

Chapter 11

Ex. 11.1 Suppose that we may write the power series $1 + a_1u + a_2u^2 + \cdots$ as the quotient of two polynomials $P(u)/Q(u)$. Show that we may assume that $P(0) = Q(0) = 1$.

Proof. Here $f(u) = 1 + a_1u + a_2u^2 + \cdots \in \mathbb{C}[[u]]$ is a formal series in the variable u .

We suppose that $f(u) = P(u)/Q(u)$, where we may assume, after simplification, that the two polynomials are relatively prime. Then $P(1)/Q(1) = 1$. Write $c = P(1) = Q(1) \in F$.

If $c = 0$, then $u \mid P(u)$ and $u \mid Q(u)$. This is impossible since $P \wedge Q = 1$. So $c \neq 0$.

Define $P_1(u) = (1/c)P(u)$, $Q_1(u) = (1/c)Q(u)$. Then $f(u) = P_1(u)/Q_1(u)$ and $P_1(0) = Q_1(0) = 1$. If we replace P, Q by P_1, Q_1 , then the pair (P_1, Q_1) has the required properties. \square

Ex. 11.2 Prove the converse to Proposition 11.1.1.

Proof. If $N_s = \sum_{j=1}^e \beta_j^s - \sum_{i=1}^d \alpha_i^s$, where α_i, β_j are complex numbers, then

$$\begin{aligned} \sum_{s=1}^{\infty} \frac{N_s u^s}{s} &= \sum_{j=1}^e \left(\sum_{s=1}^{\infty} \frac{(\beta_j u)^s}{s} \right) - \sum_{i=1}^d \left(\sum_{s=1}^{\infty} \frac{(\alpha_i u)^s}{s} \right) \\ &= - \sum_{j=1}^e \ln(1 - \beta_j u) + \sum_{i=1}^d \ln(1 - \alpha_i u). \end{aligned}$$

Here u is a variable, and both members are formal polynomials in $\mathbb{C}[[u]]$, so we don't study convergence. Nevertheless, the left member has a radius of convergence at least q^{-n} , and the right member $\min_{i,j} (1/|\beta_j|, 1/|\alpha_i|)$.

Therefore,

$$Z_f(u) = \exp \left(\sum_{s=1}^{\infty} \frac{N_s u^s}{s} \right) = \prod_{j=1}^e (1 - \beta_j u)^{-1} \prod_{i=1}^d (1 - \alpha_i u) = \frac{\prod_{i=1}^d (1 - \alpha_i u)}{\prod_{j=1}^e (1 - \beta_j u)}$$

is a rational fraction. \square

Ex. 11.3 Give the details of the proof that N_s is independent of the field F_s (see the concluding paragraph to section 1).

Proof. Suppose that E and E' are two fields containing F both with q^s elements. We first show that there is an isomorphism $\sigma : E \rightarrow E'$ which fixes the elements of F , by showing that both E and E' are isomorphic over F to $F[x]/(f(x))$ for some irreducible polynomial $f(x) \in F[x]$.

There is a primitive element $\alpha' \in E'$, i.e. such that $E' = F(\alpha')$. For example, take α' to be a primitive $q^s - 1$ root of unity : since α is a generator of E'^* , every element $\gamma \in E'^*$ is equal to α'^k for some integer k , thus $\gamma \in F(\alpha')$ (and $0 \in F(\alpha')$). This proves $E' \subset F(\alpha')$, and since $\alpha' \in E'$ and $F \subset E'$, $F(\alpha') \subset E'$, so $E' = F(\alpha')$.

Let $f(x) \in F[x]$ be the minimal polynomial of α' over F . Then

$$E' = F(\alpha') \simeq F[x]/(f(x)),$$

where the isomorphism $\sigma_1 : F(\alpha') \rightarrow F[x]/(f(x))$ maps α' to $\bar{x} = x + (f(x))$, and maps $a \in F$ on $\bar{a} = a + (f(x))$. Since α' is a root of $x^{q^s} - x$, $f(x) \mid x^{q^s} - x$.

