

Quantum Field Theory

Lectured by Prof. Si Li and Noted by Xinyu Xiang

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Warning: Lots of possible typos!!!!!!!!!!!!!! **Notations:**

- X : a smooth manifold, usually a compact manifold.
- \mathcal{E} : the space of fields, usually infinite dimensional.
- $\text{Conn}(P, X)$: the space of connections on a principal bundle P over X .
- $\text{Maps}(\Sigma, X)$: the space of maps from Σ to X .
- $\Omega^\bullet(X)$: the space of differential forms on X .
- $\Omega_c^\bullet(X)$: the space of differential forms with compact support on X .
- $\text{Vect}(M)$: the space of smooth vector fields on a manifold M , which is Lie algebra of $\text{Diff}(M)$.

1 Day I: Overall Discussion and Mathematical Preliminaries

1.1 Actions and Path Integrals

Action $S : \mathcal{E} \rightarrow \mathbf{k}$ where \mathcal{E} always has infinite dimension, and \mathbf{k} is a field (usually \mathbb{R} or \mathbb{C}).

QM in Imaginary Time $\xrightarrow{\text{Brownian Motion}}$ Wiener Measure on Phase Space

Asymptotic Analysis \longrightarrow Perturbative Renormalisation Theory

Example 1.1. *Some Examples of Classical Field Theories*

- (a) *Scalar Field Theory* $\mathcal{E} = C^\infty(X)$
- (b) *Gauge Theory* $\mathcal{E} = \text{Conn}(P, X)$
- (c) *σ Model* $\mathcal{E} = \text{Maps}(\Sigma, X)$
- (d) *Gravity* $\mathcal{E} = \text{Metrics}(X)$ (More better descriptions does not depends on the background)

1.2 Observables

Observables are functions on the space of fields, i.e. $\mathcal{O} \in C^\infty(\mathcal{E})$.

Example 1.2 (field theory). (a) Consider $X = \text{pt}$, thus $\mathcal{E} = \mathbb{R}^n$ for example.

(b) $\dim X > 0$, the new algebraic structure arise from topological structures of X .

The Key Point is: Capture the data of open sets of $X \rightarrow$ Consider the observables supported on open set U of X denoted by $\text{Obs}(U)$ where U is an open set of X .

Local data captures the open sets of X . The relations between open sets captures the global data of $X \rightarrow$ The algebraic structure of the observables is a sheaf of X .

$$\bigsqcup_i U_i \longrightarrow \bigotimes_i \text{Obs}(U_i)$$

Which implies OPE in physics and factorization algebra in mathematics.

Higher product in QFT: The generalization of products of algebra ('products in any direction instead of left and right') e.g. QM gives only left and right module of an algebra; OPE has products in various directions.

Consider the $\dim X = 2$ case in detailed

Example 1.3 (Holomorphic/Chiral Field Theory). Various angle of product $A(w)B(z)$ could be denoted by the time of $A(w)$ rotations around $B(z)$, which could be captured by the Fourier mode of $A(w)$, thus one can have

$$A(w)B(z) = \sum_{m \in \mathbb{Z}} \frac{(A_{(m)}B(z))}{(z-w)^{m+1}}$$

which is the Chiral algebra due to Beilinson and Drinfeld and associated with the Doublt cohomology $H^0_{\bar{\partial}}(\Sigma^2 - \Delta) \cong \mathbb{C}((z^m))$, where Σ^2 is the complex surface and Δ is the diagonal of Σ^2 . The higher structure could be captured by the higher cohomology $H^p_{\bar{\partial}}(\Sigma^2 - \Delta)$, which is the higher chiral algebra associated to the derived holomorphic section.

