

1 Local Transformation

$$\delta A_\mu^a = \partial_\mu \lambda^a(x) + f_{bc}^a A_\mu^b \lambda^c(x), \quad (1)$$

Here f_{abc} is the totally anti-symmetric structure constant for a semi-simple Lie algebra \mathfrak{g} , with generators $\{T_a\}_a$ and normalized Killing form δ_{ab} .

- The field strength is defined as follows:

$$\begin{aligned} F_{\mu\nu} &\equiv F_{\mu\nu}^a T_a = [D_\mu, D_\nu] = [\partial_\mu + A_\mu, \partial_\nu + A_\nu] \\ &= dA + A \wedge A \\ &= \partial_\mu A_\nu - \partial_\nu A_\mu + f_{bc}^a A_\mu^b A_\nu^c T_a \end{aligned} \quad (2)$$

Adjoint indices a, b, \dots are sometimes suppressed by contracting with T_a 's. By exploiting the anti-symmetric property of f_{bc}^a , along with the Jacobi identity, we get the infinitesimal transformation:

$$\begin{aligned} \delta F_{\mu\nu}^a &= \partial_\mu \delta A_\nu^a - \partial_\nu \delta A_\mu^a + f_{bc}^a \delta(A_\mu^b A_\nu^c) \\ &= f_{bc}^a \left(\lambda^c (\partial_\mu A_\nu^b - \partial_\nu A_\mu^b) + (A_\nu^b \partial_\mu \lambda^c - A_\mu^b \partial_\nu \lambda^c) + \delta(A_\mu^b A_\nu^c) \right) \\ &= f_{bc}^a \left(\lambda^c (F_{\mu\nu}^b - f_{de}^b A_\mu^d A_\nu^e) + (A_\nu^b (\delta A_\mu^c - f_{de}^c A_\mu^d \lambda^e) - A_\mu^b (\delta A_\nu^c - f_{de}^c A_\nu^d \lambda^e)) + \delta(A_\mu^b A_\nu^c) \right) \\ &= f_{bc}^a \left(\lambda^c (F_{\mu\nu}^b - f_{de}^b A_\mu^d A_\nu^e) - (f_{de}^c A_\nu^b A_\mu^d \lambda^e - f_{de}^c A_\mu^b A_\nu^d \lambda^e) \right) \\ &= f_{bc}^a \left(\lambda^c (F_{\mu\nu}^b - f_{de}^b A_\mu^d A_\nu^e) - (f_{de}^c A_\nu^b A_\mu^d \lambda^e - f_{de}^c A_\mu^b A_\nu^d \lambda^e) \right) \\ &= f_{bc}^a \lambda^c F_{\mu\nu}^b \end{aligned} \quad (3)$$

When contracted with T_a , this yields:

$$\delta F_{\mu\nu} = \lambda^c F_{\mu\nu}^b f_{bc}^a T_a = \lambda^c F_{\mu\nu}^b [T_b, T_c] = F_{\mu\nu} \cdot \lambda - \lambda \cdot F_{\mu\nu}, \quad (4)$$

$$\lambda = \lambda^c(x) T_c, \quad F_{\mu\nu} = F_{\mu\nu}^b T_b, \quad (5)$$

$$F_{\mu\nu} \longmapsto e^{-\Lambda^a(x) T_a} F_{\mu\nu} e^{\Lambda^a(x) T_a} \quad (6)$$

The exponentiation is valid even for local $\lambda = \lambda(x)$, since it is produced by integrating along the fiber direction $\lambda \rightarrow \Lambda$, not the spacetime direction x . This is the finite transformation w.r.t. $\Lambda(x)$.

