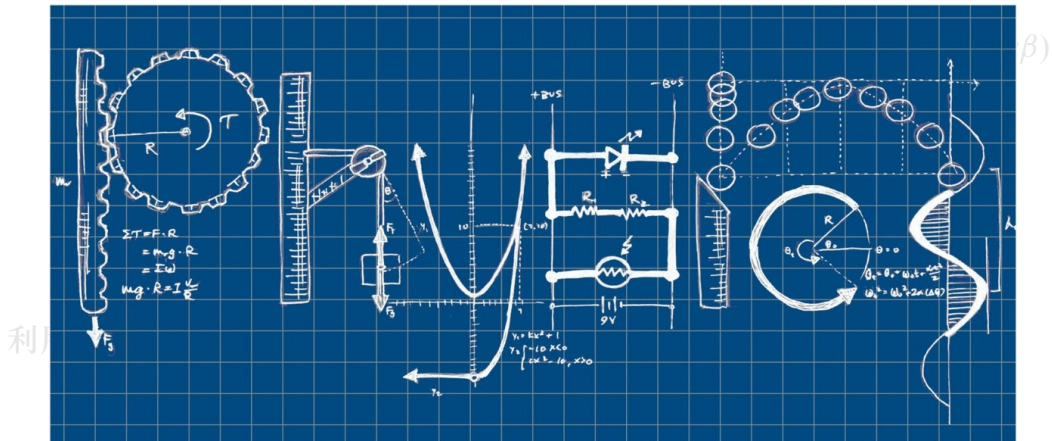


$$V(k_0) = \sum_{t=0}^{\infty} [\beta^t \ln(1 - \alpha\beta) + \beta^t \alpha \ln k_t]$$

$$= \ln(1 - \alpha\beta) \sum_{t=0}^{\infty} \beta^t + \alpha \sum_{t=0}^{\infty} \beta^t \ln k_t$$

$$= \frac{\alpha}{1 - \alpha\beta} \ln k_0 + \frac{\alpha \ln(\alpha\beta)}{1 - \alpha\beta} + \alpha \ln(\alpha\beta) \sum_{t=0}^{\infty} \left[ \frac{\beta^t}{1 - \alpha} - \frac{(\alpha\beta)^t}{1 - \alpha} \right]$$

$$= \frac{\alpha}{1 - \alpha\beta} \ln k_0 + \frac{\ln(1 - \alpha\beta)}{1 - \beta} + \frac{\alpha\beta}{(1 - \beta)(1 - \alpha\beta)} \ln(\alpha\beta)$$



$$\text{右边} = \max \{u(f(k) - y) + \beta V(y)\}$$

Do not ask what it is. Ask what you can say about it.

$$= \ln(k^\alpha - \alpha\beta k^\alpha) + \beta \left[ \frac{\alpha}{1 - \alpha\beta} \ln \alpha\beta k^\alpha + A \right]$$

$$= \ln(k^\alpha - \alpha\beta k^\alpha) + \beta \left[ \frac{\alpha}{1 - \alpha\beta} \ln \alpha\beta k^\alpha + A \right]$$

$$= \ln(1 - \alpha\beta) + \alpha \ln k + \beta \left[ \frac{\alpha}{1 - \alpha\beta} [\ln \alpha\beta + \alpha \ln k] + k \right]$$

$$= \alpha \ln k + \frac{\alpha\beta}{1 - \alpha\beta} \alpha \ln k + \ln(1 - \alpha\beta) + \frac{\alpha\beta}{1 - \alpha\beta} \ln \alpha\beta + \beta A$$

$$= \frac{\alpha}{1 - \alpha\beta} \ln k + \ln(1 - \alpha\beta) + \frac{\alpha\beta}{1 - \alpha\beta} \ln \alpha\beta + \beta A$$

$$= \frac{\alpha}{1 - \alpha\beta} \ln k + (1 - \beta)A + \beta A$$

$$= \frac{\alpha}{1 - \alpha\beta} \ln k + A$$

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所以，左边 = 右边，证毕。

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# **Part I**

## **Classical Mechanics**

# Chapter 1

## The formulation of Classical Mechanics



### 1.1 Lagrangian Formulation

$$S = \int_{t_1}^{t_2} L(q_i, \dot{q}_i, t) dt, \quad \delta q_i(t_1) = \delta q_i(t_2) = 0$$

$$\delta S = 0 \rightarrow \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = 0$$

1. If we transform the coordinates  $q$  to the  $Q$  as  $q = q(Q, t)$ , the new Lagrangian will be

$$\bar{L}(Q, \dot{Q}, t) \equiv L(q(Q, t), \dot{q}(Q, \dot{Q}, t), t)$$

We can verify that

$$\frac{d}{dt} \frac{\partial \bar{L}}{\partial \dot{Q}} - \frac{\partial \bar{L}}{\partial Q} = 0$$

2. If  $L_1 = L + \frac{d}{dt} f(q, t)$ , then  $L$  and  $L_1$  is equivalent and will generate the same dynamical equation.

**Example:**

1. The form of Lagrangian for an isolated system of particles in inertial frame:

$$L = \sum_a \frac{1}{2} m_a v_a^2 - U(\mathbf{r}_1, \mathbf{r}_2, \dots, )$$

The equation of motion is

$$m_i \ddot{\mathbf{r}}_i = -\nabla_{\mathbf{r}_i} U$$

To get the form of Lagrangian for a system of interacting particles, we must assume:

- Space and time are homogeneous and isotropic in inertial frame;
  - Galileo's relativity principle and Galilean transformation;
  - Spontaneous interaction between particles;
2. Consider a reference frame  $K$ . Suppose the  $K$  is moving with the velocity  $\mathbf{V}(t)$  and rotating with angular velocity  $\boldsymbol{\Omega}$  relative to the inertial reference frame. We use the



coordinates of the mass point in  $K$  as general coordinates, i.e.  $\mathbf{r} = (x_k, y_k, z_k)$ . Then the Lagrangian of the mass point will be

$$L = \frac{1}{2}m\mathbf{v}^2 + m\mathbf{v} \cdot (\boldsymbol{\Omega} \times \mathbf{r}) + \frac{m}{2}(\boldsymbol{\Omega} \times \mathbf{r})^2 - m\dot{\mathbf{V}} \cdot \mathbf{r} - U$$

The equation of motion will be

$$m \frac{d\mathbf{v}}{dt} = -\frac{\partial U}{\partial \mathbf{r}} - m\dot{\mathbf{V}} + m(\mathbf{r} \times \dot{\boldsymbol{\Omega}}) + 2m(\mathbf{v} \times \boldsymbol{\Omega}) + m[\boldsymbol{\Omega} \times (\mathbf{r} \times \boldsymbol{\Omega})]$$

## 1.2 Symmetry and Conservation Laws(1)

### Theorem 1.1 Nother's theorem

For  $q_i \rightarrow q_i + \delta q_i$  and  $L \rightarrow L + \delta L$ , if  $\delta L = \frac{df(q, \dot{q}, t)}{dt}$ , then we get

$$\frac{d}{dt} \left( \sum_i p^i \delta q_i - f \right) = 0 \quad (p^i = \frac{\partial L}{\partial \dot{q}_i})$$

**Example:** For an isolated system of particles in inertial frame,  $\delta L = 0$  when  $\delta \mathbf{r}_i \rightarrow \mathbf{r}_i + \delta \mathbf{a}$ , so

$$\frac{d}{dt} \left( \sum_i \mathbf{p}_i \right) = 0$$

$\delta L = 0$  when  $\delta \mathbf{r}_i \rightarrow \mathbf{r}_i + \mathbf{r}_i \times \delta \boldsymbol{\theta}$ , so

$$\frac{d}{dt} \left( \sum_i \mathbf{r}_i \times \mathbf{p}_i \right) = 0$$

**Homogeneity of time** If  $\frac{\partial L}{\partial t} = 0$ , then we get

$$\frac{dE}{dt} = 0 \quad (E = \sum_i \dot{q}_i p^i - L)$$

## 1.3 Hamilton formulation

$$p^i = \frac{\partial L}{\partial \dot{q}_i}$$

$$H(q, p, t) = \sum_i p^i \dot{q}_i - L$$



$$\dot{p}^i = -\frac{\partial H}{\partial q_i} \quad \dot{q}_i = \frac{\partial H}{\partial p^i}$$

**Example:** For an isolated system of particles in inertial frame,

$$\mathbf{p}_i = m_i \mathbf{v}_i$$

$$H(q, p, t) = \sum_i \frac{p_i^2}{2m} + U(\mathbf{r}_1, \mathbf{r}_2, \dots)$$

$$\dot{\mathbf{p}}_i = -\nabla_{\mathbf{r}_i} U \quad \dot{\mathbf{r}}_i = \frac{\mathbf{p}_i}{m_i}$$

### 1.3.1 Poisson Brackets

First, we assume the bracket operation has the following properties:

$$[f, g] = -[g, f]$$

$$[\alpha_1 f_1 + \alpha_2 f_2, \beta_1 g_1 + \beta_2 g_2] = \alpha_1 \beta_1 [f_1, g_1] + \alpha_1 \beta_2 [f_1, g_2] + \alpha_2 \beta_1 [f_2, g_1] + \alpha_2 \beta_2 [f_2, g_2]$$

$$[f_1 f_2, g_1 g_2] = f_1 [f_2, g_1] g_2 + f_1 g_1 [f_2, g_2] + g_1 [f_1, g_2] f_2 + [f_1, f_2] g_2 f_2$$

$$[f, [g, h]] + [g, [h, f]] + [h, [f, g]] = 0$$

Here,  $f, g, h$  are functions of  $p^i, q_i, t$ . Then, we assume that

$$[q_i, p^k] = \delta_i^k$$

we can derive that

$$[f, g] = \sum_k \left( \frac{\partial f}{\partial q_k} \frac{\partial g}{\partial p^k} - \frac{\partial f}{\partial p^k} \frac{\partial g}{\partial q_k} \right)$$

So the Hamilton equation can be written as

$$\dot{p}^i = [p^i, H] \quad \dot{q}_i = [q_i, H]$$

And we can also get

$$\frac{df}{dt} = [f, H] + \frac{\partial f}{\partial t} \quad \frac{d}{dt}[f, g] = \left[ \frac{df}{dt}, g \right] + \left[ f, \frac{dg}{dt} \right]$$

**Example:** For an isolated system of particles in inertial frame,

$$[r_{ia}, p_{jb}] = \delta_{ab} \delta_{ij}$$

we define  $l_a = \epsilon_{abc} r_a p_b$ , then

$$[l_a, r_b] = \epsilon_{abc} r_c \quad [l_a, p_b] = \epsilon_{abc} p_c \quad [l_a, l_b] = \epsilon_{abc} l_c$$



### 1.3.2 Canonical transformations

In Hamiltonian mechanics, a canonical transformation is a change of canonical coordinates that preserves the form of Hamilton's equations (that is, the new Hamilton's equations resulting from the transformed Hamiltonian may be simply obtained by substituting the new coordinates for the old coordinates), although it might not preserve the Hamiltonian itself.

$$Q_i = Q_i(p, q, t) \quad P_i = P_i(p, q, t)$$

$$\dot{Q}_i = \frac{\partial H'}{\partial P_i} \quad \dot{P}_i = -\frac{\partial H'}{\partial Q_i}$$

#### Proposition 1.1 Canonical condition

If  $(q_i, p^i, H) \rightarrow (Q_i, P^i, H')$  is a canonical transformation, then there exists a generating function  $F(q_i, Q_i, t)$  satisfying that

$$\sum_i p^i \dot{q}_i - H(p^i, q_i) = \sum_i P^i \dot{Q}_i - H'(Q_i, P^i) + \frac{dF}{dt}$$

Applying Legendre transformation, we can get four kinds of generating function.

1.

$$\frac{dF}{dt} = \sum_i p^i \dot{q}_i - \sum_i P^i \dot{Q}_i + (H' - H)$$

Assume  $\Phi(q_i, Q_i, t) = F$ , so

$$p^i = \frac{\partial \Phi}{\partial q_i} \quad P^i = -\frac{\partial \Phi}{\partial Q_i} \quad H' = H + \frac{\partial \Phi}{\partial t}$$

2.

$$\frac{d}{dt}(F + \sum_i P^i Q_i) = \sum_i p^i \dot{q}_i + \sum_i Q_i \dot{P}^i + (H' - H)$$

Assume  $\Phi(q_i, P^i, t) = F + \sum_i P^i Q_i$ , so

$$p^i = \frac{\partial \Phi}{\partial q_i} \quad Q_i = \frac{\partial \Phi}{\partial P^i} \quad H' = H + \frac{\partial \Phi}{\partial t}$$

3.

$$\frac{d}{dt}(F - \sum_i p^i q_i) = -\sum_i q_i \dot{p}^i - \sum_i P^i \dot{Q}_i + (H' - H)$$

Assume  $\Phi(p^i, Q_i, t) = F - \sum_i p^i q_i$ , so

$$q_i = -\frac{\partial \Phi}{\partial p^i} \quad P^i = -\frac{\partial \Phi}{\partial Q_i} \quad H' = H + \frac{\partial \Phi}{\partial t}$$



4.

$$\frac{d}{dt}(F + \sum_i P^i Q_i - \sum_i p^i q_i) = - \sum_i q_i \dot{p}^i + \sum_i Q_i \dot{P}^i + (H' - H)$$

Assume  $\Phi(p^i, P^i, t) = F + \sum_i P^i Q_i - \sum_i p^i q_i$ , so

$$q_i = -\frac{\partial \Phi}{\partial p^i} \quad Q_i = \frac{\partial \Phi}{\partial P^i} \quad H' = H + \frac{\partial \Phi}{\partial t}$$

### Theorem 1.2 The invariance of Poisson Bracket

Suppose that  $(q, p, H) \rightarrow (Q, P, H')$  is a canonical transformation and  $f(q, p, t) = F(Q, P, t)$ ,  $g(q, p, t) = G(Q, P, t)$ , then

$$[f, g]_{q,p} = [F, G]_{Q,P}$$

As a result, the condition for canonical transformation can also be stated as

$$[Q_i, Q_j]_{q,p} = 0 \quad [P^i, P^j]_{p,q} = 0 \quad [Q_i, P^j]_{q,p} = \delta_i^j$$

### 1.3.3 Evolution as canonical transformations

Let  $q_t, p_t$  be the values of the canonical variables at time  $t$ , and  $q_{t+\tau}, p_{t+\tau}$  their values at another time  $t + \tau$ . The latter are some functions of the former:

$$q_{t+\tau} = q(q_t, p_t, t, \tau) \quad p_{t+\tau} = p(q_t, p_t, t, \tau)$$

If these formulae are regarded as a transformation from the variables  $q_t, p_t$  to  $q_{t+\tau}, p_{t+\tau}$ , then this transformation is canonical. This is evident from the expression

$$dS = p_t dq_t + p_{t+\tau} dq_{t+\tau} - (H_{t+\tau} - H_t)dt$$

for the differential of the action  $S(q_t, q_{t+\tau}, t, \tau)$ , taken along the true path, passing through the points  $q$ , and  $q_{t+\tau}$  at times  $t$  and  $t + \tau$  for a given  $\tau$ .  $-S$  is the generating function of the transformation. So we have the following communication relation

$$[q_{it+\tau}, q_{jt+\tau}]_{q_t, p_t} = 0 \quad [p_{it+\tau}^i, p_{jt+\tau}^j]_{q_t, p_t} = 0 \quad [q_{it+\tau}, p_{jt+\tau}^j]_{q_t, p_t} = \delta_i^j$$

### 1.3.4 Liouville's theorem

#### Lemma 1

Let  $D$  be the Jacobian of the canonical transformation

$$\frac{\partial(Q_1, \dots, Q_s, P^1, \dots, P^s)}{\partial(q_1, \dots, q_s, p^1, \dots, p^s)}$$

Then we have

$$D = 1$$



**Theorem 1.3 Liouville's theorem**

The phase-space distribution function is constant along the trajectories of the system



**Proof:** The phase volume is invariant under canonical transformation. The change in  $p$  and  $q$  during the motion can be regarded as a canonical transformation. Suppose that each point in the region of phase space moves in the course of time in accordance with the equations of motion of the mechanical system. The region as a whole therefore moves also, but its volume remains unchanged.  $\square$

## 1.4 Symmetry and Conservation Laws(2)

Suppose  $g$  is a function of  $p$  and  $q$ . If the transformation of  $q$  and  $p$  can be described as

$$q \rightarrow q + \epsilon[q, g]$$

$$p \rightarrow p + \epsilon[p, g]$$

We can prove that

$$H \rightarrow H + \epsilon[H, g]$$

So if  $H$  is invariant under the transformation, then  $[H, g] = 0$ , that means  $\frac{dg}{dt} = 0$ , i.e.  $g$  is a conserved quantity of the motion.

## 1.5 Hamilton-Jacobi equation

We define

$$S(q, t) = \left( \int_{q_0, t_0}^{q, t} L dt \right) |_{\text{extremum}}$$

We can prove that

$$p = \frac{\partial S}{\partial q}, \quad H = -\frac{\partial S}{\partial t}$$

So, we have

$$-\frac{\partial S}{\partial t} = H(q, \frac{\partial S}{\partial q})$$

This is called Hamiltonian-Jacobi equation.

Suppose the complete integral of the Hamilton-Jacobi equation is

$$S = f(t, q_1, \dots, q_s; \alpha^1, \dots, \alpha^s) + A$$

where  $\alpha^1, \dots, \alpha^s$  and  $A$  are arbitrary constants. We effect a canonical transformation from the variables  $q, p$  to new variables, taking the function  $f(t, q, \alpha)$  as the generating function, and the quantities  $\alpha^1, \dots, \alpha^s$  as the new momenta. Let the new co-ordinates be  $\beta_1, \dots, \beta_2$ .

$$p^i = \frac{\partial f}{\partial q_i} \quad \beta_s = \frac{\partial f}{\partial \alpha_s} \quad H' = H + \frac{\partial f}{\partial t} = 0$$



So,

$$\alpha^s = \text{constant}, \beta_s = \text{constant}$$

By means of the  $s$  equations  $\beta_s = \frac{\partial f}{\partial \alpha^s}$ , the  $s$  coordinates  $q$  can be expressed in terms of the time and the  $2s$  constants. This gives the general integral of the equations of motion.

## 1.6 Symmetry and Conservation Laws(3)

If  $S$  is invariant under transformation  $q_i \rightarrow q_i + \delta q_i$ , then

$$\delta S = \left( \sum_i p^i \delta q_i \right) \Big|_{q_0, t_0}^{q, t} = 0$$

So, we have

$$\frac{d}{dt}(p^i \delta q_i) = 0$$

Further more, if

$$\delta S = \left( \sum_i p^i \delta q_i \right) \Big|_{q_0, t_0}^{q, t} = f(q_i, \dot{q}_i, t) \Big|_{q_0, t_0}^{q, t}$$

we will have conserved quantity

$$\frac{d}{dt}(p^i \delta q_i - f) = 0$$



## **Part II**

# **Classical Field Theory**

# Chapter 2

## Mechanics within special relativity



### 2.1 Basic Assumption

First, we assume there is an upper limit of velocity of propagation of interaction  $c$ . Second, we assume that inertial reference frame are all the same in describing the law of physics. Then, we can find the invariant intervals when transforming from one inertial reference frame to another,  $ds^2 = -c^2 dt^2 + dx^2 + dy^2 + dz^2$ . (In the following, we assume that  $c = 1$ .) This transformation is called Lorentz transformation, which can be written as

$$\bar{x}^\mu = \Lambda^\mu{}_\nu x^\nu$$

The invariant symbol of the vector representation of Lorentz transformation is  $\eta^{\mu\nu}$

$$\Lambda^\mu{}_\rho \Lambda^\nu{}_\sigma \eta^{\rho\sigma} = \eta^{\mu\nu},$$

where,

$$\eta_{\mu\nu} \equiv \begin{bmatrix} -1 & & & \\ & +1 & & \\ & & +1 & \\ & & & +1 \end{bmatrix}$$

The inverse matrix of  $\eta^{\mu\nu}$  is

$$\eta_{\mu\nu} = \begin{bmatrix} -1 & & & \\ & +1 & & \\ & & +1 & \\ & & & +1 \end{bmatrix}$$

We can use  $\eta^{\mu\nu}$  and its inverse  $\eta_{\mu\nu}$  to raise and lower vector indices,

$$x_\mu \equiv \eta_{\mu\nu} x^\nu$$

And we can verify the following equations,

$$\Lambda^\rho{}_\mu \Lambda^\nu{}_\rho = \delta_\mu^\nu$$

$$x^\mu = \eta^{\mu\nu} x_\nu$$

$$\bar{x}_\mu = \Lambda_\mu{}^\nu x_\nu$$

$$\Lambda_\mu{}^\rho \Lambda_\nu{}^\sigma \eta_{\rho\sigma} = \eta_{\mu\nu},$$



In a special case when the new reference frame move along  $\hat{1}$  direction with velocity  $\beta$ , we have

$$\begin{aligned}\bar{x}^0 &= \gamma x^0 - \gamma \beta x^1 \\ \bar{x}^1 &= -\gamma \beta x^0 + \gamma x^1\end{aligned}$$

Some physical quantity will behave like a tensor (vector, scalar) when transforming from one inertial frame to another. For example,

**scalar** proper time:  $d\tau$ , mass:  $m$ , electrical charge  $e$

**vector** four velocity:  $v^\mu = \frac{dx^\mu}{d\tau}$ , four momentum:  $p^\mu = mv^\mu$ , four acceleration:  $a^\mu = \frac{dv^\mu}{d\tau}$ , four force:  $f^\mu = ma^\mu$

## 2.2 "Three vector"

three velocity:  $\hat{u}^i = \frac{dx^i}{dt}$

$$u^0 = \gamma_v, u^i = \gamma \hat{u}^i$$

transformation of three velocity when we boost along  $\hat{1}$  direction:

$$\begin{aligned}\bar{\hat{v}}^1 &= \frac{\hat{v}^1 - \beta}{1 - \hat{v}^1 \beta} \\ \bar{\hat{v}}^2 &= \frac{\hat{v}^2}{\gamma(1 - \hat{v}^1 \beta)} \\ \bar{\hat{v}}^3 &= \frac{\hat{v}^3}{\gamma(1 - \hat{v}^1 \beta)}\end{aligned}$$

three momentum:  $\hat{p}^i = p^i$

$$\hat{p}^i \gamma_v \hat{v}^i$$

three acceleration:  $\hat{a}^i = \frac{dv^i}{dt}$

three force:  $\hat{f}^i = \frac{d\hat{p}^i}{dt}$

$$f^i = \gamma_v \hat{f}^i$$

Energy:  $E = p^0 = mu^0 = \gamma_v m$

## 2.3 Mechanics

Revised newton's second law:

$$f^\mu = \frac{dp^\mu}{d\tau}$$

It can be written in three vector language as

$$\hat{f}^i = \gamma_v m \hat{a}^i + \gamma_v^3 (\hat{a}^j \hat{v}_j) m \hat{v}^i$$



## 2.4 Lagrangian formulation

$$S = -m \int_a^b d\tau, \quad \delta x^\mu(a) = \delta x^\mu(b) = 0$$

$$\delta S = 0 \Rightarrow m \frac{du^\mu}{d\tau} = 0$$

## 2.5 Hamiltonian formulation

$$S = -m \int_{t_1}^{t_2} \sqrt{1 - \dot{x}_i \dot{x}^i} dt$$

$$L = -m \sqrt{1 - \dot{x}_i \dot{x}^i}$$

$$\pi^i = \frac{\partial L}{\partial \dot{x}_i} = \gamma m \eta^{ij} \dot{x}_j$$

$$H = \pi^i \dot{x}_i - L = \gamma m = \sqrt{m^2 + \pi^i \pi_i}$$

Hamilton equation

$$\dot{\pi}^i = 0, \quad \dot{x}_i = \eta_{ij} \frac{\pi^j}{\sqrt{m^2 + \pi^k \pi_k}}$$

Hamiltonian-Jacobi equation

$$H = -\frac{\partial S}{\partial t}, \quad \pi^i = \frac{\partial S}{\partial x_i}$$

If we define  $p^0 = H$ ,  $p^i = \pi^i$ , then we can verify that  $p^\mu = \frac{\partial S}{\partial x_\mu}$ . So,  $p^\mu$  is a vector under Lorentz transformation. The Hamiltonian-Jacobi equation can be written as

$$\left(\frac{\partial S}{\partial t}\right)^2 = m^2 + \left(\frac{\partial S}{\partial x}\right)^2 + \left(\frac{\partial S}{\partial y}\right)^2 + \left(\frac{\partial S}{\partial z}\right)^2$$

## 2.6 Symmetry and conservation law

Translational symmetry and conservation of momentum

$$\bar{x}^\mu = x^\mu + \delta x^\mu$$

$$\delta S = \sum m u_\mu \delta x^\mu|_a^b = 0$$

$\sum p^\mu$  is conserved.



## Rotational symmetry and conservation of angular momentum

$$\bar{x}^\mu = x^\mu + x_\nu \delta\Omega^{\mu\nu}$$

$$\delta S = \sum m u^\mu x^\nu \delta\Omega_{\mu\nu}|_a^b = 0$$

$\sum M^{\mu\nu}$  is conserved, where  $M^{\mu\nu} = x^\mu p^\nu - x^\nu p^\mu$ .



# Chapter 3

## Classical field theory



### 3.1 Lagrangian formulation

$$S = \int \mathcal{L}(\phi_a, \dot{\phi}_a, \nabla \phi_a) d^4x, \quad \delta\phi_a|_{\Sigma} = 0$$

$$\delta S = 0 \Rightarrow \partial_{\mu} \left( \frac{\partial \mathcal{L}}{\partial(\partial_{\mu} \phi_a)} \right) - \frac{\partial \mathcal{L}}{\partial \phi_a} = 0$$

#### Locality of the theory

There are no terms in the Lagrangian coupling  $\phi(\mathbf{x}, t)$  directly to  $\phi(\mathbf{y}, t)$  with  $\mathbf{x} \neq \mathbf{y}$ . The closest we get for the  $\mathbf{x}$  label is coupling between  $\phi(\mathbf{x}, t)$  and  $\phi(\mathbf{x} + \delta\mathbf{x}, t)$  through the gradient term  $\nabla\phi$ .

#### Lorentz invariance

Scalar fields:

$$\bar{\phi}(x) = \phi(\Lambda^{-1}x)$$

Vector fields:

$$\bar{A}^{\mu}(x) = \Lambda^{\mu}{}_{\nu} A^{\nu}(\Lambda^{-1}x)$$

$$\bar{A}_{\mu}(x) = (\Lambda^{-1})^{\nu}{}_{\mu} A_{\nu}(\Lambda^{-1}x) = \Lambda_{\mu}{}^{\nu} A_{\nu}(\Lambda^{-1}x)$$

$$\overline{\partial_{\mu}\phi}(x) = (\Lambda^{-1})^{\nu}{}_{\mu} \partial_{\nu}\phi(\Lambda^{-1}x) = \Lambda_{\mu}{}^{\nu} \partial_{\nu}\phi(\Lambda^{-1}x)$$

Lagrangian is a scalar, or more loosely, action is invariant under Lorentz transformation.

## 3.2 Symmetry and conservation law

### Theorem 3.1 Noether's theorem

Every continuous symmetry of the Lagrangian gives rise to a conserved current  $j^\mu(x)$  such that the equation of motion imply  $\partial_\mu j^\mu = 0$ . Suppose that the infinitesimal transformation is

$$\phi_a \rightarrow \phi_a + \delta\phi_a$$

$$\mathcal{L} \rightarrow \mathcal{L} + \delta\mathcal{L}$$

and if  $\delta\mathcal{L} = \partial_\mu K^\mu$ , we can get

$$j^\mu = -\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi_a)}\delta\phi_a + K^\mu$$

### space-time translation

$$\bar{x} = x - a$$

$$j^\mu = a_\nu T^{\mu\nu}$$

$$T^{\mu\nu} \equiv -\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi_a)}\partial^\nu\phi_a + \eta^{\mu\nu}\mathcal{L}$$

If we define  $P^\mu \equiv \int T^{0\mu} d^3x$ , then we have the law of momentum conservation:

$$\frac{dP^\mu}{dt} = 0$$

### Lorentz Transformation

$$\bar{x}^\mu = x^\mu + \delta\omega^\mu{}_\nu x^\nu$$

The infinitesimal Lorentz transformation can be written as  $I + \delta\omega^\mu{}_\nu$

$$\delta\omega^\mu{}_\nu = \begin{bmatrix} 0 & \beta_1 & \beta_2 & \beta_3 \\ \beta_1 & 0 & -\theta_3 & \theta_2 \\ \beta_2 & \theta_3 & 0 & -\theta_1 \\ \beta_3 & -\theta_2 & \theta_1 & 0 \end{bmatrix}$$

This time, we assume that

$$\bar{\phi}_a(x) = \mathcal{S}_a{}^b \phi_b(\Lambda^{-1}x)$$

In the limit of infinitesimal Lorentz transformation, we have

$$\mathcal{S}_a{}^b = \delta_a{}^b + \frac{1}{2}\delta\omega_{\alpha\beta}(\Sigma^{\alpha\beta})_a{}^b$$

$$j^\mu = \frac{1}{2}M^{\mu\nu\rho}\delta\omega_{\nu\rho}$$



$$M^{\mu\nu\rho} \equiv x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu} - \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_a)} (\Sigma^{\nu\rho})^a_b \phi_b$$

If we define  $M^{\nu\rho} \equiv \int M^{0\nu\rho} d^3x$ , then we have the law of angular momentum conservation:

$$\frac{dM^{\nu\rho}}{dt} = 0$$

### 3.3 Functional derivatives

#### Definition 3.1 Functional derivatives

Given a manifold  $M$  representing (continuous/smooth) functions  $\rho$  (with certain boundary conditions etc.), and a functional  $F$  defined as

$$F: M \rightarrow \mathbb{R} \quad \text{or} \quad F: M \rightarrow \mathbb{C},$$

the functional derivative of  $F[\rho]$ , denoted  $\frac{\delta F}{\delta \rho}$ , is defined by

$$\begin{aligned} \int \frac{\delta F}{\delta \rho}(x) \phi(x) dx &= \lim_{\epsilon \rightarrow 0} \frac{F[\rho + \epsilon \phi] - F[\rho]}{\epsilon} \\ &= \left[ \frac{d}{d\epsilon} F[\rho + \epsilon \phi] \right]_{\epsilon=0}, \end{aligned}$$

where  $\phi$  is an arbitrary function. The quantity  $\epsilon \phi$  is called the variation of  $\rho$ .

Like the derivative of a function, the functional derivative satisfies the following properties, where  $F[\rho]$  and  $G[\rho]$  are functionals:

Linearity:

$$\frac{\delta(\lambda F + \mu G)[\rho]}{\delta \rho(x)} = \lambda \frac{\delta F[\rho]}{\delta \rho(x)} + \mu \frac{\delta G[\rho]}{\delta \rho(x)},$$

where  $\lambda, \mu$  are constants.

Product rule:

$$\frac{\delta(FG)[\rho]}{\delta \rho(x)} = \frac{\delta F[\rho]}{\delta \rho(x)} G[\rho] + F[\rho] \frac{\delta G[\rho]}{\delta \rho(x)},$$

Chain rules:

If  $F$  is a functional and  $G$  an operator, then

$$\frac{\delta F[G[\rho]]}{\delta \rho(y)} = \int dx \frac{\delta F[G]}{\delta G(x)}_{G=G[\rho]} \cdot \frac{\delta G[\rho](x)}{\delta \rho(y)}.$$

If  $G$  is an ordinary differentiable function  $g$ , then this reduces to

$$\frac{\delta F[g(\rho)]}{\delta \rho(y)} = \frac{\delta F[g(\rho)]}{\delta g[\rho(y)]} \frac{dg(\rho)}{d\rho(y)}.$$



**Proposition 3.1 Properties of functional derivatives**

$$\frac{\delta F}{\delta \rho}(y) = \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \{F[\rho(x) + \epsilon \delta(x - y)] - F[\rho(x)]\}$$

$$\frac{\delta f(x)}{\delta f(y)} = \delta(x - y)$$

$$\frac{\delta}{\delta f(y)} \int g(f(x)) dx = g'(f(y))$$

$$\frac{\delta f'(x)}{\delta f(y)} = \frac{d}{dx} \delta(x - y)$$

$$\frac{\delta}{\delta f(y)} \int g(f'(x)) dx = -\frac{d}{dy} g'(f'(y))$$

**3.4 Hamiltonian formulation**

$$\pi^a(x) = \frac{\partial \mathcal{L}}{\partial \dot{\phi}_a}$$

$$\mathcal{H}(\phi_a, \nabla \phi_a, \pi^a) = \pi^a \dot{\phi}_a - \mathcal{L}$$

$$H = \int \mathcal{H} d^3x$$

Now, we can get the Hamilton equation form  $\delta S = 0$ ,

$$\dot{\phi}_a(\mathbf{x}, t) = \frac{\delta}{\delta \pi^a(\mathbf{x}, t)} H = \frac{\partial \mathcal{H}}{\partial \pi^a}$$

$$\dot{\pi}^a(\mathbf{x}, t) = -\frac{\delta}{\delta \phi_a(\mathbf{x}, t)} H = -\frac{\partial \mathcal{H}}{\partial \phi_a} + \left( \frac{\partial \mathcal{H}}{\partial \phi_{a,b}} \right)_{,b}$$

**3.4.1 Poisson bracket**

First, we define that

$$[\phi_a(\mathbf{x}), \phi_b(\mathbf{y})] \equiv [\pi^a(\mathbf{x}), \phi_b(\mathbf{y})] \equiv 0$$

$$[\phi_a(\mathbf{x}), \pi^b(\mathbf{y})] \equiv \delta_a^b \delta(\mathbf{x} - \mathbf{y})$$

then, we demand that the bracket operation has the same properties as the Poisson bracket in classical mechanics. And we also demand that

$$[\partial_x A(\mathbf{x}), B(\mathbf{y})] = \partial_x [A(\mathbf{x}), B(\mathbf{y})]$$

and

$$\left[ \int d^3x A(\mathbf{x}), B(\mathbf{y}) \right] = \int d^3x [A(\mathbf{x}), B(\mathbf{y})]$$



As a result, we can verify that

$$[W[\phi(\mathbf{x}), \pi(\mathbf{x})], Z[\phi(\mathbf{x}), \pi(\mathbf{x})]] = \int d^3x \left\{ \frac{\delta W}{\delta \phi(\mathbf{x})} \frac{\delta Z}{\delta \pi(\mathbf{x})} - \frac{\delta W}{\delta \pi(\mathbf{x})} \frac{\delta Z}{\delta \phi(\mathbf{x})} \right\}$$

Especially,

$$[\phi_a(\mathbf{x}), H] = \frac{\delta}{\delta \pi^a(\mathbf{x})} H, \quad [\pi^a(\mathbf{x}), H] = -\frac{\delta}{\delta \phi_a(\mathbf{x})} H$$

So, the Hamilton equation can be written as

$$\dot{\phi}_a = [\phi_a, H], \quad \dot{\pi}^a = [\pi^a, H]$$

Further more, we can prove that

$$\frac{dO(\phi, \pi, t)}{dt} = [O, H] + \frac{\partial O}{\partial t}$$

and

$$\frac{d[A, B]}{dt} = [A, \frac{dB}{dt}] + [\frac{dA}{dt}, B]$$

### 3.4.2 Momentum

It is easy to verify that

$$P^0 = H, \quad P^i = \int -\pi^a \partial^i \phi_a d^3x$$

And we can get the Poisson bracket

$$\begin{aligned} [\phi_a, P^\mu] &= -\partial^\mu \phi_a \\ [\pi^a, P^\mu] &= -\partial^\mu \pi^a \\ [P^\mu, P^\nu] &= 0 \end{aligned}$$

### 3.4.3 Angular momentum

It is easy to verify that

$$M^{\mu\nu} = \int (x^\mu T^{0\nu} - x^\nu T^{0\mu} - \pi^a (\Sigma^{\mu\nu})_a^b \phi_b) d^3x$$

We define that

$$\begin{aligned} M_L^{\mu\nu} &\equiv \int (x^\mu T^{0\nu} - x^\nu T^{0\mu}) d^3x & M_S^{\mu\nu} &\equiv \int (-\pi^a (\Sigma^{\mu\nu})_a^b \phi_b) d^3x \\ (L^{\mu\nu})_a^b &\equiv -(x^\mu \partial^\nu - x^\nu \partial^\mu) \delta_a^b & (S^{\mu\nu})_a^b &\equiv -(\Sigma^{\mu\nu})_a^b \end{aligned}$$

So, we can get the Poisson bracket

$$\begin{aligned} [\phi_a, M_L^{\mu\nu}] &= (L^{\mu\nu})_a^b \phi_b & [\phi_a, M_S^{\mu\nu}] &= (S^{\mu\nu})_a^b \phi_b \\ [\pi^a, M_L^{\mu\nu}] &= (L^{\mu\nu})_b^a \pi^b & [\pi^a, M_S^{\mu\nu}] &= -(S^{\mu\nu})_b^a \pi^b \end{aligned}$$





Because  $\frac{dM^{\mu\nu}}{dt} = 0$ ,  $M^{\mu\nu}$  can commute with  $\frac{d}{dt}$ , so

$$[[\phi(x), M^{\mu\nu}], M^{\rho\sigma}] = (L^{\mu\nu} + S^{\mu\nu})(L^{\rho\sigma} + S^{\rho\sigma})\phi(x)$$

At last, we can get the Poisson bracket

$$[\phi(x), [M^{\mu\nu}, M^{\rho\sigma}]] = (L^{\mu\nu}L^{\rho\sigma} - L^{\rho\sigma}L^{\mu\nu} + S^{\mu\nu}S^{\rho\sigma} - S^{\rho\sigma}S^{\mu\nu})\phi(x)$$

Since we can prove that

$$L^{\mu\nu}L^{\rho\sigma} - L^{\rho\sigma}L^{\mu\nu} = -\eta^{\nu\rho}L^{\mu\sigma} + \eta^{\sigma\mu}L^{\rho\nu} + \eta^{\mu\rho}L^{\nu\sigma} - \eta^{\sigma\nu}L^{\rho\mu}$$

if we demand that

$$S^{\mu\nu}S^{\rho\sigma} - S^{\rho\sigma}S^{\mu\nu} = -\eta^{\nu\rho}S^{\mu\sigma} + \eta^{\sigma\mu}S^{\rho\nu} + \eta^{\mu\rho}S^{\nu\sigma} - \eta^{\sigma\nu}S^{\rho\mu}$$

We will get the Poisson bracket of the  $M^{\mu\nu}$ ,

$$[M^{\mu\nu}, M^{\rho\sigma}] = -\eta^{\nu\rho}M^{\mu\sigma} + \eta^{\sigma\mu}M^{\rho\nu} + \eta^{\mu\rho}M^{\nu\sigma} - \eta^{\sigma\nu}M^{\rho\mu}$$

up to the possibility of a term on the right-hand side that commutes with  $\phi(x)$  and its derivatives.

We now define  $J_i \equiv \frac{1}{2}\epsilon_{ijk}M^{jk}$  and  $K_i \equiv M^{i0}$ , so we have

$$M^{\mu\nu} = \begin{bmatrix} 0 & -K_1 & -K_2 & -K_3 \\ K_1 & 0 & J_3 & -J_2 \\ K_2 & -J_3 & 0 & J_1 \\ K_3 & J_2 & -J_1 & 0 \end{bmatrix} \quad \left( \delta\omega_{\mu\nu} = \begin{bmatrix} 0 & -\beta_1 & -\beta_2 & -\beta_3 \\ \beta_1 & 0 & -\theta_3 & \theta_2 \\ \beta_2 & \theta_3 & 0 & -\theta_1 \\ \beta_3 & -\theta_2 & \theta_1 & 0 \end{bmatrix} \right)$$

the Poisson bracket can be written as

$$\begin{aligned} [J_i, J_j] &= \epsilon_{ijk}J_k \\ [J_i, K_j] &= \epsilon_{ijk}K_k \\ [K_i, K_j] &= -\epsilon_{ijk}J_k \end{aligned}$$

We can use the similar method to derive that

$$[P^\mu, M^{\rho\sigma}] = \eta^{\mu\sigma}P^\rho - \eta^{\mu\rho}P^\sigma$$

It can also be written as

$$\begin{aligned} [J_i, H] &= 0 \\ [J_i, P_j] &= \epsilon_{ijk}P_k \\ [K_i, H] &= P_i \\ [K_i, P_j] &= \delta_{ij}H \end{aligned}$$

At last, we define  $L_i \equiv \frac{1}{2}\epsilon_{ijk}M_L^{jk}$  and  $S_i \equiv \frac{1}{2}\epsilon_{ijk}M_S^{jk}$  we can demonstrate that

$$\begin{aligned} [L_i, S_j] &= 0 \\ [S_i, P_j] &= 0 \\ [L_i, P_j] &= \epsilon_{ijk}P_k \end{aligned}$$



## **Part III**

### **General relativity**

# Chapter 4

## Elementary Differential Geometry



### 4.1 Fundamental conception on differential manifolds

#### Definition 4.1 Manifold

**Manifold** Formally, a topological manifold is a second countable Hausdorff space that is locally homeomorphic to Euclidean space.

**Differentiable manifold** In formal terms, a differentiable manifold is a topological manifold with a globally defined differential structure.

**Tangent space** In mathematics, the tangent space of a manifold facilitates the generalization of vectors from affine spaces to general manifolds, since in the latter case one cannot simply subtract two points to obtain a vector pointing from one to the other.

**Cotangent space** Typically, the cotangent space is defined as the dual space of the tangent space at  $x$ .

#### Definition 4.2 Submanifold

##### Submanifold

**Immersed submanifolds** An immersed submanifold of a manifold  $M$  is the image  $S$  of an immersion map  $f : N \rightarrow M$ ; in general this image will not be a submanifold as a subset, and an immersion map need not even be injective (one-to-one) – it can have self-intersections.

**Injective immersion submanifolds** More narrowly, one can require that the map  $f : N \rightarrow M$  be an inclusion (one-to-one), in which we call it an injective immersion, and define an immersed submanifold to be the image subset  $S$  together with a topology and differential structure such that  $S$  is a manifold and the inclusion  $f$  is a diffeomorphism: this is just the topology on  $N$ , which in general will not agree with the subset topology: in general the subset  $S$  is not a submanifold of  $M$ , in the subset topology.

**Open submanifolds**

**Closed submanifolds**

### Definition 4.3 Embedded Submanifold

An embedded submanifold (also called a regular submanifold), is an immersed submanifold for which the inclusion map is a topological embedding. That is, the submanifold topology on  $S$  is the same as the subspace topology. Given any embedding  $f : N \rightarrow M$  of a manifold  $N$  in  $M$  the image  $f(N)$  naturally has the structure of an embedded submanifold. That is, embedded submanifolds are precisely the images of embeddings.

### Proposition 4.1

If an  $n$  dimensional injective immersed submanifold  $N$  of a  $m$  dimensional manifold  $M$  is a closed submanifold of an open submanifold of  $M$ , then for every point  $p \in f(N)$  there exists a chart  $(U \subset M, \phi : U \rightarrow \mathbb{R}^m)$  containing  $p$  such that  $\phi(f(N) \cap U)$  is the intersection of a  $n$ -dimensional plane with  $\phi(U)$ .

Closed submanifolds of an open submanifold are equal to embedded submanifolds.

## 4.2 Multi linear algebra

### Definition 4.4 Tensor

**Vector space**

**Dual space**

In mathematics, any vector space  $V$  has a corresponding dual vector space (or just dual space for short) consisting of all linear functionals on  $V$  together with a naturally induced linear structure.

**Tensor product**

$$V \otimes W = \text{Span}\{v \otimes w\} = \mathcal{L}(V^*, W^*; F)$$

$$V^* \otimes W^* = \text{Span}\{v^* \otimes w^*\} = \mathcal{L}(V, W; F)$$

$$\mathcal{L}(V, W; Z) = \mathcal{L}(V \otimes W; Z)$$

$$(\phi \otimes \psi) \otimes \xi = \phi \otimes (\psi \otimes \xi)$$

**Tensor**

$$V_s^r = V \otimes \cdots \otimes V \otimes V^* \otimes \cdots \otimes V^*$$

$$x = x^{i_1 \cdots i_r}_{k_1 \cdots k_s} e_{i_1} \otimes \cdots \otimes e_{i_r} \otimes e^{*k_1} \otimes \cdots \otimes e^{*k_s}$$

$$(x \otimes y)^{i_1 \cdots i_{r_1+r_2}}_{k_1 \cdots k_{s_1+s_2}} = x^{i_1 \cdots i_{r_1}}_{k_1 \cdots k_{s_1}} \cdot y^{i_{r_1+1} \cdots i_{r_1+r_2}}_{k_{s_1+1} \cdots k_{s_1+s_2}}$$



**Definition 4.5 Symmetric and antisymmetric tensor****Permutation** ( $\sigma \in \mathcal{P}(r)$ )

$$\sigma x(v^{*1}, \dots, v^{*r}) = x(v^{*\sigma(1)}, \dots, v^{*\sigma(r)})$$

**Symmetric contra-variant tensor**

$$\sigma x = x$$

**Antisymmetric contra-variant tensor**

$$\sigma x = \text{sgn } \sigma \cdot x$$

**Symmetrization operator**

$$S_r(x) = \frac{1}{r!} \sum_{\sigma \in \mathcal{P}(x)} \sigma x$$

**Antisymmetrization operator**

$$A_r(x) = \frac{1}{r!} \sum_{\sigma \in \mathcal{P}(x)} \text{sgn } \sigma \cdot \sigma x$$

**Definition 4.6 Exterior vector space****Exterior vector space**

$$\Lambda^r(V) = A_r(T^r(V))$$

$$\Lambda^0(V) = F \quad \Lambda^1(V) = V$$

**Wedge product**

$$\xi \wedge \eta \equiv \frac{(k+l)!}{k!l!} A_{k+l}(\xi \otimes \eta)$$

**Pull-back mapping**  $f : V \rightarrow W$  is a linear mapping, we define  $f^* : \Lambda^r(W^*) \rightarrow \Lambda^r(V^*)$  as

$$f^* \phi(v_1, \dots, v_r) = \phi(f(v_1), \dots, f(v_r)).$$

**Proposition 4.2 Properties of Wedge product**

$$(\xi_1 + \xi_2) \wedge \eta = \xi_1 \wedge \eta + \xi_2 \wedge \eta$$

$$\xi \wedge (\eta_1 + \eta_2) = \xi \wedge \eta_1 + \xi \wedge \eta_2$$

$$\xi \wedge \eta = (-1)^{kl} \eta \wedge \xi$$

$$(\xi \wedge \eta) \wedge \zeta = \xi \wedge (\eta \wedge \zeta) = \frac{(k+l+h)!}{k!l!h!} A_{k+l+h}(\xi \otimes \eta \otimes \zeta)$$

$$f^*(\phi \wedge \psi) = f^* \phi \wedge f^* \psi$$



**Proposition 4.3 Properties of exterior space**

$$\begin{aligned}
e_{i_1} \wedge \cdots \wedge e_{i_r}(v^{*1}, \dots, v^{*r}) &= \det\langle e_{i_\alpha}, v^{*\beta} \rangle \\
e_{i_1} \wedge \cdots \wedge e_{i_r}(e^{*j_1}, \dots, e^{*j_r}) &= \det\langle e_{i_\alpha}, e^{*j_\beta} \rangle = \delta_{i_1 \dots i_r}^{j_1 \dots j_r} \\
\Lambda^r(V) &= \text{Span} \{e_{i_1} \wedge \cdots \wedge e_{i_r}, 1 \leq i_1 < \cdots < i_r \leq n\} \\
(\Lambda^r(V))^* &= \Lambda^r(V^*)
\end{aligned}$$



## 4.3 Vector Bundle

**Definition 4.7 Fiber bundle**

**Fiber bundle** In mathematics, and particularly topology, a fiber bundle is a space that is locally a product space, but globally may have a different topological structure. Specifically, the similarity between a space  $E$  and a product space  $B \times F$  is defined using a continuous surjective map  $\pi : E \rightarrow B$  that in small regions of  $E$  behaves just like a projection from corresponding regions of  $B \times F$  to  $B$ . The map  $\pi$ , called the projection or submersion of the bundle, is regarded as part of the structure of the bundle. The space  $E$  is known as the total space of the fiber bundle,  $B$  as the base space, and  $F$  the fiber.