E is a field with q^s elements, so we have $x^{q^s} - x = \prod_{\alpha \in E} (x - \alpha)$. Thus $f(x) \mid \prod_{\alpha \in E} (x - \alpha)$, where $\deg(f(x)) = s \geq 1$, so $f(\alpha) = 0$ for some $\alpha \in E$. The polynomial f being irreducible over F , f is the minimal polynomial of α over F , thus $F(\alpha) \simeq F[x]/(f(x))$ is a field with q^s elements. Since $F(\alpha) \subset E$, and $|F(\alpha)| = |E|$, we conclude $E = F(\alpha)$, therefore

$$E = F(\alpha) \simeq F(x)/(f(x)),$$

where the isomorphism $\sigma_2 : F(\alpha) \rightarrow F(x)/(f(x))$ maps α to $\bar{x} = x + (f(x))$, and maps $a \in F$ on $\bar{a} = a + (f(x))$.

Then $\sigma = \sigma_1^{-1} \circ \sigma_2 : E \rightarrow E'$ is an isomorphism, and $\sigma(a) = a$ for all $a \in F$.

We can now use the isomorphism σ to induce a map

$$\bar{\sigma} \begin{cases} P^n(E) & \rightarrow P^n(E') \\ [\alpha_0, \dots, \alpha_n] & \mapsto [\sigma(\alpha_0), \dots, \sigma(\alpha_n)]. \end{cases}$$

Then $\bar{\sigma}$ is injective: if $[\sigma(\alpha_0), \dots, \sigma(\alpha_n)] = [\sigma(\beta_0), \dots, \sigma(\beta_n)]$, then there is $\lambda \in F^*$ such that $\beta_i = \lambda \sigma(\alpha_i) = \sigma(\lambda) \sigma(\alpha_i) = \sigma(\lambda \alpha_i)$, $i = 0, \dots, n$, thus $\beta_i = \lambda \alpha_i$, which proves $[\alpha_0, \dots, \alpha_n] = [\beta_0, \dots, \beta_n]$.

If $[\gamma_0, \dots, \gamma_n]$ is any projective point of $P^n(E')$, then

$$[\gamma_0, \dots, \gamma_n] = \bar{\sigma}([\sigma^{-1}(\gamma_0), \dots, \sigma^{-1}(\gamma_n)]).$$

This proves that $\bar{\sigma}$ is surjective. So $\bar{\sigma}$ is a bijection.

Now take $f(y_0, \dots, y_n) \in F[y_0, \dots, y_n]$ an homogeneous polynomial, $\bar{H}_f(E)$ the corresponding projective hypersurface in $P^n(E)$, and $\bar{H}_f(E')$ the corresponding projective hypersurface in $P^n(E')$. We show that $\bar{\sigma}(\bar{H}_f(E)) = \bar{H}_f(E')$.

Since σ is a F -isomorphism, $\sigma(f(\alpha_0, \dots, \alpha_n)) = f(\sigma(\alpha_0), \dots, \sigma(\alpha_n))$ ($\alpha_i \in E$), and similarly $\sigma^{-1}(f(\beta_0, \dots, \beta_n)) = f(\sigma^{-1}(\beta_0), \dots, \sigma^{-1}(\beta_n))$ ($\beta_i \in E'$), thus

$$\begin{aligned} [\alpha_0, \dots, \alpha_n] \in \bar{H}_f(E) &\Rightarrow f(\alpha_0, \dots, \alpha_n) = 0 \\ &\Rightarrow \sigma(f(\alpha_0, \dots, \alpha_n)) = \sigma(0) = 0 \\ &\Rightarrow f(\sigma(\alpha_0), \dots, \sigma(\alpha_n)) = 0 \\ &\Rightarrow \bar{\sigma}([\alpha_0, \dots, \alpha_n]) = [\sigma(\alpha_0), \dots, \sigma(\alpha_n)] \in \bar{H}_f(E'). \end{aligned}$$

This shows $\bar{\sigma}(\bar{H}_f(E)) \subset \bar{H}_f(E')$.