- For any matter field ψ furnishing a representation of \mathfrak{g} , we have:

$$T_a \psi = (T_a)^i_j \psi^j, \quad \delta \psi = -\lambda^a(x) T_a \psi, \quad (7)$$

$$\psi \longmapsto e^{-\Lambda^a(x) T_a} \psi, \quad (8)$$

$$D_\mu \psi \longmapsto e^{-\Lambda^a(x) T_a} D_\mu \psi, \quad (9)$$

In fact, (1) is chosen to ensure that $D_\mu \psi$ transforms gauge covariantly just like ψ . Therefore,

$$\begin{aligned} D_\mu = \partial_\mu + A_\mu &\longmapsto e^{-\Lambda^a(x) T_a} \circ D_\mu \circ e^{\Lambda^a(x) T_a} \\ &= e^{-\Lambda} \circ (\partial_\mu + A_\mu) \circ e^\Lambda \\ &= e^{-\Lambda} \circ \partial_\mu \circ e^\Lambda + e^{-\Lambda} A_\mu e^\Lambda, \quad \Lambda = \Lambda^a(x) T_a, \end{aligned} \quad (10)$$

$$A_\mu \longmapsto e^{-\Lambda} (\partial_\mu e^\Lambda) + e^{-\Lambda} A_\mu e^\Lambda = T_a \partial_\mu \Lambda^a(x) + e^{-\Lambda} A_\mu e^\Lambda \quad (11)$$

- $F^2 \equiv F \wedge F$, we have:

$$\begin{aligned} F^2 &= (dA + A \wedge A) \wedge (dA + A \wedge A) \\ &= dA \wedge dA + dA \wedge A \wedge A + A \wedge A \wedge dA + A \wedge A \wedge A \wedge A \end{aligned} \quad (12)$$

The last term is proportional to $\epsilon_{abcd} T^a T^b T^c T^d$, hence its trace will vanish; therefore,

$$\begin{aligned} \text{tr } F^2 &= \text{tr } (dA \wedge dA + dA \wedge A \wedge A + A \wedge A \wedge dA) \\ &= \text{tr } \left(d(dA \wedge A) + \frac{2}{3} d(A \wedge A \wedge A) \right) \end{aligned} \quad (13)$$

$$\begin{aligned} &= d \text{tr } \left(dA \wedge A + \frac{2}{3} A \wedge A \wedge A \right) = d\omega, \\ \omega &= \text{tr } \left(dA \wedge A + \frac{2}{3} A \wedge A \wedge A \right) \end{aligned} \quad (14)$$

■

2 Relativistic Particle

$$L = \frac{1}{2e} \left(\frac{1}{c} \frac{dX}{dt} \right)^2 - \frac{e}{2} m^2 c^4 \quad (15)$$

- For $t \mapsto t' = t - \xi(t)$, we have $X'(t') = X(t)$, therefore:

$$\delta X^\mu = -\delta t \frac{dX^\mu}{dt} = \xi(t) \dot{X}^\mu, \quad (16)$$

Or more explicitly, $X^\mu(t) \mapsto X^\mu(t) + \xi(t) \dot{X}^\mu$.

- We have:

$$\begin{aligned} \delta L &= \frac{1}{ec^2} \dot{X}_\mu \delta \dot{X}^\mu - \frac{\delta e}{2} \frac{1}{e^2 c^2} \dot{X}^2 - \frac{\delta e}{2} m^2 c^4 \\ &= \frac{1}{ec^2} \xi \dot{X}_\mu \ddot{X}^\mu + \frac{1}{ec^2} \dot{\xi} \dot{X}^2 - \frac{\delta e}{2} \frac{1}{e^2 c^2} \dot{X}^2 - \frac{\delta e}{2} m^2 c^4 \end{aligned} \quad (17)$$

For $S = \int dt L$ to be invariant, δL should be reduced to a total derivative, which can then be reduced to some vanishing boundary terms.

Consider $\delta e = \frac{d}{dt}(e\xi) = \dot{e}\xi + e\dot{\xi}$, and we have:

$$\begin{aligned} \delta L &= \frac{1}{ec^2} \xi \dot{X}_\mu \ddot{X}^\mu + \frac{1}{2ec^2} \dot{\xi} \dot{X}^2 - \frac{\dot{e}}{2e^2 c^2} \xi \dot{X}^2 - \frac{d}{dt} \left(\frac{1}{2} e \xi m^2 c^4 \right) \\ &= \frac{d}{dt} \left\{ \left(\frac{1}{2ec^2} \dot{X}^2 - \frac{e}{2} m^2 c^4 \right) \xi \right\} = \frac{d}{dt} (\xi L) \end{aligned} \quad (18)$$

Indeed we get a total derivative; therefore,

$$\delta e = \frac{d}{dt}(e\xi), \quad \delta S = \int \delta L = \int d(\xi L) = 0 \quad (19)$$

- $e(t)$ can be seen as a gauge field coupled to X , which captures the t -reparametrization redundancy through the gauge transformation parameter $\xi(t)$. A natural gauge choice is fixing $f = e(t) - 1 \equiv 0$, which is equivalent to setting $t = \tau$: the proper time, or affine parametrization for the massless case.