**Vector Bundle** In mathematics, a vector bundle is a topological construction that makes precise the idea of a family of vector spaces parameterized by another space  $X$  (for example  $X$  could be a topological space, a manifold, or an algebraic variety): to every point  $x$  of the space  $X$  we associate (or "attach") a vector space  $V(x)$  in such a way that these vector spaces fit together to form another space of the same kind as  $X$  (e.g. a topological space, manifold, or algebraic variety), which is then called a vector bundle over  $X$ .

**Tangent bundle** In differential geometry, the tangent bundle of a differentiable manifold  $M$  is a manifold  $TM$ , which assembles all the tangent vectors in  $M$ . As a set, it is given by the disjoint union of the tangent spaces of  $M$ . That is,



$$TM = \bigsqcup_{x \in M} T_x M = \bigcup_{x \in M} \{x\} \times T_x M = \bigcup_{x \in M} \{(x, y) | y \in T_x M\}$$

where  $T_x M$  denotes the tangent space to  $M$  at the point  $x$ . So, an element of  $TM$  can be thought of as a pair  $(x, v)$ , where  $x$  is a point in  $M$  and  $v$  is a tangent vector to  $M$  at  $x$ . There is a natural projection  $\pi : TM \rightarrow M$  defined by  $\pi(x, v) = x$ . This projection maps each tangent space  $T_x M$  to the single point  $x$ . A section of  $TM$  is a vector field on  $M$ , and the dual bundle to  $TM$  is the cotangent bundle, which is the disjoint union of the cotangent spaces of  $M$ .


**Cotangent bundle**  $T^*M = \bigcup_{x \in M} T_x^* M$

**Tensor bundle**  $T_s^r M = \bigcup_{x \in M} T_{sx}^r M$



## 4.4 Tangent vector field


### Theorem 4.1

Let  $M$  be a smooth manifold, and let  $Y : M \rightarrow TM$  be a vector field. If  $(U, (X_i))$  is any smooth coordinate chart on  $M$ , then  $Y$  is smooth on  $U$  if and only if its component functions with respect to this chart are smooth. 


### Theorem 4.2

Let  $M$  be a  $m$  dimensional smooth manifold and  $v$  a smooth tangent vector field on  $M$ .  $v : C^\infty(M) \rightarrow C^\infty$  satisfy that


- (1)  $\forall f, g \in C^\infty(M), v(f + g) = v(f) + v(g)$ ;
- (2)  $\forall f \in C^\infty(M), \alpha \in \mathbf{R}, v(\alpha f) = \alpha \cdot v(f)$ ;
- (3)  $\forall f, g \in C^\infty(M), v(fg) = f \cdot v(g) + g \cdot v(f)$ .

If  $\alpha : C^\infty(M) \rightarrow C^\infty(M)$  satisfy the three conditions above, there exists a unique smooth vector field  $v$  on  $M$  that  $\forall f \in C^\infty(M), v(f) = \alpha(f)$ . 

### Theorem 4.3

$\forall X, Y \in \mathcal{H}(M), [X, Y] = X \circ Y - Y \circ X \in \mathcal{H}(M)$ . 


### Proposition 4.4

- (1)  $[aX + bY, Z] = a[X, Z] + b[Y, Z]; [Z, aX + bY] = a[Z, X] + b[Z, Y]$ ;
  - (2)  $[X, Y] = -[Y, X]$ ;
  - (3)  $[X, [Y, Z]] + [Y, [Z, X]] + [Z, [X, Y]] = 0$ ;
  - (4)  $[X, Y]|_U = [X|_U, Y|_U] = (X_i \frac{\partial Y^j}{\partial u^i} - Y^i \frac{\partial X^j}{\partial u^i}) \frac{\partial}{\partial u^j}$ ;
  - (5)  $f_*[X, Y] = [f_*X, f_*Y]$ ;
- 

### Definition 4.8 One parameter differentiable transformation group

Let  $M$  be a smooth manifold and  $\phi : \mathbf{R} \times M \rightarrow M$  a smooth mapping, and  $\forall (t, p) \in \mathbf{R} \times M$ , denote  $\phi_t(p) = \phi(t, p)$ . If  $\phi$  satisfy that

- (1)  $\phi_0 = \text{id} : M \rightarrow M$ ;
- (2)  $\forall s, t \in \mathbf{R}, \phi_s \circ \phi_t = \phi_{s+t}$ ;


then  $\phi$  is called a one parameter differentiable transformation group acting on  $M$ . 

Trajectory of  $\phi$  through  $p$  on  $M$ :  $\gamma_p(t) = \phi(t, p)$ .

Vector field induced by  $\phi$ :  $X_p(f) = \langle \gamma_p, f \rangle$ .




**Proposition 4.5**


- (1)  $\gamma_q(t) = \phi(t, \phi(s, p)) = \phi(t + s, p) = \gamma_p(t + s)$ ;  
 (2)  $(\phi_s)_* X_p = X_{\phi_s(p)}$ ;  
 (3)  $\psi_* X_p = \tilde{X}_{\psi(p)}$  if  $X$  is induced by  $\phi$  and  $\tilde{X}$  is induced by  $\psi \circ \phi \circ \psi^{-1}$ .  $\psi$  is a smooth homeomorphism.   
 (4)  $[X, Y] = \lim_{t \rightarrow 0} \frac{Y_p - (\phi_t)_* Y_{\phi_t(p)}}{t} = \lim_{t \rightarrow 0} \frac{(\phi_{-t})_* Y_{\phi_t(p)} - Y}{t}$  if  $X$  is induced by  $\phi$ .

**Definition 4.9 Lie derivative**

$$\mathcal{L}_X Y \equiv \lim_{t \rightarrow 0} \frac{(\phi_{-t})_* Y_{\phi_t(p)} - Y}{t} = [X, Y]$$


$$\mathcal{L}_X f \equiv X(f)$$



**Proposition 4.6**

$$\begin{aligned}\mathcal{L}_X(Y + \lambda Z) &= \mathcal{L}_X Y + \lambda \mathcal{L}_X Z \\ \mathcal{L}_X(f \cdot Y) &= \mathcal{L}_X(f) \cdot Y + f \mathcal{L}_X Y \\ \mathcal{L}_X([Y, Z]) &= [\mathcal{L}_X Y, Z] + [Y, \mathcal{L}_X Z]\end{aligned}$$


**Theorem 4.4**

Let  $M$  be a  $n$ -dimensional smooth manifold and  $X \in \mathcal{H}(M)$ . If  $p \in M$  and  $X_p \neq 0$ ,  $\exists(V, x^i)$  and  $p \in V$  that  $X|_V = \frac{\partial}{\partial y^1}$


**Definition 4.10 Distribution**

**Distribution** Let  $M$  be a  $C^\infty$  manifold of dimension  $m$ , and let  $n \leq m$ . Suppose that for each  $x \in M$ , we assign an  $n$ -dimensional subspace  $\Delta_x \subset T_x(M)$  of the tangent space in such a way that for a neighbourhood  $N_x \subset M$  of  $x$  there exist  $n$  linearly independent smooth vector fields  $X_1, \dots, X_n$  such that for any point  $y \in N_x$ ,  $X_1(y), \dots, X_n(y)$  span  $\Delta_y$ . We let  $\Delta$  refer to the collection of all the  $\Delta_x$  for all  $x \in M$  and we then call  $\Delta$  a distribution of dimension  $n$  on  $M$ , or sometimes a  $C^\infty$   $n$ -plane distribution on  $M$ . The set of smooth vector fields  $\{X_1, \dots, X_n\}$  is called a local basis of  $\Delta$ . 





**Definition 4.11 Involutive distributions**

We say that a distribution  $\Delta$  on  $M$  is involutive if for every point  $x \in M$  there exists a local basis  $\{X_1, \dots, X_n\}$  of the distribution in a neighbourhood of  $x$  such that for all  $1 \leq i, j \leq n$ ,  $[X_i, X_j]$  is in the span of  $\{X_1, \dots, X_n\}$ . That is, if  $[X_i, X_j]$  is a linear combination of  $\{X_1, \dots, X_n\}$ . Normally this is written as  $[\Delta, \Delta] \subset \Delta$ .

Involutive distributions are the tangent spaces to foliations. Involutive distributions are important in that they satisfy the conditions of the Frobenius theorem, and thus lead to integrable systems. A related idea occurs in Hamiltonian mechanics: two functions  $f$  and  $g$  on a symplectic manifold are said to be in mutual involution if their Poisson bracket vanishes.

**Theorem 4.5 Frobenius Theorem**

If distribution  $\Delta$  on  $M$  is involutive, then  $\forall p \in M, \exists (V, x^i)$  and  $p \in V$  that  $\Delta|_V = \text{Span}\left\{\frac{\partial}{\partial y^1}, \dots, \frac{\partial}{\partial y^h}\right\}$ .

**Definition 4.12 Integrable manifold**

Let  $L^h$  be a smooth distribution on  $M$ . If  $\phi : N \rightarrow M$  is an injective immersion manifold, and  $\forall p \in N, \phi_*(T_p N) \subset L^h(\phi(p))$ , then  $(\phi, N)$  is called an integrable manifold of  $L^h$ . If  $\forall q \in M$ , there is an integrable manifold of  $L^h$  through it, we say that  $L^h$  is completely integrable.

**Theorem 4.6**

Let

$$\tau : \underbrace{A^1(M) \times \dots \times A^1(M)}_p \times \underbrace{\mathcal{H}(M) \times \dots \times \mathcal{H}(M)}_q \rightarrow c^\infty(M)$$

be a  $p + q$  multi-linear mapping, if  $\forall 1 \leq a \leq p, 1 \leq b \leq q$  and  $\mu \in C^\infty(M)$ ,

$$\begin{aligned} & \tau(\alpha^1, \dots, \mu\alpha^a, \dots, \alpha^p, v_1, \dots, v_q) \\ &= \tau(\alpha^1, \dots, \alpha^p, v_1, \dots, \mu v_b, \dots, v_q) \\ &= \mu \cdot \tau(\alpha^1, \dots, \alpha^p, v_1, \dots, v_q) \end{aligned}$$

then the mapping  $\tau$  define a  $(p, q)$  tensor for all  $x \in M$  smoothly.



**Definition 4.13 Lie derivatives**

Let  $X$  be a smooth tangent vector field on  $M$  and  $\phi_t$  the one parameter differentiable transformation group inducing it. Denote the trajectory of  $\phi_t$  through  $x$  by  $\gamma_x(t)$ . So we have linear isomorphism

$$(\phi_t^{-1})_* = (\phi_{-t})_* : T_{\gamma_x(t)}M \rightarrow T_xM$$

$$(\phi_t)^* : T_{\gamma_x(t)}^* \rightarrow T_x^*M$$

So we can induce the linear isomorphism

$$\Phi_t : T_q^p(\gamma_x(t)) \rightarrow T_q^p(x)$$

If  $S$  and  $T$  are smooth tensor fields on  $M$ ,

(1) for all  $t$  which is small enough,  $\Phi_t S$  is a smooth tensor field on  $M$  which has the same type as  $S$ , and  $\lim_{t \rightarrow 0} \Phi_t(S(\gamma_p(t))) = S(p)$ ,  $\forall p \in M$ .

(2)  $\Phi_t(S \otimes T) = \Phi_t S \otimes \Phi_t T$ .

(3)  $\Phi_t(C_b^a(S)) = C_b^a(\Phi_t(S))$ ,  $C_b^a$  is a tag for contraction.

So, we can define the Lie derivative for smooth tensor field  $\tau$  on  $M$  as

$$\mathcal{L}_X(\tau) = \lim_{t \rightarrow 0} \frac{\Phi_t(\tau) - \tau}{t}$$

**Proposition 4.7**

$$\mathcal{L}_X(\tau_1 + \lambda\tau_2) = \mathcal{L}_X\tau_1 + \lambda\mathcal{L}_X\tau_2$$

$$\mathcal{L}_X(\tau_1 \otimes \tau_2) = \mathcal{L}_X\tau_1 \otimes \tau_2 + \tau_1 \otimes \mathcal{L}_X\tau_2$$

$$C_s^r(\mathcal{L}_X\tau) = \mathcal{L}_X(C_s^r(\tau))$$

$$(\mathcal{L}_X\omega)(Y) = X(\omega(Y)) - \omega([X, Y])$$

$$\mathcal{L}_{[X, Y]} = \mathcal{L}_X \circ \mathcal{L}_Y - \mathcal{L}_Y \circ \mathcal{L}_X$$

$$\mathcal{L}_{X+Y} = \mathcal{L}_X + \mathcal{L}_Y$$

**Proposition 4.8**

$$((\mathcal{L}_X\tau)|_U)^{\mu_1, \dots, \mu_p}_{v_1, \dots, v_q} = X^\alpha \partial_\alpha \tau_{v_1, \dots, v_q}^{\mu_1, \dots, \mu_p} - \sum_{i=1}^p \tau_{v_1, \dots, v_q}^{\mu_1, \dots, \alpha, \dots, \mu_p} \partial_\alpha X^{\mu_i} + \sum_{j=1}^q \tau_{v_1, \dots, \alpha, \dots, v_q}^{\mu_1, \dots, \mu_p} \partial_{v_j} X^\alpha$$



## 4.5 Exterior differential

### Definition 4.14 Exterior form space

$$A(M) = \sum_{r=0}^m A^r(M)$$

For  $\tau \in A^r(M)$ ,

$$\tau|_U = \frac{1}{r!} \tau_{i_1 \dots i_r} dx^{i_1} \wedge \dots \wedge dx^{i_r} = \tau_{|i_1 \dots i_r|} dx^{i_1} \wedge \dots \wedge dx^{i_r}$$

$$\tau_{i_1 \dots i_r} = \tau\left(\frac{\partial}{\partial x^{i_1}}, \dots, \frac{\partial}{\partial x^{i_r}}\right)$$

$$\begin{aligned} \tau(v_1, \dots, v_r)|_U &= \tau_{|i_1 \dots i_r|} dx^{i_1} \wedge \dots \wedge dx^{i_r}(v_1, \dots, v_r) \\ &= \tau_{|i_1 \dots i_r|} \begin{vmatrix} v_1^{i_1} & \dots & v_r^{i_1} \\ \vdots & & \vdots \\ v_1^{i_r} & \dots & v_r^{i_r} \end{vmatrix} \end{aligned}$$

It is a  $r$  multi-linear mapping, and for every variable, it is  $C^\infty(M)$  linear.

### Proposition 4.9 Pullback mapping

$$f : M \rightarrow N \Rightarrow f_* : T_p M \rightarrow T_{f(p)} N \Rightarrow f^* : \wedge^r(T_{f(p)}^* N) \rightarrow \wedge^r(T_p^* M)$$

$$f^* \phi(v_1, \dots, v_r) = \phi(f_* v_1, \dots, f_* v_r)$$

$$f^* \phi|_U = \frac{1}{r!} (\phi_{\alpha_1 \dots \alpha_r} \circ f) \cdot \frac{\partial f^{\alpha_1}}{\partial x^{i_1}} \dots \frac{\partial f^{\alpha_r}}{\partial x^{i_r}} dx^{i_1} \wedge \dots \wedge dx^{i_r}$$

$$f^*(\phi \wedge \psi) = f^* \phi \wedge f^* \psi$$

### Definition 4.15 Exterior differential

Let  $M$  be a  $m$ -dimensional smooth manifold. Then  $\exists$  a unique mapping  $d : A(M) \rightarrow A(M)$  satisfy that

$$(1) d(A^r(M)) \subset A^{r+1}(M)$$

$$(2) \forall \omega_1, \omega_2 \in A(M), d(\omega_1 + \omega_2) = d\omega_1 + d\omega_2$$

$$(3) \text{ if } \omega_1 \in A^r(M), \text{ then } d(\omega_1 \wedge \omega_2) = d\omega_1 \wedge \omega_2 + (-1)^r \omega_1 \wedge d\omega_2$$

$$(4) f \in A^0(M), df \text{ is just the differential of } f$$

$$(5) \forall f \in A^0(M), d(df) = 0$$

$d$  is called exterior differential.



**Theorem 4.7**

$\forall \omega \in A^1(M), X, Y \in \mathcal{H}(M),$

$$d\omega(X, Y) = X\langle Y, \omega \rangle - Y\langle X, \omega \rangle - \langle [X, Y], \omega \rangle$$

$\forall \omega \in A^r(M), X_1, \dots, X_{r+1} \in \mathcal{H}(M),$

$$\begin{aligned} d\omega(X_1, \dots, X_{r+1}) &= \sum_{i=1}^{r+1} (-1)^{i+1} X_i(\langle X_1 \wedge \dots \wedge \hat{X}_i \wedge \dots \wedge X_{r+1}, \omega \rangle) \\ &+ \sum_{1 \leq i < j \leq r+1} (-1)^{i+j} \langle [X_i, X_j] \wedge \dots \wedge \hat{X}_i \wedge \dots \wedge \hat{X}_j \wedge \dots \wedge X_{r+1}, \omega \rangle \end{aligned}$$

**Theorem 4.8**

$$f^*(d\omega) = d(f^*\omega)$$

**Lemma 1 Poincare Lemma**

1.  $d^2 = 0$
2. Let  $U = B_0(r)$  be a spherical neighbourhood with center origin  $O$  and radius  $r$  in  $R^n$ .  $\forall \omega \in A^r(U)$  and  $d\omega = 0$ ,  $\exists \tau \in A^{r-1}(U)$ , satisfy that  $\omega = d\tau$ .

**Definition 4.16 Pfaff euqations**

Let  $\omega^\alpha (1 \leq \alpha \leq r) \in A^1(U)$  and  $U$  is an open set of  $m$ -dimensional smooth manifold  $M$ . Differential equation set  $\omega^\alpha = 0$  is called Pfaff equations.

**Definition 4.17 Integral manifold of Pfaff equations**

If there is an injective immersion submanifold  $\phi : N \rightarrow U$  satisfying that  $\phi^*\omega^\alpha = 0, (\phi, N)$  is called an integral manifold of Pfaff equation set.



**Proposition 4.10 Partial differential equations and Pfaff equations**

There is a set of first order partial differential equations

$$\frac{\partial y^\alpha}{\partial x^i} = f_i^\alpha(x^1, \dots, x^m, y^1, \dots, y^n) \quad (1 \leq i \leq m, 1 \leq \alpha \leq n)$$

$f_i^\alpha(x, y)$  is a smooth function on the open set  $U \times V \subset \mathbb{R}^m \times \mathbb{R}^n$ . The equations sets can be written as Pfaff equations on  $U \times V$

$$\omega^\alpha \equiv dy^\alpha - f_i^\alpha(x, y)dx^i = 0$$

If the partial differential equations have solution

$$y^\alpha = g^\alpha(x^1, \dots, x^m)$$

then the submanifold  $\phi : U \rightarrow U \times V$ ,

$$\phi(x^1, \dots, x^m) = (x^1, \dots, x^m, g^1(x), \dots, g^n(x))$$

is an integral manifold of the Pfaff equations, i.e.  $\phi^*\omega^\alpha = 0$

**Proposition 4.11 Distribution and Pfaff equations**

Pfaff equations  $\omega^\alpha = 0$  on open set  $V \in M$  with rank  $r$  is equivalent to a  $h = m - r$  dimensional smooth distribution locally.

$$\Delta^h(p) = \{v \in T_p M : \omega^\alpha(v) = 0, 1 \leq \alpha \leq r\}$$

If  $\phi : N \rightarrow V$  is an integral manifold of  $\omega^\alpha, \forall X \in T_p N, \omega^\alpha(\phi_* X) = \phi^*\omega_\alpha(X) = 0$ . So  $\phi_* X \in \Delta^h(p)$ , and so  $\phi : N \rightarrow V$  is an integral manifold of  $\Delta^h$ .

**Definition 4.18 Completely integrable**

Suppose  $\omega^\alpha$  is a set of  $r$  linearly independent 1 forms defined on an open set  $U \subset M$ . If  $\forall p \in U$ , Pfaff equations

$$\omega^\alpha = 0 \quad (1 \leq \alpha \leq r)$$

has an  $h = \dim M - r$  dimensional integral manifold  $\phi : N \rightarrow V$  such that  $p \in V$ , Pfaff equations are called completely integrable.



**Definition 4.19 Frobenius condition**

Frobenius condition for Pfaff equations  $\omega^\alpha = 0 (1 \leq \alpha \leq r)$  is that

$$d\omega^\alpha \equiv 0 \pmod{(\omega^1, \dots, \omega^r)}$$



**Theorem 4.9 Frobenius theorem**

Pfaff equations satisfying Frobenius condition is completely integrable.



**Definition 4.20 Orientation of manifold**

Let  $\alpha : [0, 1] \rightarrow M$  be a path on  $M$ .  $\forall t \in [0, 1]$ , assign an orientation for  $T_{\alpha(t)}M$ , denoted by  $\mu_t$ . If for  $t_0 \in [0, 1]$ , there is a local coordinate  $(U; x_i)$  of  $\alpha(t_0)$  and a neighbourhood  $[t_0 - \delta_1, t_0 + \delta_2]$  of  $t_0$  that

$$\alpha([t_0 - \delta_1, t_0 + \delta_2]) \subset U$$

and

$$\left\{ \frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^m} \right\} |_{\alpha(t)} \in \mu_t, \forall t \in [t_0 - \delta_1, t_0 + \delta_2],$$

$\mu$  is called a continuous topological orientation of  $\alpha$



**Definition 4.21 The propagation of orientation**

Let  $p, q \in M$  and  $\alpha : [0, 1] \rightarrow M$  a path connecting  $p, q$ . Assign an orientation  $\lambda$  of  $T_pM$ . If there is a continuous topological orientation of  $\alpha$   $\mu$  satisfying that  $\mu_0 = \lambda$ , then orientation  $\mu_1$  of  $T_qM$  is called the propagation of orientation  $\lambda$  along  $\alpha$ . The orientation of  $\mu_1$  is unique.



**Definition 4.22 Orientable manifold**

Let  $M$  be a  $m$  dimensional smooth manifold. If there is an atlases  $(\mathcal{A}, = \{(U_\alpha, \phi_\alpha)\})$ , making that if  $U_\alpha \cap U_\beta \neq \emptyset$ , the Jacobian of

$$\phi_\beta \circ \phi_\alpha^{-1} : \phi_\alpha(U_\alpha \cap U_\beta) \rightarrow \phi_\beta(U_\alpha \cap U_\beta)$$

is positive. Then  $M$  is called orientable manifold.



**Theorem 4.10**

Let  $M$  be a orientable connected manifold.  $\forall p \in M$ , assign an orientation  $\lambda$  for  $T_p M$ , then for all point  $q \in M$ , the propagation of  $\lambda$  along an arbitrary path define a unique orientation  $\mu$  for  $T_q M$ .

**Definition 4.23 Manifold with boundary**

A topological manifold with boundary is a Hausdorff space in which every point has a neighbourhood homeomorphic to an open subset of Euclidean half-space (for a fixed  $n$ ):

$$\mathbb{R}_+^n = \{(x_1, \dots, x_n) \in \mathbb{R}^n : x_n \geq 0\}$$

**Definition 4.24 Boundary and interior**

Let  $M$  be a manifold with boundary. The interior of  $M$ , denoted  $\text{Int } M$ , is the set of points in  $M$  which have neighbourhoods homeomorphic to an open subset of  $\mathbb{R}^n$ . The boundary of  $M$ , denoted  $\partial M$ , is the complement of  $\text{Int } M$  in  $M$ . The boundary points can be characterized as those points which land on the boundary hyperplane ( $x^n = 0$ ) of  $\mathbb{R}_+^n$  under some coordinate chart.

If  $M$  is a manifold with boundary of dimension  $n$ , then  $\text{Int } M$  is a manifold (without boundary) of dimension  $n$  and  $\partial M$  is a manifold (without boundary) of dimension  $n - 1$ .

**Theorem 4.11**

Let  $M$  be a smooth manifold with boundary and  $\partial M \neq \emptyset$ . The differential structure of  $\partial M$  can be deduced from the  $M$ , making  $\partial M$  a  $m - 1$  dimensional smooth manifold and the inclusion map  $i : \partial M \rightarrow M$  is embedding map. If  $M$  is orientable, then  $\partial M$  is also orientable.

**Definition 4.25 Induced orientation**

Let  $M$  be an orientable  $m$  dimensional smooth manifold with boundary and  $\partial M \neq \emptyset$ .  $\mathcal{A}$  is the orientation of  $M$ . For local coordinates  $(U; x^i) \in \mathcal{A}$ , when

$$\tilde{U} = U \cap \partial M = \{(x^1, \dots, x^m) \in U : x^m = 0\} \neq \emptyset$$

assign a local coordinate system  $((-1)^m \cdot x^1, x^2, \dots, x^{m-1})$  on  $\tilde{U}$ . The orientation defined by this local coordinate system is called induced orientation of  $\partial M$ .



#### Definition 4.26 Support set

Let  $M$  be a  $m$  dimensional orientable smooth manifold.  $\omega \in A^r(M)$ , the support set of  $\omega$  can be defined as

$$\text{Supp } \omega = \overline{\{p \in M : \omega(p) \neq 0\}}$$



All the  $r$ -form with compact support set is denoted as  $A_0^r(M)$ .

#### Definition 4.27 Partition of unity

Let  $\Sigma$  be an open cover of  $M$ . Then there is a family of smooth function  $g_\alpha$  on  $M$  that

1.  $\forall \alpha, 0 \leq g_\alpha \leq 1, \text{supp } g_\alpha$  is compact and there is an open set  $W_i \in \Sigma$  that  $\text{supp } g_\alpha \subset W_i$ .
2.  $\forall p \in M$ , it has a neighbourhood  $U$  which intersect finite  $\text{supp } g_\alpha$ .
3.  $\sum_\alpha g_\alpha = 1$



#### Definition 4.28 Integral of differential form with compact support

$$\phi = \left( \sum_\alpha g_\alpha \right) \cdot \phi = \sum_\alpha (g_\alpha \cdot \phi)$$

$$\int_M g_\alpha \cdot \phi = \int_{W_i} g_\alpha \cdot \phi = \int_{W_i} f(u^1, \dots, u^m) du^1 \wedge \dots \wedge du^m = \int_{W_i} f(u^1, \dots, u^m) du^1 \dots$$



$$\int_M \phi = \sum_\alpha \int_M g_\alpha \cdot \phi$$

#### Theorem 4.12 Stokes Theorem

Let  $M$  be an orientable  $m$  dimensional smooth manifold with boundary and  $\omega \in A_0^{m-1}(M)$ , then

$$\int_M d\omega = \int_{\partial M} i^* \omega$$



Here,  $\partial M$  has an orientation induced by  $M$  and  $i$  is embedding mapping.





## 4.6 Connection

### Definition 4.29 Connection

Let  $M$  be a smooth manifold and  $E$  a  $q$  dimensional real vector bundle on  $M$ .  $\Gamma(E)$  is the set of all smooth sections of  $E$  on  $M$ . The connection on  $E$  is a mapping:

$$D : \Gamma(E) \rightarrow \Gamma(T^*(M) \otimes E)$$

it satisfies that

1.  $\forall s_1, s_2 \in \Gamma(E), D(s_1 + s_2) = Ds_1 + Ds_2$
2.  $\forall s \in \Gamma(E)$  and  $\alpha \in C^\infty(M), D(\alpha s) = d\alpha \otimes s + \alpha Ds$

If  $X$  is a smooth tangent vector field on  $M$ ,  $s \in \Gamma(E)$ , then  $D_X s = \langle X, Ds \rangle$ , called absolute derivative of  $s$  along  $X$ .

### Proposition 4.12

Local representation of connection is:

$$Ds_\alpha = \sum_{1 \leq i \leq m, 1 \leq \beta \leq q} \Gamma_{\alpha i}^\beta du^i \otimes s_\beta$$

$$\omega_\alpha^\beta = \sum_{1 \leq i \leq m} \Gamma_{\alpha i}^\beta du^i$$

$$Ds_\alpha = \sum_{\beta=1}^q \omega_\alpha^\beta \otimes s_\beta$$

$$DS = \omega \otimes S$$

Transformation law of connection is:

$$S' = A \cdot S$$

$$\begin{aligned} DS' &= dA \otimes S + A \cdot DS \\ &= (dA + A \cdot \omega) \otimes S \\ &= (dA \cdot A^{-1} + A \cdot \omega \cdot A^{-1}) \otimes S' \\ \omega' &= dA \cdot A^{-1} + A \cdot \omega \cdot A^{-1} \end{aligned}$$



**Theorem 4.13**

For an arbitrary vector bundle, connection always exists.

**Theorem 4.14**

Let  $D$  be a connection of vector bundle  $E$ .  $\forall p \in M$ , there exists a local frame field  $S$  on the neighbourhood of  $p$  that  $\omega(p) = 0$ .

**Definition 4.30 Curvature matrix**

$$\Omega \equiv d\omega - \omega \wedge \omega$$

**Proposition 4.13 Transformation law of curvature matrix**

$$\Omega' = A \cdot \Omega \cdot A^{-1}$$

**Definition 4.31 Curvature operator**

$$s = \sum_{\alpha=1}^q \lambda^\alpha s_{\alpha|p}$$

$$R(X, Y)s = \sum_{\alpha, \beta=1}^q \lambda^\alpha \Omega_\alpha^\beta(X, Y) s_{\beta|p}$$

$$(R(X, Y)s)(p) = R(X_p, Y_p)s_p$$

**Proposition 4.14**

$$R(X, Y) = D_X D_Y - D_Y D_X - D_{[X, Y]}$$

**Theorem 4.15 Bianchi equation**

$$d\Omega = \omega \wedge \Omega - \Omega \wedge \omega$$



**Definition 4.32 Induced connection**

$$\begin{aligned}
d\langle s, s^* \rangle &= \langle Ds, s^* \rangle + \langle s, Ds^* \rangle \\
\langle s_\alpha, s^{*\beta} \rangle &= \delta_\alpha^\beta \Rightarrow Ds^{*\beta} = - \sum_{\alpha=1}^q \omega_\alpha^\beta \otimes s^{*\alpha} \\
D(s_1 \oplus s_2) &\equiv Ds_1 \oplus Ds_2 \\
D(s_1 \otimes s_2) &\equiv Ds_1 \otimes s_2 + s_1 \otimes Ds_2
\end{aligned}$$

**Definition 4.33 Affine connection**

$$D \frac{\partial}{\partial u^i} \equiv \omega_i^j \otimes \frac{\partial}{\partial u^j} \equiv \Gamma_{ik}^j du^k \otimes \frac{\partial}{\partial u^j}$$

**Proposition 4.15**

$$\begin{aligned}
\Gamma_{ik}^{'j} &= \Gamma_{pr}^q \frac{\partial w^j}{\partial u^q} \frac{\partial u^p}{\partial u^i} \frac{\partial u^r}{\partial u^k} + \frac{\partial^2 u^p}{\partial w^i \partial w^k} \frac{\partial w^j}{\partial u^p} \\
DX &= (dx^i + x^j \omega_j^i) \otimes \frac{\partial}{\partial u^i} = (x_{;j}^i + x^k \Gamma_{kj}^i) du^j \otimes \frac{\partial}{\partial u^i} = x_{;j}^i du^j \otimes \frac{\partial}{\partial u^i} \\
D\alpha &= (d\alpha_i - \alpha_j \omega_i^j) \otimes du^i = (\alpha_{i,j} - \alpha_k \Gamma_{ij}^k) du^j \otimes du^i = \alpha_{i;j} du^j \otimes du^i
\end{aligned}$$

**Definition 4.34 Geodesic equation**

$$\begin{aligned}
D\left(\frac{du^i(t)}{dt} \frac{\partial}{\partial u^i}\right) &= 0 \\
\frac{d^2 u^i}{dt^2} + \Gamma_{jk}^i \frac{du^j}{dt} \frac{du^k}{dt} &= 0
\end{aligned}$$

**Definition 4.35 Curvature tensor**

$$\begin{aligned}
\Omega_i^j &= \frac{1}{2} R_{ikl}^j du^k \wedge du^l \\
R &\equiv R_{ikl}^j du^i \otimes \frac{\partial}{\partial u^j} \otimes du^k \otimes du^l
\end{aligned}$$



**Proposition 4.16**

$$R_{ikl}^j = \frac{\partial \Gamma_{il}^j}{\partial u^k} - \frac{\partial \Gamma_{ik}^j}{\partial u^l} + \Gamma_{il}^h \Gamma_{hk}^j - \Gamma_{ik}^h \Gamma_{hl}^j$$

$$R_{ikl}^j = R_{prs}^q \frac{\partial w^j}{\partial u^q} \frac{\partial u^p}{\partial w^i} \frac{\partial u^r}{\partial w^k} \frac{\partial u^s}{\partial w^l}$$

$$R(X, \alpha_Y, Z, W) = \langle \alpha_Y, R(Z, W)X \rangle$$

$$R_{ikl}^j = \langle R(\frac{\partial}{\partial u^k} \frac{\partial}{\partial u^l}) \frac{\partial}{\partial u^i}, du^j \rangle$$



**Definition 4.36 Torsion tensor**

$$T_{ik}^j = \Gamma_{ki}^j - \Gamma_{ik}^j$$

$$T = T_{ik}^j \frac{\partial}{\partial u^j} \otimes du^i \otimes du^k$$



**Proposition 4.17**

$$T(X, Y) = T_{ij}^k X^i Y^j \frac{\partial}{\partial u^k}$$

$$T(X, Y) = D_X Y - D_Y X - [X, Y]$$



**Theorem 4.16**

Let  $D$  be an affine connection without torsion on  $M$ .  $\forall p \in M$ , there is a local coordinate system that  $\Gamma_{ik}^j(p)$  vanishes.



**Theorem 4.17**

Let  $D$  be an affine connection without torsion on  $M$ . Then we have Bianchi equation

$$R_{ikl;h}^j + R_{ihk;l}^j + R_{ilh;k}^j = 0$$



## 4.7 Riemann manifold

### Definition 4.37 Riemann manifold

Let  $M$  be a smooth manifold equipped with a smooth non-degenerate symmetric second order covariant tensor field  $G$ , then  $M$  is called general Riemann manifold and  $G$  is called the metric tensor of  $M$ .

If  $G$  is positive definite, then  $M$  is called Riemann manifold.

### Theorem 4.18

There must be a Riemann metric on  $m$  dimensional manifold  $M$ .

### Definition 4.38 Index lifting

$$f : T_p(M) \rightarrow T_p^*(M) \quad \alpha_X(Y) \equiv G(X, Y)$$

### Definition 4.39 Adapted connection

Let  $(M, G)$  be a general Riemann manifold and  $D$  a connection on  $M$ . If  $DG = 0$ , then  $D$  is called adapted connection on  $M$ .

### Proposition 4.18 Christoffel-Levi-Civita connection

Let  $M$  be a general Riemann manifold, then there is a unique adapted connection without torsion on  $M$ , called Christoffel-Levi-Civita connection.

As  $\omega_i^j = \Gamma_{ik}^j du^k$ ,  $dg_{ij} = g_{ik}\omega_j^k + g_{kj}\omega_i^k$ . If we denote that  $\omega_{ij} = \omega_i^j g_{jk}$  and  $\Gamma_{ijk} = \Gamma_{ik}^l g_{lj}$ , we have  $\omega_{ij} = \Gamma_{ijk} du^k$  and  $dg_{ij} = \omega_{ji} + \omega_{ij}$ . At last, we have

$$\Gamma_{ij}^k = \frac{1}{2} g^{kl} \left( \frac{\partial g_{il}}{\partial u^j} + \frac{\partial g_{jl}}{\partial u^i} - \frac{\partial g_{ij}}{\partial u^l} \right)$$



**Proposition 4.19 Curvature tensor**

If we denote that  $\Omega_{ij} = \Omega_i^k g_{kj}$  and  $R_{ijkl} = R_{ikl}^h g_{hj}$ , we will have that

$$\Omega_{ij} + \Omega_{ji} = 0, \quad \Omega_{ij} = d\omega_{ij} + \omega_i^l \wedge \omega_{jl}, \quad \Omega_{ij} = \frac{1}{2} R_{ijkl} du^k \wedge du^l$$

The properties of curvature tensor:

$$R_{ijkl} = -R_{jikl} = -R_{ijlk}$$

$$R_{ijkl} + R_{iklj} + R_{iljk} = 0$$

$$R_{ijkl} = R_{klij}$$

**Definition 4.40 Normal coordinates**

In differential geometry, normal coordinates at a point  $p$  in a differentiable manifold equipped with a symmetric affine connection are a local coordinate system in a neighbourhood of  $p$  obtained by applying the exponential map to the tangent space at  $p$ . In a normal coordinate system, the Christoffel symbols of the connection vanish at the point  $p$ , thus often simplifying local calculations. In normal coordinates associated to the Levi-Civita connection of a Riemann manifold, one can additionally arrange that the metric tensor is the Kronecker delta at the point  $p$ , and that the first partial derivatives of the metric at  $p$  vanish.

The properties of normal coordinates often simplify computations. In the following, assume that  $U$  is a normal neighbourhood centred at  $p$  in  $M$  and  $(x_i)$  are normal coordinates on  $U$ .

Let  $V$  be some vector from  $T_p M$  with components  $V^i$  in local coordinates, and  $\gamma_V$  be the geodesic with starting point  $p$  and velocity vector  $V$ , then  $\gamma_V$  is represented in normal coordinates by  $\gamma_V(t) = (tV^1, \dots, tV^n)$  as long as it is in  $U$ .

The coordinates of  $p$  are  $(0, \dots, 0)$

In Riemann normal coordinates at  $p$  the components of the Riemann metric  $g$  simplify to  $\delta_{ij}$ .

The Christoffel symbols vanish at  $p$ . In the Riemann case, so do the first partial derivatives of  $g_{ij}$ .

**Theorem 4.19**

Let  $M$  be a differentiable manifold equipped with a symmetric affine connection.  $\forall x_0 \in M$ , there is a neighbourhood  $W$  that for every point in  $W$ , there is a neighbourhood equipped with a normal coordinate system which contains  $W$ .



**Theorem 4.20**

Let  $M$  be a Riemann manifold.  $\forall O \in M$ , there is a neighbourhood with normal coordinates  $W$  that:

- (1) For every point in  $W$ , there is a neighbourhood equipped with a normal coordinates which contains  $W$ .
- (2) The geodesic connecting  $O$  and  $p \in W$  is the only shortest path connecting these two points in  $W$ .

**Theorem 4.21**

Let  $U$  be the neighbourhood with normal coordinates of  $O$ .  $\exists \epsilon > 0, \forall \delta \in (0, \epsilon)$ , the surface

$$\Sigma_\delta = \{p \in U \mid \sum_{i=1}^m (u^i(p))^2 = \delta^2\}$$

has following properties:

- (1)  $\forall p \in \Sigma_\delta$ , there is a unique shortest geodesic connecting  $p$  and  $O$  in  $U$ .
- (2) For all geodesics tangent to  $\Sigma_\delta$ , there is a neighbourhood of the cut point in which the geodesics lies outside of  $\Sigma_\delta$

**Theorem 4.22**

Let  $M$  be a Riemann manifold and  $\forall p \in M$ , there is a  $\eta$ -spherical neighbourhood  $W$  that for arbitrary two points in  $W$ , there is a unique geodesic connecting these two points.

**Definition 4.41 Cross section curvature**

$$R(X, Y, Z, W) \equiv R_{ijkl} X^i Y^j Z^k W^l$$

$$R(X, Y, Z, W) = (R(Z, W)X) \cdot Y$$

$$G(X, Y, Z, W) \equiv G(X, Z)G(Y, W) - G(X, W)G(Y, Z)$$

Let  $E$  be a two dimensional subspace of  $T_p(M)$  and  $X, Y$  two linearly independent tangent vector of  $E$ , then

$$K(E) = -\frac{R(X, Y, X, Y)}{G(X, Y, X, Y)}$$

is a function of  $E$ , which is independent of the choice of  $X, Y$ , called cross section curvature.



### Theorem 4.23

Let  $M$  be a Riemann space. The curvature tensor of  $p \in M$  is uniquely determined by the cross section curvature of all the two dimensional subspace of  $T_p(M)$ .



### Definition 4.42 Constant curvature Riemann manifold

Let  $M$  be a Riemann manifold. If all of  $K(E)$  on  $p$  is constant, then  $M$  is called isotropic on  $p$ .

If  $M$  is isotropic every where and  $K(p)$  is constant over  $M$ , then  $M$  is called constant curvature Riemann manifold.



### Theorem 4.24 F.Schur theorem

Let  $M$  be a  $m$ -dimensional connected Riemann manifold that is isotropic every where. If  $m \geq 3$ , then  $M$  is constant curvature Riemann manifold.





# Chapter 5

## A Geometrical Description of Newton Theory



### 5.1 Introduction

We choose Euclidean coordinates for our absolute space and an absolute time  $t$ , than the equation of motion can be written as

$$\frac{d^2 t}{d\lambda^2} = 0$$

$$\frac{d^2 x^i}{d\lambda^2} + \frac{\partial \Phi}{\partial x^i} \left( \frac{d\lambda}{dt} \right)^2 = 0$$

It is convenient to define that  $\Gamma_{00}^i = \frac{\partial \Phi}{\partial x^i}$ , and all other  $\Gamma_{\beta\gamma}^\alpha$  vanish. Then we can write the equation of motion as

$$\frac{d^2 x^\alpha}{d\lambda^2} + \Gamma_{\beta\gamma}^\alpha \frac{dx^\beta}{d\lambda} \frac{dx^\gamma}{d\lambda} = 0$$

Next, we can get the Riemann tensor given the connection above

$$R_{0j0}^i = -R_{00j}^i = \frac{\partial \Phi}{\partial x^i \partial x^j},$$

and all other terms vanish. It is straight forward to derive the expression of Ricci tensor,

$$R_{00} = \Phi_{ii} = \nabla^2 \Phi,$$

and all other terms vanish. So, newton gravity law can be written as

$$R_{00} = 4\pi\rho$$

### 5.2 Geometry structure of Newtonian Space-time

#### Stratification of space-time

Regard absolute time  $t$  as a scalar field defined once and for all in Newtonian space-time  $t = t(\mathcal{P})$ . The layers of space-time are the slices of constant  $t$ -the "space slices"-each of which has an identical geometric structure: the old "absolute space."

#### Flat Euclidean space

A given space slice is endowed with basis vectors  $e_i = \frac{\partial}{\partial x^i}$ ; and this basis has vanishing connection coefficients,  $\Gamma_{jk}^i = 0$ . Consequently, the geometry of each space slice is completely flat. Absolute space is Euclidean in its geometry. Each space slice is endowed with a three-dimensional metric, and its Galilean coordinate basis is orthonormal,  $e_i \cdot e_j = \delta_{ij}$ .

### Curvature of space-time

Parallel transport a vector around a closed curve lying entirely in a space slice; it will return to its starting point unchanged. But transport it forward in time by  $\Delta t$ , northerly in space by  $\Delta x_k$ , back in time by  $-\Delta t$ , and southerly by  $-\Delta x_k$  to its starting point; it will return changed by

$$\delta \mathbf{A} = -\mathcal{R}(\Delta t \frac{\partial}{\partial t}, \Delta x_k \frac{\partial}{\partial x_k}) \mathbf{A}$$

Geodesics of a space slice (Euclidean straight lines) that are initially parallel remain always parallel. But geodesics of space-time (trajectories of freely falling particles) initially parallel get pried apart or pushed together by space-time curvature,

$$\nabla_u \nabla_u \mathbf{n} + \mathcal{R}(\mathbf{n}, \mathbf{u}) \mathbf{u} = 0$$

## 5.3 Geometry formulation of Newtonian gravity

1. There exists a function  $t$  called "universal time", and a symmetric covariant derivative  $\nabla$ .
2. The 1-form  $dt$  is covariant constant, i.e.,

$$\nabla_u dt = 0 \text{ for all } \mathbf{u}.$$



**Note:** if  $\mathbf{w}$  is a spatial vector field, then  $\nabla_u \mathbf{w}$  is also spatial for every  $\mathbf{u}$ .

3. Spatial vectors are unchanged by parallel transport around infinitesimal closed curves; i.e.,

$$\mathcal{R}(\mathbf{n}, \mathbf{u}) \mathbf{w} = 0 \text{ if } \mathbf{w} \text{ is spatial, for every } \mathbf{u} \text{ and } \mathbf{n}.$$

4. All vectors are unchanged by parallel transport around infinitesimal, spatial, closed curves; i.e.,

$$\mathcal{R}(\mathbf{v}, \mathbf{w}) = 0 \text{ for every spatial } \mathbf{v} \text{ and } \mathbf{w}.$$

5. The Ricci curvature tensor has the form

$$\mathbf{Ricci} = 4\pi\rho dt \otimes dt$$

where  $\rho$  is the density of mass.

6. There exists a metric  $\cdot$  defined on spatial vectors only, which is compatible with the covariant derivative in this sense: for any spatial  $\mathbf{w}$  and  $\mathbf{v}$ , and for any  $\mathbf{u}$  whatsoever,

$$\nabla_u (\mathbf{w} \cdot \mathbf{v}) = (\nabla_u \mathbf{w}) \cdot \mathbf{v} + \mathbf{w} \cdot (\nabla_u \mathbf{v}).$$



**Note:** Axioms (1), (2), and (3) guarantee that such a spatial metric can exist.



7. The Jacobi curvature operator  $\mathcal{J}(\mathbf{u}, \mathbf{v})$ , defined for any vectors  $\mathbf{u}, \mathbf{n}, \mathbf{p}$  by

$$\mathcal{J}(\mathbf{u}, \mathbf{n})\mathbf{p} = \frac{1}{2}[\mathcal{R}(\mathbf{p}, \mathbf{n})\mathbf{u} + \mathcal{R}(\mathbf{p}, \mathbf{u})\mathbf{n}]$$

is "self-ad-joint" when operating on spatial vectors,i.e.,

$$\mathbf{v} \cdot [\mathcal{R}(\mathbf{u}, \mathbf{n})\mathbf{w}] = \mathbf{w} \cdot [\mathcal{R}(\mathbf{u}, \mathbf{n})\mathbf{v}] \text{ for all spacial } \mathbf{v}, \mathbf{w}; \text{ and for any } \mathbf{u}, \mathbf{n}.$$

8. "Ideal rods" measure the lengths that are calculated with the spatial metric; "ideal clocks" measure universal time  $t$  ( or some multiple thereof); and "freely falling particles" move along geodesics of  $\nabla$ .