1.3 de Rham Cohomology

Chain of differential forms $\Omega^\bullet(X)$

$$\Omega^\bullet(X) = \left(\dots \xrightarrow{d} \Omega^{n-1}(X) \xrightarrow{d} \Omega^n(X) \xrightarrow{d} \Omega^{n+1}(X) \xrightarrow{d} \dots \right) \quad (1.1)$$

where d is the exterior derivative, and $\Omega^n(X)$ is the space of n -forms on X . The general construction of differential forms could be constructed over open set U by

$$\Omega^n(U) = \bigoplus_{1 \leq i_1 \leq \dots \leq i_n \leq n} C^\infty(U) dx^{i_1} \wedge \dots \wedge dx^{i_n}$$

where one can prove that $d^2 = 0$ and thus $(\Omega^\bullet(U), d)$ is a cochain complex. The cohomology of it is called the de Rham cohomology $H^\bullet(X)$.

Proposition 1.1. The definition of de Rham cohomology does not depend on the choice of the open set U and the choice of the coordinate system i.e. it is intrinsic \rightarrow we can define the de Rham cochain complex on smooth manifold X .

Proof. Consider □

Definition 1.1 (de Rham Cohomology on Compact Support). Let X be a smooth manifold, then the de Rham cohomology on compact support is defined as

$$H_c^\bullet(X) = H^\bullet(\Omega_c^\bullet(X), d) \quad (1.2)$$

where $\Omega_c^\bullet(X)$ is the space of differential forms with compact support.

Theorem 1.2 (Stokes' Theorem). Let X be a smooth manifold with boundary, then for any $\omega \in \Omega^n(X)$, we have

$$\int_X d\omega = \int_{\partial X} \omega$$

which connects the local data $d\Omega^\bullet(X)$ and the global data ∂X .

Theorem 1.3 (Poincaré Lemma).

$$H^p(\mathbb{R}^n) = \begin{cases} \mathbb{R} & p = 0 \\ 0 & p > 0 \end{cases}, \quad H_c^p(\mathbb{R}^n) = \begin{cases} 0 & p < 0 \\ \mathbb{R} & p = n \end{cases}$$

Generator: $H^p(\mathbb{R}^n) \rightarrow \text{constant function}$, $H_c^p(\mathbb{R}^n) \rightarrow \text{a compact support function } \alpha = f(x)\text{vol}_n$, and $\int_{\mathbb{R}^n} \alpha = 1$.

Proof. □

Important: An *Integration* arises from the de Rham cohomology!

Observation. (1) if $\alpha = d\beta$ where $\beta \in \Omega_c^{n-1}(X)$, then $\int_X \alpha = 0$, thus the generator is α whose integral is non-zero.

(2) **Dual Site:** Integration could be captured by the cohomology

$$\int_{\mathbb{R}^n} \leftrightarrow H_c^n(\mathbb{R}^n) \cong \mathbb{R}$$

Path integral could be interpreted as the integration over \mathcal{E} , which leads to consider the cohomology of it. □

1.4 Cartan Formula

Vector fields could acts on smooth functions via

$$V(f) = V^i \frac{\partial f}{\partial x^i} = \frac{d}{dt} f(\varphi_t(x)) \Big|_{t=0} = \frac{d}{dt} \varphi_t^* f(x) \Big|_{t=0}$$

Such an action could be extended to differential forms by

$$\text{Vect}(M) \ni V : \alpha \mapsto \mathcal{L}_V \alpha = \frac{d}{dt} \varphi_t^* \alpha \Big|_{t=0}$$

which has the property $\mathcal{L}_V(\alpha \wedge \beta) = \mathcal{L}_V \alpha \wedge \beta + \alpha \wedge \mathcal{L}_V \beta$, which implies that the Lie derivative is a derivation on the algebra of differential forms with degree 0. And we have contraction ι_V which is a derivation of degree -1 on the algebra of differential forms.

$$\mathcal{L}_V = d\iota_V + \iota_V d$$

Lie derivative is homotopy trivial i.e. chain homotopic.

1.4.1 Proof of Poincaré Lemma

Use Cartan Formula, one can proof Poincaré Lemma.