The gauge invariant path integral is constructed as follows:

$$\begin{aligned}
\mathcal{Z} &= \frac{1}{\int \mathcal{D}\xi} \int \mathcal{D}X \mathcal{D}e e^{iS} \\
&= \frac{1}{\int \mathcal{D}\xi} \int \mathcal{D}X \mathcal{D}e e^{iS} \int \mathcal{D}f \delta[f] \\
&= \frac{1}{\int \mathcal{D}\xi} \int \mathcal{D}X \mathcal{D}e e^{iS} \int \mathcal{D}\xi \delta[f_\xi] \det \frac{\delta f_\xi}{\delta \xi} \\
&= \frac{1}{\int \mathcal{D}\xi} \int \mathcal{D}\xi \int \mathcal{D}X \mathcal{D}e e^{iS} \delta[f_\xi] \det \frac{\delta f_\xi}{\delta \xi} \\
&= \frac{1}{\int \mathcal{D}\xi} \int \mathcal{D}\xi \int \mathcal{D}X_\xi \mathcal{D}e_\xi e^{iS_\xi} \delta[f_\xi] \det \frac{\delta f_\xi}{\delta \xi} \Big|_{e_\xi} \\
&= \frac{1}{\int \mathcal{D}\xi} \int \mathcal{D}\xi \int \mathcal{D}X \mathcal{D}e e^{iS} \delta[f] \det \frac{\delta f_\xi}{\delta \xi} \Big|_{\xi=0} \\
&= \int \mathcal{D}X \mathcal{D}e e^{iS} \delta[f] \det \frac{\delta f_\xi}{\delta \xi} \Big|_{\xi=0}
\end{aligned} \tag{20}$$

Here the gauge-transformed quantities are marked with a ξ subscript. Note that in the final expression, f is *not* integrated out and can be *any* possible gauge-fixing function, i.e. $\left(\delta[f] \det \frac{\delta f_\xi}{\delta \xi}\right)_{\xi=0}$ is in fact f -independent.

These are the first steps of the Faddeev–Popov (FP) procedure; it achieves several things at once: first it imposes a gauge-fixing $f = 0$, and then it removes the gauge redundancy with the help of FP determinant $(\det \frac{\delta f_\xi}{\delta \xi})_{\xi=0}$, while implicitly imposing the constraints resulted from the gauge-fixing process. The constraints implemented by $(\det \frac{\delta f_\xi}{\delta \xi})_{\xi=0}$ can be made explicit with the help of BRST formalism.

The gauge-fixing term $\delta[f]$ can be replaced by a Gaussian packet with width parameter ζ . More rigorously, up to an overall constant coefficient, we have the following equivalence:

$$\delta[f] \sim \delta[f - f_0] \sim \int \mathcal{D}f_0 \exp\left(-\frac{i}{2\zeta} \int dt f_0^2\right) \delta[f - f_0] = \exp\left(i \int dt L_{gf}\right), \tag{21}$$

$$L_{gf} = -\frac{1}{2\zeta} f^2 = -\frac{1}{2\zeta} (e - 1)^2, \tag{22}$$

Here f_0 is some gauge-invariant shift of f , namely $(f_0)_\xi = f_0$. f_0 can be seen as a non-dynamical auxiliary field that enforce the gauge fixing, much similar to a Lagrange multiplier. On the other hand, the determinant can be evaluated using Faddeev–Popov (FP) ghosts b, c :

$$\det P \sim \int \mathcal{D}b \mathcal{D}c \exp\left(i \int dt \int dt' b(t) \cdot P(t, t') \cdot c(t')\right), \tag{23}$$