## 5.4 Standard formulation of Newtonian gravity

1. There exist a universal time  $t$ , a set of Cartesian space coordinates  $x_i$  (called "Galilean coordinates"), and a Newtonian gravitational potential  $\Phi$ .
2. The density of mass  $\rho$  generates the Newtonian potential by Poisson's equation,

$$\nabla^2 \Phi = \frac{\partial^2 \Phi}{\partial x^i \partial x^i} = 4\pi\rho.$$

3. The equation of motion for a freely falling particle is

$$\frac{d^2 x^i}{dt^2} + \frac{\partial \Phi}{\partial x^i} = 0.$$

4. "Ideal rods" measure the Galilean coordinate lengths; "ideal clocks" measure universal time.

## 5.5 Galilean coordinate system

The features of Galilean coordinate systems are

$$x^0(\mathcal{P}) = t(\mathcal{P})$$

$$\frac{\partial}{\partial x^i} \cdot \frac{\partial}{\partial x^j} = \delta_{ij}$$

$$\Gamma_{00}^j = \Phi_{,j} \text{ for some scalar field } \Phi, \text{ and all other } \Gamma_{\beta\gamma}^\alpha \text{ vanish.}$$

Consider following coordinate transformation:

- (1)  $x^{0'} = x^0 = t$ , both time coordinates must be universal time.
- (2) at fixed  $t$ , both sets of space coordinates must be Euclidean, so they must be related by a rotation and a translation:

$$\bar{x}^{i'}(t) = A_{i'j}(t)x^j + \bar{a}^{i'}(t)$$



We can get

$$\bar{\Gamma}_{0j'}^{i'} = \bar{\Gamma}_{j'0}^{i'} = A_{i'l} \dot{A}_{j'l}$$

$$\bar{\Gamma}_{00}^{i'} = \Phi_{,i'} + A_{i'j} (\ddot{A}_{j'} \bar{x}^{j'} - \ddot{a}^j), \text{ here, } a^j = \bar{a}^{j'} A_{j'j}$$

and all other terms vanish. So, new coordinates have the standard Galilean form if and only if

$$\dot{A}_{i'j} = 0, \quad \Phi' = \Phi - \ddot{a}^{i'} x^{i'} + C$$

Were all the matter in the universe concentrated in a finite region of space and surrounded by emptiness ("island universe"), then one could impose the global boundary condition  $\Phi \rightarrow 0$  as  $r \equiv (x^i x^i)^{\frac{1}{2}} \rightarrow \infty$ . This would single out a subclass of Galilean coordinates ("absolute" Galilean coordinates), with a unique, common Newtonian potential. The transformation from one absolute Galilean coordinate system to any other is called Galilean transformation.

## 5.6 Coordinate transformation in space

We now consider a coordinate transformation of Galilean coordinate system purely in space without any terms related with time. That means that  $\bar{x}^{i'} = y^{i'}(x^i)$  and  $t' = t$ . We can calculate the connection term in the new coordinate system.

$$\bar{\Gamma}_{00}^{i'} = \Gamma_{00}^i \frac{\partial y^{i'}}{\partial x^i}$$

$$\bar{\Gamma}_{j'k'}^{i'} = \frac{\partial^2 x^m}{\partial y^{i'} \partial y^{k'}} \frac{\partial y^{i'}}{\partial x^m}$$

The equation of motion of free fall body is that

$$\frac{d^2 t'}{d\lambda^2} = 0$$

$$\frac{d^2 \bar{x}^{i'}}{d\lambda^2} + \bar{\Gamma}_{j'k'}^{i'} \frac{d\bar{x}^{j'}}{d\lambda} \frac{d\bar{x}^{k'}}{d\lambda} + \bar{\Gamma}_{00}^{i'} \frac{dt'}{d\lambda} \frac{dt'}{d\lambda} = 0$$

We can write it compactly as

$$\frac{d^2 \bar{x}^{i'}}{dt^2} + \bar{\Gamma}_{j'k'}^{i'} \frac{d\bar{x}^{j'}}{dt} \frac{d\bar{x}^{k'}}{dt} + \bar{\Gamma}_{00}^{i'} = 0$$

We can demonstrate that

$$\bar{\Gamma}_{j'k'}^{i'} = \frac{1}{2} \bar{g}^{i'p'} (\partial_{k'} \bar{g}_{j'p'} + \partial_{j'} \bar{g}_{k'p'} - \partial_{p'} \bar{g}_{j'k'})$$

and

$$\bar{\Gamma}_{00}^{i'} = \bar{g}^{i'j'} \partial_{j'} \Phi$$

Here,  $\bar{g}$  is the metric of the space in new coordinate system.



# Chapter 6

## Geometry of Space-time



### 6.1 More on the manifold of space-time

#### 6.1.1 Hodge dual

##### Definition 6.1 Hodge dual operator

The Hodge star operator on a vector space  $V$  with a non-degenerate symmetric bilinear form (herein referred to as the inner product) is a linear operator on the exterior algebra of  $V$ , mapping  $k$ -vectors to  $(n - k)$ -vectors where  $n = \dim V$ , for  $0 \leq k \leq n$ . It has the following property, which defines it completely: given two  $k$ -vectors  $\alpha, \beta$ ,

$$\alpha \wedge (\star\beta) = \langle \alpha, \beta \rangle \omega$$

where  $\langle \cdot, \cdot \rangle$  denotes the inner product on  $k$ -vectors and  $\omega$  is the preferred unit  $n$ -vector. The inner product  $\langle \cdot, \cdot \rangle$  on  $k$ -vectors is extended from that on  $V$  by requiring that

$$\langle \alpha, \beta \rangle = \det [\langle \alpha_i, \beta_j \rangle]$$

for any decomposable  $k$ -vectors  $\alpha = \alpha_1 \wedge \cdots \wedge \alpha_k$  and  $\beta = \beta_1 \wedge \cdots \wedge \beta_k$ . The unit  $n$ -vector  $\omega$  is unique up to a sign. The preferred choice of  $\omega$  defines an orientation on  $V$ .

Given an orthonormal basis  $(e_1, \dots, e_n)$  ordered such that  $\omega = e_1 \wedge \cdots \wedge e_n$ , we see that

$$\star(e_{i_1} \wedge e_{i_2} \wedge \cdots \wedge e_{i_k}) = e_{i_{k+1}} \wedge e_{i_{k+2}} \wedge \cdots \wedge e_{i_n}$$

where  $(i_1, i_2, \dots, i_n)$  is an even permutation of  $\{1, 2, \dots, n\}$ . Of these  $\frac{n!}{2}$ , only  $\binom{n}{k}$  are independent. The first one in the usual lexicographical order reads

$$\star(e_1 \wedge e_2 \wedge \cdots \wedge e_k) = e_{k+1} \wedge e_{k+2} \wedge \cdots \wedge e_n$$

### 6.1.2 Levi-Civita tensor

#### Definition 6.2 Levi-Civita tensor

$$\epsilon_{i_1, \dots, i_n} \equiv |g|^{\frac{1}{2}} \tilde{\epsilon}_{i_1, \dots, i_n},$$

where  $\epsilon$  is Levi-Civita symbol.

#### Proposition 6.1

$$\epsilon^{i_1, \dots, i_n} = g^{i_1 j_1} \dots g^{i_n j_n} \epsilon_{j_1, \dots, j_n} = \frac{|g|^{\frac{1}{2}}}{g} \tilde{\epsilon}^{i_1, \dots, i_n} = \text{sgn}(g) \frac{1}{|g|^{\frac{1}{2}}} \tilde{\epsilon}^{i_1, \dots, i_n}$$

Using tensor index notation, the Hodge dual is obtained by contracting the indices of a  $k$ -form with the  $n$ -dimensional completely antisymmetric Levi-Civita tensor.

#### Proposition 6.2

$$(\star \eta)_{i_1, i_2, \dots, i_{n-k}} = \frac{1}{(n-k)!} \eta^{j_1, \dots, j_k} \epsilon_{j_1, \dots, j_k, i_1, \dots, i_{n-k}},$$

where  $\eta$  is an arbitrary antisymmetric tensor in  $k$  indices.

### 6.1.3 Metric-induced properties of Riemann curvature tensor

1. In a  $n$  dimensional manifold with torsion-free affine connection, the number of independent components of Riemann tensor is

$$\frac{n^3(n-1)}{2} - \frac{n^2(n-1)(n-2)}{6} = \frac{(n^2-1)n^2}{3}$$

In a  $n$  dimensional Riemann manifold, the number of independent components of Riemann tensor is

$$\left(\frac{n(n-1)}{2}\right)^2 - \frac{n^2(n-1)(n-2)}{6} = \frac{(n^2-1)n^2}{12}$$

2. The double dual of Riemann tensor

$$\bar{G}^{\alpha\beta}_{\gamma\delta} = \frac{1}{2} \tilde{\epsilon}^{\alpha\beta\mu\nu} R_{\mu\nu}{}^{\rho\sigma} \frac{1}{2} \tilde{\epsilon}_{\rho\sigma\gamma\delta} = -\frac{1}{4} \delta^{\alpha\beta\mu\nu}_{\rho\sigma\gamma\delta} R_{\mu\nu}{}^{\rho\sigma}$$

contains precisely the same amount of information as Riemann tensor, and satisfies precisely the same set of symmetries.

3. The Einstein curvature tensor, which is symmetric

$$G^\beta_\delta = \bar{G}^{\mu\beta}_{\mu\delta}; \quad G_{\beta\delta} = G_{\delta\beta}$$



4. The Bianchi identity takes a particularly simple form when rewritten in Bianchi identities terms of the double dual  $\bar{G}$ :

$$\bar{G}^{\alpha\beta}{}_{\gamma\delta}{}^{;\delta} = 0$$

and it has the obvious consequence

$$G_{\beta\delta}{}^{;\delta} = 0$$

5. The Ricci curvature tensor, which is symmetric, and the curvature scalar

$$R^\beta{}_\delta = R^{\mu\beta}{}_{\mu\delta}; \quad R_{\beta\delta} = R_{\delta\beta}; \quad R = R^\beta{}_\beta$$

which are related to the Einstein tensor by

$$G^\beta{}_\delta = R^\beta{}_\delta - \frac{1}{2}\delta^\beta{}_\delta R$$

6. The Weyl conformal tensor

$$C^{\alpha\beta}{}_{\gamma\delta} = R^{\alpha\beta}{}_{\gamma\delta} - 2\delta^{[\alpha}{}_{[\gamma} R^{\beta]}{}_{\delta]} + \frac{1}{3}\delta^{[\alpha}{}_{[\gamma} \delta^{\beta]}{}_{\delta]} R$$

possesses the same symmetries as the Riemann tensor. Weyl tensor is completely ”trace-free”; i.e., that contraction of  $C_{\alpha\beta\gamma\delta}$  on any pair of slots vanishes. Thus,  $C_{\alpha\beta\gamma\delta}$  can be regarded as the trace-free part of Riemann, and  $R_{\alpha\beta}$  can be regarded as the trace of Riemann. Riemann is determined entirely by its trace-free part  $C_{\alpha\beta\gamma\delta}$  and its trace  $R_{\alpha\beta}$

## 6.2 The coordinates of observer

### 6.2.1 Riemann normal coordinates

$$g_{\alpha\beta}(\mathcal{P}_0) = \eta_{\alpha\beta}$$

$$g_{\alpha\beta,\gamma}(\mathcal{P}_0) = 0$$

$$\Gamma^\alpha{}_{\beta\gamma}(\mathcal{P}_0) = 0$$

$$\Gamma^\alpha{}_{\beta\gamma,\mu}(\mathcal{P}_0) = -\frac{1}{3}(R^\alpha{}_{\beta\gamma\mu} + R^\alpha{}_{\gamma\beta\mu})$$

$$g_{\alpha\beta,\mu\nu}(\mathcal{P}_0) = -\frac{1}{3}(R_{\alpha\mu\beta\nu} + R_{\alpha\nu\beta\mu})$$

$$R_{\alpha\beta\gamma\delta}(\mathcal{P}_0) = g_{\alpha\delta,\beta\gamma} - g_{\alpha\gamma,\beta\delta}$$



### 6.2.2 The proper reference frame of an accelerated observer

1. Let  $\tau$  be proper time as measured by the accelerated observer's clock. Let  $\mathcal{P} = \mathcal{P}_0(\tau)$  be the observer's world line.
2. The observer carries with himself an orthonormal tetrad  $\{e_{\hat{\alpha}}\}$  with

$$e_{\hat{0}} = \mathbf{u} = \frac{d\mathcal{P}_0}{d\tau}$$

and with

$$e_{\hat{\alpha}} \cdot e_{\hat{\beta}} = \eta_{\alpha\beta}$$

3. The tetrad changes from point to point along the observer's world line, relative to parallel transport:

$$\nabla_{\mathbf{u}} e_{\hat{\alpha}} = -\boldsymbol{\Omega} \cdot e_{\hat{\alpha}}$$

$$\Omega^{\mu\nu} = a^{\mu}u^{\nu} - u^{\mu}a^{\nu} + u_{\alpha}\omega_{\beta}\epsilon^{\alpha\beta\mu\nu}$$

This transport law has the same form in curved space-time as in flat because curvature can only be felt over finite distances, not over the infinitesimal distance involved in the "first time-rate of change of a vector" (equivalence principle).

$$\mathbf{a} = \nabla_{\mathbf{u}} \mathbf{u}$$

$$\mathbf{u} \cdot \mathbf{a} = \mathbf{u} \cdot \boldsymbol{\omega} = 0$$

If  $\boldsymbol{\omega}$  were zero, the observer would be Fermi-Walker-transporting his tetrad (gyroscope-type transport). If both  $\mathbf{a}$  and  $\boldsymbol{\omega}$  were zero, he would be freely falling (geodesic motion) and would be parallel-transporting his tetrad.

4. The observer constructs his proper reference frame (local coordinate system) in a manner analogous to the Riemann-normal construction. From each event  $\mathcal{P}_0(\tau)$  on his world line, he sends out purely spatial geodesics (geodesics orthogonal to  $\mathbf{u}$ ), with affine parameter equal to proper length. The tangent vector has unit length, because the chosen affine parameter is proper length.
5. Each event near the observer's world line is intersected by precisely one of the geodesics  $\mathcal{G}[\tau, \mathbf{n}, s]$ . [Far away, this is not true; the geodesics may cross, either because of the observer's acceleration].
6. Pick an event  $\mathcal{P}$  near the observer's world line. The geodesic through it originated on the observer's world line at a specific time  $\tau$ , had original direction  $\mathbf{n} = n^{\hat{j}}e_{\hat{j}}$ ; and needed to extend a distance  $s$  before reaching  $\mathcal{P}$ . Hence, the four numbers

$$(x^{\hat{0}}, x^{\hat{1}}, x^{\hat{2}}, x^{\hat{3}}) \equiv (\tau, sn^{\hat{1}}, sn^{\hat{2}}, sn^{\hat{3}})$$

are a natural way of identifying the event  $\mathcal{P}$ . These are the coordinates of  $\mathcal{P}$  in the observer's proper reference frame.





Along the world line of observer:

$$\frac{\partial}{\partial x^{\hat{\alpha}}} = \mathbf{e}_{\hat{\alpha}}, \quad g_{\hat{\alpha}\hat{\beta}} = \mathbf{e}_{\hat{\alpha}} \cdot \mathbf{e}_{\hat{\beta}} = \eta_{\hat{\alpha}\hat{\beta}}$$

$$\Gamma_{\hat{\alpha}\hat{0}}^{\hat{\beta}} = -\Omega_{\hat{\alpha}}^{\hat{\beta}}, \quad \Gamma_{\hat{0}\hat{0}}^{\hat{0}} = 0$$

$$\Gamma_{\hat{j}\hat{0}}^{\hat{0}} = \Gamma_{\hat{0}\hat{0}}^{\hat{j}} = a^{\hat{j}}, \quad \Gamma_{\hat{k}\hat{0}}^{\hat{j}} = -\omega^{\hat{i}} \epsilon_{0\hat{i}\hat{j}\hat{k}}$$

$$\Gamma_{\hat{j}\hat{k}}^{\hat{\alpha}} = 0$$

$$g_{\hat{\alpha}\hat{\beta},\hat{0}} = 0, \quad g_{\hat{j}\hat{k},\hat{l}} = 0$$

$$g_{\hat{0}\hat{0},\hat{j}} = -2a^{\hat{j}}, \quad g_{\hat{0}\hat{j},\hat{k}} = -\epsilon_{0\hat{j}\hat{k}\hat{l}} \omega^{\hat{l}}$$

## 6.3 Hypersurfaces

### 6.3.1 Description of hypersurfaces



**Note:** We only discuss timelike and spacelike hypersurfaces in this section.

#### Normal vector

$$n^{\alpha} n_{\alpha} = \epsilon \equiv \begin{cases} -1 & \text{if } \Sigma \text{ is spacelike} \\ +1 & \text{if } \Sigma \text{ is timelike} \end{cases}$$

#### Induced metric

Suppose that the hypersurface is parametrized with equation  $x^{\alpha} = x^{\alpha}(y^a)$ , Then

$$e_a^{\alpha} = \frac{\partial x^{\alpha}}{\partial y^a}.$$

For displacements within  $\Sigma$ , we have

$$\begin{aligned} ds_{\Sigma}^2 &= g_{\alpha\beta} dx^{\alpha} dx^{\beta} \\ &= g_{\alpha\beta} \left( \frac{\partial x^{\alpha}}{\partial y^a} dy^a \right) \left( \frac{\partial x^{\beta}}{\partial y^b} dy^b \right) \\ &= h_{ab} dy^a dy^b \end{aligned}$$

where  $h_{ab} = g_{\alpha\beta} e_a^{\alpha} e_b^{\beta}$ . The completeness relation can be written as

$$g^{\alpha\beta} = \epsilon n^{\alpha} n^{\beta} + h^{ab} e_a^{\alpha} e_b^{\beta}$$



### 6.3.2 Integration on hypersurfaces

The positive volume element of the whole space time is  $dx^0 \wedge \cdots \wedge dx^{m-1}$ , the positive volume element of the hypersurfaces is  $dy^1 \wedge \cdots \wedge dy^{m-1}$ . Suppose that the coordinate in hypersurfaces is compatible with the coordinate of the whole space-time, which means that  $-dy^m \wedge dy^1 \wedge \cdots \wedge dy^{m-1}$  has the same orientation as  $dx^0 \wedge \cdots \wedge dx^{m-1}$ . Then we have that

$$\tilde{\epsilon}_{\alpha_m \alpha_1 \cdots \alpha_{m-1}} \frac{\partial x^{\alpha_m}}{\partial y^m} e_1^{\alpha_1} \cdots e_{m-1}^{\alpha_{m-1}} < 0$$

If we demand that the direction of  $n^\alpha$  is the opposite of  $\frac{\partial x^\alpha}{\partial y^m}$ , then we have

$$\tilde{\epsilon}_{\alpha_m \alpha_1 \cdots \alpha_{m-1}} n^{\alpha_m} e_1^{\alpha_1} \cdots e_{m-1}^{\alpha_{m-1}} > 0.$$

#### Surface element

We define the surface element of a hypersurface as

$$d\Sigma_\mu = \epsilon_{\mu\alpha\beta\gamma} e_1^\alpha e_2^\beta e_3^\gamma dy^1 \wedge dy^2 \wedge dy^3$$

It is easy to verify that

$$f^*(\sqrt{-g} dx^1 \wedge dx^2 \wedge dx^3) = d\Sigma_0$$

$$f^*(-\sqrt{-g} dx^0 \wedge dx^2 \wedge dx^3) = d\Sigma_1$$

and so on. We can demonstrate that

$$d\Sigma_\mu = \epsilon n_\mu |h|^{\frac{1}{2}} dy^1 \wedge dy^2 \wedge dy^3$$

#### Element of two-surface

Within the hypersurface  $\Sigma$ , we can define a two-surface  $S$ , which is parametrized with  $y^a = y^a(\theta_A)$ , then

$$e_A^a = \frac{\partial y^a}{\partial \theta^A}, \quad e_A^\alpha = \frac{\partial x^\alpha}{\partial \theta^A} = e_a^\alpha e_A^a$$

$$\sigma_{AB} = h_{AB} e_A^a e_B^b = g_{\alpha\beta} e_A^\alpha e_B^\beta$$

$$h^{ab} = \epsilon_r r^a r^b + \sigma^{AB} e_A^a e_B^b$$

$$g^{\alpha\beta} = \epsilon_n n^\alpha n^\beta + \epsilon_r r^\alpha r^\beta + \sigma^{AB} e_A^\alpha e_B^\beta$$

If we demand that the direction  $r^a$  is the opposite of that of  $\frac{\partial y^a}{\partial \theta^1}$ , then the condition of compatibility can be written as

$$\epsilon_{\mu\nu\beta\gamma} n^\mu r^\nu e_2^\beta e_3^\gamma > 0$$

We define the surface element of a two-surface as

$$dS_{\mu\nu} = \epsilon_{\mu\nu\beta\gamma} e_2^\beta e_3^\gamma d\theta^2 \wedge d\theta^3$$

It is easy to verify that

$$f^*(\sqrt{-g} dx^2 \wedge dx^3) = dS_{01}$$



and so on. We can demonstrate that

$$dS_{\alpha\beta} = \epsilon_n \epsilon_r (n_\alpha r_\beta - n_\beta r_\alpha) \sqrt{\sigma} d\theta^2 \wedge d\theta^3$$

### Theorem 6.1 Gauss-Stokes theorem

1.

$$\int_M d\omega = \int_{\partial M} i^* \omega$$

2.

$$\int_{\mathcal{V}} A^\alpha_{;\alpha} \sqrt{-g} dx^4 = \oint_{\partial \mathcal{V}} A^\alpha d\Sigma_\alpha$$

3.

$$\int_\Sigma B^{\alpha\beta}_{;\beta} d\Sigma_\alpha = \frac{1}{2} \oint_{\partial \Sigma} B^{\alpha\beta} d\Sigma_{\alpha\beta},$$

where  $B_{\alpha\beta}$  is an antisymmetric tensor

### 6.3.3 Differentiation of tangent vector fields

#### Tangent tensor field

$$A^{\alpha\beta\cdots} = A^{ab\cdots} e_a^\alpha e_b^\beta \cdots$$

$$A_{\alpha\beta\cdots} e_a^\alpha e_b^\beta \cdots = A_{ab\cdots} = h_{am} h_{bn} \cdots A^{mn\cdots}$$

#### Projection tensor

$$h^{\alpha\beta} \equiv h^{ab} e_a^\alpha e_b^\beta = g^{\alpha\beta} - \epsilon n^\alpha n^\beta$$

#### Intrinsic covariant derivative

$$A_{a|b} \equiv A_{\alpha;\beta} e_a^\alpha e_b^\beta = A_{a,b} - \Gamma_{ab}^c A_c$$

Here, the connection  $\Gamma_{ab}^c$  is compatible with  $h_{ab}$ .

#### Extrinsic curvature

$$K_{ab} \equiv n_{\alpha;\beta} e_a^\alpha e_b^\beta$$

$$A^\alpha_{;\beta} e_b^\beta = A^\alpha_{|b} e_a^\alpha - \epsilon A^a K_{ab} n^\alpha$$

$$e^\alpha_{a;\beta} e_b^\beta = \Gamma_{ab}^c e_c^\alpha - \epsilon K_{ab} n^\alpha$$



$$K_{ab} = \frac{1}{2}(\mathcal{L}_n g_{\alpha\beta})e_a^\alpha e_b^\beta$$

$$K \equiv h^{ab}K_{ab} = n_{;\alpha}^\alpha$$

**Theorem 6.2 Gauss-Codazzi theorem**

1.

$$R_{\alpha\beta\gamma}^\mu e_a^\alpha e_b^\beta e_c^\gamma = R_{abc}^m e_m^\mu + \epsilon(K_{ab|c} - K_{ac|b})n^\mu + \epsilon K_{ab}n_{;\gamma}^\mu e_c^\gamma - \epsilon K_{ac}n_{;\beta}^\mu e_b^\beta$$

2.

$$-2\epsilon G_{\alpha\beta}n^\alpha n^\beta = {}^3R + \epsilon(K^{ab}K_{ab} - K^2)$$

$$G_{\alpha\beta}e_a^\alpha n^\beta = K_{a|b}^b - K_{,a}$$

3.

$$R = {}^3R + \epsilon(K^2 - K^{ab}K_{ab}) + 2\epsilon(n_{;\beta}^\alpha n^\beta - n^\alpha n_{;\beta}^\beta)_{;\alpha}$$



# Chapter 7

## Formulation of General Relativity



Give the fields that generate mass-energy, and their time-rates of change, and give 3-geometry of space and its time-rate of change, all at one time, and solve for the 4-geometry of spacetime at that one time. Four of the ten components of Einstein's law connect the curvature of space here and now with the distribution of mass-energy here and now, and the other six equations tell how the geometry as thus determined then proceeds to evolve.

### 7.1 Basic assumptions of general relativity

1. Space-time is a four dimensional pseudo-Riemann manifold.
2. The metric of the manifold is governed by the Einstein field equation

$$G = 8\pi T.$$

3. All special relativistic laws of physics are valid in local Lorentz frames of metric.

### 7.2 Lagrangian formulation

#### 7.2.1 Mechanics

$$S[q] = \int_{\tau_1}^{\tau_2} L(x^\alpha, \frac{dx^\alpha}{d\tau}) d\tau$$

$$\delta x^\alpha(\tau_1) = 0, \delta x^\alpha(\tau_2) = 0$$

$$\delta S = 0 \Rightarrow \frac{d}{d\tau} \frac{\partial L}{\partial u^\alpha} - \frac{\partial L}{\partial x^\alpha} = 0$$

**Example:**

$$L = -m(-g_{\mu\nu}u^\mu u^\nu)^{-1/2} + eA_\mu u^\mu$$

$\Downarrow$

$$m(\frac{du_\alpha}{d\tau} - \frac{1}{2} \frac{\partial g_{uv}}{\partial x^\alpha} u^\mu u^\nu) = e(A_{\mu,\alpha} - A_{\alpha,\mu})u^\mu \Rightarrow ma_\alpha = eF_{\alpha\mu}u^\mu$$

### 7.2.2 Field Theory

$$S[q] = \int_{\mathcal{V}} \mathcal{L}(q, q_\alpha) \sqrt{-g} d^4x$$

$$\delta q|_{\partial\mathcal{V}} = 0$$

$$\delta S = 0 \Rightarrow \nabla_\alpha \left( \frac{\partial \mathcal{L}}{\partial q_{,\alpha}} \right) - \frac{\partial \mathcal{L}}{\partial q} = 0$$

**Example:**

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + A_\mu j^\mu$$

$$\Downarrow$$

$$F^{\mu\nu}{}_{;\nu} = j^\mu$$

### 7.2.3 General relativity

$$S_H[g] = \frac{1}{16\pi} \int_{\mathcal{V}} R \sqrt{-g} d^4x$$

$$S_B[g] = \frac{1}{8\pi} \oint_{\partial\mathcal{V}} \epsilon K |h|^{\frac{1}{2}} d^3y$$

$$S_0 = \frac{1}{8\pi} \oint_{\partial\mathcal{V}} \epsilon K_0 |h|^{\frac{1}{2}} d^3y$$

$$S_M[\phi; g] = \int_{\partial\mathcal{V}} \mathcal{L}(\phi, \phi_{,\alpha}; g_{\alpha\beta}) \sqrt{-g} d^4x$$

Variation of Hilbert term

$$(16\pi) \delta S_H = \int_{\mathcal{V}} G_{\alpha\beta} \delta g^{\alpha\beta} \sqrt{-g} d^4x - \oint_{\partial\mathcal{V}} \epsilon h^{\alpha\beta} \delta g_{\alpha\beta, \mu} n^\mu |h|^{\frac{1}{2}} d^3y$$

Variation of boundary term

$$16\pi \delta S_B = \oint_{\partial\mathcal{V}} \epsilon h^{\alpha\beta} \delta g_{\alpha\beta, \mu} n^\mu |h|^{\frac{1}{2}} d^3y$$



## Variation of matter action

$$\delta S_M = \int_V \left( \frac{\partial \mathcal{L}}{\partial g^{\alpha\beta}} - \frac{1}{2} \mathcal{L} g_{\alpha\beta} \right) \delta g^{\alpha\beta} \sqrt{-g} d^4x$$

Define

$$T_{\alpha\beta} \equiv -2 \frac{\partial \mathcal{L}}{\partial g^{\alpha\beta}} + \mathcal{L} g_{\alpha\beta}$$

**Example:**

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

$\Downarrow$

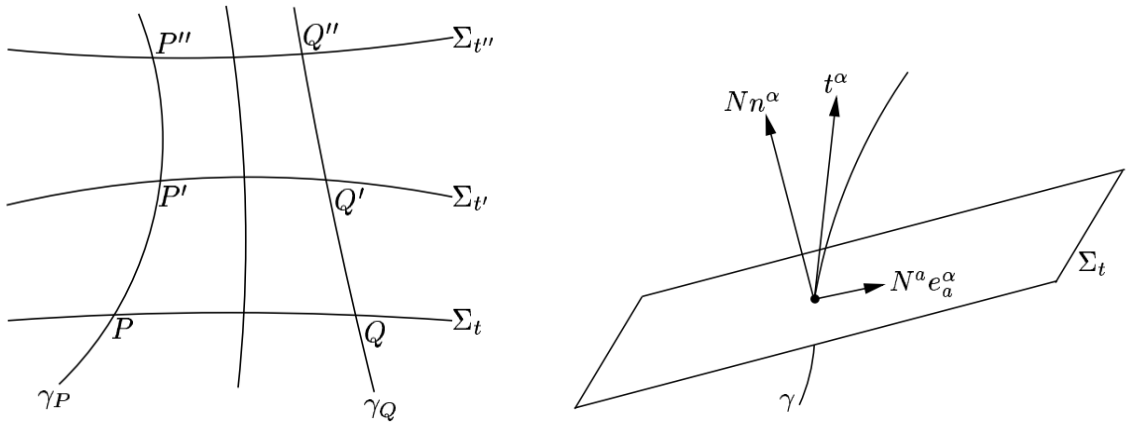
$$T_{\alpha\beta} = F_{\mu\alpha} F^\mu{}_\beta - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} g_{\alpha\beta}$$

## Nondynamical term

$K_0$  = extrinsic curvature of  $\partial\mathcal{L}$  embedded in flat space-time.

## 7.3 Hamiltonian formulation

### 7.3.1 3+1 decomposition



**Figure 7.1:** Foliation of space-time by spacelike hypersurfaces **Figure 7.2:** Decomposition of  $t^\alpha$  into lapse and shift

The space-time is foliated by spacelike hypersurfaces  $\Sigma_t$  that is described by scalar function  $t(x^\alpha)$ .  $t$  is a single valued function and the unit normal to the hypersurfaces  $n_\alpha \propto \partial_\alpha t$  is a future directed timelike vector field.

Consider a congruence of curves  $\gamma$  intersecting  $\Sigma_t$ . We use  $t$  as a parameter on the curves and the vector  $t^\alpha$  is tangent to the congruence (so,  $t^\alpha \partial_\alpha t = 1$ ). Install coordinates  $y^a$  on  $\Sigma_t$  and



impose  $y^a(P'') = y^a(P') = y^a(P)$ , so  $y^a$  is held constant on each member of the congruence. This construction defines a coordinate system  $(t, y^a)$  in  $\mathcal{V}$ .

base vector

$$t^\alpha = \left( \frac{\partial x^\alpha}{\partial t} \right)_{y^a}, \quad e_a^\alpha = \left( \frac{\partial x^\alpha}{\partial y^a} \right)_t, \quad \mathcal{L}_t e_a^\alpha = 0$$

Normal vector

$$n_\alpha = -N \partial_\alpha t, \quad n_\alpha e_a^\alpha = 0$$

Decomposition of  $t^\alpha$

$$t^\alpha = N n^\alpha + N^a e_a^\alpha$$

Metric

$$\begin{aligned} ds^2 &= g_{\alpha\beta} dx^\alpha dx^\beta \\ &= g_{\alpha\beta} (t^\alpha dt + e_a^\alpha dy^a) (t^\beta dt + e_b^\beta dy^b) \\ &= -N^2 dt^2 + h_{ab} (dy^a + N^a dt) (dy^b + N^b dt) \\ \sqrt{-g} &= N \sqrt{h} \end{aligned}$$

### 7.3.2 Field theory

$$\begin{aligned} \dot{q} &= \frac{\partial q}{\partial t}, \quad p = \frac{\partial}{\partial \dot{q}} (\sqrt{-g} \mathcal{L}) \\ \mathcal{H}(p, q, q_a) &= p \dot{q} - \sqrt{-g} \mathcal{L} \\ H &= \int_{\Sigma_t} \mathcal{H}(p, q, q_a) d^3 y \\ S &= \int_{t_1}^{t_2} dt \int_{\Sigma_t} (p \dot{q} - \mathcal{H}) d^3 y \\ \delta S = 0 &\Rightarrow \dot{p} = - \frac{\partial \mathcal{H}}{\partial q} + \left( \frac{\partial \mathcal{H}}{\partial q_{,a}} \right)_{,a}, \quad \dot{q} = \frac{\partial \mathcal{H}}{\partial p} \end{aligned}$$

**Example:** For electromagnetic field in 3+1 decomposition form, we define the electrical field as  $E_a = F_{\alpha\beta} n^\beta e_a^\alpha$ , the magnetic field as  $\epsilon_{abc} B^c = F_{\alpha\beta} e_a^\alpha e_b^\beta$ . In this definition, the equation of motion of particles in electromagnetic field can be written as

$$mA_a = \gamma e (E_a + \epsilon_{abc} v^b B^c)$$





Here,  $A_a = u_{\alpha;\beta} u^\beta e_a^\alpha$ ,  $\gamma = \frac{1}{\sqrt{1-v^2}}$ . So, the three force

$$\vec{f} = \frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{B})$$

If we adopt the coordinates  $(t, y^a)$ , it is easy to verify that

$$E^a = NF^{0a}, \quad B^a = \frac{1}{2}\epsilon^{abc}F_{bc}$$

We further define

$$\mathcal{E}^a = \sqrt{h}E^a, \quad \mathcal{B}^a = \sqrt{h}B^a, \quad \phi = -A_0, \quad \rho_e = -j^\alpha n_\alpha = Nj^0$$

If we notice that

$$F_{0a} = -h_{ab}N^2F^{0b} - F_{ab}N^b, \quad \tilde{\epsilon}_{abc}\tilde{\epsilon}_{ijk}h^{ai}h^{bj} = \frac{2h_{ck}}{h}$$

It is easy to verify that

$$\sqrt{-g}\mathcal{L} = -\mathcal{E}^a \dot{A}_a + \phi \mathcal{E}_{,a}^a - \frac{1}{2}Nh^{-\frac{1}{2}}h_{ab}(\mathcal{E}^a\mathcal{E}^b + \mathcal{B}^a\mathcal{B}^b) + \tilde{\epsilon}_{abc}N^a\mathcal{E}^b\mathcal{B}^c - \sqrt{h}\phi\rho_e + N\sqrt{h}A_a j^a$$

So,  $\pi^a = -\mathcal{E}^a$ , and we can get the Hamilton density

$$\mathcal{H} = \phi\pi_{,a}^a + \frac{1}{2}Nh^{-\frac{1}{2}}h_{ab}(\pi^a\pi^b + \mathcal{B}^a\mathcal{B}^b) + \tilde{\epsilon}_{abc}N^a\pi^b\mathcal{B}^c + \sqrt{h}\phi\rho_e - N\sqrt{h}A_a j^a$$

Then, the Hamilton equation can be written as

$$\begin{aligned} \dot{A}_a &= -\phi_a + Nh^{-\frac{1}{2}}h_{ab}\pi^b + \tilde{\epsilon}_{abc}N^a\mathcal{B}^c \\ \dot{\pi}^a &= -\tilde{\epsilon}^{jab}(Nh^{-\frac{1}{2}}h_{ij}\mathcal{B}^i)_{,b} - \tilde{\epsilon}^{cab}(\tilde{\epsilon}_{ijc}N^i\pi^j)_{,b} + N\sqrt{h}j^a \end{aligned}$$

and also the constraint equation  $\pi_{,a}^a + \sqrt{h}\rho_e = 0$ . After simplification, the Maxwell equations are

$$\begin{aligned} \frac{1}{\sqrt{h}}\frac{\partial}{\partial t}(\sqrt{h}\vec{E}) &= \nabla \times (N\vec{B} - \vec{N} \times \vec{E}) - N\vec{J} \\ \frac{1}{\sqrt{h}}\frac{\partial}{\partial t}(\sqrt{h}\vec{B}) &= -\nabla \times (N\vec{E} + \vec{N} \times \vec{B}) \\ \nabla \cdot \vec{E} &= \rho_e \\ \nabla \cdot \vec{B} &= 0 \end{aligned}$$

### 7.3.3 General relativity

$$S_G = \frac{1}{16\pi} \int_{t_1}^{t_2} dt \left\{ \int_{\Sigma_t} ({}^3R + K^{ab}K_{ab} - K^2) N\sqrt{h}d^3y + 2 \oint_{\Sigma_t} (k - k_0) N\sqrt{\sigma}d^2\theta \right\}$$

$k_0$  = extrinsic curvature of  $S_t$  embedded in flat space.



## Gravitational Hamiltonian

$$\begin{aligned}
\dot{h}_{ab} &\equiv \mathcal{L}_t h_{ab} = \mathcal{L}_t(g_{\alpha\beta} e_a^\alpha e_b^\beta) = \mathcal{L}_t(g_{\alpha\beta} e_a^\alpha e_b^\beta) = 2N K_{ab} + N_{a|b} + N_{b|a}) \\
K_{ab} &= \frac{1}{2N}(\dot{h}_{ab} - N_{a|b} - N_{b|a}) \\
p^{ab} &= \frac{\partial}{\partial \dot{h}_{ab}}(\sqrt{-g} \mathcal{L}_G) = \frac{\sqrt{h}}{16\pi}(K^{ab} - K h^{ab}) \\
\sqrt{h} K^{ab} &= 16\pi(p^{ab} - \frac{1}{2} p h^{ab}) \\
\mathcal{H}_G &= p^{ab} \dot{h}_{ab} - \sqrt{-g} \mathcal{L}_G \\
16\pi H_G &= \int_{\Sigma_t} [N(K^{ab} K_{ab} - K^2 - {}^3R) - 2N_a(K^{ab} - K h^{ab})_{|b}] \sqrt{h} d^3y \\
&\quad - 2 \oint_{S_t} [N(k - k_0) - N_a(K^{ab} - K h^{ab}) r_b] \sqrt{\sigma} d^2\theta
\end{aligned}$$

## Variation of gravitational Hamiltonian

$$\begin{aligned}
\delta N &= \delta N^a = \delta h_{ab} = 0 \text{ on } S_t \\
\delta H_G &= \int_{\Sigma_t} (\mathcal{P}^{ab} \delta h_{ab} + \mathcal{H}_{ab} \delta p^{ab} - \mathcal{C} \delta N - 2\mathcal{C}_a \delta N^a) d^3y \\
(16\pi) \mathcal{P}^{ab} &= N\sqrt{h} G^{ab} - \sqrt{h}(N^{ab} - h^{ab} N^{lc}) \\
&\quad + (16\pi)[2p^{c(a} N^{b)}_{|c} - \sqrt{h}(\frac{1}{\sqrt{h}} p^{ab} N^c)_{|c}] \\
&\quad + (16\pi)^2 [\frac{2N}{\sqrt{h}}(p_c^a p^{bc} - \frac{1}{2} p p^{ab}) - \frac{N}{2\sqrt{h}}(p^{cd} p_{cd} - \frac{1}{2} p^2) h^{ab}] \\
\mathcal{H}_{ab} &= (16\pi) \frac{2N}{\sqrt{h}}(p_{ab} - \frac{1}{2} p h_{ab}) + 2N_{(a|b)} \\
\mathcal{C} &= \frac{\sqrt{h}}{16\pi}({}^3R + K^2 - K^{ab} K_{ab}) \\
\mathcal{C}^a &= \frac{\sqrt{h}}{16\pi}(K_a{}^b - K \delta_a{}^b)_{|b}
\end{aligned}$$

## Variation of electromagnetic Hamiltonian

$$\begin{aligned}
\delta H_E &= \int_{\Sigma_t} (-\frac{1}{2} N \sqrt{h} \mathcal{I}^{ab} \delta h_{ab} + \sqrt{h} \rho \delta N - \sqrt{h} s_a \delta N^a) \\
\mathcal{I}^{ab} &= \frac{1}{2}(E^c E_c + B^c B_c) h^{ab} - E^a E^b - B^a B^b \\
\rho &= \frac{1}{2}(E^c E_c + B^c B_c) \\
s_a &= \epsilon_{abc} E^b B^c
\end{aligned}$$



## Hamilton's equations

$$\dot{h}_{ab} = \mathcal{H}_{ab}, \quad \dot{p}^{ab} = -\mathcal{P}^{ab} + \frac{1}{2}N\sqrt{h}\mathcal{I}^{ab}$$

$${}^3R + K^2 - K^{ab}K_{ab} = 16\pi\rho$$

$$(K_a{}^b - K\delta_a{}^b)_{|b} = -8\pi s_a$$



## **Part IV**

# **Quantum Mechanics**

# Chapter 8

## Linear Algebra



### 8.1 Linear Vector Space

#### 8.1.1 Definition

##### Definition 8.1 Linear vector space

A linear vector space is a set of elements, called vectors, which is closed under addition and multiplication by scalars. That is to say, if  $\phi$  and  $\psi$  are vectors then so is  $a\phi + b\psi$ , where  $a$  and  $b$  are arbitrary scalars. If the scalars belong to the field of complex (real) numbers, we speak of a complex (real) linear vector space. Henceforth the scalars will be complex numbers unless otherwise stated.

**Example:**

1. Discrete vectors, which may be represented as columns of complex numbers.
2. Spaces of functions of some type, for example the space of all differentiable functions

#### 8.1.2 Linear independence

##### Definition 8.2 Linear independence

A set of vectors  $\{\phi_n\}$  is said to be linearly independent if no non-trivial linear combination of them sums to zero; that is to say, if the equation  $\sum_n c_n \phi_n$  can hold only when  $c_n = 0$  for all  $n$ . If this condition does not hold, the set of vectors is said to be linearly dependent, in which case it is possible to express a member of the set as a linear combination of the others.

##### Definition 8.3 Dimension

The maximum number of linearly independent vectors in a space is called the dimension of the space.

#### Definition 8.4 Base

A maximal set of linearly independent vectors is called a basis for the space. Any vector in the space can be expressed as a linear combination of the basis vectors.

### 8.1.3 Inner product

#### Definition 8.5 Inner product

An inner product (or scalar product) for a linear vector space associates a scalar  $(\phi, \psi)$  with every ordered pair of vectors. It must satisfy the following properties:

1.  $(\phi, \psi) = a$  complex number
2.  $(\phi, \psi) = (\psi, \phi)^*$
3.  $(\phi, c_1\phi_1 + c_2\psi_2) = c_1(\phi, \psi_1) + c_2(\phi, \psi_2)$
4.  $(\phi, \phi) > 0$ , with equality holding if and only if  $\phi = 0$

#### Example:

1. If  $\psi$  is the column vector with elements  $a_1, a_2, \dots$ , and  $\phi$  is the column vector with elements  $b_1, b_2, \dots$ , then

$$(\psi, \phi) = a_1^*b_1 + a_2^*b_2 + \dots$$

2. If  $\psi$  and  $\phi$  are functions of  $x$ , then

$$(\phi, \psi) = \int \psi^*(x)\phi(x)w(x)dx$$

where  $w(x)$  is some non-negative weight function.

#### Definition 8.6 Norm

$$||\phi|| = (\phi, \phi)^{\frac{1}{2}}$$

#### Theorem 8.1 Schwarz's inequality

$$|(\psi, \phi)|^2 \leq (\psi, \psi)(\phi, \phi)$$



**Theorem 8.2 triangle inequality**

$$||(\psi + \phi)|| \leq ||\phi|| + ||\psi||$$

**Definition 8.7 Orthonormal**

A set of vectors  $\{\phi_n\}$  is said to be orthonormal if the vectors are pairwise orthogonal and of unit norm; that is to say, their inner products satisfy  $(\psi_m, \phi_n) = \delta_{mn}$ .

**8.1.4 Dual space****Definition 8.8 Dual vector**

Corresponding to any linear vector space  $V$  there exists the dual space of linear functionals on  $V$ . A linear functional  $F$  assigns a scalar  $F(\phi)$  to each vector  $\phi$ , such that

$$F(a\phi + b\psi) = aF(\phi) + bF(\psi)$$

for any vectors for  $\phi$  and  $\psi$ , and any scalars  $a$  and  $b$ . The set of linear functionals may itself be regarded as forming a linear space  $V'$  if we define the sum of two functionals as

$$(F_1 + F_2)(\phi) = F_1(\phi) + F_2(\phi)$$

**Theorem 8.3 Riesz theorem**

There is a one-to-one correspondence between linear functionals  $F$  in  $V'$  and vectors  $f$  in  $V$ , such that all linear functionals have the form

$$F(\phi) = (f, \phi)$$

$f$  being a fixed vector, and  $\phi$  being an arbitrary vector. Thus the spaces  $V$  and  $V'$  are essentially isomorphic.

**8.1.5 Dirac's bra and ket notation**

In Dirac's notation, which is very popular in quantum mechanics, the vectors in  $V$  are called ket vectors, and are denoted as  $|\phi\rangle$ . The linear functionals in the dual space  $V'$  are called bra vectors, and are denoted as  $\langle F|$ . The numerical value of the functional is denoted as

$$F(\phi) = \langle F|\phi\rangle$$



According to the Riesz theorem, there is a one-to-one correspondence between bras and kets. Therefore we can use the same alphabetic character for the functional (a member of  $V'$ ) and the vector (in  $V$ ) to which it corresponds, relying on the bra,  $\langle F|$ , or ket,  $|F\rangle$ , notation to determine which space is referred to. So

$$\langle F|\phi\rangle = (F, \phi)$$

Note that the Riesz theorem establishes, by construction, an antilinear correspondence between bras and kets. If  $\langle F| \leftrightarrow |F\rangle$ , then

$$c_1^* \langle F_1| + c_2^* \langle F_2| \leftrightarrow c_1 |F_1\rangle + c_2 |F_2\rangle$$

## 8.2 Linear Operators

### Definition 8.9 Linear operators

An operator on a vector space maps vectors onto vectors. A linear operator satisfies

$$A(c_1\psi_1 + c_2\psi_2) = c_1A(\psi_1) + c_2A(\psi_2)$$

Define the sum and product of operators,

$$\begin{aligned}(A + B)\psi &= A\psi + B\psi \\ AB\psi &= A(B\psi)\end{aligned}$$

Define their action to the left on bra vectors as

$$(\langle\phi|A)\psi = \langle\phi|(A\psi)$$

So we may define the operation of  $A$  on the bra space of functionals as

$$AF_\phi(\psi) = F_\phi(A\psi)$$

According to the Riesz theorem there must exist a ket vector  $\chi$  such that

$$AF_\phi(\psi) = (\chi, \psi) = F_\chi(\psi)$$

Define operator  $A^\dagger$  as

$$AF_\phi = F_{A^\dagger\chi}$$

Therefore,

$$\begin{aligned}(A^\dagger\phi, \psi) &= (\phi, A\psi) \\ \langle\phi|A^\dagger|\psi\rangle^* &= \langle\psi|A|\phi\rangle\end{aligned}$$





**Definition 8.10 Outer product**

$$(|\psi\rangle\langle\phi|)|\lambda\rangle \equiv |\psi\rangle\langle\phi|\lambda\rangle$$

**Definition 8.11 Trace**

$$\text{Tr} A \equiv \sum \langle u_j | A | u_j \rangle$$

where  $\{u_j\}$  may be any orthonormal basis. It can be shown that the value of  $\text{Tr} A$  is independent of the particular orthonormal basis that is chosen for its evaluation.