Proof. Rescaling invariance of \mathbb{R}^n leads to the Euler vector field $E = x^i \frac{\partial}{\partial x^i}$. One can consider the associated diffeomorphism φ_t , where we assume $\varphi_0 = 1$ and thus $\varphi_{-\infty}^* \alpha = 0$, thus the closed form α could be rewritten as

$$\begin{aligned} \alpha &= \varphi_0^* \alpha - \varphi_{-\infty}^* \alpha \\ &= \int_{-\infty}^0 \frac{d}{dt} \varphi_t^* \alpha dt \\ &= \int_{-\infty}^0 \mathcal{L}_E(\varphi_t^* \alpha) dt \end{aligned}$$

using the Cartan formula and $d\varphi^* = \varphi^*d$, we have

$$\alpha = d \int_{-\infty}^0 \varphi_t^* \iota_E \alpha dt = d\beta,$$

thus, the closed form α is exact, which implies that the de Rham cohomology $H^p(\mathbb{R}^n)$ is trivial for $p > 0$. The same idea could be applied to the de Rham cohomology on compact support $H_c^p(\mathbb{R}^n)$. \square

2 Day II: Classical Field Theory

Assume $\mathcal{E} = \Gamma(E, X)$ i.e. a section of a bundle $E \rightarrow X$, where X is oriented manifold. And the action would be written as $S[\phi] = \int_X \mathcal{L}[\phi(x)]$ where $\phi \in \mathcal{E}$. Lagrangian \mathcal{L} satisfies:

- (a) built up by jets of ϕ (locality);
- (b) valued in n form on X (oriented).

The solution of Euler-Lagrange equation forms $\text{Crit}(S)$, which denotes the critical of the action S .

2.1 Examples

Example 2.1 (Phase Space Quantum Mechanics). Consider $X = \mathbb{R}$, then $\mathcal{E} = \mathbb{R}^{2n}$, and the action is

$$S[\phi] = \int_{\mathbb{R}^{2n}} p dq - H(q, p) dt = \int [p\dot{q} - H] dt$$

where H is the Hamiltonian. The Euler-Lagrange equation would become $dH = -\iota_{x_*} \partial \omega$, where $x : \mathbb{R} \rightarrow \mathcal{E}$.

Example 2.2 (Scalar Field Theory). Consider (X, g) a Riemann Manifold, then $\mathcal{E} = C^\infty(X)$, and the action is

$$S[\phi] = \int_X \left[\frac{1}{2} |\nabla \phi|^2 + V(\phi) \right] d\text{vol}_g$$

where $V(\phi)$ is a potential function, and $d\text{vol}_g = \sqrt{|g|} d^d x$. Assume $\partial X = \emptyset$, then the Euler-Lagrange equation is

$$\Delta \phi = \frac{\partial V}{\partial \phi}$$

where $\Delta f = \frac{1}{\sqrt{|g|}} \partial_i (\sqrt{|g|} g^{ij} \partial_j f)$.

Example 2.3 (Chern-Simons Theory). Consider X a 3-manifold and \mathfrak{g} a semi-simple Lie algebra. Denote P is a principal \mathfrak{g} -bundle over X , then the space of fields is $\mathcal{E} = \text{Conn}(P, X)$. Assume \mathfrak{g} is equipped with a non-degenerate invariant bilinear form $\langle \cdot, \cdot \rangle$ (Killing form), then the action is

$$\text{CS}[A] = \int_X \frac{1}{2} \langle A, F_A \rangle + \frac{1}{6} \langle A, [A, A] \rangle,$$

and the Euler-Lagrange equation encoded by the flat connection $F_A = 0$.

2.2 Symmetry (1)

2.2.1 Global Symmetry and Noether's Theorem

Consider a classical action $S : \mathcal{E} \rightarrow \mathbb{R}$ with a group action $G \curvearrowright \mathcal{E}$ s.t. $S[g(\phi)] = S[\phi]$. Then G would become a global symmetry of the action S .