$$\frac{\delta f_\xi(t)}{\delta \xi(t')} \Big|_{\xi=0} = \frac{\delta}{\delta \xi(t')} \Big|_{\xi=0} \left(e + \frac{d}{dt}(e\xi) - 1\right)_{(t)} = \frac{d}{dt}(e(t) \delta(t - t')), \tag{24}$$

$$\begin{aligned}
\det \frac{\delta f_\xi(t)}{\delta \xi(t')} \Big|_{\xi=0} &\sim \int \mathcal{D}b \mathcal{D}c \exp\left(i \int dt \int dt' b(t) (e(t) \delta(t - t')) c(t')\right) \\
&\sim \int \mathcal{D}b \mathcal{D}c \exp\left(-i \int dt e \dot{b} c\right),
\end{aligned} \tag{25}$$

$$L_{gh} = -e \dot{b} c \tag{26}$$

In summary, we have:

$$\mathcal{Z} = \int \mathcal{D}X \mathcal{D}e \mathcal{D}b \mathcal{D}c e^{iS_q}, \quad S_q = \int dt L_q, \quad (27)$$

$$L_q = L + L_{gf} + L_{gh} = L - \frac{1}{2\zeta} (e-1)^2 - e\dot{b}c, \quad (28)$$

S_q is the quantum action under the gauge-fixing condition $f = e(t) - 1 = 0$. ■

3 2D σ -Model

$$\mathcal{L} = -\frac{1}{2} \partial_\alpha X^\mu \partial_\beta X_\mu \sqrt{-h} h^{\alpha\beta}, \quad X: \Sigma^{1,1} \rightarrow \mathbb{R}^{D-1,1} \quad (29)$$

- The action is diff-invariant; under $\sigma^\alpha \mapsto \sigma^\alpha + \xi^\alpha$, we have:

$$\delta X^\alpha = \mathcal{L}_\xi X^\alpha, \quad \delta h^{\alpha\beta} = \mathcal{L}_\xi h^{\alpha\beta} \quad (30)$$

\mathcal{L}_ξ is the Lie derivative along ξ^α . Note that $0 = \delta(h_{\alpha\beta} h^{\beta\gamma})$, hence we have:

$$\delta h_{\alpha\beta} = -h_{\alpha\alpha'} h_{\beta\beta'} \delta h^{\alpha'\beta'} = \xi^\gamma \partial_\gamma h_{\alpha\beta} + (\partial_\alpha \xi^\gamma) h_{\gamma\beta} + (\partial_\beta \xi^\gamma) h_{\alpha\gamma} = \mathcal{L}_\xi h_{\alpha\beta}, \quad (31)$$

$$\delta \sqrt{-h} = \frac{1}{2} \sqrt{-h} h^{\alpha\beta} \delta h_{\alpha\beta}, \quad (32)$$

Furthermore, we have $\mathcal{L}_\xi dX = d(\mathcal{L}_\xi X)$, i.e. $\partial_\alpha \delta X = \partial_\alpha \mathcal{L}_\xi X = \partial_\alpha (\xi^\gamma \partial_\gamma X) = \mathcal{L}_\xi (\partial_\alpha X)$. Note that due to the $\sqrt{-h}$ factor, \mathcal{L} is not a scalar but a *scalar density*. For convenience, define $\mathcal{L} = \tilde{\mathcal{L}} \sqrt{-h}$, then $\tilde{\mathcal{L}} = -\frac{1}{2} h^{\alpha\beta} \partial_\alpha X^\mu \partial_\beta X_\mu$ is a scalar; using chain rule, we obtain:

