \pmod 4$.

3) $\pi = -J(\chi, \rho) = a + bi$ is such that $a^2 + b^2 = p$, a odd, b even and also

$$(4 \mid b \text{ and } a \equiv 1\ [4]) \text{ or } (4 \nmid b \text{ and } a \equiv -1\ [4]).$$

If $p = A^2 + B^2$, A odd and B even, then also $p = (-A)^2 + B^2$, and $A \equiv 1 \pmod 4$ or $-A \equiv 1 \pmod 4$. So there exists a decomposition $p = A^2 + B^2$ such that $A \equiv 1 \pmod 4$. Such a decomposition is unique. Let's verify that $4 \mid b$ if $p \equiv 1 \pmod 8$, $4 \nmid b$ if $p \equiv 5 \pmod 8$.

$p = a^2 + b^2, a = 2a' + 1, b = 2b'$, so $p = 4a'^2 + 4a' + 1 + 4b'^2 = 8\frac{a'(a'+1)}{2} + 1 + 4b'^2$.

Hence $4 \mid b \iff 2 \mid b' \iff 8 \mid p - 1$.

Therefore if $p \equiv 1 \pmod 8$, $\operatorname{Re} \pi = a = A$, and if $p \equiv 5 \pmod 8$, $\operatorname{Re} \pi = a = -A$.

In conclusion, by Exercise 8.17 :

if $p = A^2 + B^2, A \equiv 1 \pmod 4$, and $N = N(x^4 + y^4 = 1)$ in $\mathbb{F}_p$,

(a) $N = p - 3 - 6A$ if $p \equiv 1 \pmod 8$,

(b) $N = p + 1 + 2A$ if $p \equiv 5 \pmod 8$.

Note : if $p \equiv -1 \pmod 4$, then there is no character of order 4 on $\mathbb{F}_p^*$, and $d = 4 \wedge (p-1) = 4 \wedge (4k+2) = 2$, so

$$N(x^4 = a) = \sum_{\chi_d = 1} \chi(a) = 1 + \rho(a) = N(x^2 = a).$$

$$\begin{aligned} N(x^4 + y^4 = 1) &= \sum_{a+b=1} N(x^4 = a) N(y^4 = b) \\ &= \sum a + b = 1 N(x^2 = a) N(y^2 = b) \\ &= N(x^2 + y^2) = 1 \end{aligned}$$

Using Chapter 8, Section 3, we obtain

$$N(x^4 + y^4 = 1) = p + 1 \text{ if } p \equiv -1 \pmod 4.$$

□

Ex. 8.19 *Find a formula for the number of solutions to $x_1^2 + x_2^2 + \cdots + x_r^2 = 0$ in $\mathbb{F}_p$.*

Proof. Let χ be the Legendre character. Then

$$\begin{aligned} N(x_1^2 + x_2^2 + \cdots + x_r^2 = 0) &= \sum_{a_1 + a_2 + \cdots + a_r = 0} N(x_1^2 = a_1) N(x_2^2 = a_2) \cdots N(x_r^2 = a_r) \\ &= \sum_{a_1 + a_2 + \cdots + a_r = 0} (1 + \chi(a_1))(1 + \chi(a_2) \cdots (1 + \chi(a_r)) \\ &= p^{r-1} + J_0(\chi, \chi, \cdots, \chi) \end{aligned}$$

(We used Proposition 8.5.1) For all k, $\chi^{2k} = \varepsilon, \chi^{2k+1} = \chi$.

• If r is odd, $\chi^r \neq \varepsilon$, so $J_0(\chi, \chi, \cdots, \chi) = 0$ (Proposition 8.5.1).

$$N(x_1^2 + x_2^2 + \cdots + x_r^2 = 0) = p^{r-1}.$$

• If r is even, $\chi^r = \varepsilon$, so $J_0(\chi, \chi, \cdots, \chi) = \chi(-1)(p-1) J(\chi, \chi, \cdots, \chi)$, where there are $r - 1$ components in the Jacobi sum (Proposition 8.5.1).