Consider the continuous symmetry i.e. G is a Lie group, then the infinitesimal action of G on \mathcal{E} is given by a vector field $V \in \text{Vect}(\mathcal{E})$, which satisfies

$$\delta_{V^\alpha} \phi = V^\alpha(\phi),$$

thus the variation of the Lagrangian is

$$\delta_{V^\alpha} \mathcal{L} = dK_\alpha,$$

where K_α is a $n-1$ form. Furthermore, one can use the Euler-Lagrange equation and its boundary contribution to obtain

$$\delta_{V^\alpha} \mathcal{L} \xrightarrow{\text{EL}=0} d\iota_{V^\alpha} \Theta = dK_\alpha,$$

thus one have the Noether's current

$$J_\alpha = \iota_{V^\alpha} \Theta - K_\alpha, \quad dJ_\alpha + EL[\phi] V_\alpha = 0, \quad (2.1)$$

which is a $n-1$ form on X and satisfies $dJ_\alpha|_{\text{Crit}(S)} = 0$ while the Euler-Lagrangian equation is satisfied. If we consider $Y_1, Y_2 \subset X$ is codimension 1 (hyper)surface, which are homologous by Σ , then we have

$$\int_{Y_1} J_\alpha - \int_{Y_2} J_\alpha = \int_\Sigma dJ_\alpha = 0, \quad \phi \in \text{Crit}(S),$$

and the integration over J_α is independent of the choice of the hyper surface, thus we can define the Noether charge as the integration over J_α on a hyper surface Y ¹.

There is an alternative way to define the Noether current, which is more suitable for practical use. In brief, one can consider the 'gauged' symmetry which would promote ϵ to become a field $\epsilon(x)$, and the variation of the action could be computed by integrating by parts, finally one can obtain

$$\delta_{V^\alpha} S = \int_X -\epsilon(x) d\hat{J}_\alpha,$$

and \hat{J} would become the Noether current which satisfies (2.1) so that \hat{J}_α is identical to J_α up to an exact form.

3 Day III: Breaking

4 Day IV: Symmetry (2)

First, we will consider finite dimensional case. We consider G as a finite dimensional Lie group, \mathfrak{g} is the Lie algebra of G and W is finite dimensional representation of G .

4.1 Chevalley-Eilenberg Cohomology

Consider $\mathfrak{g}^* \equiv \text{Hom}(\mathfrak{g}, \mathbb{K})$. Consider the exterior algebra

$$\bigwedge \mathfrak{g}^* = \bigoplus_{p=0}^{\infty} \bigwedge^p \mathfrak{g}^*.$$

Assume the basis of \mathfrak{g} is $\{e_1, \dots, e_n\}$ and of \mathfrak{g}^* is $\{c^1, \dots, c^n\}$, which satisfies $c_\alpha c_\beta = -c_\beta c_\alpha$. Thus one shall identify the algebra above as a free object in the category of differential graded algebra, which is a ring equipped with anti-commute generators

$$\bigwedge \mathfrak{g}^* = \mathbb{K}[c^1, \dots, c^n].$$

¹In physics, one always consider the Noether current which is the Hodge dual of J_α .

Consider the Lie algebra over \mathfrak{g} , which equipped with commutator $[\cdot, \cdot] : \wedge^2 \mathfrak{g} \rightarrow \mathfrak{g}$. On the dual side, one shall introduce a differential operator $d : \mathfrak{g}^* \rightarrow \mathfrak{g}^*$, and we can extend it to the exterior algebra $\wedge \mathfrak{g}^*$ by

- (1) Under the level of generators, we have $d_{\text{CE}} : \mathfrak{g}^* \rightarrow \wedge^2 \mathfrak{g}^*$;
- (2) Using the Leibniz rule, we can extend it to the exterior algebra $\wedge \mathfrak{g}^*$ by

$$d_{\text{CE}} : a \wedge b \mapsto d_{\text{CE}} a \wedge b + (-1)^{\deg a} a \wedge d_{\text{CE}} b,$$

and thus we have a differential graded algebra $(\wedge \mathfrak{g}^*, d_{\text{CE}})$, which is called the Chevalley-Eilenberg complex.