$$\begin{aligned} \delta \mathcal{L} &= \sqrt{-h} \delta \tilde{\mathcal{L}} + \tilde{\mathcal{L}} \delta \sqrt{-h} \\ &= \sqrt{-h} \mathcal{L}_\xi \tilde{\mathcal{L}} + \tilde{\mathcal{L}} \delta \sqrt{-h} \\ &= \sqrt{-h} \xi^\gamma \partial_\gamma \tilde{\mathcal{L}} + \tilde{\mathcal{L}} \delta \sqrt{-h} \\ &= \partial_\gamma (\xi^\gamma \tilde{\mathcal{L}} \sqrt{-h}) - \tilde{\mathcal{L}} (\sqrt{-h} (\partial_\gamma \xi^\gamma) + \xi^\gamma (\partial_\gamma \sqrt{-h})) + \tilde{\mathcal{L}} \delta \sqrt{-h} \\ &= \partial_\gamma (\xi^\gamma \mathcal{L}) - \tilde{\mathcal{L}} (\sqrt{-h} (\partial_\gamma \xi^\gamma) + \xi^\gamma (\partial_\gamma \sqrt{-h}) - \delta \sqrt{-h}) \\ &= \partial_\gamma (\xi^\gamma \mathcal{L}) - \tilde{\mathcal{L}} \sqrt{-h} \left(\partial_\gamma \xi^\gamma + \frac{1}{2} \xi^\gamma h^{\alpha\beta} \partial_\gamma h_{\alpha\beta} - \frac{1}{2} h^{\alpha\beta} \delta h_{\alpha\beta} \right) \\ &= \partial_\gamma (\xi^\gamma \mathcal{L}) - \tilde{\mathcal{L}} \sqrt{-h} \left(\partial_\gamma \xi^\gamma - \frac{1}{2} h^{\alpha\beta} ((\partial_\alpha \xi^\gamma) h_{\gamma\beta} + (\partial_\beta \xi^\gamma) h_{\alpha\gamma}) \right) \\ &= \partial_\gamma (\xi^\gamma \mathcal{L}) - \tilde{\mathcal{L}} \sqrt{-h} (\partial_\gamma \xi^\gamma - \partial_\gamma \xi^\gamma) \\ &= \partial_\gamma (\xi^\gamma \mathcal{L}) \end{aligned} \quad (33)$$

We see that $\delta \mathcal{L}$ is a total derivative, hence $\delta S = \int d^2\sigma \delta \mathcal{L} = 0$, i.e. the action is diff-invariant.

- The action is Weyl invariant; with $\delta h^{\alpha\beta} = -\lambda(\sigma) h^{\alpha\beta}$, we have:

$$\begin{aligned}
\delta(\sqrt{-h} h^{\alpha\beta}) &= \sqrt{-h} \delta h^{\alpha\beta} + h^{\alpha\beta} \delta\sqrt{-h} \\
&= \sqrt{-h} h^{\alpha\beta} \left(-\lambda - \frac{1}{2} h_{\alpha'\beta'} \delta h^{\alpha'\beta'} \right) \\
&= \sqrt{-h} h^{\alpha\beta} \left(-\lambda + \frac{1}{2} \lambda h_{\alpha'\beta'} h^{\alpha'\beta'} \right) \\
&= \sqrt{-h} h^{\alpha\beta} \left(-\lambda + \frac{2}{2} \lambda \right) \\
&= 0
\end{aligned} \tag{34}$$

Here we've used the fact that $h_{\alpha\beta} h^{\alpha\beta} = \delta_\alpha^\alpha = 2$. Therefore, $\delta\mathcal{L} = -\frac{1}{2} \partial_\alpha X^\mu \partial_\beta X_\mu \delta(\sqrt{-h} h^{\alpha\beta}) = 0$, i.e. the action is Weyl invariant.

- FP quantization of this system follows the same recipe as the point particle case above:

$$\mathcal{Z} = \int \mathcal{D}X \mathcal{D}h \mathcal{D}b \mathcal{D}c e^{iS_q}, \quad S_q = \int d^2\sigma \mathcal{L}_q, \tag{35}$$

$$\mathcal{L}_q = \mathcal{L} + \mathcal{L}_{gf} + \mathcal{L}_{gh} \tag{36}$$

Given gauge fixing: $f^{\alpha\beta} = h^{\alpha\beta} - h_{(0)}^{\alpha\beta}$, we have:

$$\mathcal{L}_{gf} = -\frac{1}{2\zeta} f^{\alpha\beta} f_{\alpha\beta} \sqrt{-h} = -\frac{1}{2\zeta} \left(h^{\alpha\beta} - h_{(0)}^{\alpha\beta} \right) \left(h_{\alpha\beta} - h_{\alpha\beta}^{(0)} \right) \sqrt{-h} \tag{37}$$