**Proposition 8.1**

$$\begin{aligned} (cA)^\dagger &= c^* A^\dagger \\ (A+B)^\dagger &= A^\dagger + B^\dagger \\ (AB)^\dagger &= B^\dagger A^\dagger \\ (|\psi\rangle\langle\phi|)^\dagger &= |\phi\rangle\langle\psi| \end{aligned}$$



## 8.3 Self-Adjoint operators

**Definition 8.12 Self-Adjoint operators**

An operator  $A$  that is equal to its adjoint  $A^\dagger$  is called self-adjoint. This means that it satisfies

$$\langle\phi|A|\psi\rangle = \langle\psi|A|\phi\rangle^*$$



and that the domain of  $A$  coincides with the domain of  $A^\dagger$ . An operator that only satisfies above equation is called Hermitian.



**Theorem 8.4**

If  $\langle \psi | A | \psi \rangle = \langle \psi | A | \psi \rangle^*$  for all  $|\psi\rangle$ , then it follows that  $\langle \phi_1 | A | \phi_2 \rangle = \langle \phi_2 | A | \phi_1 \rangle^*$  for all  $|\phi_1\rangle$  and  $|\phi_2\rangle$ , and hence that  $A = A^\dagger$ .

If an operator acting on a certain vector produces a scalar multiple of that same vector,

$$A|\phi\rangle = a|\phi\rangle$$

we call the vector  $|\phi\rangle$  an eigenvector and the scalar  $a$  an eigenvalue of the operator  $A$ . The antilinear correspondence between bras and kets, and the definition of the adjoint operator  $A^\dagger$ , imply that the left-handed eigenvalue equation

$$\langle \phi | A^\dagger = a^* \langle \phi |$$

**Theorem 8.5**

If  $A$  is a Hermitian operator then all of its eigenvalues are real.

**Theorem 8.6**

Eigenvectors corresponding to distinct eigenvalues of a Hermitian operator must be orthogonal.

If the orthonormal set of vectors  $\{\phi_i\}$  is complete, then we can expand an arbitrary vector  $|v\rangle$  in terms of it:

$$|v\rangle = \sum |\phi_i\rangle (\langle \phi_i | v \rangle) = \left( \sum |\phi_i\rangle \langle \phi_i| \right) |v\rangle$$

So,

$$\sum |\phi_i\rangle \langle \phi_i| = I$$

If  $A|\phi_i\rangle = a_i|\phi_i\rangle$  and the eigenvectors form a complete orthonormal set, then the operator can be reconstructed in a useful diagonal form in terms of its eigenvalues and eigenvectors:

$$A = \sum a_i |\phi_i\rangle \langle \phi_i|$$

We can define a function of an operator

$$f(A) = \sum f(a_i) |\phi_i\rangle \langle \phi_i|$$

The Hermitian operators in a finite N-dimensional vector space have complete sets of eigenvectors. But This statement does not carry over to infinite-dimensional spaces. A Hermitian operator in an infinite dimensional vector space may or may not possess a complete set of eigenvectors, depending upon the precise nature of the operator and the vector space. Instead, we have spectral theorem.



**Theorem 8.7**

To each self-adjoint operator  $A$  there corresponds a unique family of projection operators,  $E(\lambda)$ , for real  $\lambda$ , with the properties:

1. If  $\lambda_1 < \lambda_2$  then  $E(\lambda_1)E(\lambda_2) = E(\lambda_2)E(\lambda_1)E(\lambda_1)$
2. If  $\epsilon > 0$ , then  $E(\lambda + \epsilon)|\psi\rangle \rightarrow E(\lambda)|\psi\rangle$  as  $\epsilon \rightarrow 0$
3.  $E(\lambda)|\psi\rangle \rightarrow 0$  as  $\lambda \rightarrow -\infty$
4.  $E(\lambda)|\psi\rangle \rightarrow |\psi\rangle$  as  $\lambda \rightarrow \infty$
5.  $\int_{-\infty}^{\infty} \lambda E(\lambda) = A$

We can define a function of an operator

$$f(A) = \int_{-\infty}^{\infty} f(\lambda) E(\lambda)$$

Following Dirac's pioneering formulation, it has become customary in quantum mechanics to write a formal eigenvalue equation for an operator such as  $Q$  that has a continuous spectrum,

$$Q|q\rangle = q|q\rangle$$

The orthonormality condition for the continuous case takes the form

$$\langle q'|q''\rangle = \delta(q - q')$$

Evidently the norm of these formal eigenvectors is infinite, since  $\langle q|q\rangle \rightarrow \infty$ . Instead of the spectral theorem for  $Q$ , Dirac would write

$$Q = \int_{-\infty}^{\infty} q|q\rangle\langle q|dq$$

Dirac's formulation does not fit into the mathematical theory of Hilbert space, which admits only vectors of finite norm. The projection operator formally given by

$$E(\lambda) = \int_{-\infty}^{\lambda} |q\rangle\langle q|dq$$

is well defined in Hilbert space, but its derivative does not exist within the Hilbert space framework.

**Theorem 8.8**

If  $A$  and  $B$  are self-adjoint operators, each of which possesses a complete set of eigenvectors, and if  $AB = BA$ , then there exists a complete set of vectors which are eigenvectors of both  $A$  and  $B$ .



Let  $(A, B, \dots)$  be a set of mutually commutative operators that possess a complete set of common eigenvectors. Corresponding to a particular eigenvalue for each operator, there may be more than one eigenvector. If, however, there is no more than one eigenvector (apart from the arbitrary phase and normalization) for each set of eigenvalues  $(a_n, b_m, \dots)$ , then the operators  $(A, B, \dots)$  are said to be a complete commuting set of operators.

#### Theorem 8.9

Any operator that commutes with all members of a complete commuting set must be a function of the operators in that set.



## 8.4 Rigged Hilbert space

### Definition 8.13 Rigged Hilbert space

Formally, a rigged Hilbert space consists of a Hilbert space  $\mathcal{H}$ , together with a subspace  $\Phi$  which carries a finer topology, that is one for which the natural inclusion  $\Phi \subseteq \mathcal{H}$  is continuous. It is no loss to assume that  $\Phi$  is dense in  $\mathcal{H}$  for the Hilbert norm. We consider the inclusion of conjugate space  $\mathcal{H}^X$  in  $\Phi^X$ .  $\Phi^X$  is the space of  $\tau_\Phi$  continuous antilinear functional on  $\Phi$ .

For any  $\phi \in \Phi$ ,  $F \in \Phi^X$ , we define

$$\langle \phi | F \rangle \equiv F(\phi)$$

$$\langle F | \phi \rangle \equiv F^*(\phi)$$

Now by applying the Riesz representation theorem we can identify  $\mathcal{H}^X$  with  $\mathcal{H}$ . Therefore, the definition of rigged Hilbert space is in terms of a sandwich:

$$\Phi \subseteq \mathcal{H} \subseteq \Phi^X$$



There may or may not exist any solutions to the eigenvalue equation  $A|a_n\rangle = a_n|a_n\rangle$  for a self-adjoint operator  $A$  on an infinite-dimensional vector space. However, the generalized spectral theorem asserts that if  $A$  is self-adjoint in  $\mathcal{H}$  then a complete set of eigenvectors exists in the extended space  $\Phi^X$ . The precise conditions for the proof of this theorem are rather technical, so the interested reader is referred to *Gel'fand and Vilenkin (1964)* for further details.

There are many examples of rigged-Hilbert-space triplets. A Hilbert space  $\mathcal{H}$  is formed by those functions that are square-integrable. That is,  $\mathcal{H}$  consists of those functions  $\psi(x)$  for which

$$\langle \psi | \psi \rangle = \int_{-\infty}^{\infty} |\psi(x)|^2 dx \text{ is finite}$$

A nuclear space  $\Phi$  is made up of functions  $\psi(x)$  which satisfy the infinite set of conditions,

$$\int_{-\infty}^{\infty} |\psi(x)|^2 (1 + |x|)^m dx \text{ is finite for } m = 0, 1, 2, \dots$$




The functions  $\psi(x)$  which make up  $\Phi$  must vanish more rapidly than any inverse power of  $x$  in the limit  $|x| \rightarrow \infty$ . The extended space  $\Phi^X$ , which is conjugate to  $\Phi$ , consists of those functions  $\chi(x)$  for which

$$\langle \chi | \psi \rangle = \int_{-\infty}^{\infty} \chi^*(x) \psi(x) dx \text{ is finite for any } \psi \text{ in } \Phi$$

In addition to the functions of finite norm, which also lie in  $\mathcal{H}$ ,  $\Phi^X$  will contain functions that are unbounded at infinity provided the divergence is no worse than a power of  $x$ . Hence  $\Phi^X$  contains  $e^{ikx}$ , which is an eigenfunction of the operator  $D = i \frac{d}{dx}$ . It also contains the Dirac delta function,  $\delta(x - \lambda)$ , which is an eigenfunction of the operator  $X$ , defined by  $X\psi(x) = x\psi(x)$ . These two examples suffice to show that rigged Hilbert space seems to be a more natural mathematical setting for quantum mechanics than is Hilbert space.

## 8.5 Unitary operators

### Definition 8.14 Unitary operator

A unitary operator is a bounded linear operator  $U : H \rightarrow H$  on a Hilbert space  $H$  that satisfies  $UU^\dagger = U^\dagger U = I$ , where  $U^\dagger$  is the adjoint of  $U$ , and  $I : H \rightarrow H$  is the identity operator. 

Consider a family of unitary operators,  $U(s)$ , that depend on a single continuous parameter  $s$ . Let  $U(0) = I$  be the identity operator, and let  $U(s_1 + s_2) = U(s_1)U(s_2)$ . We can demonstrate that

$$\left. \frac{dU}{ds} \right|_{s=0} = iK \text{ with } K = K^\dagger$$

The Hermitian operator  $K$  is called the generator of the family of unitary operators because it determines  $U(s)$ , not only for infinitesimal  $s$ , but for all  $s$ . This can be shown by differentiating

$$U(s_1 + s_2) = U(s_1)U(s_2)$$

with respect to  $s_2$  and we can get

$$\left. \frac{dU}{ds} \right|_{s=s_1} = U(s_1)iK$$

This first order differential equation with initial condition  $U(0) = I$  has the unique solution

$$U(s) = e^{iKs}$$



## 8.6 Antiunitary operators

### Definition 8.15 Antiunitary operator

In mathematics, an antiunitary transformation, is a bijective antilinear map

$$U : H_1 \rightarrow H_2$$

between two complex Hilbert spaces such that

$$\langle Ux, Uy \rangle = \overline{\langle x, y \rangle}$$

for all  $x$  and  $y$  in  $H_1$ , where the horizontal bar represents the complex conjugate. If additionally one has  $H_1 = H_2$  then  $U$  is called an antiunitary operator.

### Proposition 8.2

1.  $\langle Ux, Uy \rangle = \overline{\langle x, y \rangle} = \langle y, x \rangle$  holds for all elements  $x, y$  of the Hilbert space and an antiunitary  $U$ .
2. When  $U$  is antiunitary then  $U^2$  is unitary. This follows from

$$\langle U^2x, U^2y \rangle = \overline{\langle Ux, Uy \rangle} = \langle x, y \rangle$$

3. For unitary operator  $V$  the operator  $VK$ , where  $K$  is complex conjugate operator, is antiunitary. The reverse is also true, for antiunitary  $U$  the operator  $UK$  is unitary.
4. For antiunitary  $U$  the definition of the adjoint operator  $U^*$  is changed into

$$\langle U^*x, y \rangle = \overline{\langle x, Uy \rangle}$$

5. The adjoint of an antiunitary  $U$  is also antiunitary and  $UU^* = U^*U = 1$ .



# Chapter 9

## Formulation of quantum mechanics



### 9.1 Axioms of quantum mechanics

1. The properties of a quantum system are completely defined by specification of its state vector  $|\psi\rangle$ . The state vector is an element of a complex Hilbert space  $\mathcal{H}$  called the space of states.
2. With every physical property  $A$  (energy, position, momentum, angular momentum, ...) there exists an associated linear, Hermitian operator  $A$  (usually called observable), which acts in the space of states. The eigenvalues of the operator are the possible values of the physical properties.
3.
  - If  $|\psi\rangle$  is the vector representing the state of a system and if  $|\phi\rangle$  represents another physical state, there exists a probability  $P(|\psi\rangle, |\phi\rangle)$  of finding  $|\psi\rangle$  in state  $|\phi\rangle$ , which is given by the squared modulus of the scalar product on  $\mathcal{H}$  :  $P(|\psi\rangle, |\phi\rangle) = |\langle\psi|\phi\rangle|^2$  (Born Rule)
  - If  $A$  is an observable with eigenvalues  $a_k$  and eigenvectors  $|k\rangle$ , given a system in the state  $|\psi\rangle$ , the probability of obtaining  $a_k$  as the outcome of the measurement of  $A$  is  $|\langle k|\psi\rangle|^2$ . After the measurement the system is left in the state projected on the subspace of the eigenvalue  $a_k$  (Wave function collapse).
4. The evolution of a closed system is unitary. The state vector  $|\psi(t)\rangle$  at time  $t$  is derived from the state vector  $|\psi(t_0)\rangle$  at time  $t_0$  by applying a unitary operator  $U(t, t_0)$ , called the evolution operator:  $|\psi(t)\rangle = U(t, t_0)|\psi(t_0)\rangle$ .

### 9.2 Transformations of States

A transformation of states can be described by  $|\psi\rangle \rightarrow U(\tau)|\psi\rangle \equiv |\psi'\rangle$ . And we demand that

$$|\langle\phi|\psi\rangle| = |\langle\phi'|\psi'\rangle|$$

#### Theorem 9.1 Wigner Theorem

Any mapping of the vector space onto itself that preserves the value of  $|\langle\phi|\psi\rangle|$  may be implemented by an operator  $U$  with  $U$  being either unitary (linear) or antiunitary (antilinear).



### Continuous transformation

Only linear operators can describe continuous transformations because every continuous transformation has a square root. Suppose, for example, that  $U(l)$  describes a displacement through the distance  $l$ . This can be done by two displacements of  $U(l/2)$ , and hence  $U(l) = U(l/2)U(l/2)$ . The product of two antilinear operators is linear, since the second complex conjugation nullifies the effect of the first. Thus, regardless of the linear or antilinear character of  $U(l/2)$ , it must be the case that  $U(l)$  is linear. A continuous operator cannot change discontinuously from linear to antilinear as a function of  $l$ , so the operator must be linear for all  $l$ .

### Transformations of observables

For an observable  $Q$ ,

$$\langle \phi' | Q | \phi' \rangle = \langle \phi | U^{-1} Q U | \phi \rangle$$

If  $U(\tau)^{-1} Q U(\tau) = \tau Q$ , we can prove that

$$U|q\rangle = |\tau q\rangle$$

Here,  $|q\rangle$  is the eigenvector of  $Q$  with eigenvalue  $q$ .

## 9.3 Schrödinger equation

$U(t, t_0)$  is unitary and  $U(t_2, t_0) = U(t_2, t_1)U(t_1, t_0)$ . We can define  $H(t_0)$  as

$$\left. \frac{d}{dt} U(t, t_0) \right|_{t=t_0} = -iH(t_0) \text{ with } H(t_0) = H(t_0)^\dagger$$

We can demonstrate that

$$\left. \frac{dU(t, t_0)}{dt} \right|_{t=t_1} = -iH(t_1)U(t_1, t_0)$$

The formal solution of the differential equation is

$$U(t, t_0) = I + (-i)^n \sum_{n=1}^{\infty} \int_{t_0}^t dt_1 \int_{t_0}^{t_1} dt_2 \cdots \int_{t_0}^{t_{n-1}} dt_n H(t_1)H(t_2) \cdots H(t_n)$$

Suppose that  $T$  stands for time ordering, placing all operators evaluated at later times to the left, the above equation can be written as

$$U(t, t_0) = I + \frac{(-i)^n}{n!} \sum_{n=1}^{\infty} \int_{t_0}^t dt_1 \int_{t_0}^{t_1} dt_2 \cdots \int_{t_0}^{t_{n-1}} dt_n T\{H(t_1)H(t_2) \cdots H(t_n)\} \equiv \exp \left[ -iT \left\{ \int_{t_0}^t H(t') dt' \right\} \right]$$

If the Hamiltonian operator  $H$  is time-dependent but the  $H$ 's at different times commute. The equation above can be simplified to

$$U(t, t_0) = \exp \left[ -i \int_{t_0}^t H(t') dt' \right]$$





If the  $H$  is time-independent, then

$$U(t, t_0) = \exp[-iH(t - t_0)]$$

Since  $|\psi(t)\rangle = U(t, t_0)|\psi(t_0)\rangle$ , we can derive the Schrödinger equation

$$\frac{d|\psi(t)\rangle}{dt} = -iH(t)|\psi(t)\rangle$$

The expectation value of an observable  $Q$  is  $\langle\psi|Q|\psi\rangle$ , denoted by  $\langle Q\rangle$ . We can then derive that

$$\frac{d\langle Q\rangle}{dt} = -i \left\{ \langle [Q, H] \rangle + \langle \frac{\partial Q}{\partial t} \rangle \right\}$$

This is called Ehrenfest's theorem.

## 9.4 Position operators

In three dimensional space, for a particle, we have three operators corresponding to the observations of its position in space,  $\mathbf{X} = (X_1, X_2, X_3)$ . If the particle has some other internal degrees of freedom, then  $\mathbf{X}$  plus some other observables  $S$ 's will form a complete commuting set of operators. The eigenstate state will be denoted by  $|\mathbf{x}, s\rangle$ , satisfying that

$$X_i|\mathbf{x}, s\rangle = x_i|\mathbf{x}, s\rangle$$

It describes a particle posited in  $\mathbf{x}$  with internal state  $s$ . And we will normalize  $|\mathbf{x}, s\rangle$  by

$$\langle \mathbf{x}, s' | \mathbf{x}, s \rangle = \delta_{ss'} \delta(\mathbf{x} - \mathbf{x}')$$

## 9.5 Momentum operators and canonical quantization

Since  $\mathbf{X}$  plus some other observables  $S$ 's form a complete commuting set of operators. So, the momentum operators can not be independent of them. Numerous experiments shows that the position and momentum of particles can not be measured simultaneously. So, we expect  $[X, P] \neq 0$ .

**Guess** For a system which has a classical correspondence, the classical equation of motion of a particle is

$$\begin{aligned} \dot{x} &= [x, H_C(x, p, t)]_C \\ \dot{p} &= [p, H_C(x, p, t)]_C \end{aligned}$$

$[\ ]_C$  is the Poisson bracket in classical mechanics. In quantum mechanics,

$$\begin{aligned} \frac{d\langle X \rangle}{dt} &= -i\langle [X, H] \rangle \\ \frac{d\langle P \rangle}{dt} &= -i\langle [P, H] \rangle \end{aligned}$$



If we assume that the classical equation of motion of a particle is an approximation of quantum mechanics, we may expect

$$[ \quad ] = i[ \quad ]_C$$

Since the Poisson bracket in classical mechanics and commutation bracket in quantum mechanics have the same algebra structure. To get the right classical equation of motion of the particle, we demand that

$$[X_i, X_j] = 0 \quad [X_i, X_j] = 0 \quad [X_i, P_j] = i\delta_{ij}$$

and

$$H = H_C(X, P, t)$$

For a general system, we formally define momentum operator  $\mathbf{P}$  by

$$[X_i, P_j] = i\delta_{ij}$$

The form of  $H$  can not be given a priori, which can be specified only by the hints from classical theory and experiments.

## 9.6 Momentum operators and translation of states

### Theorem 9.2

$$\exp(iG\lambda)A\exp(-iG\lambda) = A + i\lambda[G, A] + \cdots + \frac{i^n \lambda^n}{n!} [G, [G, [G, \cdots [G, A]]] \cdots] + \cdots$$

Define  $T(\mathbf{a}) \equiv e^{-i\mathbf{P} \cdot \mathbf{a}}$  We can get

$$T(\mathbf{a})^{-1} \mathbf{X} T(\mathbf{a}) = \mathbf{X} + \mathbf{a}$$

$$T(\mathbf{a})|x\rangle = |x + \mathbf{a}\rangle$$

So,  $T(\mathbf{a})$  is the space translation operator. Now, we can also define the momentum operator as the generator of space translation.

## 9.7 Angular momentum operators and rotation of states

We define the angular momentum operators  $\mathbf{J}$  as the generator of rotation.

$$R(\boldsymbol{\theta}) \equiv e^{-i\mathbf{J} \cdot \mathbf{n}\theta}$$

If the operator  $\mathbf{M} = (M_1, M_2, M_3)$  is a vector in configuration space and can be rotated by  $R$ , then we can demonstrate that

$$[J_i, M_j] = i\epsilon_{ijk}M_k$$

Especially,

$$[J_i, J_j] = i\epsilon_{ijk}J_k$$



### Orbital angular momentum

Orbital angular momentum of a particle is defined as  $\mathbf{L} = \mathbf{X} \times \mathbf{P}$ . It is the generator of rotation of the position of the particle, since

$$[L_i, X_j] = i\epsilon_{ijk}X_k \quad [L_i, P_j] = i\epsilon_{ijk}P_k \quad [L_i, L_j] = i\epsilon_{ijk}L_k$$

### Spin angular momentum

Experiments show that some microscopic particles possess a property called spin. The state of the spin is denoted by  $|s\rangle$ . The corresponding operators are  $\mathbf{S} = [S_1, S_2, S_3]$ , which measure the spin along the 1, 2, 3 direction. Spin operator is the generator of rotation of the spin of the particle, so we have

$$[S_i, S_j] = i\epsilon_{ijk}S_k$$

And the rotation of position and spin is independent, so

$$[S_i, L_j] = 0$$

### Total angular momentum

The total angular momentum of the particle is

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

It is the generator of the rotation of the entire system, which is equivalent to the rotation of the coordinates in opposite direction.

## 9.8 Heisenberg picture

Define

$$Q_H = U^\dagger(t, t_0)QU(t, t_0)$$

We can derive that

$$\frac{dQ_H(t)}{dt} = -i[Q_H(t), H_H(t)] + \left(\frac{\partial Q}{\partial t}\right)_H$$

Here,  $H_H(t) = U^\dagger(t, t_0)H(t)U(t, t_0)$  If the state of the system at  $t_0$  is  $|\phi_0\rangle$ , then

$$\langle Q \rangle_t = \langle \phi(t) | Q | \phi(t) \rangle = \langle \phi_0 | Q_H(t) | \phi_0 \rangle$$

If the state  $|q\rangle$  is the eigenstate of the  $Q$  with the eigenvalue  $q$ , then  $U^\dagger(t, t_0)|q\rangle$  is the eigenstate of the  $Q_H$  with eigenvalue  $q$ , which can be denoted by  $|q_H(t)\rangle$ , so we have

$$\langle q | \phi(t) \rangle = \langle q_H(t) | \phi_0 \rangle$$



## 9.9 Symmetries and conservation laws

Let  $U = e^{iKs}$  be a continuous unitary transformation with generator  $K = K^\dagger$ . To say that the Hamiltonian operator  $H$  is invariant under this transformation means that

$$U(s)^{-1}H(t)U(s) = H(t)$$

Then we can deduce that

$$[K, H(t)] = 0$$

Usually,  $K$  does not depend on time explicitly. If the above equation hold for all  $t$ , then in Heisenberg picture,

$$K_H(t) = K \quad |k_H(t)\rangle = |k\rangle$$

So,

$$\langle K \rangle_t = \langle K \rangle_{t_0} \quad \langle k|\phi(t)\rangle = \langle k|\phi_0\rangle$$

The probability distribution of the measurement of the observable  $K$  will not change with time for an arbitrary initial state. We can assume that the  $K$  is a constant of motion.



**Note:** The concept of a constant of motion should not be confused with the concept of a stationary state. Suppose that the Hamiltonian operator  $H$  is independent of  $t$ , and that the initial state vector is an eigenvector of  $H$ ,  $|\phi_0\rangle = |E_n\rangle$  with  $H|E_n\rangle = E_n|E_n\rangle$ . This describes a state having a unique value of energy  $E_n$ . So

$$|\phi(t)\rangle = e^{-iE_nt}|\phi_0\rangle$$

From this result it follows that the average of any dynamical variable  $R$ ,

$$\langle \phi(t)|R|\phi(t)\rangle = \langle E_n|R|E_n\rangle$$

is independent of  $t$  for such a state. By considering functions of  $R$  we can further show that the probability distribution is independent of time. In a stationary state the averages and probabilities of all dynamical variables are independent of time, whereas a constant of motion has its average and probabilities independent of time for all states.



# Chapter 10

## Coordinate and Momentum Representation



### 10.1 Coordinate Representation

To form a representation of an abstract linear vector space, one chooses a complete orthonormal set of basis vectors  $\{|u_i\rangle\}$  and represents an arbitrary vector  $|\psi\rangle$  by its expansion coefficients  $\{c_i\}$ , where  $|\psi\rangle = \sum c_i |u_i\rangle$ . The array of coefficients  $\langle u_i|\psi\rangle$  can be regarded as a column vector (possibly of infinite dimension), provided the basis set is discrete.

Coordinate representation is obtained by choosing as the basis set the eigenvectors  $\{|\mathbf{x}\rangle\}$  of the position operator  $\hat{X}$ . Since this is a continuous set, the expansion coefficients define a function of a continuous variable,

$$\psi(\mathbf{x}) \equiv \langle \mathbf{x}|\psi\rangle$$

We can show that the inner product of the state vector in coordinate representation is

$$\langle \phi|\psi\rangle = \int \phi^*(\mathbf{x})\psi(\mathbf{x})d^3\mathbf{x}$$

It is a matter of taste whether one says that the set of functions forms a representation of the vector space, or that the vector space consists of the functions  $\psi(\mathbf{x})$ .

The action of an operator  $A$  on the function space is related to its action on the abstract vector space by the rule

$$A\psi(\mathbf{x}) \equiv \langle \mathbf{x}|A|\psi\rangle$$

The action of an position operator in coordinate representation is

$$\hat{X}\psi(\mathbf{x}) = \mathbf{x}\psi(\mathbf{x})$$

The action of an momentum operator in coordinate representation is

$$\hat{P}\psi(\mathbf{x}) = -i\nabla\psi(\mathbf{x})$$

For a spin-less particle in the scalar potential  $W(\mathbf{x})$ ,  $H = \frac{\hat{P}^2}{2m} + W(\hat{\mathbf{X}})$ . The equation of motion in the coordinate representation is

$$\left[ -\frac{1}{2M}\nabla^2 + W(\mathbf{x}) \right] \psi(\mathbf{x}, t) = i\frac{\partial}{\partial t}\psi(\mathbf{x}, t)$$

## 10.2 Galilei transformation of Schrödinger equation

For simplicity we shall treat only one spatial dimension. Let us consider two frames of reference:  $F$  with coordinates  $x$  and  $t$ , and  $F'$  with coordinates  $x'$  and  $t'$ .  $F'$  is moving uniformly with velocity  $v$  relative to  $F$ , so that

$$x = x' + vt' \quad t = t'$$

The potential energy is given by  $W(x, t)$  in  $F$ , and by  $W'(x', t')$  in  $F'$ , with

$$W(x, t) = W'(x', t')$$

Because the requirement of invariance under Galilei transformation, we expect in  $F'$  the Schrödinger equation has the form

$$\left[ -\frac{1}{2M} \frac{\partial^2}{\partial x'^2} + W'(x') \right] \psi'(x', t') = i \frac{\partial}{\partial t'} \psi'(x', t')$$

where  $\psi'(x', t')$  is the wave function in  $F'$ . The probability density at a point in space-time must be the same in the two frames of reference

$$|\psi(x, t)|^2 = |\psi'(x', t')|^2$$

and hence we must have

$$\psi(x, t) = e^{if} \psi'(x', t')$$

where  $f$  is a real function of the coordinates. Put all the conditions above together, we can derive

$$f(x, t) = Mvx - \frac{1}{2}Mv^2t$$

apart from an irrelevant constant term.

## 10.3 Probability flux and conditions on wave functions

Define the probability flux vector

$$\mathbf{J}(\mathbf{x}, t) = \frac{1}{M} \text{Im}(\psi^* \nabla \psi)$$

We can get a continuity equation

$$\frac{d}{dt} |\psi(\mathbf{x}, t)|^2 + \nabla \cdot \mathbf{J}(\mathbf{x}, t)$$

Applying the divergence theorem, we obtain

$$\frac{\partial}{\partial t} \int_{\Omega} |\psi(\mathbf{x}, t)|^2 d^3x = - \oint_{\sigma} \mathbf{J} \cdot d\mathbf{s}$$

The equations of continuity require that the probability flux  $\mathbf{J}(\mathbf{x}, t)$  be continuous across any surface, since otherwise the surface would contain sources or sinks. Although this condition applies to all surfaces, implying that  $\mathbf{J}(\mathbf{x}, t)$  must be everywhere continuous, its practical applications are mainly to surfaces separating regions in which the potential has different analytic forms. Usually, we have the following conditions,



1.

$$\psi(x)|_{x+0} = \psi(x)|_{x-0} \quad \frac{d\psi}{dx}|_{x+0} = \frac{d\psi}{dx}|_{x-0}$$

2.

$$\psi(x)|_{x+0} = \psi(x)|_{x-0} = 0 \quad \frac{d\psi}{dx}|_{x+0} - \frac{d\psi}{dx}|_{x-0} \text{ is finite}$$

Consider next the behavior at a singular point, assumed for convenience to be the origin of coordinates. Let  $S$  be a small sphere of radius  $r$  surrounding the singularity. The probability that the particle is inside  $S$  must be finite. Suppose that  $\psi = \frac{u}{r^\alpha}$ , where  $u$  is a smooth function that does not vanish at  $r = 0$ . Then we must have  $|\psi|^2 r^3$  convergent at the origin, which implies that  $\alpha < \frac{3}{2}$ .

The net outward flow through the surface  $S$  is  $F = \oint_S J \cdot dS$ . It must vanish in the limit  $r \rightarrow 0$ , since otherwise the origin would be a point source or sink. One has  $\frac{\partial \psi}{\partial r} = r^{-\alpha} \frac{\partial u}{\partial r} - \alpha u r^{-\alpha-1}$ . The second term does not contribute to the flux, so we obtain

$$F \propto r^{2-2\alpha}$$

where the integration is over solid angle. If the integral does not vanish, then we must have  $\alpha < 1$  in order for  $F$  to vanish in the limit  $r \rightarrow 0$ . This is a stronger condition than that derived from the probability density.

Since  $|\psi|^2$  is a probability density, it must vanish sufficiently rapidly at infinity so that its integral over all configuration space is convergent and equal to 1.

The conditions that we have discussed apply to wave functions  $\psi(x)$  which represent physically realizable states, but they need not apply to the eigenfunctions of operators that represent observables. Those eigenfunctions,  $\chi(x)$ , which play the role of filter functions in computing probabilities, are only required to lie in the extended space,  $\Phi^X$ , of the rigged-Hilbert-space triplet. It has been suggested that  $\psi(x)$  be restricted to the nuclear space  $\Phi$ , rather than merely to the Hilbert space  $\mathcal{H}$ . In many cases this would amount to requiring that  $\psi(x)$  should vanish at infinity more rapidly than any inverse power of the distance.

## 10.4 Path integrals

### Theorem 10.1 Gaussian integration

$$\int dx e^{-\frac{1}{2}ax^2 + Jx} = \left(\frac{2\pi}{a}\right)^{\frac{1}{2}} e^{\frac{J^2}{2a}}$$



The time evolution of a quantum state vector,  $|\psi(t)\rangle = U(t, t_0)|\psi(t_0)\rangle$ , can be regarded as the propagation of an amplitude in configuration space,

$$\psi(x, t) = \int G(x, t; x', t_0) \psi(x', t_0) dx'$$

where

$$G(x, t; x', t_0) = \langle x, t | U(t, t_0) | x', t_0 \rangle$$



is often called the propagator.

Making use of the multiplicative property of the time development operator, it follows that the propagator can be written as

$$G(x, t; x_0, t_0) = \int \cdots \int G(x, t; x_N, t_N) \cdots G(x_1, t_1; x_0, t_0) dx_N \cdots dx_1$$

The N-fold integration is equivalent to a sum over zigzag paths that connect the initial point  $(x_0, t_0)$  to the final point  $(x, t)$ . If we now pass to the limit of  $N \rightarrow \infty$  and  $\Delta t = t_i - t_{i-1} \rightarrow 0$ , we will have the propagator expressed as a sum (or, rather, as an integral) over all paths that connect the initial point to the final point. We can show that

$$\langle x | e^{-iH\Delta t} | x' \rangle = \sqrt{\frac{M}{2i\pi\Delta t}} \exp \left\{ i \left[ \frac{M(x - x')^2}{2\Delta t^2} - V(x') \right] \Delta t \right\} \quad \Delta t \rightarrow 0$$

So,

$$G(x, t; x_0, t_0) = \lim_{N \rightarrow \infty} \int \cdots \int \left( \frac{M}{2i\pi\Delta t} \right)^{\frac{N+1}{2}} \exp \left\{ i \sum_{j=0}^N \left[ \frac{M(x_{j+1} - x_j)^2}{2\Delta t^2} - V(x_{j+1}) \right] \Delta t \right\} dx_1 \cdots dx_N$$

The final result can be expressed as

$$G(x, t; x_0, t_0) = \int \mathcal{D}[x(\tau)] e^{iS[x(\tau)]}$$

Here,  $S[x(\tau)]$  is the action associated with the path

$$S[x(\tau)] = \int_{x(\tau)} L(x, \dot{x}) d\tau$$

The integral is a functional integration over all paths  $x(\tau)$  which connect the initial point  $(x_0, t_0)$  to the final point  $(x, t)$ .

To conclude this section, let us generalize our path-integral formula to a more complicated systems. Consider a very general quantum system, described by arbitrary set of coordinates  $q_i$ , conjugate momentum  $p^i$ , and Hamiltonian  $H(q, p)$ . We can show that

$$\langle q_{k+1} | e^{-i\epsilon H} | q_k \rangle = \left( \prod_i \int \frac{dp_k^i}{2\pi} \right) \exp \left[ -i\epsilon H \left( \frac{q_{k+1} + q_k}{2}, p_k \right) \right] \exp \left[ i \sum_i p_k^i (q_{i,k+1} - q_{i,k}) \right]$$

so,

$$\langle q_N | U(t, t_0) | q_0 \rangle = \left( \prod_{i,k} \int \frac{dp_k^i dq_{i,k}}{2\pi} \right) \exp \left[ i \sum_k \left( \sum_i p_k^i (q_{i,k+1} - q_{i,k}) - \epsilon H \left( \frac{q_{k+1} + q_k}{2}, p_k \right) \right) \right]$$

There is one momentum integral for each  $k$  from 0 to  $N$ , and on coordinate integral for each  $k$  from 1 to  $N$ . The final result can be expressed as

$$\langle q_N | U(t, t_0) | q_0 \rangle = \left( \prod_i \int \mathcal{D}q(t) \mathcal{D}p(t) \right) \exp \left[ i \int_0^T dt \left( \sum_i p^i \dot{q}_i - H(q, p) \right) \right]$$

where the functions  $q(t)$  are constrained at the endpoints, but  $p(t)$  are not. The details of this generalization can be found in chapter 9.1 of *An introduction to quantum field theory* (M.E.Peskin & D.V.Schroeder)





## **Part V**

# **Quantum Field Theory**

# Chapter 11

## From classical field to quantum field



### 11.1 Motivation

The state of the field is described by an element  $|\psi\rangle$  in Hilbert space. The measurement of the field is described by an operator field  $\phi_a(\mathbf{x})$ . The mean value of the measurement of the field is described by Erenfest's theorem

$$\frac{d\langle\psi|\phi_a(\mathbf{x})|\psi\rangle}{dt} = -i\langle\psi|[\phi_a(\mathbf{x}), H_S]|\psi\rangle$$

If  $[\phi_a(\mathbf{x}), H_S]_Q = i[\phi_a(\mathbf{x}), H_S]_C$ , we can reproduce the classical field theory as an average effect of quantum field theory. We also note that the commutation relation here  $[A, B] = AB - BA$  obeys the same operation laws as the Poisson bracket in classical field theory. So, what we need here is

1. the canonical quantization

$$[\phi_a(\mathbf{x}), \phi_b(\mathbf{y})] = 0 \quad [\pi^a(\mathbf{x}), \pi^b(\mathbf{y})] = 0 \quad [\phi_a(\mathbf{x}), \pi^b(\mathbf{y})] = i\delta_a^b \delta(\mathbf{x} - \mathbf{y})$$

2. the same definition of  $\mathcal{L}, \pi^a$  and  $H$  as those in corresponding classical theory.

In Heisenberg picture, we define

$$A_H \equiv U^{-1}(t, t_0) A_S U(t, t_0)$$

Especially,

$$\phi_a(x) \equiv U^{-1}(t, t_0) \phi_a(\mathbf{x}) U(t, t_0)$$

$$\pi^a(x) \equiv U^{-1}(t, t_0) \pi^a(\mathbf{x}) U(t, t_0)$$

If  $A = f(\phi_a(\mathbf{x}), \pi^a(\mathbf{x}), t)$ , then we have  $A_H = f(\phi_a(x), \pi^a(x), t)$ .

The canonical quantization can be generalized to the field operator in any time

$$[\phi_a(\mathbf{x}, t), \phi_b(\mathbf{y}, t)] = 0 \quad [\pi^a(\mathbf{x}, t), \pi^b(\mathbf{y}, t)] = 0 \quad [\phi_a(\mathbf{x}, t), \pi^b(\mathbf{y}, t)] = i\delta_a^b \delta(\mathbf{x} - \mathbf{y})$$

The dynamics of the field can be describe by Heisenberg equation

$$\frac{d\phi_a(x)}{dt} = -i[\phi_a(x), H_H]$$

$$\frac{d\pi^a(x)}{dt} = -i[\pi^a(x), H_H]$$

whose form will be equivalent to the classical field equation.

## 11.2 Lorentz invariance in quantum field theory

$$|\bar{\psi}\rangle = U(\Lambda)|\psi\rangle$$

Scalar fields:

$$\langle\bar{\psi}|\phi(x)|\bar{\psi}\rangle = \langle\psi|\phi(\Lambda^{-1}x)|\psi\rangle$$

$$U^{-1}(\Lambda)\phi(x)U(\Lambda) = \phi(\Lambda^{-1}x)$$

Vector fields:

$$\langle\bar{\psi}|A^\mu(x)|\bar{\psi}\rangle = \langle\psi|\Lambda^\mu{}_\nu A^\nu(\Lambda^{-1}x)|\psi\rangle$$

$$U^{-1}(\Lambda)A^\mu(x)U(\Lambda) = \Lambda^\mu{}_\nu A^\nu(\Lambda^{-1}x)$$

Lorentz invariance means Lagrangian must be a scalar, or more loosely, action must be invariant under Lorentz transformation.

## 11.3 Momentum

The definition of momentum is the same as that in classical theory:

$$T^{\mu\nu} \equiv -\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi_a)}\partial^\nu\phi_a + \eta^{\mu\nu}\mathcal{L} \quad \partial_\mu T^{\mu\nu} = 0$$

and

$$P^\mu \equiv \int T^{0\mu}d^3x \quad \frac{dP^\mu}{dt} = 0$$

$$P^0 = H, \quad P^i = \int -\pi^a \partial^i \phi_a d^3x$$

We can get the commutation relation

$$[\phi_a, P^\mu] = -i\partial^\mu\phi_a$$

$$[\pi^a, P^\mu] = -i\partial^\mu\pi^a$$

$$[P^\mu, P^\nu] = 0$$

We define the translation operator  $T(s)$  by

$$T^{-1}(s)\phi_a(x)T(s) = \phi_a(x-s)$$

then we can derive that

$$T(\epsilon) = 1 - i\epsilon_\mu P^\mu \quad T(s) = e^{-iP^\mu s_\mu}$$



## 11.4 Angular Momentum

The definition of angular momentum is the same as that in classical theory:

$$M^{\mu\nu\rho} \equiv x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu} - \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_a)} (\Sigma^{\nu\rho})_a^b \phi_b$$

and

$$M^{\nu\rho} \equiv \int M^{0\nu\rho} d^3x \quad \frac{dM^{\nu\rho}}{dt} = 0$$

$$M^{\mu\nu} = \int (x^\mu T^{0\nu} - x^\nu T^{0\mu} - \pi^a (\Sigma^{\mu\nu})_a^b \phi_b) d^3x$$

We also define that

$$M_L^{\mu\nu} \equiv \int (x^\mu T^{0\nu} - x^\nu T^{0\mu}) d^3x \quad M_S^{\mu\nu} \equiv \int (-\pi^a (\Sigma^{\mu\nu})_a^b \phi_b) d^3x$$

$$(L^{\mu\nu})_a^b \equiv -i(x^\mu \partial^\nu - x^\nu \partial^\mu) \delta_a^b \quad (S^{\mu\nu})_a^b \equiv -i(\Sigma^{\mu\nu})_a^b$$

We can get the commutation relation

$$M^{\mu\nu} = M_L^{\mu\nu} + M_S^{\mu\nu}$$

$$[\phi_a, M_L^{\mu\nu}] = (L^{\mu\nu})_a^b \phi_b \quad [\phi_a, M_S^{\mu\nu}] = (S^{\mu\nu})_a^b \phi_b$$

$$[\pi^a, M_L^{\mu\nu}] = (L^{\mu\nu})_b^a \pi^b \quad [\pi^a, M_S^{\mu\nu}] = -(S^{\mu\nu})_b^a \pi^b$$

$$[M^{\mu\nu}, M^{\rho\sigma}] = i(-\eta^{\nu\rho} M^{\mu\sigma} + \eta^{\sigma\mu} M^{\rho\nu} + \eta^{\mu\rho} M^{\nu\sigma} - \eta^{\sigma\nu} M^{\rho\mu})$$

We again define  $J_i \equiv \frac{1}{2} \epsilon_{ijk} M^{jk}$  and  $K_i \equiv M^{i0}$ , the commutation relation can be written as

$$\begin{aligned} [J_i, J_j] &= i\epsilon_{ijk} J_k \\ [J_i, K_j] &= i\epsilon_{ijk} K_k \\ [K_i, K_j] &= -i\epsilon_{ijk} J_k \end{aligned}$$

Further more,

$$[P^\mu, M^{\rho\sigma}] = i(\eta^{\mu\sigma} P^\rho - \eta^{\mu\rho} P^\sigma)$$

$$\begin{aligned} [J_i, H] &= 0 \\ [J_i, P_j] &= i\epsilon_{ijk} P_k \\ [K_i, H] &= iP_i \\ [K_i, P_j] &= i\delta_{ij} H \end{aligned}$$

At last, we also define  $L_i \equiv \frac{1}{2} \epsilon_{ijk} M_L^{jk}$  and  $S_i \equiv \frac{1}{2} \epsilon_{ijk} M_S^{jk}$ . So

$$\begin{aligned} [L_i, S_j] &= 0 \\ [S_i, P_j] &= 0 \\ [L_i, P_j] &= i\epsilon_{ijk} P_k \end{aligned}$$



We define the rotation operator  $U(\Lambda)$  by

$$U^{-1}(\Lambda)\phi_a(x)U(\Lambda) = \mathcal{S}_a^b \phi_b(\Lambda^{-1}x)$$

where

$$\mathcal{S}_a^b = \delta_a^b + \frac{i}{2}\delta\omega_{\alpha\beta}(S^{\alpha\beta})_a^b$$

We can derive that

$$U(1 + \delta\omega) = 1 + \frac{i}{2}\delta\omega_{\mu\nu}M^{\mu\nu} \quad U(\Lambda) = e^{\frac{i}{2}\theta_{\mu\nu}M^{\mu\nu}}$$

$$U^{-1}(\Lambda)P^\mu U(\Lambda) = \Lambda^\mu_\nu P^\nu$$

$$U^{-1}(\Lambda)M^{\mu\nu}U(\Lambda) = \Lambda^\mu_\rho \Lambda^\nu_\sigma M^{\rho\sigma}$$

## 11.5 Anticommutation relation

We define the anticommutation relation of operators as  $\{A, B\} \equiv AB + BA$ . Suppose that the field operator and its canonical momentum operator has the following anticommutation relation

$$\{\phi_a(\mathbf{x}, t), \phi_b(\mathbf{y}, t)\} = 0 \quad \{\pi^a(\mathbf{x}, t), \pi^b(\mathbf{y}, t)\} = 0 \quad \{\phi_a(\mathbf{x}, t), \pi^b(\mathbf{y}, t)\} = i\delta_a^b \delta(\mathbf{x} - \mathbf{y})$$

If the operator  $A$  composes of the terms like  $\pi^a \mathcal{E}_a^b \phi_b$ , we can show that the value of  $[\phi_a, A]$  and  $[\pi^a, A]$  is the same as those in the theory quantized with commutation relation. It is easy to verify that the operator  $P^i$  and  $M_S^{\mu\nu}$  has the required form. The form of  $H$  is determined by the specific theory. As we can see later, the Hamiltonian of Dirac field has the required form. When it is quantized with anticommutation relation, the commutation relation between field operator and momentum, angular momentum discussed in previous section will be hold automatically.