Under the choice of basis above, we have $[e_\alpha, e_\beta] = f_{\alpha\beta}^\gamma e_\gamma$, which would lead to the derivation on the dual side

$$d_{\text{CE}} c^\alpha = \frac{1}{2} f_{\beta\gamma}^\alpha c^\beta \wedge c^\gamma \equiv \frac{1}{2} f_{\beta\gamma}^\alpha c^\beta c^\gamma.$$

Using the Leibniz rule, we can extend it to the exterior algebra $\wedge \mathfrak{g}^*$. Using the Jacobi identity, one can prove that $d_{\text{CE}}^2 = 0$ (left as exercise), thus we have a cochain complex $(\wedge \mathfrak{g}^*, d_{\text{CE}})$ which is a differential graded algebra (dga), where the generator c^α is called the 'ghost field' in physics, the degree is 'ghost number' and d_{CE} is BRST operator.

Proof. Consider d_{CE}^2 acts on c^α , the higher structure could be derived from Leibniz's rule.

$$\begin{aligned} d_{\text{CE}}^2 c^\alpha &= \frac{1}{2} f_{\beta\gamma}^\alpha \left[\frac{1}{2} f_{\rho\lambda}^\beta c^\rho c^\lambda c^\gamma - \frac{1}{2} f_{\rho\lambda}^\gamma c^\beta c^\rho c^\lambda \right] \\ &= -\frac{1}{2} f_{\gamma\beta}^\alpha f_{\rho\lambda}^\beta c^\rho c^\lambda c^\gamma \\ &= \frac{1}{12} f_{\beta[\gamma}^\alpha f_{\rho\lambda]}^\beta c^\rho c^\lambda c^\gamma \\ &= 0 \end{aligned}$$

□

Let M be a \mathfrak{g} representation where $\rho : \mathfrak{g} \rightarrow \text{End}(M)$ satisfies

$$\rho(a)\rho(b)m - \rho(b)\rho(a)m = \rho([a, b])m, \quad a, b \in \mathfrak{g}, m \in M.$$

Consider the free $\wedge^\bullet \mathfrak{g}^*$ -module generated by M :

$$\wedge^\bullet \mathfrak{g}^* \otimes M,$$

there is a natural extension of the Chevalley-Eilenberg differential d_{CE} on it, which is defined by

- (1) $d_{\text{CE}} : M \rightarrow \mathfrak{g}^* \otimes M$ is dual of $\mathfrak{g} \otimes M \xrightarrow{\rho} M$;
- (2) $d_{\text{CE}}(a \otimes m) : d_{\text{CE}}(a) \otimes m + (-1)^{|a|} a \wedge d_{\text{CE}} m$

where we can prove that $d_{\text{CE}}^2 = 0$ and thus we have a cochain complex $\wedge^\bullet \mathfrak{g}^* \otimes M$.

We denote $\wedge^p \mathfrak{g}^* \otimes M$ be $C^p(\mathfrak{g}^*, M)$, then we shall find that it is $C^p(\mathfrak{g}^*)$ -module, i.e.

$$C^p(\mathfrak{g}^*) \otimes C^q(\mathfrak{g}^*, M) \ni a \otimes v \mapsto a \wedge v \in C^{p+q}(\mathfrak{g}^*, M),$$

which is compatible with derivation

$$d_{\text{CE}}(a \wedge v) = d_{\text{CE}} a \wedge v + (-1)^{|a|} a \wedge d_{\text{CE}} v,$$

where $m \in M$ and $a \in \wedge^\bullet \mathfrak{g}^*$. The derivation could be written explicitly with basis a_k of M and its dual basis b^k :

$$d_{\text{CE}} = (\rho_\alpha)_i^k b^i a_k c^\alpha + \frac{1}{2} f_{\beta\gamma}^\alpha c^\beta c^\gamma a_\alpha,$$

which could be easily verified that $d_{\text{CE}}^2 = 0$.