The FP ghost term \mathcal{L}_{gh} is given by functional determinant; we have:

$$\left. \frac{\delta f_\xi^{\alpha\beta}(\sigma)}{\delta \xi^\gamma(\sigma')} \right|_0 = \left. \frac{\delta}{\delta \xi^\gamma(\sigma')} \right|_0 (\mathcal{L}_\xi h^{\alpha\beta} - \lambda h^{\alpha\beta})_{(\sigma)} \tag{38}$$

$$= \delta(\sigma - \sigma') \partial_\gamma h^{\alpha\beta} - \delta_\gamma^\alpha \partial^\beta \delta(\sigma - \sigma') - \delta_\gamma^\beta \partial^\alpha \delta(\sigma - \sigma') \tag{39}$$

$$= -\delta_\gamma^\alpha \nabla^\beta \delta(\sigma - \sigma') - \delta_\gamma^\beta \nabla^\alpha \delta(\sigma - \sigma'), \tag{40}$$

$$\left. \frac{\delta f_\xi^{\alpha\beta}(\sigma)}{\delta \lambda(\sigma')} \right|_0 = -\delta(\sigma - \sigma') h^{\alpha\beta}, \tag{41}$$

Here we've replaced ∂ with ∇ which commutes with the metric $h_{\alpha\beta}$. Define $\Xi^\Gamma = (\xi^\gamma, \lambda)$ to combine all gauge parameters, and use fermionic FP ghosts: $b_{\alpha\beta}$, $c^\Gamma = (c^\gamma, c')$ to contract the indices; after some integration by parts, we have:

$$\det \frac{\delta f_\xi^{\alpha\beta}(\sigma)}{\delta \Xi^\Gamma(\sigma')} \Big|_0 \sim \int \mathcal{D}b_{\alpha\beta} \mathcal{D}c^\gamma \mathcal{D}c' \exp \left(i \int d^2\sigma \sqrt{-h} b_{\alpha\beta} \left(-\nabla^\beta c^\alpha - \nabla^\alpha c^\beta - h^{\alpha\beta} c' \right) \right) \tag{42}$$

To simplify the action, it is common¹ to integrate c' out, which constrains $b_{\alpha\beta}$ to be symmetric traceless: $b_{\alpha\beta} h^{\alpha\beta} = b_\alpha^\alpha = 0$. The resulting $b_{\alpha\beta}$ has 2 degrees of freedom, same as c^γ .

¹ References: Tong: <http://damtp.cam.ac.uk/user/tong/string.html>, and also Polchinski.

In the end, we have:

$$\det \frac{\delta f_{\xi}^{\alpha\beta}(\sigma)}{\delta \Xi^{\Gamma}(\sigma')} \Big|_0 \sim \int \mathcal{D}b_{\alpha\beta} \mathcal{D}c^{\gamma} \exp \left(-2i \int d^2\sigma \sqrt{-h} b_{\alpha\beta} \nabla^{\alpha} c^{\beta} \right) \quad (43)$$

Therefore, FP quantization with $f^{\alpha\beta} = h^{\alpha\beta} - h_{(0)}^{\alpha\beta}$ yields:

$$\mathcal{Z} = \int \mathcal{D}X \mathcal{D}h^{\alpha\beta} \mathcal{D}b_{\alpha\beta} \mathcal{D}c^{\gamma} e^{iS_q}, \quad S_q = \int d^2\sigma \mathcal{L}_q, \quad \mathcal{L}_q = \mathcal{L} + \mathcal{L}_{gf} + \mathcal{L}_{gh}, \quad (44)$$

$$\mathcal{L}_{gf} = -\frac{1}{2\zeta} f^{\alpha\beta} f_{\alpha\beta} \sqrt{-h} = -\frac{1}{2\zeta} \left(h^{\alpha\beta} - h_{(0)}^{\alpha\beta} \right) \left(h_{\alpha\beta} - h_{\alpha\beta}^{(0)} \right) \sqrt{-h}, \quad (45)$$

$$\mathcal{L}_{gh} = -2b_{\alpha\beta} \nabla^{\alpha} c^{\beta} \sqrt{-h} \quad (46)$$

■