By Theorem 3, $J(\chi, \chi, \cdots, \chi) g(\chi^{r-1}) = g(\chi)^{r-1}$, and $g(\chi^{r-1}) = g(\chi)$, so

$$J(\chi, \chi, \cdots, \chi) = g(\chi)^{r-2}.$$

$g(\chi)^2 = \chi(-1)p$, therefore $\chi^{r-2} = \chi(-1)^{(r/2)-1} p^{(r/2)-1)} = (-1)^{((p-1)/2)(r/2-1)} p^{(r/2)-1)}$. So

$$N(x_1^2 + x_2^2 + \cdots + x_r^2 = 0) = p^{r-1} + (-1)^{\frac{p-1}{2}\frac{r}{2}} (p-1) p^{\frac{r}{2}-1}.$$

(Verified in C++ with small values of p and r.)

Conclusion :

$$\left\{ \begin{array}{lcll} N(x_1^2 + x_2^2 + \cdots + x_r^2 = 0) & = & p^{r-1} & \text{if } r \text{ is odd} \\ & = & p^{r-1} + (-1)^{\frac{p-1}{2}\frac{r}{2}} (p-1) p^{\frac{r}{2}-1} & \text{if } r \text{ is even.} \end{array} \right.$$

□

Ex. 8.20 *Generalize Proposition 8.6.1 by finding an explicit formula for the number of solutions to $a_1x_1^2 + a_2x_2^2 + \cdots + a_rx_r^2 = 1$ in $\mathbb{F}_p$.*

Proof. Write χ the Legendre character.

$$\begin{aligned} N(a_1x_1^2 + \cdots + a_rx_r^2 = 1) &= \sum_{a_1u_1+\cdots+a_ru_r=1} N(x_1^2 = u_1)\cdots N(x_r^2 = u_r) \\ &= \sum_{a_1u_1+\cdots+a_ru_r=1} (1+\chi(u_1)\cdots(1+\chi(u_r)) \qquad (v_i = a_iu_i) \\ &= \sum_{v_1+\cdots+v_r=1} (1+\chi(a_1)^{-1}\chi(v_1))\cdots(1+\chi(a_r^{-1})\chi(v_r)) \\ &= p^{r-1} + \chi(a_1^{-1})\cdots\chi(a_r^{-1})J(\chi,\chi,\cdots,\chi) \end{aligned}$$

$\chi(a_i^{-1}) = \overline{\chi(a_i)} = \chi(a_i) = \left(\frac{a_i}{p}\right)$

$J(\chi,\chi,\cdots,\chi)$ is computed in Chapter 5 Section 6. We obtain

$$\left\{ \begin{aligned} N(a_1x_1^2 + \cdots + a_rx_r^2 = 1) &= p^{r-1} + \left(\tfrac{a_1}{p}\right)\cdots\left(\tfrac{a_r}{p}\right)(-1)^{\frac{r-1}{2}\frac{p-1}{2}}p^{\frac{r-1}{2}} && \text{if } r \text{ is odd} \\ &= p^{r-1} - \left(\tfrac{a_1}{p}\right)\cdots\left(\tfrac{a_r}{p}\right)(-1)^{\frac{r}{2}\frac{p-1}{2}}p^{\frac{r}{2}-1} && \text{if } r \text{ is even.} \end{aligned} \right.$$

□

Ex. 8.21 *Suppose that $p \equiv 1 \pmod d$, $\zeta = e^{2\pi i/p}$, and consider $\sum_x \zeta^{ax^d}$. Show that $\sum_x \zeta^{ax^d} = \sum_r m(r)\zeta^{ar}$, where $m(r) = N(x^d = r)$.*

Proof. Let $A_r = \{x \in \mathbb{F}_p \mid x^d = r\}$

Then $\mathbb{F}_p = \coprod_r A_r$, thus

$$\sum_{x\in\mathbb{F}_p} \zeta^{ax^d} = \sum_{r\in\mathbb{F}_p}\sum_{x\in A_r} \zeta^{ax^d} = \sum_{r\in\mathbb{F}_p} |A_r|\zeta^{ar} = \sum_{r\in\mathbb{F}_p} m(r)\zeta^{ar},$$

where $m(r) = |A_r| = N(x^d = r)$ □

Ex. 8.22 *(continuation) Prove that $\sum_x \zeta^{ax^d} = \sum_\chi g_a(\chi)$, where the sum is over all χ such that $\chi^d = \varepsilon, \chi \neq \varepsilon$. Assum that $p \nmid a$.*

Proof. By Exercise 8.21,

$$S = \sum_{x\in\mathbb{F}_p} \zeta^{ax^d} = \sum_{r\in\mathbb{F}_p} m(r)\zeta^{ar}.$$

