

# Volunteer Exercise

## 1. Toy model for Index theorem

### 1.1 Index theorem on a point

First let us consider the index theorem in the simplest setting, namely on a point. Since a vector bundle over a point is just a vector space, we consider an index of a linear map. Let  $A : \mathbb{R}^r \rightarrow \mathbb{R}^s$  be a linear map (a  $r \times s$  matrix). Compute

$$\dim \text{Ker} A - \dim \text{Coker} A .$$

### 1.2 Index theorem on $\mathbb{R}$

Next, we consider the index theorem on  $\mathbb{R}$ . More explicitly, we consider solutions of ordinary differential equations

$$D = \frac{d}{dx} + A(x) , \quad D^* = -\frac{d}{dx} + A(x)$$

where  $A$  takes the value of symmetric matrices. We require solutions to converge to zero at infinity. For  $f, g \in C^\infty(\mathbb{R})$  which decay at infinity, it is easy to see

$$\int_{-\infty}^{\infty} (Df, g) dx = \int_{-\infty}^{\infty} (f, D^*g) dx$$

where we use the fact that  $A$  is a symmetric matrix. Therefore,  $D^*$  is the adjoint operator of  $D$ .

Let  $A : \mathbb{R} \rightarrow \text{Sym}(r, \mathbb{R})$  be a function taking its value on  $r \times r$  symmetric matrices  $\text{Sym}(r, \mathbb{R})$ , and for sufficiently large  $R$ , it is subject to

$$A(x) = \begin{cases} A_- & (x \leq -R) \\ A_+ & (x \geq R) \end{cases}$$

for some matrices  $A_-$  and  $A_+$ . We consider the following ordinary differential equations for vector valued functions  $f(x), g(x)$  i.e.,  $f, g : \mathbb{R} \rightarrow \mathbb{R}^r$ :

$$Df(x) = f'(x) + A(x)f(x) = 0 , \tag{1}$$

$$D^*g(x) = -g'(x) + A(x)g(x) = 0 . \tag{2}$$

Show that these equations are linear. Namely, if  $\alpha(x)$  and  $\beta(x)$  are solutions of the equation, then  $p\alpha(x) + q\beta(x)$  is also a solution for  $p, q \in \mathbb{R}$ . In other words, the space of solutions is a linear space.

For any initial value  $f(x_0), g(x_0)$  for a fixed point  $x_0 \in \mathbb{R}$ , the theory of ordinary differential equations tells us that the solution exists uniquely. Namely,

$$f(x) = P \exp \left( - \int_{x_0}^x A(\tilde{x}) d\tilde{x} \right) \cdot f(x_0) ,$$
$$g(x) = P \exp \left( \int_{x_0}^x A(\tilde{x}) d\tilde{x} \right) \cdot g(x_0) ,$$

where  $P$  represents the ordered integral. As a result, solutions are determined by an initial value and the space of solutions is therefore an  $r$ -dimensional vector space. We denote the spaces of solutions to (1) and (2) by  $E$  and  $F$ , respectively. For  $f \in E$  and  $g \in F$ , show that its inner product is independent of a position  $x \in \mathbb{R}$ :

$$\frac{d}{dx}(f(x), g(x)) = 0 .$$

Therefore, one can consider  $E$  and  $F$  are dual to each other, i.e.  $E^* = F$ .

We, however, restrict ourselves to solutions which decay at infinity. We write the space of such solutions

$$\begin{aligned} E \supset E_0 &:= \{f(x) | f'(x) + A(x)f(x) = 0, \lim_{x \rightarrow \pm\infty} f(x) = 0\} . \\ F \supset F_0 &:= \{g(x) | -g'(x) + A(x)g(x) = 0, \lim_{x \rightarrow \pm\infty} g(x) = 0\} , \end{aligned}$$

Changing the function  $A(x)$  on a compact interval  $-R \leq x \leq R$ , the dimensions of  $E_0$  and  $F_0$  may vary. A remarkable fact is that the difference between the dimensions of  $E_0$  and  $F_0$  does not change, even though  $A(x)$  varies. Let us see this more precisely by assuming that eigenvalues of  $A_{\pm}$  do not contain zeros.

Suppose that  $A_{\pm}$  has an eigenvalue  $\lambda$  for an eigenvector  $v$ . Then, the solution to (1) and (2) has asymptotic

$$f(x) = e^{-\lambda x} v, \quad g(x) = e^{\lambda x} v \quad \text{for } x \geq R .$$

Whether or not the solution converge to zero as  $x \rightarrow \pm\infty$  is dependent of the sign of the eigenvalue  $\lambda$ .