# Chapter 12

## Spin 0 Fields



### 12.1 Klein-Gordon fields

Lagrangian

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m^2\phi^2 + \Omega_0$$

Field equation

$$(\partial^\mu\partial_\mu - m^2)\phi = 0$$

Hamiltonian

$$\pi = \dot{\phi}$$

$$\mathcal{H} = \frac{1}{2}\pi^2 + \frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m^2\phi^2 - \Omega_0$$

$$H = \int \mathcal{H} d^3x$$

Momentum and angular momentum

$$T^{\mu\nu} = \partial^\mu\phi\partial^\nu\phi - \eta^{\mu\nu}\left(\frac{1}{2}\partial^\mu\phi\partial_\mu\phi + \frac{1}{2}m^2\phi^2 - \Omega_0\right)$$

$$P^0 = H \quad P^i = \int -\pi\nabla^i\phi d^3x$$

$$J_k = \int -\pi\epsilon_{ijk}x^j\nabla^k\phi d^3x$$

## 12.2 Canonical quantization Formulation

### Canonical quantization

$$\begin{aligned} [\phi(\mathbf{x}, t), \phi(\mathbf{y}, t)] &= 0 \\ [\pi(\mathbf{x}, t), \pi(\mathbf{y}, t)] &= 0 \\ [\phi(\mathbf{x}, t), \pi(\mathbf{y}, t)] &= i\delta(\mathbf{x} - \mathbf{y}) \end{aligned}$$

### Fourier expansion

$$\begin{aligned} \phi(\mathbf{x}, t) &= \int \widetilde{d\mathbf{k}} [a(\mathbf{k})e^{i\mathbf{k}\cdot\mathbf{x}} + a^\dagger(\mathbf{k})e^{-i\mathbf{k}\cdot\mathbf{x}}] \\ \pi(\mathbf{x}, t) &= -i \int \widetilde{d\mathbf{k}} \omega [a(\mathbf{k})e^{i\mathbf{k}\cdot\mathbf{x}} - a^\dagger(\mathbf{k})e^{-i\mathbf{k}\cdot\mathbf{x}}] \end{aligned}$$

Here,  $k^2 = \mathbf{k}^2 - \omega^2 = -m^2$ ,  $kx = \mathbf{k} \cdot \mathbf{x} - \omega t$ ,  $\widetilde{d\mathbf{k}} = \frac{d^3\mathbf{k}}{(2\pi)^3 2\omega}$

$$\begin{aligned} a(\mathbf{k}) &= \int d^3x e^{-i\mathbf{k}\cdot\mathbf{x}} (i\pi + \omega\phi) \\ a^\dagger(\mathbf{k}) &= \int d^3x e^{i\mathbf{k}\cdot\mathbf{x}} (-i\pi + \omega\phi) \end{aligned}$$

$$\begin{aligned} [a(\mathbf{p}), a(\mathbf{q})] &= 0 \\ [a^\dagger(\mathbf{p}), a^\dagger(\mathbf{q})] &= 0 \\ [a(\mathbf{p}), a^\dagger(\mathbf{q})] &= (2\pi)^3 2\omega \delta(\mathbf{p} - \mathbf{q}) \end{aligned}$$

### Operator represented by $a$ and $a^\dagger$

$$\begin{aligned} H &= \int \widetilde{d\mathbf{k}} \omega a^\dagger(\mathbf{k})a(\mathbf{k}) + (\mathcal{E}_0 - \Omega_0)V \quad \mathcal{E}_0 = \frac{1}{2}(2\pi)^{-3} \int d^3k \omega \\ P^i &= \int \widetilde{d\mathbf{k}} k^i a^\dagger(\mathbf{k})a(\mathbf{k}) \end{aligned}$$

### Particles

$$\begin{aligned} [H, a(\mathbf{k})] &= -\omega a(\mathbf{k}) \quad [H, a^\dagger(\mathbf{k})] = \omega a^\dagger(\mathbf{k}) \\ [P^i, a(\mathbf{k})] &= -k^i a(\mathbf{k}) \quad [P^i, a^\dagger(\mathbf{k})] = k^i a^\dagger(\mathbf{k}) \end{aligned}$$

Let  $|p\rangle = a^\dagger(\mathbf{p})|0\rangle$ , so

$$H|p\rangle = \omega_p|p\rangle \quad P^i|p\rangle = p^i|p\rangle$$

So, we interpret the state  $|p\rangle$  as the momentum eigenstate of a single particle of mass  $m$ . We can also show that  $J_i|p=0\rangle = 0$ , so the particle carries no internal angular momentum.



### Causality

The amplitude for a particle to propagate from  $y$  to  $x$  is  $\langle 0|\phi(x)\phi(y)|0\rangle$ , denoted by  $D(x-y)$ .

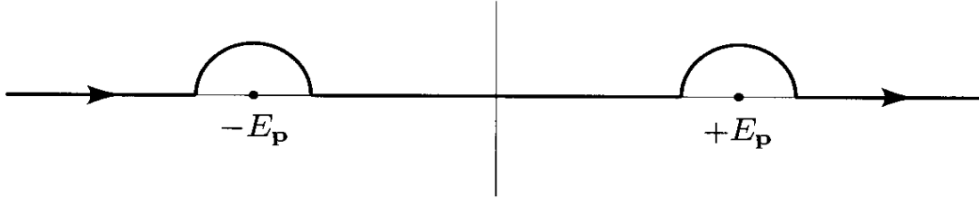
$$D(x-y) = \int \widetilde{dk} e^{ik(x-y)}$$

$$[\phi(x), \phi(y)] = D(x-y) - D(y-x)$$

If  $x-y$  is space-like, a continuous Lorentz transformation can take  $(x-y)$  to  $-(x-y)$ . So  $[\phi(x), \phi(y)] = 0$  for space-like  $x-y$ . A measurement performed at one point can not affect a measurement at another point whose separation is space-like.

### The Klein-Gordon propagator

$$D_R(x-y) \equiv \theta(x^0 - y^0) \langle 0|\phi(x)\phi(y)|0\rangle = \int \frac{d^4p}{(2\pi)^4} \frac{-i}{p^2 + m^2} e^{ip(x-y)}$$

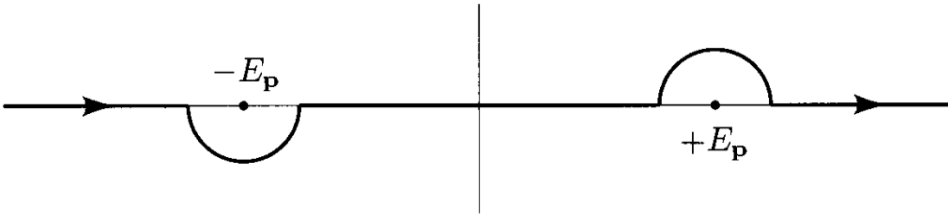


**Figure 12.1:** Retarded Green Function

$$(\partial^2 - m^2)D_R(x-y) = i\delta(x-y)$$

$$D_F(x-y) \equiv \langle 0|T\phi(x)\phi(y)|0\rangle = \int \frac{d^4p}{(2\pi)^4} \frac{-i}{p^2 + m^2 - i\epsilon} e^{ip(x-y)}$$

Here,  $T$  stands for time ordering, placing all operators evaluated at later times to the left.



**Figure 12.2:** Feynman Green Function

## 12.3 Perturbation theory for canonical quantization

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4$$

$$H = H_0 + H_{int} \quad H_{int} = \int d^3x \frac{\lambda_0}{4!}\phi^4(\mathbf{x})$$





### 12.3.1 Perturbation expansion of correlation functions



**Note:** The ground state of the interaction field theory is denoted by  $|\Omega\rangle$ , the ground state of the free field theory is denoted by  $|0\rangle$ . The zero of energy is defined by  $H_0|0\rangle = 0$  and  $E_0 = \langle\Omega|H|\Omega\rangle$ .

$$\phi(t_0, \mathbf{x}) = \int \frac{d^3p}{(2\pi)^3} (a(\mathbf{p})e^{i\mathbf{p}\cdot\mathbf{x}} + a^\dagger(\mathbf{p})e^{-i\mathbf{p}\cdot\mathbf{x}})$$

$$\phi(t, \mathbf{x}) = e^{iH(t-t_0)}\phi(t_0, \mathbf{x})e^{-iH(t-t_0)}$$

$$\phi_I(t, \mathbf{x}) \equiv e^{iH_0(t-t_0)}\phi(t_0, \mathbf{x})e^{-iH_0(t-t_0)}$$

$$H_I(x) = \int d^3x \frac{\lambda_0^4}{4!} \phi_I^4$$

The perturbation expansion of correlation functions is

$$\langle\Omega|T\{\phi(x)\phi(y)\}|\Omega\rangle = \lim_{T \rightarrow \infty(1-i\epsilon)} \frac{\langle 0|T\left\{\phi_I(x)\phi_I(y)\exp\left[-i\int_{-T}^T dt H_I\right]\right\}|0\rangle}{\langle 0|T\left\{\exp\left[-i\int_{-T}^T dt H_I\right]\right\}|0\rangle}$$

The proof can be found in chapter 4.2 of *An introduction to quantum field theory* (M.E.Peskin & D.V.Schroeder)

#### Theorem 12.1 Wick's theorem

$$T\{\phi(x_1)\phi(x_2)\cdots\phi(x_n)\} = N\{\phi(x_1)\phi(x_2)\cdots\phi(x_n) + \text{all possible contractions}\}$$

Normal order : all the  $a$ 's are to the right of all the  $a^\dagger$ .

The proof can be found in chapter 4.3 of *An introduction to quantum field theory* (M.E.Peskin & D.V.Schroeder)

**Example:**

$$\begin{aligned} \langle 0|T\{\phi_I(x_1)\phi_I(x_2)\phi_I(x_3)\phi_I(x_4)\}|0\rangle &= D_F(x_1-x_2)D_F(x_3-x_4) \\ &+ D_F(x_1-x_3)D_F(x_2-x_4) \\ &+ D_F(x_1-x_4)D_F(x_2-x_3) \end{aligned}$$

### 12.3.2 Feynman diagram

Expand  $\langle 0|T\left\{\phi_I(x)\phi_I(y)\exp\left[-i\int_{-T}^T dt H_I\right]\right\}|0\rangle$  to the first order of  $\lambda_0$

$$\begin{aligned} &\langle 0|T\left\{\phi_I(x)\phi_I(y)\frac{-i\lambda_0}{4!}\int d^4z\phi_I(z)\phi_I(z)\phi_I(z)\phi_I(z)\right\}|0\rangle \\ &= 3 \cdot \left(\frac{-i\lambda_0}{4!}\right)D_F(x-y)\int d^4z D_F(z-x)D_F(z-y) \\ &+ 12 \cdot \left(\frac{-i\lambda_0}{4!}\right)\int d^4z D_F(x-z)D_F(y-z)D_F(z-z) \end{aligned}$$



It can be represented by the so called Feynman diagram.



**Figure 12.3:** Feynman diagram representation of perturbation expansion

The symmetry factor of the first diagram is  $S = \frac{4!}{3} = 8$ . The symmetry factor of the second diagram is  $S = \frac{4!}{12} = 2$ . The Feynman rules for  $\phi^4$  theory are:

1. For each propagator,  $P = D_F(x - y)$
2. For each vertex,  $V = (-i\lambda_0) \int d^4z$
3. For each external point,  $E = 1$
4. Divided by the symmetry factor

At last, we can prove that

$$\langle \Omega | T \{ \phi_I(x_1) \phi_I(x_2) \cdots \phi_I(x_n) \} | \Omega \rangle = \text{sum of all E-connected diagrams with n external points}$$

Here, the "E-disconnected" means disconnected from all external points", being called "vacuum bubbles". They vacuum bubbles in  $\langle 0 | T \{ \phi_I(x_1) \phi_I(x_2) \cdots \phi_I(x_n) \exp \left[ -i \int_{-T}^T dt H_I \right] \} | 0 \rangle$  are all cancelled by the  $\langle 0 | T \{ \exp \left[ -i \int_{-T}^T dt H_I \right] \} | 0 \rangle$ .

## 12.4 Path integral formulation

### 12.4.1 Basic formulation

Recall the path integrals formulation in quantum mechanics, we have

$$\langle \phi_b(\mathbf{x}) | e^{-iHT} | \phi_a(\mathbf{x}) \rangle = \int \mathcal{D}\phi \mathcal{D}\pi \exp \left[ i \int_0^T d^4x \left( \pi \dot{\phi} - \frac{1}{2} \pi^2 - \frac{1}{2} (\nabla \phi)^2 - V(\phi) \right) \right]$$

Here,  $\langle \phi_b(\mathbf{x}) |$  is the eigenstate of  $\phi_S(\mathbf{x}) = \phi_H(\mathbf{x}, 0)$  with eigenvalue  $\phi_b(\mathbf{x})$  at time  $t = T$ ,  $| \phi_a(\mathbf{x}) \rangle$  is the eigenstate of  $\phi_S(\mathbf{x})$  with eigenvalue  $\phi_a(\mathbf{x})$  at time  $t = 0$ .

Since the exponential is quadratic in  $\pi$ , we can complete the square and evaluate the  $\mathcal{D}(\pi)$  integral to obtain

$$\langle \phi_b(\mathbf{x}) | e^{-iHT} | \phi_a(\mathbf{x}) \rangle = \int \mathcal{D}\phi \exp \left[ i \int_0^T d^4x \mathcal{L} \right]$$

Now we can abandon the Hamiltonian formalism and take the the equation above to define the Hamiltonian dynamics.



**Note:** We emphasize that in this subsection,  $\phi_H$  denotes the Heisenberg picture of field whose value is operators,  $\phi_S$  denotes the Schrödinger picture of field,  $\phi(x)$  is classical field whose value is ordinary number.



### Correlation function

$$\langle \Omega | T \phi_H(x_1) \phi_H(x_2) | \Omega \rangle = \lim_{T \rightarrow \infty(1-i\epsilon)} \frac{\int \mathcal{D}\phi \phi(x_1) \phi(x_2) \exp \left[ i \int_T^T d^4x \mathcal{L} \right]}{\int \mathcal{D}\phi \exp \left[ i \int_T^T d^4x \mathcal{L} \right]}$$

The proof can be found in chapter 9.2 of *An introduction to quantum field theory* (M.E.Peskin & D.V.Schroeder).

### Functional derivatives and the generating functional

We define the generating functional as

$$Z[J] \equiv \int \mathcal{D}\phi \exp \left[ i \int d^4x \mathcal{L} + J(x) \phi(x) \right]$$

We can prove that

$$\langle \Omega | T \phi_H(x_1) \cdots \phi_H(x_n) | \Omega \rangle = \frac{1}{Z_0} \left( -i \frac{\delta}{\delta J(x_1)} \right) \cdots \left( -i \frac{\delta}{\delta J(x_n)} \right) Z[J] |_{J=0}$$

Here,  $Z_0 \equiv Z[J = 0]$ .

### 12.4.2 Free field theory

In Klein-Gordon field theory,

$$\int d^4x [\mathcal{L}_0(\phi) + J\phi] = \int d^4x \left[ \frac{1}{2} \phi (\partial^2 - m^2 + i\epsilon) \phi + J\phi \right]$$

Define

$$\phi'(x) \equiv \phi(x) + \int d^4y (-i D_F(x-y)) J(y)$$

Recall that  $(\partial^2 - m^2) D_F(x-y) = i\delta(x-y)$ , we can derive that

$$\int d^4x [\mathcal{L}_0 + J\phi] = \int d^4x \left[ \frac{1}{2} \phi' (\partial^2 - m^2 + i\epsilon) \phi' \right] - \int d^4x d^4y \frac{1}{2} J(x) [-i D_F(x-y)] J(y)$$

After integration, we can know that

$$Z[J] = Z_0 \exp \left[ -\frac{1}{2} \int d^4x d^4y J(x) D_F(x-y) J(y) \right]$$

So,

$$\langle 0 | T \phi_H(x_1) \phi_H(x_2) | 0 \rangle = \frac{1}{Z_0} - \frac{\delta}{\delta J(x_1)} \frac{\delta}{\delta J(x_2)} \exp \left[ -\frac{1}{2} \int d^4x d^4y J(x) D_F(x-y) J(y) \right] |_{J=0} = D_F(x_1-x_2)$$



## 12.5 Perturbation theory for path integral quantization

$$\begin{aligned}
\mathcal{L} &= -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4 \\
\mathcal{L} &= \mathcal{L}_0 + \mathcal{L}_1 \quad \mathcal{L}_1 = -\frac{\lambda_0}{4!}\phi^4(x) \\
Z[J] &= \int \mathcal{D}\phi e^{i\int d^4x[\mathcal{L}_0+\mathcal{L}_1+J\phi]} \\
&= e^{i\int d^4x\mathcal{L}_1(\frac{1}{i}\frac{\delta}{\delta J(x)})} \int \mathcal{D}\phi e^{i\int d^4x[\mathcal{L}_0+J\phi]} \\
&\propto e^{i\int d^4x\mathcal{L}_1(\frac{1}{i}\frac{\delta}{\delta J(x)})} \exp[-\frac{1}{2}\int d^4y d^4z J(y)D_F(y-z)J(z)] \\
&= \sum_{V=0}^{\infty} \frac{1}{V!} \left[ \frac{-i\lambda_0}{4!} \int d^4x \left( \frac{1}{i} \frac{\delta}{\delta J(x)} \right)^4 \right]^V \times \sum_{P=0}^{\infty} \frac{1}{P!} \left[ -\frac{1}{2} \int d^4y d^4z J(y)D_F(y-z)J(z) \right]^P
\end{aligned}$$

If we focus on a term with particular values of  $V$  and  $P$ , then the number of surviving sources (after we take all the functional derivatives) is  $E = 2P - 4V$ . The  $4V$  functional derivatives can act on the  $2P$  sources in  $\frac{(2P)!}{(2P-4V)!}$  different combinations. However, many of the resulting expressions are algebraically identical.

To organize them, we introduce Feynman diagrams similar to that in perturbation theory of canonical quantization. In these diagrams, a line segment stands for a propagator  $D_F(x-y)$ , a filled circle at one end of a line segment for a source  $i\int d^4x J(x)$ , and a vertex joining four line segments for  $-i\lambda_0\int d^4z$ .

For each diagram, we can assign a symmetry factor  $S_P$  similar to that in perturbation theory for canonical quantization. Due to the fact that some external sources are identical here, usually  $S_P \neq S_C$ . But when calculating the correlation function, the exchange of the order of functional derivatives to identical sources can eliminate the difference.

We can demonstrate that

$$Z[J] \propto \exp\left(\sum_I C_I\right)$$

Here,  $C_I$  stands for a particular connected diagram, including its symmetry factor. We define  $W[J]$  as

$$Z[J] \equiv Z_0 \exp(-iW[J])$$

As,  $W[0] = 0$ , we know

$$-iW[J] = \sum_{I \neq \{0\}} C_I$$

The notation  $I \neq \{0\}$  means that the vacuum diagrams are omitted from the sum.

The detailed discussion can be found in chapter 9 of *Quantum field theory* (M. Srednicki).



## 12.6 Symmetries in the functional formalism

### Equations of motion

The correlation function of the field theory is given by

$$\langle \Omega | T \phi_H(x_1) \cdots \phi_H(x_n) | \Omega \rangle = Z_0^{-1} \int \mathcal{D}\phi e^{iS} \phi(x_1) \cdots \phi(x_n)$$

The equation of motion of classical field theory will be give by

$$\frac{\delta S}{\delta \phi(x)} = 0$$

In quantum field theory, we derive the equation of motion by claim that the path integral will be invariant under the infinitesimal change of field, i.e.  $\phi(x) \rightarrow \phi(x) + \epsilon(x)$ . Define

$$Z[\phi(x_1), \dots, \phi(x_n)] \equiv \int \mathcal{D}\phi e^{iS} \phi(x_1) \cdots \phi(x_n)$$

We know

$$\delta Z = \int \mathcal{D}\phi e^{iS} \left\{ \int d^4x \epsilon(x) \left[ i \frac{\delta S}{\delta \phi(x)} \phi(x_1) \cdots \phi(x_n) + \delta(x - x_1) \cdots \phi(x_n) + \cdots + \phi(x_1) \cdots \delta(x - x_n) \right] \right\}$$

so

$$\left\langle \frac{\delta S}{\delta \phi(x)} \phi(x_1) \cdots \phi(x_n) \right\rangle = \sum_{i=1}^n \langle \phi(x_1) \cdots (i\delta(x - x_i)) \cdots \phi(x_n) \rangle$$

**Example:** For Klein-Gordon field,

$$\mathcal{L} = -\frac{1}{2} \phi^\mu \phi \partial_\mu \phi - \frac{1}{2} m \phi^2$$

The variation of  $S$  gives

$$\frac{\delta S}{\delta \phi(x)} = (\partial^2 - m^2) \phi(x)$$

So, we can get

$$(\partial^2 - m^2) \langle T \phi(x) \phi(x_1) \rangle = i \delta(x - x_1)$$

### Conservation law

Consider a local field theory of a set of fields  $\phi_a(x)$ , governed by a Lagrangian  $\mathcal{L}(\phi)$ . An infinitesimal symmetry transformation on the fields  $\phi_a$  will be of the general form

$$\phi_a(x) \rightarrow \phi_a(x) + \epsilon \Delta \phi_a(x)$$

We assume that when  $\epsilon$  is a constant, the action is invariant under this transformation. Then the Lagrangian must be invariant up to a total divergence:

$$\mathcal{L}[\phi] \rightarrow \mathcal{L}[\phi] + \epsilon \partial_\mu K^\mu$$



If the symmetry parameter  $\epsilon$  depend on  $x$ , the variation of Lagrangian will be

$$L[\phi] \rightarrow \mathcal{L}[\phi] + (\partial_\mu \epsilon) \Delta \phi_a \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_a)} + \epsilon \partial_\mu K^\mu$$

So,

$$\frac{\delta S}{\delta \epsilon(x)} = \partial_\mu j^\mu \quad j^\mu = -\frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_a)} \Delta \phi_a + K^\mu$$

If the measure  $\mathcal{D}\phi$  is invariant under the transformation, we can derive similarly that

$$\langle \partial_\mu j^\mu(x) \phi(x_1) \cdots \phi(x_n) \rangle = \sum_{i=1}^n \langle \phi(x_1) \cdots (i \Delta \phi(x_i) \delta(x - x_i)) \cdots \phi(x_n) \rangle$$

## 12.7 Cross section and the S-matrix

Recall the definition of cross section

$$\sigma \equiv \frac{\text{Number of Events}}{\text{Time} \times \text{Incident Flux}}$$

Consider a  $2 \rightarrow n$  process:

$$p_1 + p_2 \rightarrow \{p_j\}$$

Suppose the volume of the space in which the scattering process takes place is  $V$ , the duration of the scattering process is  $T$ . So, the incident flux is

$$\Phi = \frac{|\mathbf{v}_1 - \mathbf{v}_2|}{V},$$

and the number of events is

$$N = \frac{|\langle i|S|f \rangle|^2}{|\langle i|i \rangle| |\langle f|f \rangle|} d\Pi.$$

Here,  $d\Pi$  is the region of final state momenta at which we are looking

$$d\Pi = \prod_j \frac{V}{(2\pi)^3} d^3 p_j$$

Recall that

$$\delta^{(3)}(0) = \frac{V}{(2\pi)^3} \quad \delta^{(4)}(0) = \frac{VT}{(2\pi)^4} \quad \langle p|p \rangle = (2\pi)^3 2\omega \delta^{(3)}(0)$$

We can calculate that

$$|\langle i|S|f \rangle|^2 = |\mathcal{M}|^2 VT (2\pi)^4 \delta(\sum_j p_j - p_1 - p_2) \quad \langle i|i \rangle = (2E_1 V)(2E_2 V) \quad \langle f|f \rangle = \prod_j (2E_j V)$$

At last, putting everything together, we have

$$d\sigma = \frac{1}{(2E_1)(2E_2)|\mathbf{v}_1 - \mathbf{v}_2|} |\mathcal{M}|^2 d\Pi_{\text{LIPS}}$$

where,

$$d\Pi_{\text{LIPS}} = \prod_j \frac{d^3 p_j}{(2\pi)^3} \frac{1}{2E_j} (2\pi)^4 \delta(\sum_j p_j - p_1 - p_2)$$

is called the Lorentz-invariant phase space (LIPS).

All the factors of  $V$  and  $T$  have dropped out, so now it is trivial to take  $V \rightarrow \infty$  and  $T \rightarrow \infty$ .



### Decay rates

The definition of decay rates is

$$\Gamma \equiv \frac{\text{Number of Events}}{\text{Time}}$$

Consider a  $1 \rightarrow n$  process:

$$p_1 \rightarrow \{p_j\}$$

We can derive the decay rates by the similar method,

$$d\Gamma = \frac{1}{2E_1} |\mathcal{M}|^2 d\Pi_{\text{LIPS}}$$

### Special cases

For  $2 \rightarrow 2$  scattering in the center-of-mass frame

$$p_1 + p_2 \rightarrow p_3 + p_4$$

Then

$$d\Pi_{\text{LIPS}} = \frac{d^3 p_3}{(2\pi)^3} \frac{1}{2E_3} \frac{d^3 p_4}{(2\pi)^3} \frac{1}{2E_4} (2\pi)^4 \delta(p_3 + p_4 - p_1 - p_2)$$

We can now integrate over  $\mathbf{p}_4$  to give

$$d\Pi_{\text{LIPS}} = \frac{1}{16\pi^2} d\Omega \int dp_f \frac{p_f^2}{E_3 E_4} \delta(E_3 + E_4 - E_{CM})$$

where  $p_f = |\mathbf{p}_3| = |\mathbf{p}_4|$ ,  $E_3 = \sqrt{p_f^2 + m_3^2}$ ,  $E_4 = \sqrt{p_f^2 + m_4^2}$  and  $E_{CM} = E_1 + E_2$ . Define  $x(p_f) \equiv E_3 + E_4 - E_{CM}$ , we can get

$$\frac{dx}{dp_f} = \frac{E_3 + E_4}{E_3 E_4} p_f$$

So,

$$d\Pi_{\text{LIPS}} = \frac{1}{16\pi^2} d\Omega \frac{p_f}{E_{CM}} \theta(E_{CM} - m_3 - m_4)$$

Plugging this into the general equation for cross section, we can get

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 E_{CM}^2} \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} |\mathcal{M}|^2 \theta(E_{CM} - m_3 - m_4)$$

If all the masses are equal then this formula simplifies further

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 E_{CM}^2} |\mathcal{M}|^2$$



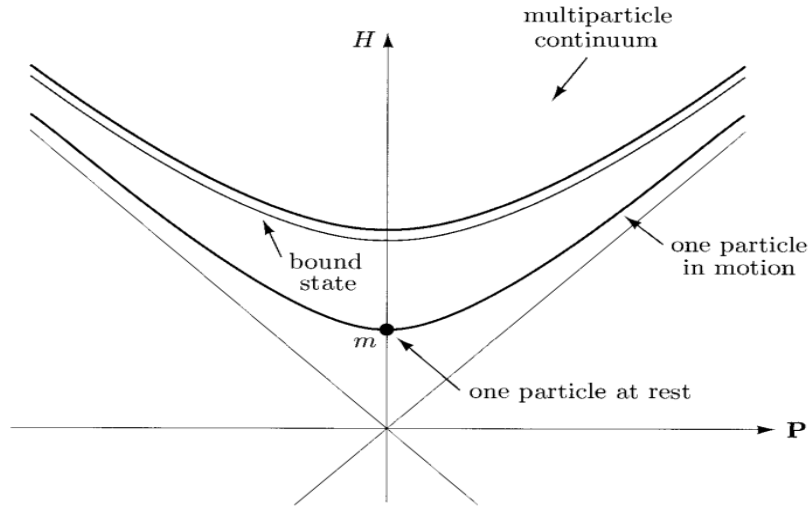
## 12.8 LSZ reduction formula

### 12.8.1 Field strength renormalization

The completeness relation:

$$1 = |\Omega\rangle\langle\Omega| + \sum_{\lambda} \int \frac{d^3p}{(2\pi)^3} \frac{1}{2E_p} |\lambda_p\rangle\langle\lambda_p|$$

Here,  $E_p = \sqrt{m_\lambda^2 + \mathbf{p}^2}$



**Figure 12.4:** Particle's energy-momentum relation

Assume for now  $x^0 > y^0$  and define  $\langle\Omega|\phi(x)\phi(y)|\Omega\rangle_C = \langle\Omega|\phi(x)\phi(y)|\Omega\rangle - \langle\Omega|\phi(x)|\Omega\rangle\langle\Omega|\phi(y)|\Omega\rangle$  as connected two point function. (The term  $\langle\Omega|\phi(x)|\Omega\rangle\langle\Omega|\phi(y)|\Omega\rangle$  is usually zero by symmetry; for higher spin fields, it is zero by Lorentz invariance.) The connected two point function is

$$\langle\Omega|\phi(x)\phi(y)|\Omega\rangle_C = \sum_{\lambda} \int \frac{d^3p}{(2\pi)^3} \frac{1}{2E_p} \langle\Omega|\phi(x)|\lambda_p\rangle\langle\lambda_p|\phi(y)|\Omega\rangle$$

It can be verified that

$$\langle\Omega|\phi(x)|\lambda_p\rangle = \langle\Omega|\phi(0)|\lambda_0\rangle e^{ipx}|_{p^0=E_p}$$

So,

$$\langle\Omega|\phi(x)\phi(y)|\Omega\rangle_C = \sum_{\lambda} \int \frac{d^4p}{(2\pi)^4} \frac{-i}{p^2 + m_\lambda^2 - i\epsilon} e^{ip(x-y)} |\langle\Omega|\phi(0)|\lambda_0\rangle|^2$$

Analogous expressions hold for the case  $y^0 > x^0$ , and both cases can be summarized as

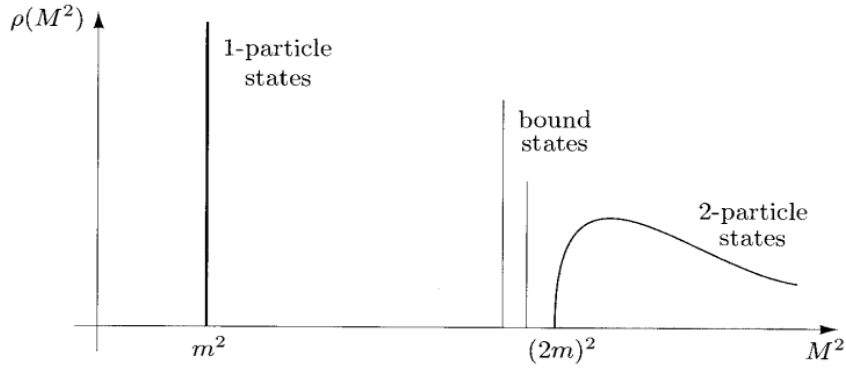
$$\langle\Omega|T\phi(x)\phi(y)|\Omega\rangle_C = \int_0^\infty \frac{dM^2}{2\pi} \rho(M^2) D_F(x-y; M^2)$$

and

$$\rho(M^2) = \sum_{\lambda} (2\pi) \delta(M^2 - m^2) |\langle\Omega|\phi(0)|\lambda_0\rangle|^2$$







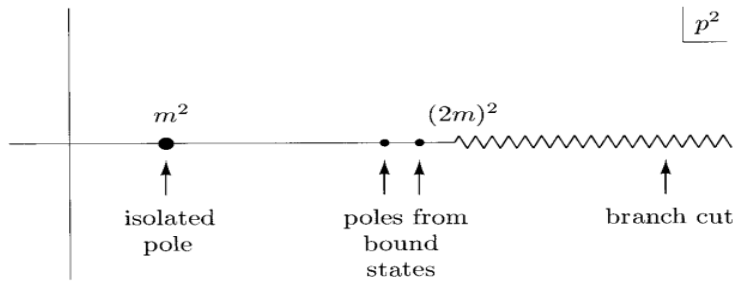
**Figure 12.5:** The structure of the spectral density function  $\rho(M^2)$

The one-particle state contribute an isolated delta function to the spectral density function, so

$$\rho(M^2) = 2\pi\delta(M^2 - m^2) \cdot Z + (\text{nothing else until } M^2 \gtrsim (2m)^2)$$

$Z = |\langle\Omega|\phi(0)|\lambda_0\rangle|^2$  is called field-strength renormalization.  $m$  is the physical mass of a single particle of the  $\phi$  boson. The Fourier transformation of the two point function is

$$\begin{aligned} & \int d^4x e^{-ipx} \langle\Omega|T\phi(x)\phi(0)|\Omega\rangle_C \\ &= \int_0^\infty \frac{dM^2}{2\pi} \rho(M^2) \frac{-i}{p^2 + M^2 - i\epsilon} = \frac{-iZ}{p^2 + m^2 - i\epsilon} + \int_{\sim 4m^2}^\infty \frac{dM^2}{2\pi} \rho(M^2) \frac{-i}{p^2 + M^2 - i\epsilon} \end{aligned}$$



**Figure 12.6:** The structure of the two point function in Fourier space



### 12.8.2 LSZ reduction formula

#### Theorem 12.2 LSZ reduction formula

$$\prod_1^n \int d^4 x_i e^{-ip_i x_i} \prod_1^m d^4 y_j e^{ik_j y_j} \langle \Omega | T \{ \phi(x_1) \cdots \phi(x_n) \phi(y_1) \cdots \phi(y_m) \} | \Omega \rangle$$

$$\underset{p_i^0 \rightarrow E_{\mathbf{p}_i}, k_i^0 \rightarrow E_{\mathbf{k}_i}}{\sim} \left( \prod_1^n \frac{-\sqrt{Z}i}{p_i^2 + m^2 - i\epsilon} \right) \left( \prod_1^m \frac{-\sqrt{Z}i}{k_i^2 + m^2 - i\epsilon} \right) \langle \mathbf{p}_1 \cdots \mathbf{p}_n | S | \mathbf{k}_1 \cdots \mathbf{k}_m \rangle$$

The  $\sim$  means the two sides of the expression share the same singular structure around  $p_i^0 \rightarrow E_{\mathbf{p}_i}$ ,  $k_i^0 \rightarrow E_{\mathbf{k}_i}$ . The proof can be found in chapter 7.2 of *An introduction to quantum field theory* (M.E.Peskin & D.V.Schroeder). To express the formula above in the language of Feynman diagrams, we consider the S-matrix element for 2-particle  $\rightarrow$  2-particle for example. Note the disconnected diagram should be disregarded because they do not have the singularity structure with a product of four poles indicated by on the right side of the LSZ reduction formula. So, the exact four point function

$$\prod_1^2 \int d^4 x_i e^{-ip_i x_i} \prod_1^2 d^4 y_j e^{ik_j y_j} \langle \omega | T \{ \phi(x_1) \phi(x_2) \phi(y_1) \phi(y_2) \} | \Omega \rangle$$

has the general form showed as below.

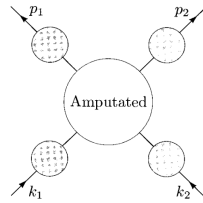


Figure 12.7: Amputated Feynman diagram



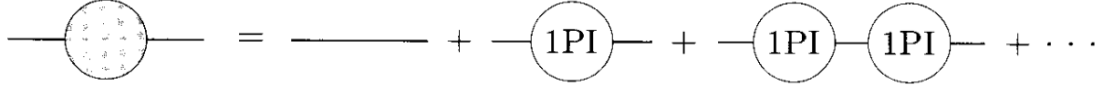
**Note:** One-particle-irreducible, or 1PI for short, refers to diagrams that is still connected after one line is cut

We can sum up the corrections to each external leg. Let  $-iM^2(p^2)$  denote the sum of all 1PI insertions into the scalar propagator:

$$-iM^2(p^2) = \text{[diagram of a tadpole on a line]} + \text{[diagram of a self-energy loop on a line]} + \text{[diagram of a bubble on a line]} + \cdots = \text{[diagram of a circle labeled 1PI on a line]}$$

Figure 12.8: Diagram representation of 1PI propagator





**Figure 12.9:** Diagram representation of exact propagator

Then the exact propagator can be written as a geometric series in Figure 2.9.

The result is  $\frac{-i}{p^2 + m_0^2 + M^2}$ . If we expand each resummed propagator about the physical particle pole, we see that each external leg of the four-point amplitude contributes

$$\frac{-i}{p^2 + m_0^2 + M^2} \underset{p^0 \rightarrow E_p}{\sim} \frac{-iZ}{p^2 + m^2} + (\text{regular})$$

Thus, the sum of diagrams contains a product of four point poles:

$$\frac{-iZ}{p_1^2 + m^2} \frac{-iZ}{p_2^2 + m^2} \frac{-iZ}{k_1^2 + m^2} \frac{-iZ}{k_2^2 + m^2}$$

So, the S matrix element can be represented by

$$\langle \mathbf{p}_1 \mathbf{p}_2 | S | \mathbf{k}_1 \mathbf{k}_2 \rangle = (\sqrt{Z})^4 \text{Amp.}$$

**Figure 12.10:** Feynman diagram representation of LSZ reduction formula

It is easy to be generalized to the more complicated scattering cases. After Fourier transforming the n-point function to momentum space and cutting off the external legs, the Feynman rules for S-matrix element can be stated as follows:

1. For each propagator,  $P = \frac{-i}{p^2 + m_0^2 - i\epsilon}$ ;
2. For each vertex,  $V = -i\lambda_0$ ;
3. For each external point,  $E = 1$ ;
4. Impose momentum conservation at each vertex;
5. Integrate over each undetermined loop momentum:  $\int \frac{d^4 p}{(2\pi)^4}$ ;
6. Divided by the symmetry factor;
7. Multiply the total momentum conservation factor  $(2\pi)^4 \delta(\sum p_f - \sum p_i)$

We can write  $\langle f | S | i \rangle = (Z_1)^{\frac{n_s}{2}} i \mathcal{M} (2\pi)^4 \delta(\sum p_f - \sum p_i)$  for convenience.



## 12.9 Renormalization

Renormalization, the procedure in quantum field theory by which divergent parts of a calculation, leading to nonsensical infinite results, are absorbed by redefinition into a few measurable quantities, so yielding finite answers.

### 12.9.1 Counting of ultraviolet divergence

Consider a pure scalar theory in  $d$  dimensions with a  $\phi^n$  interaction term

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{n!}\phi^n$$

Let  $N$  be the number of external lines in the diagram,  $P$  the number of propagators,  $V$  the number of vertices. The number of the loops in the diagram is  $L = P - V + 1$ . There are  $n$  lines meeting at each vertex, so  $nV = 2P + N$ . Loosely speaking, each loop has an integral  $d^d p$ , each propagator has a factor  $p^{-2}$ , so the superficial degrees of divergence is

$$D = dL - 2P = d + [n(\frac{d-2}{2}) - d]V - (\frac{d-2}{2})N$$

According the superficial degrees of divergence of the diagram. These three possible types of ultraviolet behaviour of quantum field theories. We will refer to them as follows

1. Super-renormalizable theory: Only a finite number of Feynman diagrams superficially diverge.
2. renormalizable theory: Only a finite number of amplitudes superficially diverge; however, divergences occur at all orders in perturbation theory.
3. Non-renormalizable theory: All amplitudes are divergent at a sufficiently high order in perturbation theory.

So, for  $\phi^4$  theory in four dimension,  $D = 4 - N$ . It is a renormalizable theory. For  $\phi^3$  theory in four dimension,  $D = 4 - V - N$ . It is a super-renormalizable theory. For  $\phi^6$  theory in four dimension,  $D = 4 + 2V - N$ . It is a Non-renormalizable theory.

The superficial degrees of freedom can also be derived from dimensional analysis. The dimension of  $\lambda$  is  $d - \frac{n(d-2)}{2}$ . Now consider an arbitrary diagram with  $N$  external lines. One way that such a diagram could arise is from an interaction term  $\eta\phi^N$  in the Lagrangian. The dimension of  $\eta$  would then be  $d - \frac{N(d-2)}{2}$ , and therefore we conclude that any (amputated) diagram with  $N$  external lines has dimension  $d - \frac{N(d-2)}{2}$ . In our theory with only the  $\lambda\phi^n$  vertex, if the diagram has  $V$  vertices, its divergent part is proportional to  $\lambda^V \Lambda^D$ , where  $\Lambda$  is a high momentum cut-off and  $D$  is the superficial degree of divergence. Applying dimensional analysis, we find

$$d - \frac{N(d-2)}{2} = V[d - \frac{n(d-2)}{2}] + D$$

Note that the quantity that multiplies  $V$  in this expression is just the dimension of the coupling constant  $\lambda$ . Thus we can characterize the three degrees of renormalizability in a second way:



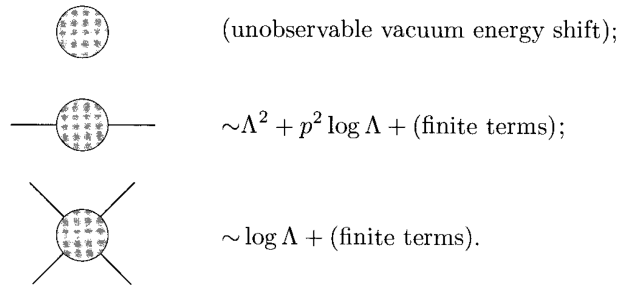
1. Super-renormalizable: Coupling constant has positive mass dimension.
2. renormalizable: Coupling constant is dimensionless.
3. Non-renormalizable: Coupling constant has negative mass dimension.

### 12.9.2 Renormalized perturbation theory

The Lagrangian of  $\phi^4$  theory is

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda_0}{4!}\phi^4$$

We write  $m_0$  and  $\lambda_0$ , to emphasize that these are the bare values of the mass and coupling constant, not the values measured in experiments. Since the theory is invariant under  $\phi \rightarrow -\phi$ , all amplitudes with an odd number of external legs vanish. The only divergent amplitudes are therefore



**Figure 12.11:** Divergence of  $\phi^4$  theory

Ignoring the vacuum diagram, these amplitudes contain three infinite constants. Our goal is to absorb these constants into the three unobservable parameters of the theory: the bare mass, the bare coupling constant, and the field strength. To accomplish this goal, it is convenient to reformulate the perturbation expansion so that these unobservable quantities do not appear explicitly in the Feynman rules. Recall that the exact two-point function has the form

$$\int d^4x \langle \Omega | \phi(x) \phi(0) | \Omega \rangle e^{-ipx} = \frac{-iZ}{p^2 + m^2} + \text{terms regular at } p^2 = m^2$$

We can eliminate the  $Z$  from this equation by rescaling the field:  $\phi = Z^{\frac{1}{2}}\phi_r$ . We also define

$$\delta_Z = Z - 1 \quad \delta_m = Zm_0^2 - m^2 \quad \delta_\lambda = \lambda_0 Z^2 - \lambda$$

Then the Lagrangian becomes

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\phi_r\partial_\mu\phi_r - \frac{1}{2}m^2\phi_r^2 - \frac{\lambda}{4!}\phi_r^4 - \frac{1}{2}\delta_Z\partial^\mu\phi_r\partial_\mu\phi_r - \frac{1}{2}\delta_m\phi_r^2 - \frac{\delta\lambda}{4!}\phi_r^4$$

The last three terms, known as counter-terms, have absorbed the infinite but unobservable shifts between the bare parameters and the physical parameters. We give precise definitions of



$$\begin{aligned}
 \text{---} \bigcirc \text{---} &= \frac{-i}{p^2 + m^2} + (\text{terms regular at } p^2 = m^2); \\
 \left( \text{---} \bigcirc \text{---} \right)_{\text{amputated}} &= -i\lambda \quad \text{at } s = 4m^2, t = u = 0.
 \end{aligned}$$

Figure 12.12: Renormalization condition

the physical mass and coupling constant as Figure 2.12.

The renormalization scheme here is called on-shell (OS) scheme. Other renormalization scheme would be introduced later. These equations are called renormalization conditions. Our new Lagrangian gives a new set of Feynman rules as Figure 2.13.

$$\begin{aligned}
 \text{---} \overleftarrow{p} \text{---} &= \frac{-i}{p^2 + m^2 + i\epsilon} \\
 \text{---} \bullet \text{---} &= -i\lambda \\
 \text{---} \otimes \text{---} &= -i(p^2 \delta_Z + \delta_m) \\
 \text{---} \otimes \text{---} &= -i\delta_\lambda
 \end{aligned}$$

Figure 12.13: Feynman rules for renormalized perturbation theory

We can use these new Feynman rules to compute any amplitude in  $\phi^4$  theory. The procedure is as follows. Compute the desired amplitude as the sum of all possible diagrams created from the propagator and vertices shown above. The loop integrals in the diagrams will often diverge, so one must introduce a regulator. The result of this computation will be a function of the three unknown parameters  $\delta_Z$ ,  $\delta_m$ , and  $\delta_\lambda$ . Adjust (or "renormalise") these three parameters as necessary to maintain the renormalization conditions. After this adjustment, the expression for the amplitude should be finite and independent of the regulator.

This procedure, using Feynman rules with counter-terms, is known as renormalized perturbation theory.