Conversely,

$$\begin{aligned} [\beta_0, \dots, \beta_n] \in \bar{H}_f(E') &\Rightarrow f(\beta_0, \dots, \beta_n) = 0 \\ &\Rightarrow \sigma^{-1}(f(\beta_0, \dots, \beta_n)) = \sigma^{-1}(0) = 0 \\ &\Rightarrow f(\sigma^{-1}(\beta_0), \dots, \sigma^{-1}(\beta_n)) = 0 \\ &\Rightarrow \bar{\sigma}^{-1}([\beta_0, \dots, \beta_n]) = [\sigma^{-1}(\beta_0), \dots, \sigma^{-1}(\beta_n)] \in \bar{H}_f(E). \end{aligned}$$

If we define $\alpha_i = \sigma^{-1}(\beta_i)$, $i = 0, \dots, n$, then $[\alpha_0, \dots, \alpha_n] \in \bar{H}_f(E)$, and $[\beta_0, \dots, \beta_n] = \bar{\sigma}([\alpha_0, \dots, \alpha_n]) \in \bar{\sigma}(\bar{H}_f(E))$. This shows $\bar{H}_f(E') \subset \bar{\sigma}(\bar{H}_f(E))$, and so

$$\bar{\sigma}(\bar{H}_f(E)) = \bar{H}_f(E').$$

Since $\bar{\sigma}$ is a bijection,

$$N_s = |\bar{H}_f(E)| = |\bar{H}_f(E')| = N'_s.$$

So N_s is independent of the choice of the extension $F_s = \mathbb{F}_{q^s}$ of $F = \mathbb{F}_q$. □

Ex. 11.4 Calculate the zeta function of $x_0x_1 - x_2x_3 = 0$ over \mathbb{F}_p .

Proof. Here $F = \mathbb{F}_p$, and $F_s = \mathbb{F}_{p^s}$.

To calculate N_s , we calculate the number of points at infinity (such that $x_0 = 0$), and the numbers of affine points of the curve $\overline{H}_f(\mathbb{F}_{p^s})$ associate to

$$f(x_0, x_1, x_2, x_3) = x_0x_1 - x_2x_3.$$

- To estimate the number of points at infinity, we calculate first the cardinality of the set

$$U = \{(\alpha_0, \alpha_1, \alpha_2, \alpha_3) \in F_s^4 \mid \alpha_0\alpha_1 - \alpha_2\alpha_3 = 0, \alpha_0 = 0\}.$$

Then α_1 takes an arbitrary value $a \in F_s$. Write

$$U_a = \{(\alpha_0, \alpha_1, \alpha_2, \alpha_3) \in U \mid \alpha_1 = a\}.$$

Then $U_a = \{(\alpha_0, \alpha_1, \alpha_2, \alpha_3) \in F_s^4 \mid \alpha_0 = 0, \alpha_1 = a, \alpha_2\alpha_3 = 0\}$, thus $U_a = A \cup B$, where

$$A = \{(\alpha_0, \alpha_1, \alpha_2, \alpha_3) \in U_a \mid \alpha_2 = 0\},$$

$$B = \{(\alpha_0, \alpha_1, \alpha_2, \alpha_3) \in U_a \mid \alpha_3 = 0\}.$$

Since $\alpha_0, \alpha_1, \alpha_3$ are fixed in A , the map $A \rightarrow F_s$ defined by $(\alpha_0, \alpha_1, \alpha_2, \alpha_3) \mapsto \alpha_2$ is a bijection, therefore $|A| = p^s$, and similarly $|B| = p^s$. But $A \cap B = \{(0, 0, 0, 0)\}$, thus

$$|U_a| = |A| + |B| - |A \cap B| = 2p^s - 1.$$

Since U is the disjoint union of the U_a , thus

$$|U| = \sum_{a \in F_s} |U_a| = \sum_{a \in F_s} (2p^s - 1) = 2p^{2s} - p^s.$$

Therefore the number of projective points $[\alpha_0, \alpha_1, \alpha_2, \alpha_3] \in P^3(F_s)$ at infinity (such that $\alpha_0 = 0$) is

$$N_\infty = \frac{|U| - 1}{p^s - 1} = \frac{2p^{2s} - p^s - 1}{p^s - 1} = 2p^s + 1.$$

- Now we calculate the number of points of the affine surface $H_f(\mathbb{F}_s)$ associate to the equation $y_1 = y_2y_3$ (where $y_i = x_i/x_0$).