Proof. There is a general way to prove $d_{CE}^2 = 0$, which is to note that, under the dual transformation, one have identity $\langle d_{CE}\varphi_1, c_1 m_1 \rangle = \langle \varphi_1, \rho(c_1) m_1 \rangle$, $\langle d_{CE}\varphi_2, c_1 \wedge c_2 \rangle = \langle \varphi_2, [c_1, c_2] \rangle$ and Leibniz's law, so that:

$$\begin{aligned} \langle d_{CE}^2 \varphi, c_1 \wedge c_2 \otimes m_1 \rangle &= \langle \varphi, \rho([c_1, c_2])m + (-1)(\rho(c_1)\rho(c_2)m + \rho(c_2)\rho(c_1)m) \rangle \xrightarrow{\text{g rep.}} 0, \\ \langle d_{CE}^2 \varphi, c_1 \wedge c_2 \wedge c_3 \rangle &\xrightarrow{\text{Jacobian}} 0, \end{aligned}$$

where we note that the dual of $c_1 \wedge c_2$ has degree 1 graded. \square

4.2 Differential Graded Lie Algebra

We define a \mathbb{Z} -graded vector space

$$W = \bigoplus_{n \in \mathbb{Z}} W_n,$$

where W_n is degree of n component.

1. **Degree Shift:** $W[n]_m \equiv W_{n+m}$;
2. **Dual:** W^* denote the linear dual of W

$$W_n^* = \text{Hom}(W_{-n}, \mathbb{K});$$

3. **Symmetry and Anti-Symmetry:** $\text{Sym}^{\otimes n}(V) = V^{\otimes n} / \sim$ where $a \otimes b \sim (-1)^{|a||b|} b \otimes a$, and $\bigwedge^V = V^{\otimes n} / \sim$ where $a \otimes b \sim (-1)^{|a||b|+1} b \otimes a$;

which has a natural isomorphism between $\bigwedge^m(V[1])$ and $\text{Sym}^m(V)[m]$

Proposition 4.1. *Let V be a dga, then:*

$$\bigwedge^m(V[1]) \cong \text{Sym}^m(V)[m].$$

Proof. Consider the subspace generated by ideals

$$a \otimes b \sim (-1)^{(|a|+1)(|b|+1)+1} b \otimes a = (-1)^{|a||b|+|a|+|b|} b \otimes a, \quad a, b \in V[1],$$

$$a \otimes b \sim (-1)^{|a||b|} b \otimes a, \quad a, b \in V,$$

where $|a|$ is the degree of a in V , thus the total degree in $V[1]$ is $|a| + |b| + 2$. The element in the left hand side is

$$\frac{1}{n!} \left(a_1 a_2 \cdots a_n + (-1)^{(|a_1|+1)(\sum_{i=2}^n |a_i|+n-1)+n-1} a_2 \cdots a_n a_1 + \cdots \right) \in \bigwedge^n(V[1]),$$

and the element in the right hand side is

$$\frac{1}{n!} \left(a_1 a_2 \cdots a_n + (-1)^{|a_1| \sum_{i=2}^n |a_i|} a_2 \cdots a_n a_1 + \cdots \right) \in \text{Sym}^n(V)[n].$$

Consider the shuffle map

$$a_1 \otimes a_2 \otimes \cdots \otimes a_n \rightarrow a_n \otimes a_{n-1} \otimes \cdots \otimes a_1,$$

the overall sign in $\text{Sym}^m(V)[m]$ and $\bigwedge^m(V[1])$ is the same, which is

$$(-1)^{\sum_{1 \leq i < j \leq n} |a_i||a_j|} = (-1)^{\sum_{1 \leq i < j \leq n} |a_i||a_j| + 2 \sum_{i=1}^n |a_i|},$$

where the first term is the sign of the anti-symmetry monomials and the second term is the sign of the symmetry monomials. \square

Definition 4.1 (Differential Graded Lie Algebra). *A DGLA is a \mathbb{Z} -graded space*

$$\mathfrak{g} = \bigoplus_{m \in \mathbb{Z}} \mathfrak{g}_m$$

together with bilinear map $[\cdot, \cdot] : \mathfrak{g} \otimes \mathfrak{g} \rightarrow \mathfrak{g}$ satisfying