### Mandelstam variable

In theoretical physics, the **Mandelstam variable** are numerical quantities that encode the energy, momentum, and angles of particles in a scattering process in a Lorentz-invariant fashion. They are used for scattering processes of two particles to two particles. The Mandelstam



variables  $s, t, u$  are then defined by

$$\begin{aligned}s &= -(p_1 + p_2)^2 = -(p_3 + p_4)^2 \\ t &= -(p_1 - p_3)^2 = -(p_2 - p_4)^2 \\ u &= -(p_1 - p_4)^2 = -(p_2 - p_3)^2\end{aligned}$$

Where  $p_1$  and  $p_2$  are the four-momenta of the incoming particles and  $p_3$  and  $p_4$  are the four-momenta of the outgoing particles.  $s$  is also known as the square of the center-of-mass energy (invariant mass) and  $t$  is also known as the square of the four-momentum transfer. We can verify that

$$s + t + u = m_1^2 + m_2^2 + m_3^2 + m_4^2$$

### 12.9.3 Techniques for renormalization

#### Feynman's formula

##### Theorem 12.3 Feynman's formula

$$\frac{1}{A_1 \cdots A_n} = \int dF_n (x_1 A_1 + \cdots + x_n A_n)^{-n}$$

where the integration measure over the Feynman parameters  $x_i$  is

$$\int dF_n = (n-1)! \int_0^1 dx_1 \cdots dx_n \delta(x_1 + \cdots + x_n - 1)$$

This measure is normalized so that

$$\int dF_n = 1$$

A generalization of Feynman's formula is

$$\frac{1}{A_1^{\alpha_1} \cdots A_n^{\alpha_n}} = \frac{\Gamma(\sum_i \alpha_i)}{\prod_i \Gamma(\alpha_i)} \frac{1}{(n-1)!} \int dF_n \frac{\prod_i x_i^{\alpha_i-1}}{(\sum_i x_i A_i)^{\sum_i \alpha_i}}$$

#### Wick rotation

For an integral  $\int d^d q f(q^2 - i\epsilon)$ , if the integrand vanishes fast enough as  $|q_0| \rightarrow \infty$ , we can rotate this contour clockwise by  $\frac{\pi}{2}$ , so that it runs from  $-i\infty$  to  $i\infty$ . In making this Wick rotation, the contour does not pass over any poles. (The  $i\epsilon$  are needed to make this statement unambiguous.) Thus the value of the integral is unchanged. It is now convenient to define a Euclidean  $d$ -dimensional vector  $\bar{q}$  via  $q^0 = i\bar{q}_d$  and  $q_j = \bar{q}_j$ ; then  $q^2 = \bar{q}^2$ , where

$$\bar{q}^2 = \bar{q}_1^2 + \cdots + \bar{q}_d^2$$

Also,  $d^d q = i d^d \bar{q}$ . Therefore, in general,

$$\int d^d q f(q^2 - i\epsilon) = i \int d^d \bar{q} f(\bar{q}^2)$$



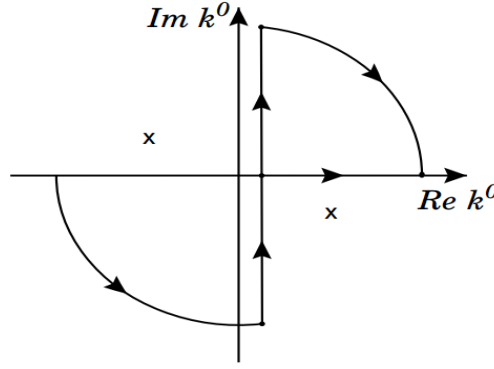


Figure 12.14: Wick rotation

### Dimensional regularization

Dimensional regularization is a method for regularizing integrals in the evaluation of Feynman diagrams. For example, if one wishes to evaluate a loop integral which is logarithmically divergent in four dimensions, like

$$\int \frac{d^d p}{(2\pi)^d} \frac{1}{(p^2 + m^2)^2}$$

One first rewrites the integral in some way so that the number of variables integrated over does not depend on  $d$ , and then we formally vary the parameter  $d$ , to include non-integral values like  $d = 4 - \epsilon$ .

$$\int_0^\infty \frac{dp}{(2\pi)^{4-\epsilon}} \frac{2\pi^{(4-\epsilon)/2}}{\Gamma(\frac{4-\epsilon}{2})} \frac{p^{3-\epsilon}}{(p^2 + m^2)^2} = \frac{2^{\epsilon-4} \pi^{\frac{\epsilon}{2}-1}}{\sin(\frac{\pi\epsilon}{2}) \Gamma(1-\frac{\epsilon}{2})} m^{-\epsilon} = \frac{1}{8\pi^2 \epsilon} - \frac{1}{16\pi^2} \left( \ln \frac{m^2}{4\pi} + \gamma \right) + \mathcal{O}(\epsilon)$$

There is a useful formula for calculating the integral

$$\int \frac{d^d \bar{q}}{(2\pi)^d} \frac{(\bar{q}^2)^a}{(\bar{q}^2 + D)^b} = \frac{\Gamma(b-a-\frac{1}{2}d) \Gamma(a+\frac{1}{2}d)}{(4\pi)^{d/2} \Gamma(b) \Gamma(\frac{1}{2}d)} D^{-(b-a-d/2)}$$

If  $a = 0$ , then the formula will be

$$\int \frac{d^d \bar{q}}{(2\pi)^d} \frac{1}{(\bar{q}^2 + D)^b} = \frac{\Gamma(b-\frac{1}{2}d)}{(4\pi)^{d/2} \Gamma(b)} D^{-(b-d/2)}$$

### 12.9.4 One loop structure of $\phi^4$ theory

First consider the basic two-particle scattering amplitude, If we define  $p = p_1 + p_2$ , then the second diagram of Figure 2.15 is

$$\frac{(-i\lambda)^2}{2} \int \frac{d^4 k}{(2\pi)^4} \frac{-i}{k^2 + m^2} \frac{-i}{(k+m)^2 + m^2} \equiv (-i\lambda)^2 iV(-p^2)$$

So the entire amplitude is therefore

$$i\mathcal{M} = -i\lambda + (-i\lambda)^2 [iV(s) + iV(t) + iV(u)] - i\delta_\lambda + \mathcal{O}(\lambda^3)$$





$$\begin{aligned}
i\mathcal{M}(p_1 p_2 \rightarrow p_3 p_4) &= \text{Diagram with a central shaded circle and four external lines labeled } p_1, p_2, p_3, p_4 \\
&= \text{Diagram with two crossing lines} + \left( \text{Diagram with a loop} + \text{Diagram with a loop} + \text{Diagram with a loop} \right) + \text{Diagram with a loop} + \dots
\end{aligned}$$

**Figure 12.15:** Feynman diagram representation of two-particle scattering to one loop

To keep  $\lambda$  dimensionless in dimensional regularization, we can make the transformation  $\lambda \rightarrow \lambda \tilde{\mu}^\epsilon$ . Here,  $\mu$  is an arbitrary number with mass dimension 1 and  $\epsilon \equiv 4 - d$ .

We can calculate that

$$V(-p^2) = -\frac{1}{32\pi^2} \int_0^1 \left( \frac{2}{\epsilon} + \ln\left(\frac{\mu^2}{D(-p^2)}\right) \right)$$

where  $\mu \equiv \sqrt{4\pi}e^{-\gamma/2}\tilde{\mu}$ ,  $D(-p^2) = x(1-x)p^2 + m^2$

The renormalization condition implies that

$$\delta_\lambda = -\lambda^2[V(4m^2) + 2V(0)] + \mathcal{O}(\lambda^3)$$

So,

$$i\mathcal{M} = -i\lambda - \frac{i\lambda^2}{32\pi^2} \int_0^1 dx \left[ \ln\left(\frac{D(s)}{D(4m^2)}\right) + \ln\left(\frac{D(t)}{D(0)}\right) + \ln\left(\frac{D(u)}{D(0)}\right) \right] + \mathcal{O}(\lambda^3)$$

To determine  $\delta_Z$  and  $\delta_m$  we must compute the two-point function. Define  $-iM(p^2)$  as the sum of all one-particle-irreducible insertions into the propagator. The full two-point function is given by

$$\frac{-i}{p^2 + m^2 + M^2}$$

The renormalization conditions require that the pole in this full propagator occur at  $p^2 = -m^2$  and have residue 1. These two conditions are equivalent, respectively, to

$$M^2(p^2)|_{p^2=-m^2} = 0 \quad \frac{d}{dp^2}M^2(p^2)|_{p^2=-m^2} = 0$$

We can calculate that

$$-iM^2(p^2) = \frac{i\lambda}{32\pi^2} \left( \frac{2}{\epsilon} + \ln\left(\frac{\mu^2}{m^2}\right) + 1 \right) m^2 - i(p^2\delta_Z + \delta_m)$$

So, to the order of  $\lambda$ ,

$$\delta_Z = \mathcal{O}(\lambda^2) \quad \delta_m = \frac{\lambda}{32\pi^2} \left( \frac{2}{\epsilon} + \ln\left(\frac{\mu^2}{m^2}\right) + 1 \right) m^2 + \mathcal{O}(\lambda^2) \quad M^2(p^2) = \mathcal{O}(\lambda^2)$$

The detailed calculation can be found in chapter 10.2 of *An introduction to quantum field theory* (M.E.Peskin & D.V.Schroeder) and will be eliminated here.



### Perturbation theory to all orders

We begin by summing all one-particle irreducible diagrams with two external lines; this gives us the self-energy. We next sum all 1PI diagrams with four external lines; this gives us the four-point vertex function  $V_4(k_1, k_2, k_3, k_4)$ . Order by order in  $\lambda$ , we must adjust the value of the lagrangian coefficients  $\delta_Z$ ,  $\delta_m$ , and  $\delta_\lambda$  to maintain the conditions  $M^2(-m^2) = 0$ ,  $\frac{dM^2}{dp^2}(-m^2) = 0$ , and  $V_4(s = 4m^2) = 0$ .

Next we will construct the  $n$ -point vertex functions  $V_n$  with  $4 < n \leq E$ , where  $E$  is the number of external lines in the process of interest. We compute these using a skeleton expansion. This means that we draw all the contributing 1PI diagrams, but omit diagrams that include either propagator or three-point vertex corrections. That is, we include only diagrams that are not only 1PI, but also 2PI and 3PI: they remain connected when any one, two, or three lines are cut. (Cutting three lines may isolate a single treelevel vertex, but nothing more complicated.) Then we take the propagators and vertices in these diagrams to be given by the exact propagator  $\frac{-i}{p^2 + m^2 + M^2(p^2)}$  and vertex  $V_4(k_1, k_2, k_3, k_4)$ , rather than by the tree-level propagator and vertex. We then sum these skeleton diagrams to get  $V_n$  for  $4 < n \leq E$ . Order by order in  $\lambda$ , this procedure is equivalent to computing  $V_n$  by summing the usual set of contributing 1PI diagrams.

Next we draw all tree-level diagrams that contribute to the process of interest (which has  $E$  external lines), including not only four-point vertices, but also  $n$ -point vertices. Then we evaluate these diagrams using the exact propagator for internal lines, and the exact 1PI vertices  $V_n$ ; external lines are assigned a factor of one. We sum these tree diagrams to get the scattering amplitude. Order by order in  $\lambda$ , this procedure is equivalent to computing the scattering amplitude by summing the usual set of contributing diagrams.

Thus we now know how to compute an arbitrary scattering amplitude to arbitrarily high order. The procedure is the same in any quantum field theory; only the form of the propagators and vertices change, depending on the spins of the fields.

### 12.9.5 Modified minimal-subtraction scheme

The Lagrangian of  $\phi^4$  theory is

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4 - \frac{1}{2}\delta_Z\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}\delta_m\phi^2 - \frac{\delta\lambda}{4!}\phi^4$$

For minimal-subtraction scheme, we do not demand that  $m$  be the physics mass of the field and  $\phi$  create a normalized one-particle state. The physical meaning of  $\lambda$  is not expressed directly as well. Instead we choose  $\delta_Z$ ,  $\delta_m$  and  $\delta_\lambda$  to cancel the infinities, and nothing more; we say that  $\delta_Z$ ,  $\delta_m$  and  $\delta_\lambda$  have no finite parts. It is called the modified minimal-subtraction or  $\overline{\text{MS}}$  scheme. ("modified" because we introduced  $\mu$  via  $\lambda \rightarrow \lambda\tilde{\mu}^\epsilon$ , with  $\mu \equiv \sqrt{4\pi}e^{-\gamma/2}\tilde{\mu}$ ; had we set  $\mu = \tilde{\mu}$  instead, the scheme would be just plain minimal subtraction or MS.)

For loop corrections to propagator,

$$\delta_Z = \mathcal{O}(\lambda^2) \quad \delta_m = \left[ \frac{\lambda}{16\pi^2} + \mathcal{O}(\lambda^2) \right] \frac{1}{\epsilon} m^2 \quad M^2(p^2) = \frac{\lambda}{32\pi^2} (\ln(\frac{m^2}{\mu^2}) - 1) m^2 + \mathcal{O}(\lambda^2)$$



Firstly, in the  $\overline{\text{MS}}$  scheme, the propagator will no longer have a pole at  $k^2 = -m^2$ . The pole will be somewhere else. However, by definition, the actual physical mass  $m_{ph}$  of the particle is determined by the location of this pole:  $k^2 = -m_{ph}^2$ . Thus, the Lagrangian parameter  $m$  is no longer the same as  $m_{ph}$ . The relation of  $m$  and  $m_{ph}$  is

$$m_{ph}^2 = M^2(-m_{ph}^2) + m^2$$

To the lowest order,

$$m_{ph}^2 = \left[ 1 + \frac{\lambda}{32\pi^2} (\ln(\frac{m^2}{\mu^2}) - 1) \right] m^2$$

Because  $m_{ph}$  is independent of  $\mu$ , according to  $\frac{d}{d\mu} m_{ph} = 0$ , it can be derived that

$$\frac{dm}{d \ln \mu} = \left[ \frac{\lambda}{32\pi^2} + \mathcal{O}(\lambda^2) \right] m$$

Furthermore, the residue of this pole is no longer one. Let us call the residue  $R$ . So, in the LSZ formula, we get a net factor of  $\sqrt{R}$  for each external line when using the  $\overline{\text{MS}}$  scheme. And in  $\phi^4$  theory,

$$R = 1 + \mathcal{O}(\lambda^2)$$

For loop corrections to vertex,

$$\delta_\lambda = \left[ \frac{3\lambda^2}{16\pi^2} + \mathcal{O}(\lambda^3) \right] \frac{1}{\epsilon}$$

$$i\mathcal{M} = -i\lambda - \frac{i\lambda^2}{32\pi^2} \int_0^1 dx \left[ \ln\left(\frac{D(s)}{\mu^2}\right) + \ln\left(\frac{D(t)}{\mu^2}\right) + \ln\left(\frac{D(u)}{\mu^2}\right) \right] + \mathcal{O}(\lambda^3)$$

### 12.9.6 The renormalization group

The Lagrangian of  $\phi^4$  theory is

$$\mathcal{L} = -\frac{1}{2} \partial^\mu \phi_0 \partial_\mu \phi_0 - \frac{1}{2} m_0^2 \phi_0^2 - \frac{\lambda_0}{4!} \phi_0^4$$

It can be written as

$$\mathcal{L} = -\frac{1}{2} Z_\phi \partial^\mu \phi \partial_\mu \phi - \frac{1}{2} Z_m m^2 \phi^2 - Z_\lambda \mu^\epsilon \frac{\lambda}{4!} \phi^4$$

So,

$$\phi_0 = Z_\phi^{1/2} \phi \quad m_0 = Z_\phi^{-1/2} Z_m^{1/2} m \quad \lambda = Z_\phi^{-2} Z_\lambda \lambda \tilde{\mu}^\epsilon$$

After using dimensional regularization, the infinities coming from loop integrals take the form of inverse powers of  $\epsilon$ . In the  $\overline{\text{MS}}$  renormalization scheme, we choose the  $Z$ s to cancel off these powers of  $1/\epsilon$ , and nothing more. Therefore the  $Z$ s can be written as

$$Z_\phi = 1 + \sum_{n=1}^{\infty} \frac{a_n(\lambda)}{\epsilon^n}$$

$$Z_m = 1 + \sum_{n=1}^{\infty} \frac{b_n(\lambda)}{\epsilon^n}$$

$$Z_\lambda = 1 + \sum_{n=1}^{\infty} \frac{c_n(\lambda)}{\epsilon^n}$$



In  $\phi^4$  theory,  $a_1 = \mathcal{O}(\lambda^2)$ ,  $b_1 = \frac{\lambda}{16\pi^2} + \mathcal{O}(\lambda^2)$ ,  $c_1 = \frac{3\lambda}{16\pi^2} + \mathcal{O}(\lambda^2)$

Remember that bare fields and parameters must be independent of  $\mu$ . Define

$$G(\lambda, \epsilon) \equiv \ln(Z_\phi^{-2} Z_\lambda) = \sum_{n=1}^{\infty} \frac{G_n(\lambda)}{\epsilon^n}$$

We can calculate  $G_1 = c_1 - 2a_1 = \frac{3\lambda}{16\pi^2} + \mathcal{O}(\lambda^2)$ . As  $\ln \lambda_0 = G + \ln \lambda + \epsilon \ln \tilde{\mu}$ . From the independence of  $\lambda_0$ , we can derive

$$\left(1 + \frac{\lambda G'_1}{\epsilon} + \dots\right) \frac{d\lambda}{d \ln \mu} + \epsilon \lambda = 0$$

In a renormalizable theory, we should have

$$\frac{d\lambda}{d \ln \mu} = -\epsilon \lambda + \beta(\lambda)$$

So

$$\beta(\lambda) = \lambda^2 G'_1(\lambda)$$

In  $\phi^4$  theory, we have  $\beta(\lambda) = \frac{3\lambda^2}{16\pi^2} + \mathcal{O}(\lambda^3)$ . Define

$$M(\lambda, \epsilon) \equiv \ln(Z_m^{1/2} Z_\phi^{-1/2}) = \sum_{n=1}^{\infty} \frac{M_n(\lambda)}{\epsilon^n}$$

We can calculate  $M_1 = \frac{1}{2}b_1 - \frac{1}{2}a_1 = \frac{\lambda}{32\pi^2} + \mathcal{O}(\lambda^2)$ . As  $\ln m_0 = M + \ln m$ , define the anomalous dimension of the mass

$$\gamma_m(\lambda) \equiv \frac{1}{m} \frac{dm}{d \ln \mu}$$

From the independence of  $m_0$ , we can derive

$$\gamma_m(\lambda) = \lambda M'_1$$

In  $\phi^4$  theory, we have  $\gamma_m(\lambda) = \frac{\lambda}{32\pi^2} + \mathcal{O}(\lambda^2)$ . We can expand  $\ln Z_\phi$  as

$$\ln Z_\phi = \frac{a_1}{\epsilon} + \frac{a_2 - \frac{1}{2}a_1^2}{\epsilon^2}$$

Define the anomalous dimension of the field

$$\gamma_\phi(\lambda) = \frac{1}{2} \frac{d \ln Z_\phi}{d \ln \mu}$$

We can derive

$$\gamma_\phi(\lambda) = -\frac{1}{2} \lambda a'_1$$

In  $\phi^4$  theory, we have  $\gamma_m(\lambda) = \mathcal{O}(\lambda^2)$ .



## Callen-Symanzik equation

$$G^{(n)}(x_1, \dots, x_n) \equiv \langle \Omega | T \phi(x_1) \cdots \phi(x_n) | \Omega \rangle_C$$

As  $G_0^{(n)} = Z_\phi^{n/2} G^{(n)}$ , from the independence of bare Green's function, we have

$$\left( \frac{\partial}{\partial \ln \mu} + \beta(\lambda) \frac{\partial}{\partial \lambda} + \gamma_m(\lambda) m \frac{\partial}{\partial m} + n \gamma_\phi(\lambda) \right) G^n(x_1, \dots, x_n; \lambda, m, \mu) = 0$$

## 12.10 Spontaneous symmetry breaking

### 12.10.1 Effective action

$$Z[J] = e^{-iE[J]} = \int \mathcal{D}\phi \exp \left[ i \int d^4x (\mathcal{L}[\phi] + J\phi) \right]$$

Define

$$\phi_{\text{cl}}(x) \equiv \langle \Omega | \phi(x) | \Omega \rangle_J$$

So, we can derive

$$\frac{\delta}{\delta J(x)} E[J] = -\phi_{\text{cl}}(x)$$

Define

$$\Gamma[\phi_{\text{cl}}] \equiv -E[J] - \int d^4y J(y) \phi_{\text{cl}}(y)$$

We can verify that

$$\frac{\delta}{\delta \phi_{\text{cl}}(x)} \Gamma[\phi_{\text{cl}}] = -J(x)$$

If the external source is set to zero, the effective action satisfy the equation

$$\frac{\delta}{\delta \phi_{\text{cl}}(x)} \Gamma[\phi_{\text{cl}}] = 0$$

The solution to this equation are the values of  $\langle \phi(x) \rangle$  in the stable quantum states of the theory. For a translational-invariant vacuum state, we will find a solution in which  $\phi_{\text{cl}}$  is independent of  $x$ . For the field theory that the possible vacuum states are invariant under translations and Lorentz transformations, for each possible vacuum states, the corresponding solution  $\phi_{\text{cl}}$  will be a constant, independent of  $x$ . If  $T$  is the time extent of the region and  $V$  is its three dimensional volume, we can write

$$\Gamma[\phi_{\text{cl}}] = -(VT) \cdot V_{\text{eff}}(\phi_{\text{cl}})$$

The coefficient  $V_{\text{eff}}$  is called effective potential. The condition that  $\Gamma[\phi_{\text{cl}}]$  has an extreme then reduces to the simple equation

$$\frac{\partial}{\partial \phi_{\text{cl}}} V_{\text{eff}}(\phi_{\text{cl}}) = 0$$

A system with spontaneously broken symmetry will have several minimum of  $V_{\text{eff}}$ , all with the same energy by virtue of the symmetry. The choice of one among these vacuum is the spontaneous symmetry breaking.



### 12.10.2 Computation of the effective action

Decompose the Lagrangian into a piece depending on renormalized parameters and one containing the counter-terms

$$\mathcal{L} = \mathcal{L}_1 + \delta\mathcal{L}$$

Define  $J_1$  by

$$\frac{\delta\mathcal{L}_1}{\delta\phi}\big|_{\phi=\phi_{\text{cl}}} + J_1(x) = 0$$

Define  $\delta J$  by

$$J(x) = J_1(x) + \delta J(x)$$

So, we have

$$e^{-iE[J]} = \int \mathcal{D}\phi e^{i \int d^4x (\mathcal{L}_1 + J_1\phi)} e^{i \int d^4x (\delta\mathcal{L} + \delta J\phi)}$$

Replace  $\phi$  by  $\phi_{\text{cl}} + \eta$ ,

$$\begin{aligned} \int d^4x (\mathcal{L}_1 + J_1\phi) &= \int d^4x (\mathcal{L}_1[\phi_{\text{cl}}] + J_1\phi_{\text{cl}}) + \int d^4x \eta(x) \left( \frac{\delta\mathcal{L}_1}{\delta\phi} + J_1 \right) \\ &+ \frac{1}{2} \int d^4x d^4y \eta(x)\eta(y) \frac{\delta^2\mathcal{L}_1}{\delta\phi(x)\delta\phi(y)} \\ &+ \frac{1}{3!} \int d^4x d^4y d^4z \eta(x)\eta(y)\eta(z) \frac{\delta^3\mathcal{L}_1}{\delta\phi(x)\delta\phi(y)\delta\phi(z)} + \dots \end{aligned}$$

The term linear in  $\eta$  vanishes by definition of  $J_1$ . Keeping only the term up to quadratic order in  $\eta$  and still neglecting the counter-terms, we have a pure Gaussian integral, which can be evaluated in terms of a functional determinant:

$$\begin{aligned} &\int \mathcal{D}\eta \exp \left[ i \left( \int (\mathcal{L}_1[\phi_{\text{cl}}] + J_1\phi_{\text{cl}}) + \frac{1}{2} \int \eta \frac{\delta^2\mathcal{L}_1}{\delta\phi\delta\phi} \eta \right) \right] \\ &= \exp \left[ i \int (\mathcal{L}_1[\phi_{\text{cl}}] + J_1\phi_{\text{cl}}) \right] \left( \det \left[ \frac{\delta^2\mathcal{L}_1}{\delta\phi\delta\phi} \right] \right)^{-\frac{1}{2}} \end{aligned}$$

Finally, put back the effects of the counter-term Lagrangian, writing it as

$$(\delta\mathcal{L}[\phi_{\text{cl}}] + \delta J\phi_{\text{cl}}) + (\delta\mathcal{L}[\phi_{\text{cl}} + \eta] - \delta\mathcal{L}[\phi_{\text{cl}}] + \delta J\eta)$$

Define

$$\mathcal{L}_2 = \left( \frac{1}{3!} \int d^4x d^4y d^4z \eta(x)\eta(y)\eta(z) \frac{\delta^3\mathcal{L}_1}{\delta\phi(x)\delta\phi(y)\delta\phi(z)} + \dots \right) + (\delta\mathcal{L}[\phi_{\text{cl}} + \eta] - \delta\mathcal{L}[\phi_{\text{cl}}] + \delta J\eta)$$

So

$$e^{-iE[J]} = \exp \left[ i \int (\mathcal{L}_1[\phi_{\text{cl}}] + J_1\phi_{\text{cl}} + \delta\mathcal{L}[\phi_{\text{cl}}] + \delta J\phi_{\text{cl}}) \right] e^{i \int \mathcal{L}_2(\frac{1}{i} \frac{\delta}{\delta I})} \int \mathcal{D}\eta e^{i \int \left( \frac{1}{2} \eta \frac{\delta^2\mathcal{L}_1}{\delta\phi\delta\phi} \eta + I\eta \right)}$$

Therefore, define propagator as

$$D_F \equiv i \left( \frac{\delta^2\mathcal{L}_1}{\delta\phi\delta\phi} \right)^{-1}$$



We have

$$e^{-iE[J]} = \exp \left[ i \int (\mathcal{L}_1[\phi_{cl}] + J_1\phi_{cl} + \delta\mathcal{L}[\phi_{cl}] + \delta J\phi_{cl}) \right] \left( \det \left[ \frac{\delta^2 \mathcal{L}_1}{\delta\phi\delta\phi} \right] \right)^{-\frac{1}{2}} e^{i \int \mathcal{L}_2(\frac{1}{i} \frac{\delta}{\delta I})} \int \mathcal{D}\eta e^{i \int (-\frac{1}{2} I D_F I)} \Big|_{I=0}$$

Similar to the procedure in the perturbation theory for path integral quantization, we can get a perturbation expansion for  $iE[J]$  using connected Feynman diagram,

$$-iE[J] = i \int (\mathcal{L}_1[\phi_{cl}] + J_1\phi_{cl} + \delta\mathcal{L}[\phi_{cl}] + \delta J\phi_{cl}) - \frac{1}{2} \log \det \left[ \frac{\delta^2 \mathcal{L}_1}{\delta\phi\delta\phi} \right] + \text{connected diagrams}$$

From this equation,  $\Gamma$  follows directly:

$$\Gamma[\phi_{cl}] = \int d^4x \mathcal{L}_1[\phi_{cl}] + \frac{i}{2} \log \det \left[ \frac{\delta^2 \mathcal{L}_1}{\delta\phi\delta\phi} \right] - i \text{ connected diagrams} + \int d^4x \delta\mathcal{L}[\phi_{cl}]$$

Notice that there are no terms remaining that depend explicitly on  $J$ ; thus,  $\Gamma$  is expressed as a function of  $\phi_{cl}$ , as it should be. The Feynman diagrams contributing to  $\Gamma[\phi_{cl}]$  have no external lines, and the simplest ones turn out to have two loops. The lowest-order quantum correction to  $\Gamma$  is given by the functional determinant.

The last term provides a set of counter-terms that can be used to satisfy the renormalization conditions on  $\Gamma$  and, in the process, to cancel divergences that appear in the evaluation of the functional determinant and the diagrams. The renormalization conditions will determine all of the counter-terms in  $\delta\mathcal{L}$ . However, the formalism we have constructed contains a new counter-term  $\delta J$ . That coefficient is determined by  $\langle \eta \rangle = 0$ . In practice, we will satisfy this condition by simply ignoring any one-particle-irreducible one-point diagram, since any such diagram will be cancelled by adjustment of  $\delta J$ .

### 12.10.3 The effective action as a generating functional

$E[J]$  is called the generating of connected correlation functions,

$$\frac{\delta^n E[J]}{\delta J(x_1) \cdots \delta J(x_n)} = i^{n+1} \langle \phi(x_1) \cdots \phi(x_n) \rangle_{\text{conn}}$$

The effective action  $\Gamma[\phi_{cl}]$  is the generating functional of one-particle-irreducible correlation functional,

$$\begin{aligned} \frac{\delta \Gamma[\phi_{cl}]}{\delta \phi_{cl}(x)} &= 0 \\ \frac{\delta^2 \Gamma[\phi_{cl}]}{\delta \phi_{cl}(x) \delta \phi_{cl}(y)} &= i D^{-1}(x, y) \end{aligned}$$

Here,  $D(x, y) = \langle \phi(x) \phi(y) \rangle_{\text{conn}}$ . When  $n \geq 3$ ,

$$\frac{\delta^n \Gamma[\phi_{cl}]}{\delta \phi_{cl}(x_1) \cdots \delta \phi_{cl}(x_n)} = -i \langle \phi(x_1) \cdots \phi(x_n) \rangle_{\text{1PI}}$$

The proof of statements above can be found in chapter 10.2 of *An introduction to quantum field theory* (M.E.Peskin & D.V.Schroeder)



The chapter 21 of *Quantum field theory* (M. Srednicki) gives an constructive way to define the effective action.

$$\Gamma[\phi] \equiv \frac{1}{2} \int \frac{d^d k}{(2\pi)^d} \tilde{\phi}(-k) (-k^2 - m^2 - M^2(k^2)) \tilde{\phi}(k) + \frac{1}{n!} \int \frac{d^d k_1}{(2\pi)^d} \cdots \frac{d^d k_n}{(2\pi)^d} (2\pi)^d \delta(k_1 + \cdots + k_n) V_n(k_1, \dots, k_n)$$

Here  $\tilde{\phi}(k) = \int d^d x e^{-ikx} \phi(x)$ , and  $iV_n(k_1, \dots, k_n)$  equals the value of 1PI Feynman diagram in momentum space. The effective action has the property that the tree-level Feynman diagrams it generates give the complete scattering amplitude of the original theory. The author also proved that this definition is equivalent to the definition from *An introduction to quantum field theory* (M.E. Peskin & D.V. Schroeder).

### 12.10.4 Renormalization and symmetry

Consider first the computation of the effective potential for constant classical fields, in a field theory with an arbitrary number of fields  $\phi^i$ . The effective potential has mass dimension 4, so we expect that  $V_{\text{eff}}(\phi_{\text{cl}})$  will have divergent terms up to  $\Lambda^4$ . To understand these divergences, expand  $V_{\text{eff}}(\phi_{\text{cl}})$  in a Taylor series:

$$V_{\text{eff}}(\phi_{\text{cl}}) = A_0 + A_2^{ij} \phi_{\text{cl}}^i \phi_{\text{cl}}^j + A_4^{ijkl} \phi_{\text{cl}}^i \phi_{\text{cl}}^j \phi_{\text{cl}}^k \phi_{\text{cl}}^l + \cdots$$

In theories without a symmetry of  $\phi \rightarrow \phi$ , there might also be terms linear and cubic in  $\phi^i$ ; we omit these for simplicity. The coefficients  $A_0, A_2, A_4$  have mass dimension, respectively, 4, 2, and 0; thus we expect them to contain  $\Lambda^4, \Lambda^2$ , and  $\log \Lambda$  divergences, respectively. The power-counting analysis predicts that all higher terms in the Taylor series expansion should be finite.

The constant term  $A_0$  is independent of  $\phi_{\text{cl}}$ ; it has no physical significance. However, the divergences in  $A_2$  and  $A_4$  appear in physical quantities, since these coefficients enter the inverse propagator and the irreducible four-point function and therefore appear in the computation of S-matrix elements. There is one further coefficient in the effective action that has non-negative mass dimension by power counting; this is the coefficient of the term quadratic in  $\partial_\mu \phi_{\text{cl}}$ , which appears when the effective action is evaluated for a non-constant background field:

$$\Delta\Gamma[\phi_{\text{cl}}] = \int d^4 x B_2^{ij} \partial_\mu \phi_{\text{cl}}^i \partial^\mu \phi_{\text{cl}}^j$$

All other coefficients in the Taylor expansion of the effective action in powers of  $\phi_{\text{cl}}$  are finite by power counting.

We can now argue that the counter-terms of the original Lagrangian suffice to remove the divergences that might appear in the computation of  $\Gamma[\phi_{\text{cl}}]$ . The argument proceeds in two steps. We first use the BPHZ theorem to argue that the divergences of Green's functions can be removed by adjusting a set of counter-terms corresponding to the possible operators that can be added to the Lagrangian with coefficients of mass dimension greater than or equal to zero. The coefficients of these counter-terms are in 1-to-1 correspondence with the coefficients  $A_2, A_4$ , and  $B_2$  of the effective action. Next, we use the fact that the effective action is manifestly invariant to the original Symmetry group of the model. This is true even if the vacuum state of the model has spontaneous symmetry breaking, since the method we presented for computing the effective action is manifestly invariant to the original symmetry of the Lagrangian.





Combining these two results, we conclude that the effective action can always be made finite by adjusting the set of counter-terms that are invariant to the original symmetry of the theory, even if this symmetry is spontaneously broken.

### 12.10.5 Goldstone's theorem

#### Theorem 12.4 Goldstone's theorem

Goldstone's theorem examines a generic continuous symmetry which is spontaneously broken; i.e., its currents are conserved, but the ground state is not invariant under the action of the corresponding charges. Then, necessarily, new massless (or light, if the symmetry is not exact) scalar particles appear in the spectrum of possible excitations. There is one scalar particle - called a Nambu-Goldstone boson — for each generator of the symmetry that is broken, i.e., that does not preserve the ground state.

A general continuous symmetry transformation has the form

$$\phi^a \rightarrow \phi^a + \alpha \Delta^a(\phi)$$

where  $\alpha$  is an infinitesimal parameter and  $\Delta^a$  is some function of all the  $\phi$ 's. Specialize to constant fields; then the derivative terms in  $\mathcal{L}$  vanish and the potential alone must be invariant. This condition can be written

$$V(\phi^a) = V(\phi^a + \alpha \Delta^a(\phi)) \quad \text{or} \quad \Delta^a(\phi) \frac{\partial}{\partial \phi^a} V(\phi) = 0$$

The effective potential  $V_{\text{eff}}$  encapsulates the full solution to the theory, including all orders of quantum corrections. At the same time, it satisfies the general properties of the classical potential: It is invariant to the symmetries of the theory, and its minimum gives the vacuum expectation value of  $\phi_{\text{cl}}$ . So

$$\Delta^a(\phi) \frac{\partial}{\partial \phi^a} V_{\text{eff}}(\phi) = 0$$

Now differentiate with respect to  $\phi^b$ , and set  $\phi = \phi_{\text{cl}}$

$$0 = \left( \frac{\partial \Delta^a}{\partial \phi^b} \right)_{\phi_{\text{cl}}} \left( \frac{\partial V_{\text{eff}}}{\partial \phi^a} \right)_{\phi_{\text{cl}}} + \Delta^a(\phi_{\text{cl}}) \left( \frac{\partial^2}{\partial \phi^a \partial \phi^b} V_{\text{eff}} \right)_{\phi_{\text{cl}}}$$

The first term vanishes since  $\phi_{\text{cl}}$  is a minimum of  $V_{\text{eff}}$ , so the second term must also vanish. If the transformation leaves  $\phi_{\text{cl}}$  unchanged (i.e., if the symmetry is respected by the ground state), then  $\Delta^a(\phi_{\text{cl}}) = 0$  and this relation is trivial. A spontaneously broken symmetry is precisely one for which  $\Delta^a(\phi_{\text{cl}}) \neq 0$ ; in this case  $\Delta^a(\phi_{\text{cl}})$  is the vector with eigenvalue zero.



We now argue that the presence of such a zero eigenvalue implies the existence of a massless scalar particle. Effective action's second functional derivative is the inverse propagator

$$i\tilde{D}_{ij}^{-1}(p^2) = \int d^4x e^{-ip(x-y)} \frac{\delta\Gamma}{\delta\phi^i \delta\phi^j}(x, y)$$

A particle of mass  $m$  corresponds to a zero eigenvalue of this matrix equation at  $p^2 = -m^2$ . Now set  $p = 0$ . This implies that we differentiate  $\Gamma[\phi_{\text{cl}}]$  with respect to constant fields. Thus, we can replace  $\Gamma[\phi_{\text{cl}}]$  by its value with constant classical fields, which is just the effective potential. We find that the quantum field theory contains a scalar particle of zero mass when the matrix of second derivatives,

$$\frac{\partial^2}{\partial\phi_{\text{cl}}^i \partial\phi_{\text{cl}}^j} V_{\text{eff}}$$

has a zero eigenvalue. This completes the proof of Goldstone's theorem.

## 12.11 Linear sigma model

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi^i\partial^\mu\phi^i + \frac{1}{2}\mu^2(\phi^i)^2 - \frac{\lambda}{4}[(\phi^i)^2]^2$$

The Lagrangian is invariant under the symmetry

$$\phi^i \rightarrow R^{ij}\phi^j$$

for any  $N \times N$  orthogonal group in  $N$  dimensions, also called the  $N$ -dimensional orthogonal group or simply  $O(N)$ .



# Chapter 13

## Vector Field



### 13.1 Vector field

Consider a vector field  $A^\mu(x)$ . Here the index  $\mu$  is a vector index that takes on four possible values. Under a Lorentz transformation, we have

$$U(\Lambda)^{-1} A^\mu(x) U(\Lambda) = \Lambda^\mu{}_\nu A^\nu(\Lambda^{-1}x)$$

For an infinitesimal transformation, we can write

$$\delta^\mu{}_\nu + \delta\omega^\mu{}_\nu = \delta^\mu{}_\nu + \frac{i}{2} \delta\omega_{\rho\sigma} (S_V^{\rho\sigma})^\mu{}_\nu$$

Here

$$(S_V^{\rho\sigma})^\mu{}_\nu = -i(\eta^{\rho\mu}\delta^\sigma{}_\nu - \eta^{\sigma\mu}\delta^\rho{}_\nu)$$

It is obvious that  $A^{\dagger\mu}$  is also a vector field. We know that  $\eta^{\mu\nu}$  is invariant under Lorentz transformation, i.e.

$$\Lambda^\mu{}_\rho \Lambda^\nu{}_\sigma \eta^{\rho\sigma} = \eta^{\mu\nu}$$

We can use  $\eta^{\mu\nu}$  and its inverse  $\eta_{\mu\nu}$  to raise and lower vector indices of the vector field,

$$A_\mu \equiv \eta_{\mu\nu} A^\nu$$

And we can verify the following equations

$$\Lambda^\mu{}_\nu \Lambda_\mu{}^\rho = \delta_\nu^\rho$$

$$A^\mu(x) = \eta^{\mu\nu} A_\nu(x)$$

$$\Lambda_\mu{}^\rho \Lambda_\nu{}^\sigma \eta_{\rho\sigma} = \eta_{\mu\nu}$$

$$U(\Lambda)^{-1} A_\mu(x) U(\Lambda) = \Lambda_\mu{}^\nu A_\nu(\Lambda^{-1}x)$$

Define  $C_i \equiv \frac{1}{2} \epsilon_{ijk} S_V^{jk}, D_i \equiv S_V^{i0}$ . For example, we have

$$(C_3)_\mu{}^\nu = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

The eigenvectors of  $C_3$  are

$$[(-1, [(0, 1, -i, 0)], 1), (1, [(0, 1, i, 0)], 1), (0, [(1, 0, 0, 0), (0, 0, 0, 1)], 2)]$$

We further define  $N_i \equiv \frac{1}{2}(C_i - iD_i)$  and  $N_i^\dagger \equiv \frac{1}{2}(C_i + iD_i)$ . For example, we have

$$(N_1)_\mu{}^\nu = \begin{pmatrix} 0 & -\frac{1}{2} & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{2}i \\ 0 & 0 & \frac{1}{2}i & 0 \end{pmatrix}$$

The eigenvectors of  $N_1$  are

$$\left[ \left( -\frac{1}{2}, [(1, 1, 0, 0), (0, 0, 1, -i)], 2 \right), \left( \frac{1}{2}, [(1, -1, 0, 0), (0, 0, 1, i)], 2 \right) \right]$$

And we can conclude that vector is in the  $(2, 2)$  representation of the Lie algebra of the Lorentz group.

## 13.2 Electromagnetic field and gauge invariance

The Lagrangian of EM field is

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Here,

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad \text{and} \quad A^\mu = (\phi, \mathbf{A})$$

So,

$$F_{0i} = \dot{A}^i + \nabla_i \phi \equiv -E^i \quad \text{and} \quad F_{ij} = \nabla_i A^j - \nabla_j A^i \equiv \epsilon_{ijk} B^k$$

We can derive the equation of motion of the EM field by variation method,

$$\partial_\mu F^{\mu\nu} = 0$$

It can be rewritten in terms of  $\mathbf{E}$  and  $\mathbf{B}$ , i.e. Maxwell equations:

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 0 & \frac{\partial \mathbf{E}}{\partial t} &= \nabla \times \mathbf{B} \\ \nabla \cdot \mathbf{B} &= 0 & \frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \end{aligned}$$

The massless vector field  $A_\mu$  has 4 components, which would naively seem to tell us that the gauge field has 4 degrees of freedom. But there are two related comments which will ensure that quantizing the gauge field  $A_\mu$  gives rise to 2 degrees of freedom, rather than 4.

- The field  $A_0$  has no kinetic term  $\dot{A}_0$  in the Lagrangian: it is not dynamical. This means that if we are given some initial data  $A_i$  and  $\dot{A}_i$  at a time  $t_0$ , then the field  $A_0$  is fully determined by the equation of motion  $\nabla \cdot \mathbf{E} = 0$ , which, expanding out, reads

$$\nabla^2 A_0 = \nabla \cdot \frac{\partial \mathbf{A}}{\partial t}$$

So  $A_0$  is not independent: we don't get to specify  $A_0$  on the initial time slice.



- If we transform the EM field as

$$A_\mu \rightarrow A_\mu + \partial_\mu \lambda(x)$$

we can derive that

$$F_{\mu\nu} \rightarrow F_{\mu\nu} \quad \mathcal{L} \rightarrow \mathcal{L}$$

The seemed infinite number of symmetries, one for each function  $\lambda(x)$ , is to be viewed as a redundancy in our description. That is, two states related by a gauge symmetry are to be identified: they are the same physical state. One way to see that this interpretation is necessary is to notice that Maxwell's equations are not sufficient to specify the evolution of  $A_\mu$ . The equations read,

$$(\eta_{\mu\nu} \partial^2 - \partial_\mu \partial_\nu) A^\nu = 0$$

But the operator  $(\eta_{\mu\nu} \partial^2 - \partial_\mu \partial_\nu)$  is not invertible: it annihilates any function of the form  $\partial_\mu \lambda$ . This means that given any initial data, we have no way to uniquely determine  $A_\mu$  at a later time since we can't distinguish between  $A_\mu$  and  $A_\mu + \partial_\mu \lambda$ . This would be problematic if we thought that  $A_\mu$  is a physical object. However, if we're happy to identify  $A_\mu$  and  $A_\mu + \partial_\mu \lambda$  as corresponding to the same physical state, then our problems disappear.

The picture that emerges for the theory of electromagnetism is of an enlarged phase space, foliated by gauge orbits. All states that lie along a given gauge orbit can be reached by a gauge transformation and are identified. To make progress, we pick a representative from each gauge orbit. It doesn't matter which representative we pick after all, they're all physically equivalent. But we should make sure that we pick a "good" gauge, in which we cut the orbits. Here we'll look at two different gauges:

- Coulomb Gauge:  $\nabla \cdot \mathbf{A} = 0$

We can make use of the residual gauge transformations in Lorentz gauge to pick  $\nabla \cdot \dot{\mathbf{A}} = 0$ . We have as a consequence  $A_0 = 0$ . Coulomb gauge is sometimes called radiation gauge.

- Lorentz Gauge:  $\partial^\mu A_\mu = 0$

In fact this condition doesn't pick a unique representative from the gauge orbit. We're always free to make further gauge transformations with  $\partial^\mu \partial_\mu \lambda = 0$ , which also has non-trivial solutions. As the name suggests, the Lorentz gauge has the advantage that it is Lorentz invariant.

## 13.3 Canonical quantization of EM field

### 13.3.1 Canonical quantization in Coulomb gauge

Canonical momentum and Hamiltonian

$$\pi^0 = \frac{\partial \mathcal{L}}{\partial \dot{A}_0} = 0 \quad \pi^i = \frac{\partial \mathcal{L}}{\partial (\partial_0 A_i)} = \dot{A}^i + \nabla_i \phi = -E^i$$



$$\mathcal{H} = \frac{1}{2}(\boldsymbol{\pi}^2 + \mathbf{B}^2) + (\boldsymbol{\pi} \cdot \boldsymbol{\nabla})A_0$$

Integration by parts can give

$$H = \int d^3x \frac{1}{2}(\boldsymbol{\pi}^2 + \mathbf{B}^2)$$

### Momentum and angular momentum

$$P^0 = H \quad \vec{P} = \int -\boldsymbol{\pi} \vec{\nabla} \mathbf{A} d^3x$$

$$\vec{J} = - \int \boldsymbol{\pi} (\vec{x} \times \vec{\nabla} + i\vec{C}) \mathbf{A} d^3x \quad \vec{S} = -i \int \boldsymbol{\pi} \vec{C} \mathbf{A} d^3x$$

### Canonical quantization

In Coulomb gauge, we have

$$A_0 = \pi^0 = 0 \quad \pi^i = \dot{A}^i$$

Three pairs of  $A_i$  and  $\pi^i$  are not independent from each other. They must satisfy the constraint equations

$$\boldsymbol{\nabla} \cdot \mathbf{A} = 0 \quad \boldsymbol{\nabla} \cdot \boldsymbol{\pi} = 0$$

A reasonable quantization condition can be written as

$$[A_i(\mathbf{x}, t), A_j(\mathbf{x}', t)] = 0 \quad [\pi^i(\mathbf{x}, t), \pi^j(\mathbf{x}', t)] = 0$$

$$[A_i(\mathbf{x}, t), \pi^j(\mathbf{x}', t)] = i \left( \delta_i^j - \frac{\partial_i \partial^j}{\nabla^2} \right) \delta(\mathbf{x} - \mathbf{x}') \equiv i \int \frac{d^3k}{(2\pi)^3} \left( \delta_i^j - \frac{k_i k^j}{k^2} \right) e^{i\mathbf{k} \cdot (\mathbf{x} - \mathbf{x}')} \delta(t - t')$$

In this case, we can verify that

$$\dot{A}_i = -i[A_i(\mathbf{x}, t), H] = \pi_i(\mathbf{x}, t)$$

$$\dot{\pi}^i = -i[\pi^i(\mathbf{x}, t), H] = \nabla^2 A^i(\mathbf{x}, t)$$

It is constant with the field equation we derive from Euler-Lagrange equation.

### Fourier expansion

$$\mathbf{A}(\mathbf{x}) = \sum_{r=\pm} \int \widetilde{dp} [a_r(\mathbf{p}) \boldsymbol{\epsilon}_r(\mathbf{p}) e^{i\mathbf{p} \cdot \mathbf{x}} + a_r^\dagger(\mathbf{p}) \boldsymbol{\epsilon}_r^*(\mathbf{p}) e^{-i\mathbf{p} \cdot \mathbf{x}}]$$

And we can derive from constraint condition that

$$\boldsymbol{\epsilon} \cdot \mathbf{p} = 0$$

We will choose  $\boldsymbol{\epsilon}$  to satisfy that

$$\boldsymbol{\epsilon}_r \cdot \boldsymbol{\epsilon}_s^* = \delta_{rs}$$



So, the completeness relation for the polarization vectors is

$$\sum_{r=\pm} \epsilon_r^i(\mathbf{p}) \epsilon_r^{*j}(\mathbf{p}) = \delta^{ij} - \frac{p^i p^j}{|\mathbf{p}|^2}$$

**Example:** If  $\mathbf{p} = (0, 0, p)$ , we usually choose

$$\epsilon_+ = \frac{1}{\sqrt{2}}(1, i, 0) \quad \epsilon_- = \frac{1}{\sqrt{2}}(1, -i, 0)$$

$\epsilon_+$  corresponds to left-handed rotation and it is the eigenvectors of the space-part of  $C_3$  with eigenvalue  $+1$ .  $\epsilon_-$  corresponds to right-handed rotation and it is eigenvector of the space-part of  $C_3$  with eigenvalue  $-1$ .

We can further derive from above discussion that

$$\pi(x) = -i \sum_{r=\pm} \int \widetilde{dp} \omega [a_r(\mathbf{p}) \epsilon_r(\mathbf{p}) e^{ipx} - a_r^\dagger(\mathbf{p}) \epsilon_r^*(\mathbf{p}) e^{-ipx}]$$

$$a_r(\mathbf{p}) = \epsilon_r^* \int d^3x e^{-ikx} (i\boldsymbol{\pi} + \omega \mathbf{A})$$

$$a_r^\dagger(\mathbf{p}) = \epsilon_r \int d^3x e^{ikx} (-i\boldsymbol{\pi} + \omega \mathbf{A})$$

$$[a_r(\mathbf{p}), a_{r'}(\mathbf{p}')] = 0 \quad [a_r^\dagger(\mathbf{p}), a_{r'}^\dagger(\mathbf{p}')] = 0 \quad [a_r(\mathbf{p}), a_{r'}^\dagger(\mathbf{p}')] = (2\pi)^3 2\omega \delta_{rr'} \delta(\mathbf{p} - \mathbf{p}')$$

### Operator represented by $a$ and $a^\dagger$

Define that

$$N(\mathbf{p}, r) \equiv a_r^\dagger(\mathbf{p}) a_r(\mathbf{p})$$

So, we can derive

$$H = \sum_{r=\pm} \int \widetilde{dp} \omega N(\mathbf{p}, r) + 2\mathcal{E}_0 V$$

$$\vec{P} = \sum_{r=\pm} \int \widetilde{dp} \vec{p} N(\mathbf{p}, r)$$

$$\vec{S} = \sum_{r,s=\pm} \int \widetilde{dp} \frac{1}{2} (\epsilon_s^* \vec{C} \epsilon_r - \epsilon_r \vec{C} \epsilon_s^*) a_s^\dagger(\mathbf{p}) a_r(\mathbf{p})$$

From above equation, we can say that  $a_r^\dagger(\mathbf{p})$  create an photon with energy  $\omega$ , momentum  $\mathbf{p}$  and spin angular momentum along the direction of momentum  $r$ .