The maps

$$u \left\{ \begin{array}{ccc} F_s^2 & \rightarrow & H_f(F_s) \\ (\beta, \gamma) & \mapsto & (\beta\gamma, \beta, \gamma) \end{array} \right. \quad \left\{ \begin{array}{ccc} H_f(F_s) & \rightarrow & F_s^2 \\ (\alpha, \beta, \gamma) & \mapsto & (\beta, \gamma) \end{array} \right.$$

satisfy $u \circ v = \text{id}, v \circ u = \text{id}$, so u is a bijection. With more informal words, the arbitrary choice of $\beta, \gamma \in F_s$ gives the affine point (α, β, γ) , where $\alpha = \beta\gamma$.

This gives $|H_f(F_s)| = p^{2s}$.

Therefore

$$N_s = |\overline{H}_f(F_s)| = p^{2s} + 2p^s + 1.$$

We obtain in $\mathbb{C}[[u]]$

$$\begin{aligned}\sum_{s=1}^{\infty} \frac{N_s u^s}{s} &= \sum_{s=1}^{\infty} \frac{(p^2 u)^s}{s} + 2 \sum_{s=1}^{\infty} \frac{(pu)^s}{s} + \sum_{s=1}^{\infty} \frac{u^s}{s} \\ &= -\ln(1 - p^2 u) - 2 \ln(1 - pu) - \ln(1 - u).\end{aligned}$$

This gives

$$Z_f(u) = (1 - p^2 u)^{-1} (1 - pu)^{-2} (1 - u)^{-1}.$$

Note: The result for N_s is verified with the naive and very slow following code in Sage:

```
def N(p,s):
    Fs = GF(p^s)
    counter = 0
    for x in Fs:
        for y in Fs:
            for z in Fs:
                for t in Fs:
                    if x*y == z*t:
                        counter += 1
    return (counter - 1)/(p^s - 1)

p, s = 5, 3
print N(p,s), p^(2*s) + 2*p^s + 1
```

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There is a misprint in the “Selected Hints for the Exercises” in Ireland-Rosen p.371. \square

Ex. 11.5 Calculate as explicitly as possible the zeta function of $a_0 x_0^2 + a_1 x_1^2 + \cdots + a_n x_n^2$ over \mathbb{F}_q , where q is odd. The answer will depend on whether n is odd or even and whether $q \equiv 1 \pmod{4}$ or $q \equiv 3 \pmod{4}$.

Proof. Since q is odd, there is a unique character χ of order 2 over $F = \mathbb{F}_q$, and a unique character of order 2 over $F_s = \mathbb{F}_{q^s}$. We first compute the number in \mathbb{F}_q^{n+1} of solutions of the equation $f(x_0, \dots, x_n) = 0$, where $f(x_0, \dots, x_n) = a_0 x_0^2 + \cdots + a_n x_n^2 \in F[x_0, \dots, x_n]$.

$$\begin{aligned}N(a_0 x_0^2 + \cdots + a_n x_n^2 = 0) &= \sum_{a_0 u_0 + \cdots + a_n u_n = 0} N(x_0^2 = u_0) \cdots N(x_n^2 = u_n) \\ &= \sum_{a_0 u_0 + \cdots + a_n u_n = 0} (1 + \chi(u_0)) \cdots (1 + \chi(u_n)) \\ &= \sum_{v_0 + \cdots + v_n = 0} (1 + \chi(a_0^{-1}) \chi(v_0)) \cdots (1 + \chi(a_n^{-1}) \chi(v_n)) \quad (v_i = a_i u_i) \\ &= q^n + \chi(a_0^{-1}) \cdots \chi(a_n^{-1}) J_0(\chi, \chi, \dots, \chi),\end{aligned}$$

Indeed $J_0(\varepsilon, \dots, \varepsilon) = q^{l-1}$, and $J_0(\chi_0, \dots, \chi_n) = 0$ if some but not all of the χ_i are trivial (generalization of Proposition 8.5.1).