1. (graded bracket) $[\mathfrak{g}_\alpha, \mathfrak{g}_\beta] \subset \mathfrak{g}_{\alpha+\beta}$, $[\cdot, \cdot] \in \text{Hom}(\mathfrak{g} \otimes \mathfrak{g}, \mathfrak{g})$,
2. (graded skew-symmetry) $[a, b] = -(-1)^{|a||b|}[b, a]$ ($[\cdot, \cdot] : \wedge^2 \mathfrak{g} \rightarrow \mathfrak{g}$),
3. (graded Jacobi Identity) $[[a, b], c] = [a, [b, c]] - (-1)^{|a||b|}[b, [a, c]]$,

with a degree 1 map $d : \mathfrak{g} \rightarrow \mathfrak{g}$ (i.e., $d : \mathfrak{g}_\alpha \rightarrow \mathfrak{g}_{\alpha+1}$) satisfying $d^2 = 0$ and

4. (graded Leibniz rule) $d[a, b] = [da, b] + (-1)^{|a|}[a, db]$.

Example 4.1 (de-Rham + Lie = DGLA). *Let X be a manifold, \mathfrak{g} a Lie algebra.*

- $(\Omega^\bullet(X), d)$ de Rham complex,
- $(\Omega^\bullet(X) \otimes \mathfrak{g}, d, [\cdot, \cdot])$ is DGLA,
- $\Omega^p(X) \otimes \mathfrak{g}$: degree p component,
- $d : \Omega^p \otimes \mathfrak{g} \rightarrow \Omega^{p+1} \otimes \mathfrak{g}$ de Rham, $d(\alpha \otimes h) = d\alpha \otimes h$,
- $[\cdot, \cdot]$ induced from \mathfrak{g} ,
- Let $\alpha_{1,2} \in \Omega^\bullet(X)$, $h_{1,2} \in \mathfrak{g}$, then $[\alpha_1 \otimes h_1, \alpha_2 \otimes h_2] = \alpha_1 \wedge \alpha_2 \otimes [h_1, h_2]$,

\rightsquigarrow DGLA in Chern-Simons theory.

Example 4.2 (Dolbeault + Lie = DGLA). *Let X be a complex manifold. Let*

- $(\Omega^{0,*}(X), \bar{\partial})$ Dolbeault Complex,
- $(\sum_{\bar{i}_1, \dots, \bar{i}_p} \varphi_{\bar{i}_1 \dots \bar{i}_p} d\bar{z}^{\bar{i}_1} \wedge \dots \wedge d\bar{z}^{\bar{i}_p})$ where $\bar{\partial} = d\bar{z}^{\bar{i}} \frac{\partial}{\partial \bar{z}^{\bar{i}}}$,
- $T_X \otimes_{\mathbb{C}} \mathbb{C} = T_X^{1,0} \oplus T_X^{0,1}$, where we shall choose the basis as

$$\text{Span}\left\{\frac{\partial}{\partial z^i}\right\}, \quad \text{Span}\left\{\frac{\partial}{\partial \bar{z}^{\bar{i}}}\right\},$$

which leads that $(\Omega^{0,*}(X, T_X^{1,0}), \bar{\partial}, [\cdot, \cdot])$ is a DGLA.

Explicitly, let $\{z^i\}$ be local holomorphic coordinates. $\alpha \in \Omega^{0,p}(X, T_X^{1,0})$ takes the form

$$\alpha = \sum_{i, \bar{j}} \alpha_{\bar{j}}^i d\bar{z}^{\bar{j}} \otimes \frac{\partial}{\partial z^i}, \quad d\bar{z}^{\bar{j}} = d\bar{z}^{\bar{j}_1} \wedge \dots \wedge d\bar{z}^{\bar{j}_p},$$

$$\bar{\partial}\alpha = \sum_i \bar{\partial}\alpha_{\bar{j}}^i d\bar{z}^{\bar{j}} \otimes \frac{\partial}{\partial z^i} = \sum_i \frac{\partial \alpha_{\bar{j}}^i}{\partial \bar{z}^{\bar{k}}} d\bar{z}^{\bar{k}} \wedge d\bar{z}^{\bar{j}} \otimes \frac{\partial}{\partial z^i}.$$