### Propagator

$$G_F(x-y)_{ij} \equiv \langle 0 | T A_i(x) A_j(y) | 0 \rangle = \int \frac{d^4p}{(2\pi)^4} \frac{-i}{p^2 - i\epsilon} \left( \delta_{ij} - \frac{p_i p_j}{|\mathbf{p}|^2} \right) e^{ip(x-y)}$$



### 13.3.2 Canonical quantization in Lorentz gauge

#### Undefined metric formalism

Modify the Maxwell Lagrangian introducing a new term

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2\xi}(\partial_\mu A^\mu)^2$$

The equations of motion are now

$$\partial^2 A_\mu - (1 - \frac{1}{\xi})\partial^\mu(\partial \cdot A) = 0$$

Canonical momentums are

$$\pi^0 = \frac{1}{\xi}\partial \cdot A = \frac{1}{\xi}(-\dot{A}_0 + \partial_i A^i) \quad \pi^i = \dot{A}^i + \nabla^i A^0 = -E^i$$

Hamiltonian is

$$\mathcal{H} = \frac{1}{2}(\boldsymbol{\pi}^2 + \mathbf{B}^2 - \xi\pi^0\pi^0) + (\boldsymbol{\pi} \cdot \nabla)A_0 + \pi^0(\nabla \cdot \mathbf{A})$$

$$H = \int \left[ \frac{1}{2}(\boldsymbol{\pi}^2 + \mathbf{B}^2 - \xi\pi^0\pi^0) - A_0(\nabla \cdot \boldsymbol{\pi}) + \pi^0(\nabla \cdot \mathbf{A}) \right] d^3x$$

We remark that the above Lagrangian and the equations of motion, reduce to Maxwell theory in the gauge  $\partial \cdot A = 0$ . This why we say that our choice corresponds to a class of Lorenz gauges with parameter  $\xi$ . With this abuse of language (in fact we are not setting  $\partial \cdot A = 0$ , otherwise the problems would come back) the value of  $\xi = 1$  is known as the Feynman gauge and  $\xi = 0$  as the Landau gauge. From now on we will take the case of the so-called Feynman gauge, where  $\xi = 1$ . Then the equation of motion coincide with the Maxwell theory in the Lorenz gauge. In Feymann gauge, the canonical quantization conditions can be written as

$$[A_\mu(\mathbf{x}, t), A_\nu(\mathbf{x}', t)] = 0 \quad [\pi^\mu(\mathbf{x}, t), \pi^\nu(\mathbf{x}', t)] = 0 \quad [A_\mu(\mathbf{x}, t), \pi^\nu(\mathbf{x}', t)] = i\delta_\mu^\nu \delta(\mathbf{x} - \mathbf{x}')$$

we can also derive that

$$[\dot{A}_\mu(\mathbf{x}, t), \dot{A}_\nu(\mathbf{x}', t)] = 0 \quad [A_\mu(\mathbf{x}, t), \dot{A}_\nu(\mathbf{x}', t)] = i\eta_{\mu\nu} \delta(\mathbf{x} - \mathbf{x}')$$

#### Fourier expansion

$$A(x) = \sum_{\lambda=0}^3 \int \widetilde{dp} [a_\lambda(\mathbf{p})\epsilon_\lambda(\mathbf{p})e^{ipx} + a_\lambda^\dagger(\mathbf{p})\epsilon_\lambda^*(\mathbf{p})e^{-ipx}]$$

where  $\epsilon_{\lambda\mu}$  are a set of four independent 4-vectors. We will now make a choice for these 4-vectors. We choose  $\epsilon_{1\mu}$  and  $\epsilon_{2\mu}$  orthogonal to  $k^\mu$  and  $n^\mu$ , such that

$$\epsilon_{\lambda\mu}\epsilon_\lambda^{*\mu} = \delta_{\lambda\lambda'} \quad \lambda, \lambda' = 1, 2$$





After, we choose  $\epsilon_{3\mu}$  in the plane  $(k^\mu, n^\mu)$  and perpendicular to  $n^\mu$  such that

$$\epsilon_{3\mu} n^\mu = 0 \quad \epsilon_{3\mu} \epsilon_3^{*\mu} = 1$$

Finally we choose  $\epsilon_{0\mu} = n_\mu$ . The vectors  $\epsilon_{1\mu}$  and  $\epsilon_{2\mu}$  are called transverse polarizations, while  $\epsilon_{3\mu}$  and  $\epsilon_{0\mu}$  longitudinal and scalar polarizations, respectively.

In general we can show that

$$\epsilon_\lambda \cdot \epsilon_{\lambda'}^* = \eta_{\lambda\lambda'} \quad \eta^{\lambda\lambda'} \epsilon_{\lambda\mu} \epsilon_{\lambda'\nu}^* = \eta_{\mu\nu}$$

We can further derive from above discussion that

$$\dot{A}(x) = -i \sum_{\lambda=0}^3 \int \widetilde{dp} \omega [a_\lambda(\mathbf{p}) \epsilon_\lambda(\mathbf{p}) e^{ipx} - a_\lambda^\dagger(\mathbf{p}) \epsilon_\lambda^*(\mathbf{p}) e^{-ipx}]$$

$$a_\lambda(\mathbf{p}) = \eta_{\lambda\lambda'} \epsilon_{\lambda'}^* \cdot \int d^3x e^{-ipx} (i\dot{A} + \omega A)$$

$$a_\lambda^\dagger(\mathbf{p}) = \eta_{\lambda\lambda'} \epsilon_{\lambda'} \cdot \int d^3x e^{ipx} (-i\dot{A} + \omega A)$$

$$[a_\lambda(\mathbf{p}), a_{\lambda'}(\mathbf{p}')] = 0 \quad [a_\lambda^\dagger(\mathbf{p}), a_{\lambda'}^\dagger(\mathbf{p}')] = 0 \quad [a_\lambda(\mathbf{p}), a_{\lambda'}^\dagger(\mathbf{p}')] = (2\pi)^3 2\omega \eta_{\lambda\lambda'} \delta(\mathbf{p} - \mathbf{p}')$$

### Indefinite metric problem

We Introduce the vacuum state defined by

$$a_\lambda(\mathbf{p})|0\rangle = 0$$

To see the problem with the sign we construct the one-particle state with scalar polarization, that is

$$|1\rangle = \int \widetilde{dp} a_0^\dagger(\mathbf{p})|0\rangle$$

and calculate its norm

$$\langle 1|1\rangle = -\langle 0|0\rangle \int \widetilde{dp} |f(p)|^2$$

The state  $|1\rangle$  has a negative norm.

To solve this problem we note that we are not working anymore with the classical Maxwell theory because we modified the Lagrangian. What we would like to do is to impose the condition  $\partial \cdot A = 0$ , but that is impossible as an equation for operators. We can, however, require that condition on a weaker form, as a condition only to be verified by the physical states.

More specifically, we require that the part of  $\partial \cdot A$  that contains the annihilation operator (positive frequencies) annihilates the physical states,

$$\partial^\mu A_\mu^+ |\psi\rangle = 0$$

The states  $|\psi\rangle$  can be written in the form

$$|\psi\rangle = |\psi_T\rangle |\phi\rangle$$



where  $|\psi_T\rangle$  is obtained from the vacuum with creation operators with transverse polarization and  $|\phi\rangle$  with scalar and longitudinal polarization.

$\partial^\mu A_\mu^+$  contains only scalar and longitudinal polarizations

$$\partial^\mu A_\mu^+ = i \sum_{\lambda=0,3} \int \widetilde{dp} a_\lambda(\mathbf{p})(p \cdot \epsilon_\lambda(\mathbf{p})) e^{ipx}$$

Therefore the previous condition becomes

$$i \sum_{\lambda=0,3} (p \cdot \epsilon_\lambda(\mathbf{p})) a_\lambda(\mathbf{p}) |\phi\rangle = 0$$

The condition is equivalent to,

$$(a_0(\mathbf{p}) - a_3(\mathbf{p})) |\phi\rangle = 0$$

We can construct  $|\phi\rangle$  as a linear combination of states  $|\phi\rangle$  with  $n$  scalar or longitudinal photons:

$$|\phi\rangle = C_0 |\phi_0\rangle + C_1 |\phi\rangle + \dots \quad \text{Here, } |\phi_0\rangle \equiv |0\rangle$$

The states  $|\phi_n\rangle$  are eigenstates of the operator number for scalar or longitudinal photons

$$N' |\phi_n\rangle = n |\phi_n\rangle$$

where,

$$N' = \int \widetilde{dp} [a_3^\dagger(\mathbf{p}) a_3(\mathbf{p}) - a_0^\dagger(\mathbf{p}) a_0(\mathbf{p})]$$

Then

$$n \langle \phi_n | \phi_n \rangle = \langle \phi_n | N' | \phi_n \rangle = 0$$

This means that

$$\langle \phi_n | \phi_n \rangle = \delta_{n0}$$

that is, for  $n \neq 0$ , the state  $|\phi_n\rangle$  has zero norm. We have then for the general state  $|\phi\rangle$ ,

$$\langle \phi | \phi \rangle = |C_0|^2 \geq 0$$

and the coefficients  $C_i (i = 1, 2, \dots)$  are arbitrary.

### Operator represented by $a$ and $a^\dagger$

Define that

$$N'(\mathbf{p}) \equiv a_3^\dagger(\mathbf{p}) a_3(\mathbf{p}) - a_0^\dagger(\mathbf{p}) a_0(\mathbf{p})$$

$$N(\mathbf{p}, 1) \equiv a_1^\dagger(\mathbf{p}) a_1(\mathbf{p}) \quad N(\mathbf{p}, 2) \equiv a_2^\dagger(\mathbf{p}) a_2(\mathbf{p}) \quad N_T(\mathbf{p}) \equiv N(\mathbf{p}, 1) + N(\mathbf{p}, 2)$$

We have that

$$\langle \psi | N'(\mathbf{p}) | \psi \rangle = 0 \quad \langle \psi | N_T(\mathbf{p}) | \psi \rangle = \langle \psi_T | N_T(\mathbf{p}) | \psi_T \rangle$$

We can derive

$$H = \int \widetilde{dp} \omega [N'(\mathbf{p}) + N_T(\mathbf{p})] + 2\mathcal{E}_0 V$$



$$\vec{P} = \int \widetilde{dp} \vec{p} [N'(\mathbf{p}) + N_T(\mathbf{p})]$$

So, the arbitrariness of  $C_i (i = 1, 2, \dots)$  does not affect the physical observables. Only the physical transverse polarizations contribute to the result. Two states that differ only in their timelike and longitudinal photon content,  $|\phi_n\rangle$  with  $n \geq 1$  are said to be physically equivalent. We can think of the gauge symmetry of the classical theory as descending to the Hilbert space of the quantum theory.

It is important to note that although for the average values of the physical observables only the transverse polarizations contribute, the scalar and longitudinal polarizations are necessary for the consistency of the theory. In particular they show up when we consider complete sums over the intermediate states.

### Propagator

$$G_F(x - y)_{\mu\nu} \equiv \langle 0 | T A_\mu(x) A_\nu(y) | 0 \rangle = \int \frac{d^4 p}{(2\pi)^4} \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon} e^{ip(x-y)}$$

It is easy to verify that  $G_F(x - y)_{\mu\nu}$  is the Green's function of the equation of motion, that for  $\xi = 1$  is the wave equation, that is

$$\partial^2 G_F(x - y)_{\mu\nu} = i\eta_{\mu\nu} \delta(x - y)$$

For the general case,  $\xi \neq 0$ , the equal times commutation relations are more complicated. And the propagator will be

$$G_F(x - y)_{\mu\nu} = \int \frac{d^4 p}{(2\pi)^4} \left[ \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon} + i(1 - \xi) \frac{p_\mu p_\nu}{(p^2 - i\epsilon)^2} \right] e^{ip(x-y)}$$

## 13.4 Perturbation theory for canonical quantization

### 13.4.1 Lagrangian of QED

The Lagrangian of QED is

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\cancel{D} - m_0)\Psi + e_0 j^\mu A_\mu,$$

where  $j^\mu \equiv \bar{\Psi}\gamma^\mu\Psi$ . Usually, we also define a covariant derivative,

$$D_\mu \Psi \equiv \partial_\mu \Psi - ie_0 A_\mu \Psi$$

So, the Lagrangian can also be written as

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\cancel{D} - m_0)\Psi$$

The Lagrangian is invariant under the gauge transformation

$$A_\mu(x) \rightarrow A_\mu(x) + \frac{1}{e_0} \partial_\mu \alpha(x) \quad \Psi(x) \rightarrow e^{i\alpha(x)} \Psi(x)$$



### 13.4.2 Coulomb gauge

The constraint equations are

$$\nabla \cdot \mathbf{A} = 0 \quad \nabla^2 A_0 = e_0 j^0$$

The solution for  $A_0$  is

$$A_0(\mathbf{x}, t) = -e_0 \int d^3 x' \frac{j^0(\mathbf{x}', t)}{4\pi |\mathbf{x} - \mathbf{x}'|}$$

Finally, we can derive that

$$H = H_D + H_M + H_{\text{int}}$$

where,

$$H_D = \int d^3 x \left[ \frac{1}{2} (\vec{\mathbf{E}}^2 + \vec{\mathbf{B}}^2) \right] \quad H_M = \int d^3 x \left[ \bar{\Psi} (\vec{\alpha} \cdot \vec{\nabla} + i\beta m) \Psi \right]$$

$$H_{\text{int}} = \int d^3 x \left[ -e_0 \mathbf{j} \cdot \mathbf{A} + \frac{e_0^2}{2} \int d^3 x' \frac{j^0(\mathbf{x}) j^0(\mathbf{x}')}{4\pi |\mathbf{x} - \mathbf{x}'|} \right]$$

The perturbation expansion of correlation functions is

$$\langle \Omega | T \{ \Psi(x) \bar{\Psi}(y) A(z) \} | \Omega \rangle = \lim_{T \rightarrow \infty (1-i\epsilon)} \frac{\langle 0 | T \left\{ \Psi_I(x) \bar{\Psi}_I(y) A_I(z) \exp \left[ -i \int_{-T}^T dt H_I \right] \right\} | 0 \rangle}{\langle 0 | T \left\{ \exp \left[ -i \int_{-T}^T dt H_I \right] \right\} | 0 \rangle}$$

Here,  $\int_{-T}^T dt H_I$  can be written as

$$\left[ - \int d^4 x e_0 \bar{\Psi}_I \gamma \Psi_I \cdot \mathbf{A}_I \right] + \left[ \int d^4 x \int d^4 x' \frac{e_0^2 \delta(t-t')}{4\pi |\mathbf{x} - \mathbf{x}'|} \frac{1}{2} \bar{\Psi}_I(\mathbf{x}, t) \gamma^0 \Psi_I(\mathbf{x}, t) \bar{\Psi}_I(\mathbf{x}', t') \gamma^0 \Psi_I(\mathbf{x}', t') \right]$$

Wick's theorem for photons takes is similar to that in  $\phi^4$  theory:

$$T \{ A_I(x_1) A_I(x_2) A_I(x_3) \cdots \} = N \{ A_I(x_1) A_I(x_2) A_I(x_3) \cdots + \text{all possible contractions} \}$$

**Example:**

$$\langle 0 | T \{ A_{Ii}(x_1) A_{Ij}(x_2) A_{Ik}(x_3) A_{Il}(x_4) \} | 0 \rangle$$

$$= G_F(x_1 - x_2)_{ij} G_F(x_3 - x_4)_{kl} + G_F(x_1 - x_3)_{ik} G_F(x_2 - x_4)_{jl} + G_F(x_1 - x_4)_{il} G_F(x_2 - x_3)_{jk}$$

Now we can derive the Feynman rule for QED theory. Firstly, we evaluate this term,

$$\langle 0 | T \left\{ \Psi_{Ia}(x) \bar{\Psi}_{Ib}(y) A_{Ii}(z) (ie_0) \int d^4 w \bar{\Psi}_I(w) \gamma \Psi_I(w) \cdot A_I(w) \right\} | 0 \rangle$$

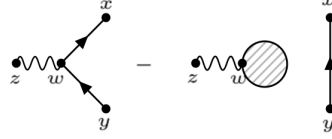
After contraction, it can be written as

$$- (ie_0) S_F(x - y)_{ab} \int d^4 w G_F(z - w)_{ik} \text{Tr}[\gamma^k S_F(w - w)]$$

$$+ (ie_0) \int d^4 w G_F(w - z)_{ik} [S_F(x - w) \gamma^k S_F(w - y)]_{ab}$$

It can be represented by the following Feynman diagram.



**Figure 13.1:** Feynman diagram representation of perturbation expansion

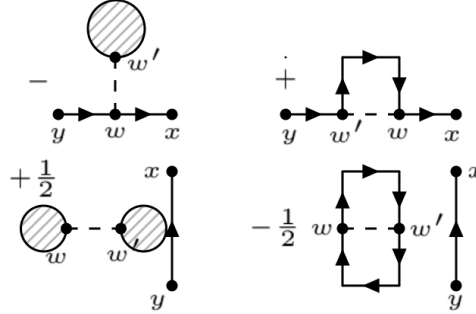
Secondly, we evaluate this term,

$$\langle 0|T \left\{ \Psi_{Ia}(x) \bar{\Psi}_{Ib}(y) \int d^4w \int d^4w' \frac{-ie_0^2 \delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} \frac{1}{2} \bar{\Psi}_I(w) \gamma^0 \Psi_I(w) \bar{\Psi}_I(w') \gamma^0 \Psi_I(w') \right\} |0\rangle$$

After contraction, it can be written as

$$\begin{aligned} & - (ie_0)^2 \int d^4w d^4w' \frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} [S_F(x - w) \gamma^0 S_F(w - y)]_{ab} \text{Tr}[\gamma^0 S_F(w' - w)] \\ & + (ie_0)^2 \int d^4w d^4w' \frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} [S_F(x - w) \gamma^0 S_F(w - w') \gamma^0 S_F(w' - y)]_{ab} \\ & + \frac{1}{2} (ie_0)^2 S_F(x - y)_{ab} \int d^4w d^4w' \frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} \text{Tr}[\gamma^0 S_F(w - w)] \text{Tr}[\gamma^0 S_F(w' - w')] \\ & - \frac{1}{2} (ie_0)^2 S_F(x - y)_{ab} \int d^4w d^4w' \frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} \text{Tr}[\gamma^0 S_F(w - w') \gamma^0 S_F(w' - w)] \end{aligned}$$

It can be represented by the following Feynman diagram.

**Figure 13.2:** Feynman diagram representation of perturbation expansion

Before we write down Feymann rules, we notice that the offending non-local interaction comes from the  $A_0$  component of the gauge field, we could try to redefine the propagator to include a  $G_F(x - y)_{00}$  piece which will capture this term. We can verify that

$$\frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} = \int \frac{d^4p}{(2\pi)^4} \frac{ie^{ip(w-w')}}{|\mathbf{p}|^2}$$

So we can combine the non-local interaction with the transverse photon propagator by defining a new photon propagator

$$G_F(p)_{\mu\nu} \equiv \begin{cases} \frac{i}{|\mathbf{p}|^2} & \mu, \nu = 0 \\ \frac{-i}{p^2 - i\epsilon} \left( \delta_{ij} - \frac{p_i p_j}{|\mathbf{p}|^2} \right) & \mu = i \neq 0, \nu = j \neq 0 \\ 0 & \text{otherwise} \end{cases}$$



With this propagator, the wavy photon line now carries a  $\mu\nu = 0, 1, 2, 3$  index, with the extra  $\mu = 0$  component taking care of the instantaneous interaction.

The Feynman rules for QED are:

1. For each Fermion propagator from  $y$  to  $x$ ,  $P = S_F(x - y)$
2. For each vector propagator,  $P = G_F(x - y)$
3. For each vertex,  $V = (ie_0\gamma^\mu) \int d^4w$
4. For each external point,  $E = 1$
5. Divided by the symmetry factor

### 13.4.3 Lorentz Gauge

In Lorentz gauge,

$$\mathcal{H}_{int} = -e_0 \bar{\Psi} \gamma^\mu \Psi A_\mu$$

The Feynman rules for QED in Lorentz gauge will be the same as that in Coulomb gauge expect for that the vector propagator will be

$$G_F(p)_{\mu\nu} = \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon} + i(1 - \xi) \frac{p_\mu p_\nu}{(p^2 - i\epsilon)^2}$$

Especially, for Feynman gauge  $\xi = 1$ , we have

$$G_F(p)_{\mu\nu} = \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon}$$

## 13.5 Path integral quantization

### 13.5.1 Path integral formulation for free EM field

The correlation function is given by

$$\langle \Omega | T A_H(x_1) A_H(x_2) | \Omega \rangle = \lim_{T \rightarrow \infty(1-i\epsilon)} \frac{\int \mathcal{D}A \exp \left[ i \int_{-T}^T d^4x \left( -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right) \right] A(x_1) A(x_2)}{\int \mathcal{D}A \exp \left[ i \int_{-T}^T d^4x \left( -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right) \right]}$$

The generating function is

$$Z[J] = \int \mathcal{D}A \exp \left[ i \int d^4x \left( -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right) + J^\mu A_\mu \right]$$

We can verify that

$$S = \int d^4x \left( -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right) = \frac{1}{2} \int d^4x A_\mu(x) (\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu) A_\nu(x)$$



Notice that  $(\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu)$  is singular, since for any  $\alpha(x)$ ,

$$(\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu) \partial_\mu \alpha(x) = 0$$

This difficulty is due to gauge invariance:  $\alpha(x)$  is gauge equivalent to 0. The functional is badly defined because we are redundantly integrating over a continuous infinity of physically equivalent field configurations. To fix the problem, we would like to isolate the interesting part of the functional integral, which counts each physical configuration only once.

Let  $G(A)$  be some function that we wish to set equal zero as a gauge-fixing condition. We could constrain the functional integral to cover only the configurations with  $G(A) = 0$  by inserting a functional delta function,  $\delta(G(A))$ . To do so, we insert 1 in the path integral:

$$1 = \int \mathcal{D}\alpha(x) \delta(G(A(\alpha))) \det \left( \frac{\delta G}{\delta \alpha} \right)$$

where,

$$A_\mu(\alpha(x)) = A_\mu(x) + \frac{1}{e_0} \partial_\mu \alpha(x)$$

We set the gauge fixing function as  $G(A) = \partial^\mu A_\mu - \omega(x)$ , so  $G(A(\alpha)) = \partial^\mu A_\mu + \frac{1}{e_0} \partial^2 \alpha - \omega(x)$ . It is obvious that  $\det \left( \frac{\delta G}{\delta \alpha} \right)$  is equivalent to  $\det(\partial^2)/e_0$ , which is independent of  $A$ . So,

$$Z_0[A] = \det \left( \frac{\delta G}{\delta \alpha} \right) \int \mathcal{D}\alpha \int \mathcal{D}A e^{iS[A]} \delta(G(A(\alpha)))$$

Now change variables from  $A$  to  $A(\alpha)$ . This is a simple shift, so  $\mathcal{D}A = \mathcal{D}A(\alpha)$ . Also, by gauge invariance,  $S[A] = S[A(\alpha)]$ . Since  $A(\alpha)$  is now just a dummy integration variable, we can rename it back to  $A$ , so

$$Z_0[A] = \det \left( \frac{\delta G}{\delta \alpha} \right) \int \mathcal{D}\alpha \int \mathcal{D}A e^{iS[A]} \delta(\partial^\mu A_\mu - \omega(x))$$

Since the above equation holds for any  $\omega(x)$ , so we have

$$\begin{aligned} Z_0[A] &= N(\xi) \int \mathcal{D}\omega \exp \left[ -i \int d^4x \frac{\omega^2}{2\xi} \right] \det(\partial^2) \int \mathcal{D}\alpha \int \mathcal{D}A e^{iS[A]} \delta(\partial^\mu A_\mu - \omega(x)) \\ &= N(\xi) \frac{\det(\partial^2)}{e_0} \int \mathcal{D}\alpha \int \mathcal{D}A e^{iS[A]} \exp \left[ -i \int d^4x \frac{1}{2\xi} (\partial^\mu A_\mu)^2 \right] \\ &= W(\xi) \int \mathcal{D}A \exp \left[ \frac{i}{2} \int d^4x A_\mu (\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu + \frac{1}{\xi} \partial^\mu \partial^\nu) A_\nu \right] \end{aligned}$$

And we rewrite the generating function as

$$Z[J] = W(\xi) \int \mathcal{D}A \exp \left[ \frac{i}{2} \int d^4x A_\mu (\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu + \frac{1}{\xi} \partial^\mu \partial^\nu) A_\nu + J^\mu A_\mu \right]$$

Define

$$A'(x) = A(x) - i \int d^4y G_F(x-y) J(y)$$

Recall that

$$(\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu + \frac{1}{\xi} \partial^\mu \partial^\nu) G_F(x-y)_{\nu\rho} = i \delta_\rho^\mu \delta(x-y)$$



We can derive that

$$Z[J] = Z_0[A] \exp \left[ -\frac{1}{2} \int d^4x d^4y J^\mu(x) G_F(x-y)_{\mu\nu} J^\nu(y) \right]$$

The two point correlation functions are

$$\langle 0 | T A_H(x_1) A_H(x_2) | 0 \rangle = Z_0^{-1} \left( -i \frac{\delta}{\delta J(x_1)} \right) \left( -i \frac{\delta}{\delta J(x_2)} \right) Z[J] \Big|_{J=0} = G_F(x_1 - x_2)$$

### 13.5.2 Perturbation theory for path integral quantization

We use QED theory as an example.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\cancel{\partial} - m_0)\Psi + e_0 \bar{\Psi} \gamma^\mu \Psi A_\mu$$

As we stated in section 4.1, the Lagrangian of QED is also invariant under a general gauge transformation. And we also notice that the measure  $\mathcal{D}\Psi \mathcal{D}\bar{\Psi}$  is invariant under gauge transformation. By the similar method, we can show that

$$Z_0 \equiv \int \mathcal{D}A \mathcal{D}\Psi \mathcal{D}\bar{\Psi} e^{iS[A, \Psi, \bar{\Psi}]} = W(\xi) \int \mathcal{D}A \mathcal{D}\Psi \mathcal{D}\bar{\Psi} e^{iS[A, \Psi, \bar{\Psi}]} \exp \left[ -i \int d^4x \frac{1}{2\xi} (\partial^\mu A_\mu)^2 \right]$$

So, define

$$\mathcal{L}_0 \equiv -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2\xi} (\partial^\mu A_\mu)^2 + \bar{\Psi}(i\cancel{\partial} - m_0)\Psi \quad \mathcal{L}_1 \equiv e_0 \bar{\Psi} \gamma^\mu \Psi A_\mu$$

$$\begin{aligned} Z[J] &= W(\xi) \int \mathcal{D}A \mathcal{D}\bar{\Psi} \mathcal{D}\Psi e^{i \int d^4x [\mathcal{L}_0 + \mathcal{L}_1 + JA + \bar{\eta}\Psi + \bar{\Psi}\eta]} \\ &= W(\xi) e^{i \int d^4x \mathcal{L}_1(\frac{1}{i} \frac{\delta}{\delta J(x)}, \frac{1}{i} \frac{\delta}{\delta \bar{\eta}(x)}, -\frac{1}{i} \frac{\delta}{\delta \eta(x)})} \int \mathcal{D}\phi \mathcal{D}\bar{\Psi} \mathcal{D}A e^{i \int d^4y [\mathcal{L}_0 + JA + \bar{\eta}\Psi + \bar{\Psi}\eta]} \\ &\propto e^{i \int d^4x \mathcal{L}_1(\frac{1}{i} \frac{\delta}{\delta J(x)}, \frac{1}{i} \frac{\delta}{\delta \bar{\eta}(x)}, -\frac{1}{i} \frac{\delta}{\delta \eta(x)})} \exp \left[ - \int d^4y d^4z \frac{1}{2} J(y) G_F(y-z) J(z) + \bar{\eta}(y) S_F(y-z) \eta(z) \right] \\ &= \sum_{V=0}^{\infty} \frac{1}{V!} [i e_0 \int d^4x (\frac{1}{i} \frac{\delta}{\delta J^\mu(x)} \cdot -\frac{1}{i} \frac{\delta}{\delta \eta(x)} \cdot \gamma^\mu \cdot \frac{1}{i} \frac{\delta}{\delta \bar{\eta}(x)})]^V \\ &\times \sum_{P_1=0}^{\infty} \frac{1}{P_1!} \left[ -\frac{1}{2} \int d^4y_1 d^4z_1 J(y_1) G_F(y_1 - z_1) J(z_1) \right]^{P_1} \\ &\times \sum_{P_2=0}^{\infty} \frac{1}{P_2!} \left[ - \int d^4y_2 d^4z_2 \bar{\eta}(y_2) S_F(y_2 - z_2) \eta(z_2) \right]^{P_2} \end{aligned}$$

If we focus on a term with particular values of  $V$ ,  $P_1$  and  $P_2$ , then the number of surviving scalar sources is  $E_1 = 2P_1 - V$ , the number of surviving fermion sources is  $E_2 = 2P_2 - 2V$ . We can introduce Feynman diagrams as in the  $\phi^4$  theory. In these diagrams, a wavy line segment stands for a vector propagator  $G_F(x-y)$ , a line with an arrow pointing from  $y$  to  $x$  for a fermion propagator  $S_F(x-y)$ , a filled circle at one end of a wavy line segment for a vector source  $i \int d^4x J(x)$ , a filled circle at the start of a line with an arrow for a fermion source  $i \int d^4x \eta(x)$ , a filled circle at the end of a line with an arrow for an anti-fermion source  $i \int d^4x \bar{\eta}(x)$ , a vertex joining three line segments for  $i e_0 \gamma^\mu \int d^4x$ .





### 13.5.3 Ward-Takahashi identity (1)

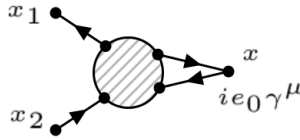
The Noether current of the symmetry  $\Psi \rightarrow e^{i\alpha}\Psi$  is  $j^\mu = \bar{\Psi}\gamma^\mu\Psi$ . Recall the conservation law in functional formalism

$$\langle \partial_\mu j^\mu(x) \phi(x_1) \cdots \phi(x_n) \rangle = \sum_{i=1}^n \langle \phi(x_1) \cdots (i\Delta\phi(x_i)\delta(x-x_i)) \cdots \phi(x_n) \rangle$$

So, we can write the charge conservation law as

$$ie_0\partial_\mu \langle \Omega | T j^\mu \Psi(x_1) \bar{\Psi}(x_2) | \Omega \rangle = -ie_0\delta(x-x_1) \langle \Omega | T \Psi(x_1) \bar{\Psi}(x_2) | \Omega \rangle + ie_0\delta(x-x_2) \langle \Omega | T \Psi(x_1) \bar{\Psi}(x_2) | \Omega \rangle$$

Notice that  $i\langle \Omega | T j^\mu \psi(x_1) \bar{\Psi}(x_2) | \Omega \rangle$  can be represented by



**Figure 13.3:** Feynman diagram representation of correlation function

From the diagram, we have

$$\langle A_\nu(y) \rangle = \int d^4x G_F(x-y)_{\mu\nu} ie \langle j^\mu(x) \rangle = \int \frac{d^4p}{(2\pi)^4} e^{-ipy} G_F(p)_{\mu\nu} \int d^4x e^{ipx} ie \langle j^\mu(x) \rangle$$

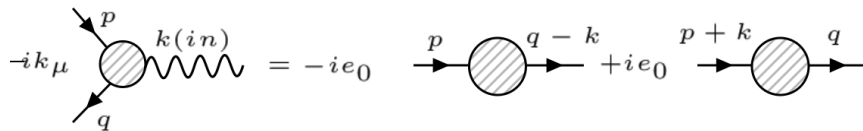
So,

$$\int d^4x \langle A_\nu(x) \rangle e^{ikx} = G_F(p)_{\mu\nu} \int d^4x e^{ikx} ie \langle j^\mu(x) \rangle$$

Compute the Fourier transformation of the equation of charge conservation by integrating

$$\int d^4x e^{ikx} \int d^4x_1 e^{-iqx_1} \int d^4x_2 e^{ipx_2}$$

We can get



**Figure 13.4:** Feynman diagram representation of Ward identity

Note that in the diagram above, the external leg of photon will be cut-off, but external leg of fermion will remain. The above equation can be generated to the diagram with  $n$  external fermions. Another proof of Ward-Takahashi identity by calculating the Feynman diagram directly can be found in chapter 7.4 of *An introduction to quantum field theory* (M.E.Peskin & D.V.Schroeder)



## 13.6 Exact propagator of photon

### 13.6.1 Photon self-energy

The exact propagator of photon is

$$\mathcal{G}(x)_{\mu\nu} = \langle \Omega | T \{ A_\mu(x) A_\nu(0) | \Omega \rangle_C$$

Its Fourier transformation can be represented by the following diagram.



**Figure 13.5:** Feynman diagram representation of exact propagator of photon

Let us define  $i\Pi^{\mu\nu}$  to be the sum of all 1-particle-irreducible insertions into the photon propagator. So, we have

$$\mathcal{G}(k) = G_F(k) + G_F(k)(i\Pi(k))G_F(k) + \cdots = G_F(k) \frac{1}{1 - i\Pi(k)G_F(k)}$$

Hence,

$$(i\mathcal{G})^{-1} = (iG_F)^{-1} - \Pi$$

Recall that

$$iG_F(p)_{\mu\nu} = \frac{\eta_{\mu\nu}}{k^2 - i\epsilon} - (1 - \xi) \frac{k_\mu k_\nu}{(k^2 - i\epsilon)^2} = \frac{1}{k^2 - i\epsilon} (P_{\mu\nu}^T + \xi P_{\mu\nu}^L)$$

Here,

$$P_{\mu\nu}^T \equiv \eta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} \quad P_{\mu\nu}^L \equiv \frac{k_\mu k_\nu}{k^2}$$

We can derive that

$$(iG_F)^{-1}(k)_{\mu\nu} = k^2 (P_{\mu\nu}^T + \frac{1}{\xi} P_{\mu\nu}^L)$$

We may also expand  $i\Pi^{\mu\nu}$  as

$$\Pi^{\mu\nu} = P_T^{\mu\nu} f_T(k^2) + P_L^{\mu\nu} f_L(k^2) = \eta^{\mu\nu} f_T + \frac{k^\mu k^\nu}{k^2} (f_L - f_T)$$

Therefore,

$$(i\mathcal{G})^{-1}(k)_{\mu\nu} = (k^2 - f_T(k^2)) P_{\mu\nu}^T + (\frac{k^2}{\xi} - f_L(k^2)) P_{\mu\nu}^L$$

$$\mathcal{G}(k)_{\mu\nu} = \frac{-i}{k^2 - f_T(k^2)} P_{\mu\nu}^T + \frac{-i}{\frac{k^2}{\xi} - f_L(k^2)} P_{\mu\nu}^L$$

We observe that if  $f_{T,L}(k^2 = 0) \neq 0$ , a mass will be generated for the photon. Because  $\Pi(k)$  comes from 1PI diagrams, it should not be singular at  $k^2 = 0$ , and so  $f_L - f_T = O(k^2)$ , as  $k \rightarrow 0$ . We will show that gauge invariance ensures that no mass is generated from the loop corrections



### 13.6.2 Ward identities(2)

We define the generating functional for connected diagrams

$$Z[J, \eta, \bar{\eta}] = e^{-iE[J, \eta, \bar{\eta}]}$$

For example,

$$\mathcal{G}(x - y)_{\mu\nu} = -i \frac{\delta^2 E[J, \eta, \bar{\eta}]}{\delta J^\mu(x) \delta J^\nu(y)} \Big|_{J, \eta, \bar{\eta}=0}$$

Recall, for infinitesimal gauge transformations,  $\delta A_\mu = \partial_\mu \lambda$ ,  $\delta \Psi = ie_0 \lambda \Psi$  and  $\delta \bar{\Psi} = -ie_0 \lambda \bar{\Psi}$ . For a change of variables in the path integral,  $Z[J, \eta, \bar{\eta}]$  will remain the same. Recall that

$$Z[J, \eta, \bar{\eta}] = W(\xi) \int \mathcal{D}A \mathcal{D}\bar{\Psi} \mathcal{D}\Psi e^{i \int d^4x [\mathcal{L}_0 + \mathcal{L}_1 + JA + \bar{\eta}\Psi + \bar{\Psi}\eta]}$$

The change of action is

$$\delta S = -\frac{1}{\xi} \int d^4x \partial_\mu A^\mu \partial^2 \lambda + \int d^4x J^\mu \partial_\mu \lambda + ie_0 \bar{\eta} \Psi \lambda - ie_0 \bar{\Psi} \eta \lambda$$

Hence, we must have

$$\int d^4x \lambda(x) W(\xi) \int \mathcal{D}A \mathcal{D}\bar{\Psi} \mathcal{D}\Psi e^{iS} \left[ -\frac{1}{\xi} \partial^2 \partial_\mu A^\mu - \partial_\mu J^\mu + ie_0 (\bar{\eta} \Psi - \bar{\Psi} \eta) \right]$$

Since

$$\langle A_\mu(x) \rangle_{J, \eta, \bar{\eta}} = -\frac{\delta E}{\delta J^\mu} \quad \langle \Psi(x) \rangle_{J, \eta, \bar{\eta}} = -\frac{\delta E}{\delta \bar{\eta}} \quad \langle \bar{\Psi}(x) \rangle_{J, \eta, \bar{\eta}} = \frac{\delta E}{\delta \eta}$$

The above equation can be written as

$$\frac{1}{\xi} \partial^2 \partial^\mu \frac{\delta E}{\delta J^\mu} - \partial_\mu J^\mu - ie_0 \left[ \bar{\eta} \frac{\delta E}{\delta \bar{\eta}} + \frac{\delta E}{\delta \eta} \eta \right] = 0$$

We can derive that

$$\frac{1}{\xi} \partial^2 \partial^\mu \frac{\delta^2 E[J, \eta, \bar{\eta}]}{\delta J^\mu(x) \delta J^\nu(y)} \Big|_{J, \eta, \bar{\eta}=0} - \partial_\nu \delta(x - y) = 0$$

that is,

$$\frac{i}{\xi} \partial^2 \partial^\mu \mathcal{G}(x - y)_{\mu\nu} + \partial_\nu \delta(x - y) = 0$$

or, written in momentum-space,

$$-\frac{i}{\xi} k^2 k^\mu \mathcal{G}(k)_{\mu\nu} + k_\nu = 0$$

So

$$-\frac{k^2}{k^2 - \xi f_L(k^2)} k_\nu + k_\nu = 0$$

Which means  $f_L(k^2) = 0$  and so, we have  $f_T(k^2) \rightarrow O(k^2)$  as  $k^2 \rightarrow 0$ . The exact propagator of photon is

$$\mathcal{G}(k)_{\mu\nu} = \frac{-i}{k^2(1 - \pi(k^2))} P_{\mu\nu}^T + \frac{-i\xi}{k^2} P_{\mu\nu}^L$$

where  $\pi(k^2) \equiv \frac{f_T(k^2)}{k^2}$



## 13.7 LSZ reduction formula

### 13.7.1 LSZ reduction formula and Feynman rules

Suppose that the probability for the quantum field to create or annihilate an exact one-particle eigenstate of  $H$  is  $Z_3$ , i.e.

$$\langle \Omega | A(0) | p, \lambda \rangle = \sqrt{Z_3} \epsilon_\lambda(p)$$

In Feynman gauge, because the norm of  $|p, 0\rangle$  is negative, the expansion of orthogonal complete set will be written as

$$\frac{d^3q}{(2\pi)^3} \frac{1}{2E_q} \eta^{\lambda\lambda'} |p, \lambda\rangle \langle p, \lambda'|$$

We have demonstrated that photon will remain massless when interacting with charged fermions. And recall that  $\sum_\lambda \xi_\lambda(p) \xi_\lambda^*(p) = \eta_{\mu\nu}$ . So, we can derive by the similar method in  $\phi^4$  theory that

$$\int d^4x e^{-ipx} \langle \Omega | T A_\mu(x) A_\nu(0) | \Omega \rangle_C = \frac{-iZ_3 \eta_{\mu\nu}}{p^2 - i\epsilon} + \dots$$

The LSZ reduction formula for fermions would take the form as

#### Theorem 13.1 LSZ reduction formula

$$\begin{aligned} & \langle \mathbf{p}_1 \cdots \mathbf{p}_n | S | \mathbf{k}_1 \cdots \mathbf{k}_m \rangle \\ &= \prod_1^n \int d^4x_i e^{-ip_i x_i} \prod_1^m \int d^4y_j e^{ik_j y_j} \\ &\times \left( \frac{i}{\sqrt{Z_3}} \right)^{m+n} [p_1^2 \epsilon_{\lambda_1}^{*\mu_1}(p_1)] \cdots [p_n^2 \epsilon_{\lambda_n}^{*\mu_n}(p_n)] [k_1^2 \epsilon_{\lambda'_1}^{\nu_1}(k_1)] \cdots [k_m^2 \epsilon_{\lambda'_m}^{\nu_m}(k_m)] \\ &\times \langle \Omega | T \{ A_{\mu_1}(x_1) \cdots A_{\mu_n}(x_n) A_{\nu_1}(y_1) \cdots A_{\nu_m}(y_m) \} | \Omega \rangle \end{aligned}$$

The LSZ reduction formula in other gauge would give similar procedure for calculating scattering amplitude: Fourier transform the Green function in position space to momentum space, cut-off the external legs and multiply the polarization vector of asymptotic states. (Note there is still an extra factor  $\sqrt{Z_3}^{m+n}$  to multiply, similar to the  $\phi^4$  theory).

Finally, we list the Feynmann rules of QED in momentum space as follows:

1. For each incoming electron, draw a solid line with an arrow pointed towards the vertex, and label it with the electron's four-momentum,  $p_i$ .
2. For each outgoing electron, draw a solid line with an arrow pointed away from the vertex, and label it with the electron's four-momentum,  $p'_i$ .
3. For each incoming positron, draw a solid line with an arrow pointed away from the vertex, and label it with minus the positron's four-momentum,  $-p_i$ .
4. For each outgoing positron, draw a solid line with an arrow pointed towards the vertex, and label it with minus the positron's four-momentum,  $-p'_i$ .



5. For each incoming photon, draw a wavy line with an arrow pointed towards the vertex, and label it with the photon's four-momentum,  $k_i$ .
6. For each outgoing photon, draw a wavy line with an arrow pointed away from the vertex, and label it with the photon's four-momentum,  $k'_i$ .
7. The only allowed vertex joins two solid lines, one with an arrow pointing towards it and one with an arrow pointing away from it, and one wavy line. Using this vertex, join up all the external lines, including extra internal lines as needed. In this way, draw all possible diagrams that are topologically inequivalent.
8. Assign each internal line its own four-momentum. Think of the four-momenta as flowing along the arrows, and conserve four-momentum at each vertex.
9. The value of a diagram consists of the following factors:
  - for each incoming photon,  $\epsilon_\lambda^\mu(k)$ ; for each outgoing photon,  $\epsilon_\lambda^{*\mu}(k)$ ;
  - for each incoming electron,  $u_r(\mathbf{k})$ ; for each outgoing electron,  $\bar{u}_s(\mathbf{p})$ ;
  - for each incoming positron,  $\bar{v}_{\bar{r}}(\bar{\mathbf{k}})$ ; for each outgoing positron,  $v_{\bar{s}}(\bar{\mathbf{p}})$ ;
  - for each vertex,  $ie_0\gamma^\mu$ ; for each internal photon,  $G_F(p)$ ; for each internal fermion,  $S_F(p)$ .
10. Spinor indices are contracted by starting at one end of a fermion line: specifically, the end that has the arrow pointing away from the vertex. The factor associated with the external line is either  $\bar{u}$  or  $\bar{v}$ . Go along the complete fermion line, following the arrows backwards, and write down (in order from left to right) the factors associated with the vertices and propagators that you encounter. The last factor is either a  $u$  or  $v$ . Repeat this procedure for the other fermion lines, if any. The vector index on each vertex is contracted with the vector index on either the photon propagator (if the attached photon line is internal) or the photon polarization vector (if the attached photon line is external).
11. The overall sign of a tree diagram is determined by drawing all contributing diagrams in a standard form: all fermion lines horizontal, with their arrows pointing from left to right, and with the left endpoints labeled in the same fixed order (from top to bottom); if the ordering of the labels on the right endpoints of the fermion lines in a given diagram is an even (odd) permutation of an arbitrarily chosen fixed ordering, then the sign of that diagram is positive (negative)
12. Each closed fermion loop contributes an extra minus sign.
13. Value of  $i\mathcal{M}$  is given by a sum over the values of the contributing diagrams.
14.  $\langle f|S|i\rangle = (Z_2)^{\frac{n_f}{2}}(Z_3)^{\frac{n_p}{2}}i\mathcal{M}\delta(\sum p_f - \sum p_i)$



### 13.7.2 Ward Takahashi identity (3)

Suppose the invariant matrix element for a process is  $\mathcal{M}$ , if we replace the polarization state vector  $\epsilon_\lambda^\mu$  (or  $\epsilon_\lambda^{*\mu}$ ) of one incoming (or outgoing) photon with its momentum vector  $k^\mu$ , we have

$$k^\mu \mathcal{M}_\mu = 0$$

**Proof:** Without losing generality, we can consider a physical process with a single incoming and outgoing fermion lines respectively. So, the ward identities states that

$$-ik_\mu F^\mu(k; p, q) = ie_0 [F_0(p + k, q) - F_0(p, q - k)]$$

Here,  $F$  keeps the external fermion legs but cuts external photon lines. According to the LSZ reduction formula, from each diagram a contribution to an S matrix element by taking the coefficient of the product of poles

$$\left( \frac{-i}{\not{p} + m} \right) \left( \frac{-i}{\not{q} + m} \right)$$

But the terms on the right hand side contain one of these poles, but neither contains both poles. So they contribute nothing to S-matrix. So, we can have

$$k^\mu \mathcal{M}_\mu = 0$$

□

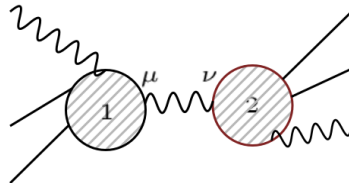
We also note that when calculating invariant matrix element, the main difference between different gauge are photon propagator. In Coulomb gauge, we have

$$G_F(p)_{\mu\nu} \equiv \begin{cases} \frac{i}{|\mathbf{p}|^2} & \mu, \nu = 0 \\ \frac{-i}{p^2 - i\epsilon} \left( \delta_{ij} - \frac{p_i p_j}{|\mathbf{p}|^2} \right) & \mu = i \neq 0, \nu = j \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

In Lorentz gauge, we have

$$G_F(p)_{\mu\nu} = \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon} + i(1 - \xi) \frac{p_\mu p_\nu}{(p^2 - i\epsilon)^2}$$

We now argue that the lead to the same  $\mathcal{M}$  element. For a general process, it can be represented as follows.