As $d \mid p-1$, by Proposition 8.1.5,

$$m(r) = N(x^d = r) = \sum_{\chi^d=\varepsilon} \chi(r).$$

Therefore

$$S = \sum_{r\in\mathbb{F}_p}\sum_{\chi^d=\varepsilon} \chi(r)\zeta^{ar} = \sum_{\chi^d=\varepsilon}\sum_{r\in\mathbb{F}_p} \chi(r)\zeta^{ar}.$$

If $\chi = \varepsilon$, $\sum\limits_{r\in\mathbb{F}_p} \chi(r)\zeta^{ar} = \sum\limits_{r\in\mathbb{F}_p} \zeta^{ar} = 0$, since $a \not\equiv 0 \pmod p$.

By definition $g_a(\chi) = \sum_r \chi(r)\zeta^{ar}$, so, if $d \mid p-1$, $p \nmid a$,

$$\sum_{x\in\mathbb{F}_p} \zeta^{ax^d} = \sum_{\chi^d=\varepsilon,\,\chi\neq\varepsilon} g_a(\chi)$$

□

Ex. 8.23 *Let $f(x_1, x_2, \dots, x_n) \in \mathbb{F}_p[x_1, x_2, \dots, x_n]$. Let N be the number of zeros of f in $\mathbb{F}_p$. Show that $N = p^{n-1} + p^{-1} \sum_{a \neq 0} (\sum_{x_1,\dots,x_n} \zeta^{af(x_1,\dots,x_n)})$.*

Proof. Let $A_r = \{(x_1, x_2, \cdots, x_n) \in \mathbb{F}_p^n \mid f(x_1, x_2, \cdots, x_n) = r\}$. Then $\mathbb{F}_p^n = \coprod_{r \in \mathbb{F}_p} A_r$, so, for all $a \in \mathbb{F}_p$,

$$\begin{aligned}
\sum_{(x_1,x_2,\cdots,x_n)\in\mathbb{F}_p^n} \zeta^{af(x_1,x_2,\cdots,x_n)} &= \sum_{r\in\mathbb{F}_p} \sum_{(x_1,x_2,\cdots,x_n)\in A_r} \zeta^{ar} \\
&= \sum_{r\in\mathbb{F}_p} |A_r| \zeta^{ar}
\end{aligned}$$

Let $m(r) = |A_r| = N(f(x_1, x_2, \cdots, x_n) = r)$. Then

$$\begin{aligned}
\sum_{a\in\mathbb{F}_p} \sum_{(x_1,x_2,\cdots,x_n)\in\mathbb{F}_p^n} \zeta^{af(x_1,x_2,\cdots,x_n)} &= \sum_{a\in\mathbb{F}_p} \sum_{r\in\mathbb{F}_p} m(r)\zeta^{ar} \\
&= \sum_{r\in\mathbb{F}_p} m(r) \sum_{a\in\mathbb{F}_p} \zeta^{ar}
\end{aligned}$$

As $\sum_{a\in\mathbb{F}_p} \zeta^{ar} = 0$ if $r \neq 0$, and $\sum_{a\in\mathbb{F}_p} \zeta^{ar} = p$ if $r = 0$, we obtain

$$\sum_{a\in\mathbb{F}_p} \sum_{(x_1,x_2,\cdots,x_n)\in\mathbb{F}_p^n} \zeta^{af(x_1,x_2,\cdots,x_n)} = m(0)p = pN.$$

Moreover

$$\sum_{a\in\mathbb{F}_p} \sum_{(x_1,x_2,\cdots,x_n)\in\mathbb{F}_p^n} \zeta^{af(x_1,x_2,\cdots,x_n)} = p^n + \sum_{a\in\mathbb{F}_p^*} \sum_{(x_1,x_2,\cdots,x_n)\in\mathbb{F}_p^n} \zeta^{af(x_1,x_2,\cdots,x_n)},$$

so

$$pN = p^n + \sum_{a\in\mathbb{F}_p^*} \sum_{(x_1,x_2,\cdots,x_n)\in\mathbb{F}_p^n} \zeta^{af(x_1,x_2,\cdots,x_n)}.$$

In conclusion,

$$N = p^{n-1} + p^{-1} \sum_{a\in\mathbb{F}_p^*} \sum_{(x_1,x_2,\cdots,x_n)\in\mathbb{F}_p^n} \zeta^{af(x_1,x_2,\cdots,x_n)}.$$