We estimate $J_0(\chi, \dots, \chi)$, where there are $n + 1$ entries of χ .

- If n is even, then $\chi^{n+1} = \chi \neq \varepsilon$, thus $J_0(\chi, \dots, \chi) = 0$ (Proposition 8.5.1(d)), and so

$$N(a_0x_0^2 + \dots + a_nx_n^2 = 0) = q^n,$$

and the number of projective points on the hypersurface is given by

$$N_1 = \frac{q^n - 1}{q - 1} = q^{n-1} + \dots + q + 1.$$

- If n is odd, then $\chi^{n+1} = \varepsilon$, thus $J_0(\chi, \dots, \chi) = \chi(-1)(q-1)J(\chi, \dots, \chi)$, with n entries of χ (same Proposition).

By Theorem 3 of chapter 8,

$$J(\chi, \dots, \chi) = \frac{g(\chi)^n}{g(\chi)} = g(\chi)^{n-1}.$$

Since $g(\chi)^2 = g(\chi)g(\chi)^{-1} = \chi(-1)q$ (Exercise 10.22),

$$\begin{aligned} \frac{1}{q-1} J_0(\chi, \dots, \chi) &= \chi(-1)g(\chi)^{n-1} \\ &= \chi(-1)g(\chi)^{n-1} \\ &= \frac{\chi(-1)g(\chi)^{n+1}}{g(\chi)^2} \\ &= \frac{1}{q} g(\chi)^{n+1}. \end{aligned}$$

Therefore

$$N(a_0x_0^2 + \dots + a_nx_n^2 = 0) = q^n + \chi(a_0)^{-1} \dots \chi(a_n)^{-1} \frac{q-1}{q} g(\chi)^{n_1},$$

and

$$N_1 = q^{n-1} + \dots + q + 1 + \frac{1}{q} \chi(a_0)^{-1} \dots \chi(a_n)^{-1} g(\chi)^{n+1}.$$

To conclude this first part,

$$\begin{aligned} N_1 &= q^{n-1} + \dots + q + 1 && \text{if } n \text{ is even,} \\ N_1 &= q^{n-1} + \dots + q + 1 + \frac{1}{q} \chi(a_0)^{-1} \dots \chi(a_n)^{-1} g(\chi)^{n+1} && \text{if } n \text{ is odd.} \end{aligned}$$

To compute N_s , we must replace q by q^s and χ by χ_s , the character of order 2 on F_s . Then

$$\begin{aligned} N_s &= q^{s(n-1)} + \dots + q^s + 1 && \text{if } n \text{ is even,} \\ N_s &= q^{s(n-1)} + \dots + q^s + 1 + \frac{1}{q^s} \chi_s(a_0)^{-1} \dots \chi_s(a_n)^{-1} g(\chi_s)^{n+1} && \text{if } n \text{ is odd.} \end{aligned}$$

(These two results can also be obtained by using the equations (1) and (2) in Theorem 2 of Chapter 10.)

It remains to study χ_s in the odd case.

Since $\chi_s^2 = \varepsilon$, for all $\alpha \in F_s$, $\chi_s(\alpha)^{-1} = \chi_s(\alpha)$, and $\chi_s(\alpha) = -1 \in \mathbb{C}$ if $\alpha^{\frac{q^s-1}{2}} = -1 \in F_s$, $\chi_s(\alpha) = 1$ otherwise.