Let $\alpha = \sum_i \alpha_{\bar{j}}^i d\bar{z}^{\bar{j}} \otimes \frac{\partial}{\partial z^i}$ and $\beta = \sum_m \beta_{\bar{M}}^m d\bar{z}^{\bar{M}} \otimes \frac{\partial}{\partial z^i}$. The Lie bracket is

$$[\alpha, \beta] = \sum_i \left(\alpha_{\bar{j}}^j \partial_j \beta_{\bar{M}}^i - \beta_{\bar{M}}^j \partial_j \alpha_{\bar{j}}^i \right) d\bar{z}^{\bar{j}} \wedge d\bar{z}^{\bar{M}} \otimes \frac{\partial}{\partial z^i}$$

On $\text{deg} = 0$ component, this is the standard Lie bracket of $(1,0)$ vector fields. Finally, one can verify that $(\Omega^{0,*}(X, T_X^{1,0}), \bar{\partial}, [\cdot, \cdot])$ is a DGLA. \rightsquigarrow Mathematics: Deformation of complex structures \longleftrightarrow Physics: B-twisted topological string (Kodaira-Spencer gravity)

We can consider the Chevalley-Eilenberg complex for a DGLA $(\mathfrak{g}, d, [\cdot, \cdot])$.

Definition 4.2 (Chevalley-Eilenberg Complex). *For a DGLA $(\mathfrak{g}, d, [\cdot, \cdot])$, the Chevalley-Eilenberg complex is defined as*

$$C^\bullet(\mathfrak{g}) = \text{Sym}^\bullet(\mathfrak{g}^*[-1]) = \bigwedge^\bullet \mathfrak{g}^*[-\bullet],$$

equipped with the CE differential $d_{\text{CE}} = d_1 + d_2$, where

- (1) $d_1 : \mathfrak{g}^*[-1] \rightarrow \mathfrak{g}^*[-1]$ is the dual of $d : \mathfrak{g} \rightarrow \mathfrak{g}$;
- (2) $d_2 : \mathfrak{g}^*[-1] \rightarrow \text{Sym}^2(\mathfrak{g}^*[-1]) \cong \bigwedge^2 \mathfrak{g}^*[-2]$ is the dual of $[\cdot, \cdot] : \bigwedge^2 \mathfrak{g} \rightarrow \mathfrak{g}$;
- (3) (Graded Leibniz rule) The derivation extends to

$$d_{\text{CE}} : \text{Sym}(\mathfrak{g}^*[-1]) \rightarrow \text{Sym}(\mathfrak{g}[-1])$$

via the graded Leibniz rule

$$d_{\text{CE}}(ab) = d_{\text{CE}}a \cdot b + (-1)^{|a|} a \cdot d_{\text{CE}}b,$$

and satisfies $d_{\text{CE}}^2 = 0$.

Remark 4.1. If \mathfrak{g} degenerated to the ordinary Lie algebra, which would be 'bosonic' fields. However, the basic object to build CE complex for ordinary Lie algebra is 'fermionic' fields. So we need to impose $[-1]$ into the definition of CE complex of DGLA.

Definition 4.3 (DGLA-module). *Let \mathfrak{g} be a DGLA. A \mathfrak{g} -module is a cochain complex (M, d_M) with bilinear map*

$$\mathfrak{g} \otimes M \rightarrow M$$

where $C^\bullet(\mathfrak{g}, M) = \text{Sym}(\mathfrak{g}^*[-1]) \otimes M$ satisfying

- (1) d_M is the dual of $\rho : \mathfrak{g}_n \otimes M_p \rightarrow M_{n+p}$,
- (2) $d_{\mathfrak{g}}$ is the dual of $[\cdot, \cdot] : \rho(a)\rho(b)m - (-1)^{|a||b|}\rho(b)\rho(a)m = \rho([a, b]) \cdot m$,
- (3) (Chevalley-Eilenberg differential) $d_{\text{CE}} = d_M + d_{\mathfrak{g}}$,
- (4) (Leibniz's law) $d_{\text{CE}}(a \otimes m) = (d_{\mathfrak{g}}a)m + (-1)^{|a|} a \cdot d_M m$,

4.3 Homotopic Lie Algebra (L_∞ Algebra)

5 Day V: Perturbation Theory