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

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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 $x = g^{n/a}$. □

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 $\mathrm{Im}\varphi \simeq F^*/\ker\varphi$ is a subgroup with cardinality $|F^*|/|\ker\varphi| = (q-1)/n$, and $\mathrm{Im}\varphi$ 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.

□

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.

□

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 $i, 0 \leq i \leq q-1$ 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 $\mathrm{Card}\, F[\zeta] = q^f$, 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. $\square$

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)
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$\square$