If $a \in F$, $a^{\frac{q-1}{2}} = \pm 1 = \varepsilon$. Since q is odd, $1 + q + \cdots + q^{s-1} \equiv s \pmod{2}$, thus

$$a^{\frac{q^s-1}{2}} = a^{\frac{q-1}{2}(1+q+\cdots+q^{s-1})} = \varepsilon^{1+q+\cdots+q^{s-1}} = \varepsilon^s,$$

so

$$\chi_s(a) = \chi(a)^s \quad (a \in F).$$

We know that $g(\chi_s)^2 = \chi_s(-1)q^s$ (Ex. 10.22), thus, as n is odd,

$$\begin{aligned} g(\chi_s)^{n+1} &= [g(\chi_s)^2]^{\frac{n+1}{2}} \\ &= \chi_s(-1)^{\frac{n+1}{2}} q^{s\frac{n+1}{2}}. \end{aligned}$$

If $q \equiv 1 \pmod{4}$, then $(-1)^{\frac{q-1}{2}} = 1$, so -1 is a square in \mathbb{F}_q . In this case, -1 is a square in \mathbb{F}_{q^s} , and $\chi_s(-1) = 1$ for all $s \geq 1$. In this case, using $a_i \in F$,

$$\begin{aligned} N_s &= q^{s(n-1)} + \cdots + q^s + 1 + \chi_s(a_0) \cdots \chi_s(a_n) q^{s\frac{n-1}{2}} \\ &= q^{s(n-1)} + \cdots + q^s + 1 + [\chi(a_0) \cdots \chi(a_n)]^s q^{s\frac{n-1}{2}} \end{aligned}$$

If $q \equiv -1 \pmod{4}$, then $\chi(-1) = (-1)^{\frac{q-1}{2}} = -1$, and

$$\chi_s(-1) = \chi(-1)^s = (-1)^s,$$

thus

$$\frac{1}{q^s} g(\chi_s)^{n+1} = (-1)^{s\frac{n+1}{2}} q^{s\frac{n-1}{2}}.$$

This gives for odd integers n , and $q \equiv -1 \pmod{4}$,

$$\begin{aligned} N_s &= q^{s(n-1)} + \cdots + q^s + 1 + (-1)^{s\frac{n+1}{2}} \chi_s(a_0) \cdots \chi_s(a_n) q^{s\frac{n-1}{2}} \\ &= q^{s(n-1)} + \cdots + q^s + 1 + [(-1)^{\frac{n+1}{2}} \chi(a_0) \cdots \chi(a_n)]^s q^{s\frac{n-1}{2}}. \end{aligned}$$

To collect all these cases, we have proved

$$\begin{aligned} N_s &= q^{s(n-1)} + \cdots + q^s + 1 && \text{if } n \equiv 0 \pmod{2}, \\ N_s &= q^{s(n-1)} + \cdots + q^s + 1 + [\chi(a_0) \cdots \chi(a_n)]^s q^{s\frac{n-1}{2}} && \text{if } n \equiv 1 \pmod{2}, q \equiv +1 \pmod{4}, \\ N_s &= q^{s(n-1)} + \cdots + q^s + 1 + [(-1)^{\frac{n+1}{2}} \chi(a_0) \cdots \chi(a_n)]^s q^{s\frac{n-1}{2}} && \text{if } n \equiv 1 \pmod{2}, q \equiv -1 \pmod{4}. \end{aligned} \quad (4)$$

If n is even this gives, as in paragraph 1,

$$Z_f(u) = (1 - q^{n-1}u)^{-1} \cdots (1 - qu)^{-1} (1 - u)^{-1}.$$

In the case $n \equiv 1 \pmod{2}, q \equiv +1 \pmod{4}$, we write for simplicity $\varepsilon = \chi(a_0) \cdots \chi(a_n) = \pm 1$. Then

$$\begin{aligned} \sum_{s=1}^{\infty} \frac{N_s u^s}{s} &= \sum_{m=0}^{n-1} \left(\sum_{s=1}^{\infty} \frac{(q^m u)^s}{s} \right) + \sum_{s=1}^{\infty} \frac{(\varepsilon q^{\frac{n-1}{2}} u)^s}{s} \\ &= - \sum_{m=0}^{n-1} \ln(1 - q^m u) - \ln(1 - \varepsilon q^{\frac{n-1}{2}} u). \end{aligned}$$

Therefore

$$Z_f(u) = \left[\prod_{m=0}^{n-1} (1 - q^m u)^{-1} \right] (1 - \chi(a_0) \cdots \chi(a_n) q^{\frac{n-1}{2}} u)^{-1}.$$

(Same calculation in the last case, with $\varepsilon = (-1)^{\frac{n+1}{2}} \chi(a_0) \cdots \chi(a_n)$.)