Let us define  $E_{\pm}$  be the solution which converges to zero as  $x \rightarrow \pm\infty$ . Then, show that  $E_0 = E_+ \cap E_-$ . In addition, using the fact that  $F = E^*$  is dual to  $E$ , show that  $F_0 = E_+^{\perp} \cap E_-^{\perp}$ . Thus, show that

$$\dim E_0 - \dim F_0 = \dim E_+ + \dim E_- - r .$$

Consequently, show that the index theorem on  $\mathbb{R}$  is

$$\dim E_0 - \dim F_0 = \frac{1}{2}(\text{sign}(A_-) - \text{sign}(A_+)) ,$$

where  $\text{sign}(B)$  for a square matrix  $B$  denotes the number of positive eigenvalues of  $B$  subtracted by the number of negative eigenvalues. This is the index theorem on  $\mathbb{R}$ , which captures the essential points of supersymmetric quantum mechanics. (Although the supersymmetric quantum mechanics in the lecture note corresponds to the case of  $r = 1$ , we can generalize it to an arbitrary  $r$ .)

## 2. Superfield formalism

In the lecture, I introduce to supersymmetric quantum mechanics. In this exercise, we will formulate it in a more concise way.

Let us write fermionic creation and annihilation operators as follows:

$$\bar{\psi} = \sigma_+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad \psi = \sigma_- = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \quad [\bar{\psi}, \psi] = \sigma_3.$$

Then, the Hamiltonian can be written as

$$H = \frac{1}{2}p^2 + \frac{1}{2}W'(x)^2 - \frac{1}{2}[\psi, \bar{\psi}]W''(x),$$

Show that the action can be written as

$$S = \int dt \left[ \frac{1}{2}\dot{x}^2 + i\bar{\psi}\partial_t\psi - \frac{1}{2}W'(x)^2 + \frac{1}{2}[\psi, \bar{\psi}]W''(x) \right]. \quad (3)$$

Then, show that the action is invariant under the supersymmetric transformation

$$\begin{aligned} \delta x &= \bar{\epsilon}\psi + \bar{\psi}\epsilon, \\ \delta\bar{\psi} &= \bar{\epsilon}(i\partial_t x - W'(x)), \\ \delta\psi &= -\epsilon(i\partial_t x + W'(x)), \end{aligned}$$

where  $\epsilon$  and  $\bar{\epsilon}$  are two infinitesimal anti-commuting parameters.

Let us show that the action (3) can be obtained by using superfield formalism. Superfields are defined on the space  $(x; \theta, \bar{\theta})$  where  $x$  is the space coordinate and  $\theta, \bar{\theta}$  are Grassmann variables subject to

$$\{\theta, \bar{\theta}\} = \{\theta, \theta\} = \{\bar{\theta}, \bar{\theta}\} = 0.$$

Let us define the following superfield

$$\Phi(x, \theta, \bar{\theta}) = x + i\theta\psi - i\bar{\psi}\bar{\theta} + \theta\bar{\theta}D,$$

where  $D$  is introduced as an auxiliary field. Acting the following derivative on it

$$D_\theta = \partial_\theta - i\bar{\theta}\partial_t,$$

show that

$$D_\theta\Phi = i\psi - \bar{\theta}D - i\bar{\theta}\dot{x} + \bar{\theta}\theta\dot{\psi}.$$

Similarly, show that

$$D_{\bar{\theta}}\bar{\Phi} = -i\bar{\psi} - \theta D + i\theta\dot{x} + \bar{\theta}\theta\dot{\bar{\psi}},$$

where  $D_{\bar{\theta}} = \partial_{\bar{\theta}} - i\theta\partial_t$ . Then, one can write the action in the superspace

$$S = \int dt d\bar{\theta} d\theta \left( \frac{1}{2}|D_\theta\Phi|^2 - W(\Phi) \right).$$

Using the rule of the Grassmann integral

$$\int \theta d\theta = \int \bar{\theta} d\bar{\theta} = 1, \quad \int d\theta = \int d\theta^* = 0,$$

show that the action is indeed equal to

$$S = \int dt \left[ \frac{1}{2}\dot{x}^2 + \bar{\psi}[\partial_t - W''(x)]\psi + \frac{1}{2}D^2 + DW'(x) \right].$$

By substituting the equation of motion  $D = W'(x)$ , we obtain the previous action (3)

$$S = \int dt \left[ \frac{1}{2}\dot{x}^2 + \bar{\psi}[\partial_t - W''(x)]\psi - \frac{1}{2}W'(x)^2 \right].$$