□

Ex. 8.24 *(continuation) Let $f(x_1, x_2, \dots, x_n) = a_1 x_1^{m_1} + a_2 x_2^{m_2} + \cdots + a_n x_n^{m_n}$. Let $d_i = (m_i, p-1)$. Show that $N = p^{n-1} + p^{-1} \sum_{a\neq 0} \prod_{i=1}^n \sum_{\chi_i} g_{aa_i}(\chi_i)$ where χ_i runs over all characters such that $\chi_i^{d_i} = \varepsilon$ and $\chi_i \neq \varepsilon$.*

Proof. By Exercise 8.2,

$$N = N(a_1 x_1^{m_1} + \cdots a_n x_n^{m_n} = 0) = N(a_1 x_1^{d_1} + \cdots a_n x_n^{d_n} = 0),$$

where $d_i = m_i \wedge (p-1)$ divides $p - 1$.

By Exercise 8.23,

$$N = p^{n-1} + p^{-1} \sum_{a \in \mathbb{F}_p^*} \sum_{(x_1, x_2, \cdots, x_n) \in \mathbb{F}_p^n} \zeta^{a(a_1 x_1^{d_1} + \cdots a_n x_n^{d_n})}$$

By Exercise 8.22, since $p \nmid a, p \nmid a_i$,

$$\begin{aligned}
\sum_{(x_1, x_2, \cdots, x_n) \in \mathbb{F}_p^n} \zeta^{a(a_1 x_1^{d_1} + \cdots a_n x_n^{d_n})} &= \left(\sum_{x_1 \in \mathbb{F}_p} \zeta^{a a_1 x_1^{d_1}} \right) \cdots \left(\sum_{x_1 \in \mathbb{F}_p} \zeta^{a a_n x_n^{d_n}} \right) \\
&= \left(\sum_{\chi_1^{d_1} = \varepsilon,\, \chi_1 \neq \varepsilon} g_{a a_1}(\chi_1) \right) \cdots \left(\sum_{\chi_n^{d_n} = \varepsilon,\, \chi_n \neq \varepsilon} g_{a a_n}(\chi_n) \right) \\
&= \prod_{i=1}^{n} \sum_{\chi_i^{d_i} = \varepsilon,\, \chi_i \neq \varepsilon} g_{a a_i}(\chi_i)
\end{aligned}$$

In conclusion,

$$N = p^{n-1} + p^{-1} \sum_{a \in \mathbb{F}_p^*} \prod_{i=1}^{n} \sum_{\chi_i^{d_i} = \varepsilon, \chi_i \neq \varepsilon} g_{a a_i}(\chi_i)$$

□

Ex. 8.25 *Deduce from Exercise 8.24 that* $|N - p^{n-1}| \leq (p-1)(d_1 - 1) \cdots (d_n - 1) p^{(n/2)-1}$.

Proof. As $|g_{a a_i}(\chi_i)| = \sqrt{p}$,

$$\left| \sum_{\chi_i^{d_i} = \varepsilon,\, \chi_i \neq \varepsilon} g_{a a_i}(\chi_i) \right| \leq \sqrt{p}\ n_i,$$

where $n_i = \mathrm{Card}\, \{\chi_i \neq \varepsilon \mid \chi_i^{d_i} = \varepsilon\}$.

As $d_i \mid p - 1$, there exists exactly d_i characters of order dividing d_i, so $n_i = d_i - 1$:

$$\left| \sum_{\chi_i^{d_i} = \varepsilon,\, \chi_i \neq \varepsilon} g_{a a_i}(\chi_i) \right| \leq \sqrt{p}(d_i - 1).$$

By Exercise 8.24,

$$N = p^{n-1} + p^{-1} \sum_{a \in \mathbb{F}_p^*} \prod_{i=1}^{n} \sum_{\chi_i^{d_i} = \varepsilon, \chi_i \neq \varepsilon} g_{a a_i}(\chi_i)$$

so

$$|N - p^{n-1}| \leq p^{-1}(p-1)\sqrt{p}(d_1 - 1) \cdots \sqrt{p}(d_n - 1),$$

that is

$$|N - p^{n-1}| \leq (p-1)(d_1 - 1) \cdots (d_n - 1) p^{\frac{n}{2} - 1}$$

□