We obtain

$$\begin{aligned} Z_f(u) &= P(u) && \text{if } n \equiv 0 \pmod{2}, \\ Z_f(u) &= P(u)(1 - \chi(a_0) \cdots \chi(a_n) q^{\frac{n-1}{2}} u)^{-1} && \text{if } n \equiv 1 \pmod{2}, q \equiv +1 \pmod{4}, \\ Z_f(u) &= P(u)(1 - (-1)^{\frac{n+1}{2}} \chi(a_0) \cdots \chi(a_n) q^{\frac{n-1}{2}} u)^{-1} && \text{if } n \equiv 1 \pmod{2}, q \equiv -1 \pmod{4}, \end{aligned}$$

where $P(u) = (1 - q^{n-1}u)^{-1} \cdots (1 - qu)^{-1}(1 - u)^{-1}$.

(These results are consistent with the example $N_s = q^{2s} + q^s + 1 + \chi_s(-1)q^s$ given in paragraph 1 for the surface defined by $-y_0^2 + y_1^2 + y_2^2 + y_3^2 = 0$, where $n = 3$ is odd.

$$\begin{aligned} Z_f(u) &= (1 - q^2u)^{-1}(1 - qu)^{-1}(1 - u)^{-1}(1 - \chi(-1)qu)^{-1} \\ &= \begin{cases} (1 - q^2u)^{-1}(1 - qu)^{-2}(1 - u)^{-1} & \text{if } q \equiv 1 \pmod{4}, \\ (1 - q^2u)^{-1}(1 - qu)^{-1}(1 - u)^{-1}(1 + qu)^{-1} & \text{if } q \equiv -1 \pmod{4}. \end{cases} \end{aligned}$$

□

Ex. 11.6 Consider $x_0^3 + x_1^3 + x_2^3 = 0$ as an equation over F_4 , the field with four elements. Show that there are nine points on the curve in $P^2(F_4)$. Calculate the zeta function. [Answer: $(1 + 2u)^2 / ((1 - u)(1 - 4u))$.]

Proof. Since $q = 4 \equiv 1 \pmod{3}$, we can apply Theorem 2 of Chapter 10. Let χ be a character of order 3 over $F = \mathbb{F}_4$. The only other character of order 3 is then χ^2 . Thus

$$N_1 = q + 1 + \frac{1}{q-1} \sum_{i,j,k} J_0(\chi^i, \chi^j, \chi^k),$$

where the sum is over all $(i, j, k) \in \{1, 2\}^3$ such that $i + j + k \equiv 0 \pmod{3}$, that is $(1, 1, 1)$ and $(2, 2, 2)$. Thus

$$N_1 = q + 1 + \frac{1}{q-1} (J_0(\chi, \chi, \chi) + J_0(\chi^2, \chi^2, \chi^2)).$$

Using $\frac{1}{q-1} J_0(\chi^k, \chi^k, \chi^k) = \frac{1}{q} g(\chi^k)^3$ for $k = 1, 2$, we obtain

$$N_1 = q + 1 + \frac{1}{q} (g(\chi)^3 + g(\chi^2)^3).$$

Consider $\mathbb{F}_4 = \mathbb{F}_2[x]/(x^2 + x + 1)$, where $a = \bar{x} = x + (x^2 + x + 1)$ is a generator of \mathbb{F}_4^* . Then $\mathbb{F}_4 = \{0, 1, a, a^2 = a + 1\}$. We compute $g(\chi)$ for the character χ of order 3 defined by

$$\frac{t}{\chi(t)} \mid \begin{array}{cccc} 0 & 1 & a & a^2 \\ 0 & 1 & \omega & \omega^2 \end{array}$$

where $\omega = e^{\frac{2i\pi}{3}}$.

