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. □

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

$$\begin{aligned}\sum_{s=1}^\infty\frac{N_su^s}{s}&=\sum_{j=1}^e\left(\sum_{s=1}^\infty\frac{(\beta_ju)^s}{s}\right)-\sum_{i=1}^d\left(\sum_{s=1}^\infty\frac{(\alpha_iu)^s}{s}\right)\\&=-\sum_{j=1}^e\ln(1-\beta_ju)+\sum_{i=1}^d\ln(1-\alpha_iu).\end{aligned}$$

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,

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

is a rational fraction. □

Ex. 11.3 *Give the details of the proof that N_s is independant 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 a isomorphism $\sigma:E\to E'$ which fixes the elements of F, by showing that 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 $\sigma_1:F(\alpha')\to F(x)/(f(x))$ maps α' to $\overline{x}=x+(f(x))$, and maps $a\in F$ on $\overline{a}=a+(f(x))$. 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 $\sigma_2 : F(\alpha) \to F(x)/(f(x))$ maps α to $\overline{x} = x + (f(x))$, and maps $a \in F$ on $\overline{a} = a + (f(x))$.

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

We can now use the isomorphism σ to induce a map

$$\overline{\sigma} \left\{ \begin{array}{ccc} P^n(E) & \to & P^n(E') \\ [\alpha_0, \ldots, \alpha_n] & \mapsto & [\sigma(\alpha_0), \ldots, \sigma(\alpha_n)]. \end{array} \right.$$

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

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

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

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

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

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

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

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

Conversely,

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

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

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

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

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

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

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 le 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 $A \to F_s$ defined by $(\alpha_0, \alpha_1, \alpha_2, \alpha_3) \mapsto \alpha_3$ 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

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

  satisfy $u \circ v = \mathrm{id}, v \circ u = \mathrm{id}$, 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 $\mathbb{C}[[u]]$

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

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 wether* 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 $f(x_0, \dots, x_n) = a_0 x_0^2 + \cdots + a_n x_n^2 \in F[x_0, \dots, x_n]$.

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

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
$$N(a_0x_0^2 + \cdots + a_nx_n^2 = 0) = q^n,$$
and the number of projective points on the hypersurface is given by
$$N_1 = \frac{q^n - 1}{q - 1} = q^{n-1} + \cdots + q + 1.$$

- 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
$$N(a_0x_0^2 + \cdots + a_nx_n^2 = 0) = q^n + \chi(a_0)^{-1} \cdots \chi(a_n)^{-1} \frac{q-1}{q} g(\chi)^{n_1},$$
  and
$$N_1 = q^{n-1} + \cdots + q + 1 + \frac{1}{q}\chi(a_0)^{-1} \cdots \chi(a_n)^{-1} g(\chi)^{n+1}.$$

To conclude this first part,
$$\begin{array}{ll} N_1 = q^{n-1} + \cdots + q + 1 & \text{if } n \text{ is even,}\\ N_1 = q^{n-1} + \cdots + q + 1 + \frac{1}{q}\chi(a_0)^{-1} \cdots \chi(a_n)^{-1} g(\chi)^{n+1} & \text{if } n \text{ is odd.}\end{array}$$

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

(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

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

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

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

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

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

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 $n \equiv 1 \ (2), q \equiv +1 \ (4)$, 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

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

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.

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

□