for each $t \in \mathbb{F}_4$, $\text{tr}(a) = a + a^2 \in \mathbb{F}_2$, so the traces are $\text{tr}(1) = 1 + 1 = 0$, $\text{tr}(a) = a + a^2 = 1$, $\text{tr}(a^2) = a^2 + a^4 = a^2 + a = 1$. Therefore

$$\begin{aligned} g(\chi) &= \sum_{t \in \mathbb{F}_4} \chi(t) \zeta_2^{\text{tr}(t)} \\ &= \sum_{t \in \mathbb{F}_4} \chi(t) (-1)^{\text{tr}(t)} \\ &= 1 - \omega - \omega^2 \\ &= 2. \end{aligned}$$

(This is in accordance with $|g(\chi)| = q^{1/2} = 2$.) Then $g(\chi^2) = g(\chi^{-1}) = \chi(-1)\overline{g(\chi)} = g(\chi) = 2$. Therefore

$$\begin{aligned} N_1 &= q + 1 + \frac{1}{q}g(\chi)^3 + \frac{1}{q}g(\chi^2)^3 \\ &= 5 + \frac{1}{4}(8 + 8) \\ &= 9. \end{aligned}$$

There are nine points on the curve with equation $x_0^3 + x_1^3 + x_2^3 = 0$ in $P^2(F_4)$ (this is verified with a naive program in Sage).

Now we compute N_s . We must replace $q = 4$ by $q^s = 4^s$, and χ by χ_s , a character with order 3 on $F_s = \mathbb{F}_{4^s}$.

We obtain

$$N_s = q^s + 1 + \frac{1}{q^s} (g(\chi_s)^3 + g(\chi_s^2)^3).$$

Now we compute $g(\chi_s)^3$. By the generalization of Corollary of Proposition 8.3.3.,

$$g(\chi_s)^3 = q^s J(\chi_s, \chi_s),$$

thus

$$N_s = q^s + 1 + J(\chi_s, \chi_s) + J(\chi_s^2, \chi_s^2).$$

We know that $|J(\chi_s, \chi_s)|^2 = q^s = 4^s$ (generalization of Corollary of Theorem 1). Writing $J(\chi_s, \chi_s) = a + b\omega$, $a, b \in \mathbb{Z}$, we search the solutions of

$$|a + b\omega|^2 = a^2 - ab + b^2 = 4^s.$$

Since $\mathbb{Z}[\omega]$ is a PID, the factorization in primes is unique. Here 2 is a prime element of $\mathbb{Z}[\omega]$, and $(a + b\omega)(a + b\omega^2) = 2^{2s}$, therefore $a + b\omega = \varepsilon 2^k$, $a + b\omega^2 = \zeta 2^l$, where $l, k \in \mathbb{N}$ and ε, ζ are units. Moreover $2^k = |a + b\omega| = |a + b\omega^2| = 2^l$, so $k = l = s$. This shows that every solution $a + b\omega$ of $|a + b\omega|^2 = 4^s$ is associated to 2^s :

$$|a + b\omega|^2 = 4^s \iff a + b\omega \in \{-2^s, -1 - 2^s\omega, -2^s\omega, 2^s, 1 + 2^s\omega, 2^s\omega\}.$$

Moreover, we know that $a \equiv -1 \pmod{3}$, $b \equiv 0 \pmod{3}$ (generalization of Proposition 8.3.4.). Therefore

$$J(\chi_s, \chi_s) = a + b\omega = -(-2)^s,$$

and similarly $J(\chi_s^2, \chi_s^2) = -(-2)^s$. This gives

$$N_s = 4^s + 1 - 2(-2)^s.$$

For $s = 1$, we find anew $N_1 = 9$.

Then

$$\begin{aligned} \sum_{s=1}^{\infty} \frac{N_s u^s}{s} &= \sum_{s=1}^{\infty} \frac{(4u)^s}{s} + \sum_{s=1}^{\infty} \frac{u^s}{s} - 2 \sum_{s=1}^{\infty} \frac{(-2u)^s}{s} \\ &= -\ln(1 - 4u) - \ln(1 - u) - 2\ln(1 + 2u). \end{aligned}$$

This gives

$$Z_f(u) = \frac{(1 + 2u)^2}{(1 - 4u)(1 - u)}.$$

This is the first example where Z_f has a zero, which satisfies the Riemann hypothesis for curves. \square