**Figure 13.6:** Feynman diagram representation of a QED process

The value of the diagram is

$$\mathcal{M}_1^\mu G_F(k)_{\mu\nu} \mathcal{M}_2^\nu$$



and  $k_\mu \mathcal{M}_1^\mu = 0$ ,  $k_\nu \mathcal{M}_2^\nu = 0$ . So the factor  $\xi$  in Lorentz gauge is irrelevant to the value of  $\mathcal{M}$ . As for Coulomb gauge, denote  $\mathcal{M}_1^\mu$  as  $\alpha^\mu$ ,  $\mathcal{M}_2^\mu$  as  $\beta^\mu$ , so

$$\alpha^\mu G_F(k)_{\mu\nu} \beta^\nu = i \left( -\frac{\alpha \cdot \beta}{k^2} + \frac{(\alpha \cdot \mathbf{k})(\beta \cdot \mathbf{k})}{k^2 \mathbf{k}^2} + \frac{\alpha^0 \beta^0}{\mathbf{k}^2} \right)$$

Using the fact that  $\alpha \cdot \mathbf{k} + \alpha^0 k_0 = 0$ , we can verify that

$$\alpha^\mu G_F(k)_{\mu\nu} \beta^\nu = \alpha^\mu \left( -\frac{i\eta_{\mu\nu}}{k^2} \right) \beta^\nu$$

So, the invariant matrix element is gauge invariant.

## 13.8 Renormalization

### 13.8.1 Renormalized quantum electrodynamics

The Lagrangian of QED is

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\not{\partial} - m_0)\Psi + e_0 j^\mu A_\mu,$$

Suppose the number of external photons is  $N_\gamma$ , the number of external fermions is  $N_e$ , the number of photon propagator (after amputation) is  $P_\gamma$ , the number of fermion propagator is  $P_e$ , the number of vertex is  $V$ . So we know the number of loops is

$$L = P_\gamma + P_e - V + 1$$

We also know that

$$V = 2P_\gamma + N_\gamma \quad 2V = 2P_e + N_e$$

So, the superficial divergence is

$$D = 4L - 2P_\gamma - P_e = 4 - N_\gamma - \frac{3}{2}N_e$$

Recall that  $C$  is a symmetry of QED, so  $C|\Omega\rangle = |\Omega\rangle$ . But  $j^\mu$  changes sign under charge conjugation,  $Cj^\mu(x)C^\dagger = -j^\mu(x)$ , so its vacuum expectation value must vanish:

$$\langle\Omega|Tj^\mu(x)|\Omega\rangle = \langle\Omega|TC^\dagger Cj^\mu(x)C^\dagger C|\Omega\rangle = -\langle\Omega|Tj^\mu(x)|\Omega\rangle = 0$$

So, the amplitude with  $N_\gamma = 1$ ,  $N_e = 0$  will vanish. Similarly, we can verify that the diagram with  $N_\gamma = 3$ ,  $N_e = 0$  will also vanish.

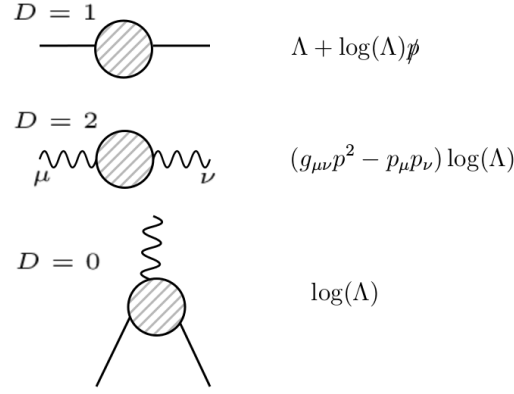
As for the amplitude with  $N_\gamma = 4$ , the superficial divergence  $D = 0$ . So the only divergence must be of the form  $\log \Lambda$ . But the ward identity implies that

$$K^\mu \mathcal{M}_{\mu\nu\sigma\rho} = 0$$

So, the divergent terms must vanish.

If we neglect the vacuum term with  $N_\gamma = 0$ ,  $N_e = 0$ , there are only three divergent amplitude terms left.





**Figure 13.7:** Feynman diagram representation of divergent amplitude in QED

We need four counter terms to eliminate all the divergence. The Lagrangian can be written as

$$\mathcal{L} = \mathcal{L}_1 + \mathcal{L}_{ct}$$

Here,

$$\begin{aligned}\mathcal{L}_1 &= -\frac{1}{4}F_r^{\mu\nu}F_{r\mu\nu} + i\bar{\Psi}_r\gamma^\mu\partial_\mu\Psi_r - m\bar{\Psi}_r\Psi_r + e\bar{\Psi}_r\gamma^\mu\Psi_r A_{r\mu} \\ \mathcal{L}_{ct} &= -\frac{1}{4}\delta_3 F_r^{\mu\nu}F_{r\mu\nu} + i\delta_2\bar{\Psi}_r\gamma^\mu\partial_\mu\Psi_r - \delta_m\bar{\Psi}_r\Psi_r + e\delta_1\bar{\Psi}_r\gamma^\mu\Psi_r A_{r\mu} \\ A &= \sqrt{Z_3}A_r \quad \Phi = \sqrt{Z_2}\Phi_r \quad \delta_3 = Z_3 - 1 \quad \delta_2 = Z_2 - 1 \\ \delta_m &= Z_2 m_0 - m \quad \delta_1 = Z_1 - 1 = (e_0/e)Z_2 Z_3^{\frac{1}{2}} - 1\end{aligned}$$

The Feynman rules of counter terms are:

$$\begin{aligned}-\frac{1}{4}\delta_3 F_r^{\mu\nu}F_{r\mu\nu} &\quad -i(\eta^{\mu\nu}q^2 - q^\mu q^\nu)\delta_3 \\ i\bar{\Psi}_r(\delta_2\not{\partial} - \delta_m)\Psi_r &\quad -i(\delta_2\not{p} + \delta_m) \\ e\delta_1\bar{\Psi}_r\gamma^\mu\Psi_r A_{r\mu} &\quad ie\gamma^\mu\delta_1\end{aligned}$$

We also denote the renormalized 1PI component of exact propagator of photon as  $i(\eta^{\mu\nu}q^2 - q^\mu q^\nu)\Pi_r(q^2)$ , the renormalized 1PI component of exact propagator of fermion as  $-i\Sigma_r(\not{p})$ , the renormalized exact amputated photon-fermion-antifermion vertex as  $ie\Gamma_r^\mu(p, p')$ .

So, renormalized exact propagator of photon is

$$\mathcal{G}_r(q)_{\mu\nu} = \frac{-i}{q^2(1 - \Pi_r(q^2))}P_{\mu\nu}^T$$

renormalized exact propagator of fermion is

$$\mathcal{S}_r(p) = \frac{-i}{\not{p} + m + \Sigma_r(\not{p})}$$





The on-shell renormalization conditions are

$$\begin{aligned}\Sigma_r(\not{p} = -m) &= 0 \\ \frac{d}{d\not{p}}\Sigma_r(\not{p})\Big|_{\not{p}=-m} &= 0 \\ \Pi_r(q^2 = 0) &= 0 \\ ie\Gamma_r^\mu(p = p', p^2 = -m^2) &= ie\gamma^\mu\end{aligned}$$

Recall the ward identity, we have

$$ie\sqrt{Z_2}\partial_\mu\langle\Omega|Tj_r^\mu\Psi_r(x_1)\bar{\Psi}_r(x_2)|\Omega\rangle = -ie\delta(x-x_1)\langle\Omega|T\Psi_r(x_1)\bar{\Psi}_r(x_2)|\Omega\rangle + ie\delta(x-x_2)\langle\Omega|T\Psi_r(x_1)\bar{\Psi}_r(x_2)|\Omega\rangle$$

In momentum space, we have

$$-k_\mu Z_2 Z_1^{-1} \mathcal{S}_r(p+k)[ie\Gamma_r^\mu(p+k, p)]\mathcal{S}_r(p) \frac{1}{1 - \Pi_r(k^2)} = e(\mathcal{S}_r(p+k) - \mathcal{S}_r(p))$$

So,

$$Z_2 Z_1^{-1} k_\mu [\Gamma_r^\mu(p+k, p)] \frac{1}{1 - \Pi_r(k^2)} = \not{k} + \Sigma_r(\not{k} + \not{p}) - \Sigma_r(\not{p})$$

Since  $\Gamma_r$ ,  $\Pi_r$  and  $\Sigma_r$  are all finite by renormalization, so  $Z_1/Z_2$  must be finite. In  $\overline{MS}$  renormalization scheme, we immediately get

$$Z_1 = Z_2$$

In on-shell renormalization scheme, taking the limit of  $k \rightarrow 0$ , we can also get that

$$Z_1 = Z_2$$

So, we know

$$e = \sqrt{Z_3}e_0$$

This means that the relation between the bare and renormalized electric charge depends only on the photon field strength renormalization, not on quantities particular to the fermions, leading to a universal electric charge which has the same value for all species.

In the following subsection, we would omit the subscript  $r$  unless it is necessary to emphasis the difference of bare field and renormalized fields.

### 13.8.2 One loop structure of QED

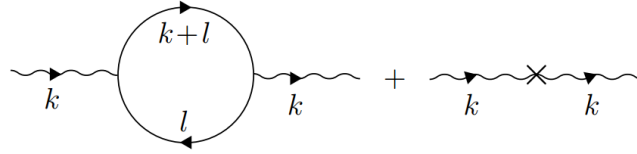
#### Photon propagator

$$\Pi(k^2) = -\frac{e^2}{\pi^2} \int_0^1 dx x(1-x) \left[ \frac{1}{\epsilon} - \frac{1}{2} \ln\left(\frac{D}{\mu^2}\right) \right] - \delta_3 + O(e^4)$$

where  $D = x(1-x)k^2 + m^2 - i\epsilon$  and  $\mu^2 = 4\pi e^{-\gamma} \tilde{\mu}^2$ . Impose the OS renormalization condition  $\Pi(0) = 0$ , we have

$$\begin{aligned}\delta_3 &= -\frac{e^2}{6\pi^2} \left[ \frac{1}{\epsilon} - \ln\left(\frac{m}{\mu}\right) \right] + O(e^4) \\ \Pi(k^2) &= \frac{e^2}{2\pi^2} \int_0^1 dx x(1-x) \ln\left(\frac{D}{m^2}\right) + O(e^4)\end{aligned}$$





**Figure 13.8:** The one-loop and counterterm corrections to the photon propagator

### Fermion propagator

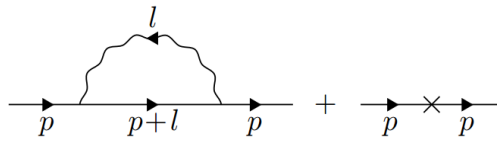
The exact renormalized fermion propagator in OS renormalization can be written in Lehmann–Kallen form as

$$iS(\not{p}) = \frac{1}{\not{p} + m - i\epsilon} + \int_{m_{th}}^{\infty} ds \frac{\rho_{\Psi}(s)}{\not{p} + \sqrt{s} - i\epsilon}$$

We see that the first term has a pole at  $\not{p} = -m$  with residue one. This residue corresponds to the field normalization that is needed for the validity of the LSZ formula.

There is a problem, however: in quantum electrodynamics, the threshold mass  $m_{th}$  is  $m$ , corresponding to the contribution of a fermion and a zero energy photon. Thus the second term has a branch point at  $\not{p} = -m$ . The pole in the first term is therefore not isolated, and its residue is ill defined.

This is a reflection of an underlying infrared divergence, associated with the massless photon. To deal with it, we must impose an infrared cutoff that moves the branch point away from the pole. The most direct method is to change the denominator of the photon propagator from  $k^2$  to  $k^2 + m_{\gamma}^2$ , where  $m_{\gamma}$  is a fictitious photon mass. Ultimately, we must deal with this issue by computing cross sections that take into account detector inefficiencies. In quantum electrodynamics, we must specify the lowest photon energy  $\omega_{min}$  that can be detected. Only after computing cross sections with extra undetectable photons, and then summing over them, is it safe to take the limit  $m_{\gamma} \rightarrow 0$ .



**Figure 13.9:** The one-loop and counterterm corrections to the fermion propagator

$$\Sigma(\not{p}) = \frac{e^2}{8\pi^2} \int_0^1 dx \left( (2 - \epsilon)(1 - x)\not{p} + (4 - \epsilon)m \right) \left[ \frac{1}{\epsilon} - \frac{1}{2} \ln\left(\frac{D}{\mu^2}\right) \right] + \delta_2 \not{p} + \delta_m + O(e^4)$$

where  $D = x(1 - x)p^2 + xm^2 + (1 - x)m_{\gamma}^2$ . The fitness of  $\Sigma(\not{p})$  requires that

$$\delta_2 = -\frac{e^2}{8\pi^2} \left( \frac{1}{\epsilon} + \text{finite} \right) + O(e^4)$$

$$\delta_m/m = -\frac{e^2}{2\pi^2} \left( \frac{1}{\epsilon} + \text{finite} \right) + O(e^4)$$

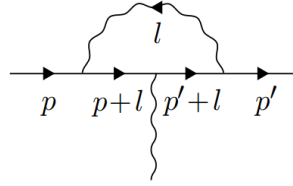


Impose the OS renormalization condition  $\Sigma(-m) = 0$  and  $\Sigma'(-m) = 0$ , we have

$$\Sigma(\not{p}) = -\frac{e^2}{8\pi^2} \int_0^1 dx ((1-x)\not{p} + 2m) \ln\left(\frac{D}{D_0}\right) + \kappa_2(\not{p} + m) + O(e^4)$$

where  $D_0 = x^2 m^2 + (1-x)m_\gamma^2$  and  $\kappa_2 = -2 \ln(m/m_\gamma) + 1$ .

### Vertex



**Figure 13.10:** The one-loop correction to the photon-fermion-fermion vertex

$$\Gamma^\mu(p, p') = (1 + \delta_1)\gamma^\mu + \frac{e^2}{8\pi^2} \left[ \left( \frac{1}{\epsilon} - 1 - \frac{1}{2} \int dF_3 \ln(D/\mu^2) \right) \gamma^\mu + \frac{1}{4} \int dF_3 \frac{\tilde{N}^\mu}{D} \right] + O(e^4)$$

where

$$\int dF_3 = 2 \int_0^1 dx_1 dx_2 dx_3 \delta(x_1 + x_2 + x_3 - 1)$$

$$D = x_1(1-x_1)p^2 + x_2(1-x_2)p'^2 - 2x_1x_2p \cdot p' + (x_1+x_2)m^2 + x_3m_\gamma^2$$

$$\tilde{N}^\mu = \gamma_\nu [x_1 \not{p} - (1-x_2)\not{p}' + m] \gamma^\mu [-(1-x_1)\not{p} + x_2 \not{p}' + m] \gamma^\nu$$

Fitness of  $\Gamma^\mu$  requires that

$$\delta_1 = -\frac{e^2}{8\pi^2} \left( \frac{1}{\epsilon} + \text{finite} \right) + O(e^4)$$

Impose the OS renormalization condition  $\Gamma_r^\mu(p = p', p^2 = -m^2) = \gamma^\mu$ , we have

$$\Gamma^\mu(p, p') = \gamma^\mu - \frac{e^2}{16\pi^2} \int dF_3 \left[ (\ln(D/D_0) + 2\kappa_1) \gamma^\mu - \frac{\tilde{N}^\mu}{2D} \right] + O(e^4)$$

where

$$D_0 = (1-x_3)^2 m^2 + x_3 m_\gamma^2 \quad \kappa_1 = -2 \ln(m/m_\gamma) + \frac{5}{2}$$



# Chapter 14

## Vector Field



### 14.1 Vector field

Consider a vector field  $A^\mu(x)$ . Here the index  $\mu$  is a vector index that takes on four possible values. Under a Lorentz transformation, we have

$$U(\Lambda)^{-1} A^\mu(x) U(\Lambda) = \Lambda^\mu{}_\nu A^\nu(\Lambda^{-1}x)$$

For an infinitesimal transformation, we can write

$$\delta^\mu{}_\nu + \delta\omega^\mu{}_\nu = \delta^\mu{}_\nu + \frac{i}{2} \delta\omega_{\rho\sigma} (S_V^{\rho\sigma})^\mu{}_\nu$$

Here

$$(S_V^{\rho\sigma})^\mu{}_\nu = -i(\eta^{\rho\mu}\delta^\sigma{}_\nu - \eta^{\sigma\mu}\delta^\rho{}_\nu)$$

It is obvious that  $A^{\dagger\mu}$  is also a vector field. We know that  $\eta^{\mu\nu}$  is invariant under Lorentz transformation, i.e.

$$\Lambda^\mu{}_\rho \Lambda^\nu{}_\sigma \eta^{\rho\sigma} = \eta^{\mu\nu}$$

We can use  $\eta^{\mu\nu}$  and its inverse  $\eta_{\mu\nu}$  to raise and lower vector indices of the vector field,

$$A_\mu \equiv \eta_{\mu\nu} A^\nu$$

And we can verify the following equations

$$\Lambda^\mu{}_\nu \Lambda_\mu{}^\rho = \delta_\nu^\rho$$

$$A^\mu(x) = \eta^{\mu\nu} A_\nu(x)$$

$$\Lambda_\mu{}^\rho \Lambda_\nu{}^\sigma \eta_{\rho\sigma} = \eta_{\mu\nu}$$

$$U(\Lambda)^{-1} A_\mu(x) U(\Lambda) = \Lambda_\mu{}^\nu A_\nu(\Lambda^{-1}x)$$

Define  $C_i \equiv \frac{1}{2} \epsilon_{ijk} S_V^{jk}$ ,  $D_i \equiv S_V^{i0}$ . For example, we have

$$(C_3)_\mu{}^\nu = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

The eigenvectors of  $C_3$  are

$$[(-1, [(0, 1, -i, 0)], 1), (1, [(0, 1, i, 0)], 1), (0, [(1, 0, 0, 0), (0, 0, 0, 1)], 2)]$$

We further define  $N_i \equiv \frac{1}{2}(C_i - iD_i)$  and  $N_i^\dagger \equiv \frac{1}{2}(C_i + iD_i)$ . For example, we have

$$(N_1)_\mu{}^\nu = \begin{pmatrix} 0 & -\frac{1}{2} & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{2}i \\ 0 & 0 & \frac{1}{2}i & 0 \end{pmatrix}$$

The eigenvectors of  $N_1$  are

$$\left[ \left( -\frac{1}{2}, [(1, 1, 0, 0), (0, 0, 1, -i)], 2 \right), \left( \frac{1}{2}, [(1, -1, 0, 0), (0, 0, 1, i)], 2 \right) \right]$$

And we can conclude that vector is in the  $(2, 2)$  representation of the Lie algebra of the Lorentz group.

## 14.2 Electromagnetic field and gauge invariance

The Lagrangian of EM field is

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Here,

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad \text{and} \quad A^\mu = (\phi, \mathbf{A})$$

So,

$$F_{0i} = \dot{A}^i + \nabla_i \phi \equiv -E^i \quad \text{and} \quad F_{ij} = \nabla_i A^j - \nabla_j A^i \equiv \epsilon_{ijk} B^k$$

We can derive the equation of motion of the EM field by variation method,

$$\partial_\mu F^{\mu\nu} = 0$$

It can be rewritten in terms of  $\mathbf{E}$  and  $\mathbf{B}$ , i.e. Maxwell equations:

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 0 & \frac{\partial \mathbf{E}}{\partial t} &= \nabla \times \mathbf{B} \\ \nabla \cdot \mathbf{B} &= 0 & \frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \end{aligned}$$

The massless vector field  $A_\mu$  has 4 components, which would naively seem to tell us that the gauge field has 4 degrees of freedom. But there are two related comments which will ensure that quantizing the gauge field  $A_\mu$  gives rise to 2 degrees of freedom, rather than 4.

- The field  $A_0$  has no kinetic term  $\dot{A}_0$  in the Lagrangian: it is not dynamical. This means that if we are given some initial data  $A_i$  and  $\dot{A}_i$  at a time  $t_0$ , then the field  $A_0$  is fully determined by the equation of motion  $\nabla \cdot \mathbf{E} = 0$ , which, expanding out, reads

$$\nabla^2 A_0 = \nabla \cdot \frac{\partial \mathbf{A}}{\partial t}$$

So  $A_0$  is not independent: we don't get to specify  $A_0$  on the initial time slice.



- If we transform the EM field as

$$A_\mu \rightarrow A_\mu + \partial_\mu \lambda(x)$$

we can derive that

$$F_{\mu\nu} \rightarrow F_{\mu\nu} \quad \mathcal{L} \rightarrow \mathcal{L}$$

The seemed infinite number of symmetries, one for each function  $\lambda(x)$ , is to be viewed as a redundancy in our description. That is, two states related by a gauge symmetry are to be identified: they are the same physical state. One way to see that this interpretation is necessary is to notice that Maxwell's equations are not sufficient to specify the evolution of  $A_\mu$ . The equations read,

$$(\eta_{\mu\nu} \partial^2 - \partial_\mu \partial_\nu) A^\nu = 0$$

But the operator  $(\eta_{\mu\nu} \partial^2 - \partial_\mu \partial_\nu)$  is not invertible: it annihilates any function of the form  $\partial_\mu \lambda$ . This means that given any initial data, we have no way to uniquely determine  $A_\mu$  at a later time since we can't distinguish between  $A_\mu$  and  $A_\mu + \partial_\mu \lambda$ . This would be problematic if we thought that  $A_\mu$  is a physical object. However, if we're happy to identify  $A_\mu$  and  $A_\mu + \partial_\mu \lambda$  as corresponding to the same physical state, then our problems disappear.

The picture that emerges for the theory of electromagnetism is of an enlarged phase space, foliated by gauge orbits. All states that lie along a given gauge orbit can be reached by a gauge transformation and are identified. To make progress, we pick a representative from each gauge orbit. It doesn't matter which representative we pick after all, they're all physically equivalent. But we should make sure that we pick a "good" gauge, in which we cut the orbits. Here we'll look at two different gauges:

- Coulomb Gauge:  $\nabla \cdot \mathbf{A} = 0$

We can make use of the residual gauge transformations in Lorentz gauge to pick  $\nabla \cdot \dot{\mathbf{A}} = 0$ . We have as a consequence  $A_0 = 0$ . Coulomb gauge is sometimes called radiation gauge.

- Lorentz Gauge:  $\partial^\mu A_\mu = 0$

In fact this condition doesn't pick a unique representative from the gauge orbit. We're always free to make further gauge transformations with  $\partial^\mu \partial_\mu \lambda = 0$ , which also has non-trivial solutions. As the name suggests, the Lorentz gauge has the advantage that it is Lorentz invariant.

## 14.3 Canonical quantization of EM field

### 14.3.1 Canonical quantization in Coulomb gauge

Canonical momentum and Hamiltonian

$$\pi^0 = \frac{\partial \mathcal{L}}{\partial \dot{A}_0} = 0 \quad \pi^i = \frac{\partial \mathcal{L}}{\partial (\partial_0 A_i)} = \dot{A}^i + \nabla_i \phi = -E^i$$



$$\mathcal{H} = \frac{1}{2}(\boldsymbol{\pi}^2 + \mathbf{B}^2) + (\boldsymbol{\pi} \cdot \boldsymbol{\nabla})A_0$$

Integration by parts can give

$$H = \int d^3x \frac{1}{2}(\boldsymbol{\pi}^2 + \mathbf{B}^2)$$

### Momentum and angular momentum

$$P^0 = H \quad \vec{P} = \int -\boldsymbol{\pi} \vec{\nabla} A d^3x$$

$$\vec{J} = - \int \boldsymbol{\pi} (\vec{x} \times \vec{\nabla} + i\vec{C}) \mathbf{A} d^3x \quad \vec{S} = -i \int \boldsymbol{\pi} \vec{C} \mathbf{A} d^3x$$

### Canonical quantization

In Coulomb gauge, we have

$$A_0 = \pi^0 = 0 \quad \pi^i = \dot{A}^i$$

Three pairs of  $A_i$  and  $\pi^i$  are not independent from each other. They must satisfy the constraint equations

$$\boldsymbol{\nabla} \cdot \mathbf{A} = 0 \quad \boldsymbol{\nabla} \cdot \boldsymbol{\pi} = 0$$

A reasonable quantization condition can be written as

$$[A_i(\mathbf{x}, t), A_j(\mathbf{x}', t)] = 0 \quad [\pi^i(\mathbf{x}, t), \pi^j(\mathbf{x}', t)] = 0$$

$$[A_i(\mathbf{x}, t), \pi^j(\mathbf{x}', t)] = i \left( \delta_i^j - \frac{\partial_i \partial^j}{\nabla^2} \right) \delta(\mathbf{x} - \mathbf{x}') \equiv i \int \frac{d^3k}{(2\pi)^3} \left( \delta_i^j - \frac{k_i k^j}{\mathbf{k}^2} \right) e^{i\mathbf{k} \cdot (\mathbf{x} - \mathbf{x}')} \delta(t - t')$$

In this case, we can verify that

$$\dot{A}_i = -i[A_i(\mathbf{x}, t), H] = \pi_i(\mathbf{x}, t)$$

$$\dot{\pi}^i = -i[\pi^i(\mathbf{x}, t), H] = \nabla^2 A^i(\mathbf{x}, t)$$

It is constant with the field equation we derive from Euler-Lagrange equation.

### Fourier expansion

$$\mathbf{A}(\mathbf{x}) = \sum_{r=\pm} \int \widetilde{dp} [a_r(\mathbf{p}) \boldsymbol{\epsilon}_r(\mathbf{p}) e^{i\mathbf{p} \cdot \mathbf{x}} + a_r^\dagger(\mathbf{p}) \boldsymbol{\epsilon}_r^*(\mathbf{p}) e^{-i\mathbf{p} \cdot \mathbf{x}}]$$

And we can derive from constraint condition that

$$\boldsymbol{\epsilon} \cdot \mathbf{p} = 0$$

We will choose  $\boldsymbol{\epsilon}$  to satisfy that

$$\boldsymbol{\epsilon}_r \cdot \boldsymbol{\epsilon}_s^* = \delta_{rs}$$



So, the completeness relation for the polarization vectors is

$$\sum_{r=\pm} \epsilon_r^i(\mathbf{p}) \epsilon_r^{*j}(\mathbf{p}) = \delta^{ij} - \frac{p^i p^j}{|\mathbf{p}|^2}$$

**Example:** If  $\mathbf{p} = (0, 0, p)$ , we usually choose

$$\epsilon_+ = \frac{1}{\sqrt{2}}(1, i, 0) \quad \epsilon_- = \frac{1}{\sqrt{2}}(1, -i, 0)$$

$\epsilon_+$  corresponds to left-handed rotation and it is the eigenvectors of the space-part of  $C_3$  with eigenvalue  $+1$ .  $\epsilon_-$  corresponds to right-handed rotation and it is eigenvector of the space-part of  $C_3$  with eigenvalue  $-1$ .

We can further derive from above discussion that

$$\pi(x) = -i \sum_{r=\pm} \int \widetilde{dp} \omega [a_r(\mathbf{p}) \epsilon_r(\mathbf{p}) e^{ipx} - a_r^\dagger(\mathbf{p}) \epsilon_r^*(\mathbf{p}) e^{-ipx}]$$

$$a_r(\mathbf{p}) = \epsilon_r^* \int d^3x e^{-ikx} (i\boldsymbol{\pi} + \omega \mathbf{A})$$

$$a_r^\dagger(\mathbf{p}) = \epsilon_r \int d^3x e^{ikx} (-i\boldsymbol{\pi} + \omega \mathbf{A})$$

$$[a_r(\mathbf{p}), a_{r'}(\mathbf{p}')] = 0 \quad [a_r^\dagger(\mathbf{p}), a_{r'}^\dagger(\mathbf{p}')] = 0 \quad [a_r(\mathbf{p}), a_{r'}^\dagger(\mathbf{p}')] = (2\pi)^3 2\omega \delta_{rr'} \delta(\mathbf{p} - \mathbf{p}')$$

### Operator represented by $a$ and $a^\dagger$

Define that

$$N(\mathbf{p}, r) \equiv a_r^\dagger(\mathbf{p}) a_r(\mathbf{p})$$

So, we can derive

$$H = \sum_{r=\pm} \int \widetilde{dp} \omega N(\mathbf{p}, r) + 2\mathcal{E}_0 V$$

$$\vec{P} = \sum_{r=\pm} \int \widetilde{dp} \vec{p} N(\mathbf{p}, r)$$

$$\vec{S} = \sum_{r,s=\pm} \int \widetilde{dp} \frac{1}{2} (\epsilon_s^* \vec{C} \epsilon_r - \epsilon_r \vec{C} \epsilon_s^*) a_s^\dagger(\mathbf{p}) a_r(\mathbf{p})$$

From above equation, we can say that  $a_r^\dagger(\mathbf{p})$  create an photon with energy  $\omega$ , momentum  $\mathbf{p}$  and spin angular momentum along the direction of momentum  $r$ .

### Propagator

$$G_F(x-y)_{ij} \equiv \langle 0 | T A_i(x) A_j(y) | 0 \rangle = \int \frac{d^4p}{(2\pi)^4} \frac{-i}{p^2 - i\epsilon} \left( \delta_{ij} - \frac{p_i p_j}{|\mathbf{p}|^2} \right) e^{ip(x-y)}$$





### 14.3.2 Canonical quantization in Lorentz gauge

#### Undefined metric formalism

Modify the Maxwell Lagrangian introducing a new term

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2\xi}(\partial_\mu A^\mu)^2$$

The equations of motion are now

$$\partial^2 A_\mu - (1 - \frac{1}{\xi})\partial^\mu(\partial \cdot A) = 0$$

Canonical momentums are

$$\pi^0 = \frac{1}{\xi}\partial \cdot A = \frac{1}{\xi}(-\dot{A}_0 + \partial_i A^i) \quad \pi^i = \dot{A}^i + \nabla^i A^0 = -E^i$$

Hamiltonian is

$$\mathcal{H} = \frac{1}{2}(\boldsymbol{\pi}^2 + \mathbf{B}^2 - \xi\pi^0\pi^0) + (\boldsymbol{\pi} \cdot \boldsymbol{\nabla})A_0 + \pi^0(\boldsymbol{\nabla} \cdot \mathbf{A})$$

$$H = \int \left[ \frac{1}{2}(\boldsymbol{\pi}^2 + \mathbf{B}^2 - \xi\pi^0\pi^0) - A_0(\boldsymbol{\nabla} \cdot \boldsymbol{\pi}) + \pi^0(\boldsymbol{\nabla} \cdot \mathbf{A}) \right] d^3x$$

We remark that the above Lagrangian and the equations of motion, reduce to Maxwell theory in the gauge  $\partial \cdot A = 0$ . This why we say that our choice corresponds to a class of Lorenz gauges with parameter  $\xi$ . With this abuse of language (in fact we are not setting  $\partial \cdot A = 0$ , otherwise the problems would come back) the value of  $\xi = 1$  is known as the Feynman gauge and  $\xi = 0$  as the Landau gauge. From now on we will take the case of the so-called Feynman gauge, where  $\xi = 1$ . Then the equation of motion coincide with the Maxwell theory in the Lorenz gauge. In Feymann gauge, the canonical quantization conditions can be written as

$$[A_\mu(\mathbf{x}, t), A_\nu(\mathbf{x}', t)] = 0 \quad [\pi^\mu(\mathbf{x}, t), \pi^\nu(\mathbf{x}', t)] = 0 \quad [A_\mu(\mathbf{x}, t), \pi^\nu(\mathbf{x}', t)] = i\delta_\mu^\nu \delta(\mathbf{x} - \mathbf{x}')$$

we can also derive that

$$[\dot{A}_\mu(\mathbf{x}, t), \dot{A}_\nu(\mathbf{x}', t)] = 0 \quad [A_\mu(\mathbf{x}, t), \dot{A}_\nu(\mathbf{x}', t)] = i\eta_{\mu\nu} \delta(\mathbf{x} - \mathbf{x}')$$

#### Fourier expansion

$$A(x) = \sum_{\lambda=0}^3 \int \widetilde{dp} [a_\lambda(\mathbf{p})\epsilon_\lambda(\mathbf{p})e^{ipx} + a_\lambda^\dagger(\mathbf{p})\epsilon_\lambda^*(\mathbf{p})e^{-ipx}]$$

where  $\epsilon_{\lambda\mu}$  are a set of four independent 4-vectors. We will now make a choice for these 4-vectors. We choose  $\epsilon_{1\mu}$  and  $\epsilon_{2\mu}$  orthogonal to  $k^\mu$  and  $n^\mu$ , such that

$$\epsilon_{\lambda\mu}\epsilon_\lambda^{*\mu} = \delta_{\lambda\lambda'} \quad \lambda, \lambda' = 1, 2$$



After, we choose  $\epsilon_{3\mu}$  in the plane  $(k^\mu, n^\mu)$  and perpendicular to  $n^\mu$  such that

$$\epsilon_{3\mu} n^\mu = 0 \quad \epsilon_{3\mu} \epsilon_3^{*\mu} = 1$$

Finally we choose  $\epsilon_{0\mu} = n_\mu$ . The vectors  $\epsilon_{1\mu}$  and  $\epsilon_{2\mu}$  are called transverse polarizations, while  $\epsilon_{3\mu}$  and  $\epsilon_{0\mu}$  longitudinal and scalar polarizations, respectively.

In general we can show that

$$\epsilon_\lambda \cdot \epsilon_{\lambda'}^* = \eta_{\lambda\lambda'} \quad \eta^{\lambda\lambda'} \epsilon_{\lambda\mu} \epsilon_{\lambda'\nu}^* = \eta_{\mu\nu}$$

We can further derive from above discussion that

$$\dot{A}(x) = -i \sum_{\lambda=0}^3 \int \widetilde{dp} \omega [a_\lambda(\mathbf{p}) \epsilon_\lambda(\mathbf{p}) e^{ipx} - a_\lambda^\dagger(\mathbf{p}) \epsilon_\lambda^*(\mathbf{p}) e^{-ipx}]$$

$$a_\lambda(\mathbf{p}) = \eta_{\lambda\lambda'} \epsilon_{\lambda'}^* \cdot \int d^3x e^{-ipx} (i\dot{A} + \omega A)$$

$$a_\lambda^\dagger(\mathbf{p}) = \eta_{\lambda\lambda'} \epsilon_{\lambda'} \cdot \int d^3x e^{ipx} (-i\dot{A} + \omega A)$$

$$[a_\lambda(\mathbf{p}), a_{\lambda'}(\mathbf{p}')] = 0 \quad [a_\lambda^\dagger(\mathbf{p}), a_{\lambda'}^\dagger(\mathbf{p}')] = 0 \quad [a_\lambda(\mathbf{p}), a_{\lambda'}^\dagger(\mathbf{p}')] = (2\pi)^3 2\omega \eta_{\lambda\lambda'} \delta(\mathbf{p} - \mathbf{p}')$$

### Indefinite metric problem

We Introduce the vacuum state defined by

$$a_\lambda(\mathbf{p})|0\rangle = 0$$

To see the problem with the sign we construct the one-particle state with scalar polarization, that is

$$|1\rangle = \int \widetilde{dp} a_0^\dagger(\mathbf{p})|0\rangle$$

and calculate its norm

$$\langle 1|1\rangle = -\langle 0|0\rangle \int \widetilde{dp} |f(p)|^2$$

The state  $|1\rangle$  has a negative norm.

To solve this problem we note that we are not working anymore with the classical Maxwell theory because we modified the Lagrangian. What we would like to do is to impose the condition  $\partial \cdot A = 0$ , but that is impossible as an equation for operators. We can, however, require that condition on a weaker form, as a condition only to be verified by the physical states.

More specifically, we require that the part of  $\partial \cdot A$  that contains the annihilation operator (positive frequencies) annihilates the physical states,

$$\partial^\mu A_\mu^+ |\psi\rangle = 0$$

The states  $|\psi\rangle$  can be written in the form

$$|\psi\rangle = |\psi_T\rangle |\phi\rangle$$



where  $|\psi_T\rangle$  is obtained from the vacuum with creation operators with transverse polarization and  $|\phi\rangle$  with scalar and longitudinal polarization.

$\partial^\mu A_\mu^+$  contains only scalar and longitudinal polarizations

$$\partial^\mu A_\mu^+ = i \sum_{\lambda=0,3} \int \widetilde{dp} a_\lambda(\mathbf{p})(p \cdot \epsilon_\lambda(\mathbf{p})) e^{ipx}$$

Therefore the previous condition becomes

$$i \sum_{\lambda=0,3} (p \cdot \epsilon_\lambda(\mathbf{p})) a_\lambda(\mathbf{p}) |\phi\rangle = 0$$

The condition is equivalent to,

$$(a_0(\mathbf{p}) - a_3(\mathbf{p})) |\phi\rangle = 0$$

We can construct  $|\phi\rangle$  as a linear combination of states  $|\phi\rangle$  with  $n$  scalar or longitudinal photons:

$$|\phi\rangle = C_0 |\phi_0\rangle + C_1 |\phi\rangle + \dots \quad \text{Here, } |\phi_0\rangle \equiv |0\rangle$$

The states  $|\phi_n\rangle$  are eigenstates of the operator number for scalar or longitudinal photons

$$N' |\phi_n\rangle = n |\phi_n\rangle$$

where,

$$N' = \int \widetilde{dp} [a_3^\dagger(\mathbf{p}) a_3(\mathbf{p}) - a_0^\dagger(\mathbf{p}) a_0(\mathbf{p})]$$

Then

$$n \langle \phi_n | \phi_n \rangle = \langle \phi_n | N' | \phi_n \rangle = 0$$

This means that

$$\langle \phi_n | \phi_n \rangle = \delta_{n0}$$

that is, for  $n \neq 0$ , the state  $|\phi_n\rangle$  has zero norm. We have then for the general state  $|\phi\rangle$ ,

$$\langle \phi | \phi \rangle = |C_0|^2 \geq 0$$

and the coefficients  $C_i (i = 1, 2, \dots)$  are arbitrary.

### Operator represented by $a$ and $a^\dagger$

Define that

$$N'(\mathbf{p}) \equiv a_3^\dagger(\mathbf{p}) a_3(\mathbf{p}) - a_0^\dagger(\mathbf{p}) a_0(\mathbf{p})$$

$$N(\mathbf{p}, 1) \equiv a_1^\dagger(\mathbf{p}) a_1(\mathbf{p}) \quad N(\mathbf{p}, 2) \equiv a_2^\dagger(\mathbf{p}) a_2(\mathbf{p}) \quad N_T(\mathbf{p}) \equiv N(\mathbf{p}, 1) + N(\mathbf{p}, 2)$$

We have that

$$\langle \psi | N'(\mathbf{p}) | \psi \rangle = 0 \quad \langle \psi | N_T(\mathbf{p}) | \psi \rangle = \langle \psi_T | N_T(\mathbf{p}) | \psi_T \rangle$$

We can derive

$$H = \int \widetilde{dp} \omega [N'(\mathbf{p}) + N_T(\mathbf{p})] + 2\mathcal{E}_0 V$$



$$\vec{P} = \int \widetilde{dp} \vec{p} [N'(\mathbf{p}) + N_T(\mathbf{p})]$$

So, the arbitrariness of  $C_i (i = 1, 2, \dots)$  does not affect the physical observables. Only the physical transverse polarizations contribute to the result. Two states that differ only in their timelike and longitudinal photon content,  $|\phi_n\rangle$  with  $n \geq 1$  are said to be physically equivalent. We can think of the gauge symmetry of the classical theory as descending to the Hilbert space of the quantum theory.

It is important to note that although for the average values of the physical observables only the transverse polarizations contribute, the scalar and longitudinal polarizations are necessary for the consistency of the theory. In particular they show up when we consider complete sums over the intermediate states.

### Propagator

$$G_F(x-y)_{\mu\nu} \equiv \langle 0 | T A_\mu(x) A_\nu(y) | 0 \rangle = \int \frac{d^4 p}{(2\pi)^4} \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon} e^{ip(x-y)}$$

It is easy to verify that  $G_F(x-y)_{\mu\nu}$  is the Green's function of the equation of motion, that for  $\xi = 1$  is the wave equation, that is

$$\partial^2 G_F(x-y)_{\mu\nu} = i\eta_{\mu\nu} \delta(x-y)$$

For the general case,  $\xi \neq 0$ , the equal times commutation relations are more complicated. And the propagator will be

$$G_F(x-y)_{\mu\nu} = \int \frac{d^4 p}{(2\pi)^4} \left[ \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon} + i(1-\xi) \frac{p_\mu p_\nu}{(p^2 - i\epsilon)^2} \right] e^{ip(x-y)}$$

## 14.4 Perturbation theory for canonical quantization

### 14.4.1 Lagrangian of QED

The Lagrangian of QED is

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\cancel{D} - m_0)\Psi + e_0 j^\mu A_\mu,$$

where  $j^\mu \equiv \bar{\Psi}\gamma^\mu\Psi$ . Usually, we also define a covariant derivative,

$$D_\mu \Psi \equiv \partial_\mu \Psi - ie_0 A_\mu \Psi$$

So, the Lagrangian can also be written as

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\cancel{D} - m_0)\Psi$$

The Lagrangian is invariant under the gauge transformation

$$A_\mu(x) \rightarrow A_\mu(x) + \frac{1}{e_0} \partial_\mu \alpha(x) \quad \Psi(x) \rightarrow e^{i\alpha(x)} \Psi(x)$$



### 14.4.2 Coulomb gauge

The constraint equations are

$$\nabla \cdot \mathbf{A} = 0 \quad \nabla^2 A_0 = e_0 j^0$$

The solution for  $A_0$  is

$$A_0(\mathbf{x}, t) = -e_0 \int d^3 x' \frac{j^0(\mathbf{x}', t)}{4\pi |\mathbf{x} - \mathbf{x}'|}$$

Finally, we can derive that

$$H = H_D + H_M + H_{\text{int}}$$

where,

$$H_D = \int d^3 x \left[ \frac{1}{2} (\vec{\mathcal{E}} \cdot \vec{\mathcal{E}} + i\beta m) \Psi \right] \quad H_M = \int d^3 x \frac{1}{2} (\boldsymbol{\pi}^2 + \mathbf{B}^2)$$

$$H_{\text{int}} = \int d^3 x \left[ -e_0 \mathbf{j} \cdot \mathbf{A} + \frac{e_0^2}{2} \int d^3 x' \frac{j^0(\mathbf{x}) j^0(\mathbf{x}')}{4\pi |\mathbf{x} - \mathbf{x}'|} \right]$$

The perturbation expansion of correlation functions is

$$\langle \Omega | T \{ \Psi(x) \bar{\Psi}(y) A(z) \} | \Omega \rangle = \lim_{T \rightarrow \infty (1-i\epsilon)} \frac{\langle 0 | T \left\{ \Psi_I(x) \bar{\Psi}_I(y) A_I(z) \exp \left[ -i \int_{-T}^T dt H_I \right] \right\} | 0 \rangle}{\langle 0 | T \left\{ \exp \left[ -i \int_{-T}^T dt H_I \right] \right\} | 0 \rangle}$$

Here,  $\int_{-T}^T dt H_I$  can be written as

$$\left[ - \int d^4 x e_0 \bar{\Psi}_I \boldsymbol{\gamma} \Psi_I \cdot \mathbf{A}_I \right] + \left[ \int d^4 x \int d^4 x' \frac{e_0^2 \delta(t-t')}{4\pi |\mathbf{x} - \mathbf{x}'|} \frac{1}{2} \bar{\Psi}_I(\mathbf{x}, t) \gamma^0 \Psi_I(\mathbf{x}, t) \bar{\Psi}_I(\mathbf{x}', t') \gamma^0 \Psi_I(\mathbf{x}', t') \right]$$

Wick's theorem for photons takes is similar to that in  $\phi^4$  theory:

$$T \{ A_I(x_1) A_I(x_2) A_I(x_3) \cdots \} = N \{ A_I(x_1) A_I(x_2) A_I(x_3) \cdots + \text{all possible contractions} \}$$

**Example:**

$$\langle 0 | T \{ A_{Ii}(x_1) A_{Ij}(x_2) A_{Ik}(x_3) A_{Il}(x_4) \} | 0 \rangle$$

$$= G_F(x_1 - x_2)_{ij} G_F(x_3 - x_4)_{kl} + G_F(x_1 - x_3)_{ik} G_F(x_2 - x_4)_{jl} + G_F(x_1 - x_4)_{il} G_F(x_2 - x_3)_{jk}$$

Now we can derive the Feynman rule for QED theory. Firstly, we evaluate this term,

$$\langle 0 | T \left\{ \Psi_{Ia}(x) \bar{\Psi}_{Ib}(y) A_{Ii}(z) (ie_0) \int d^4 w \bar{\Psi}_I(w) \boldsymbol{\gamma} \Psi_I(w) \cdot \mathbf{A}_I(w) \right\} | 0 \rangle$$

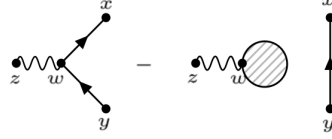
After contraction, it can be written as

$$- (ie_0) S_F(x - y)_{ab} \int d^4 w G_F(z - w)_{ik} \text{Tr}[\gamma^k S_F(w - w)]$$

$$+ (ie_0) \int d^4 w G_F(w - z)_{ik} [S_F(x - w) \gamma^k S_F(w - y)]_{ab}$$

It can be represented by the following Feynman diagram.





**Figure 14.1:** Feynman diagram representation of perturbation expansion

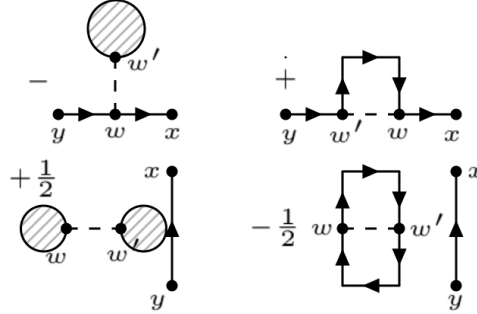
Secondly, we evaluate this term,

$$\langle 0|T \left\{ \Psi_{Ia}(x) \bar{\Psi}_{Ib}(y) \int d^4w \int d^4w' \frac{-ie_0^2 \delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} \frac{1}{2} \bar{\Psi}_I(w) \gamma^0 \Psi_I(w) \bar{\Psi}_I(w') \gamma^0 \Psi_I(w') \right\} |0\rangle$$

After contraction, it can be written as

$$\begin{aligned} & - (ie_0)^2 \int d^4w d^4w' \frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} [S_F(x - w) \gamma^0 S_F(w - y)]_{ab} \text{Tr}[\gamma^0 S_F(w' - w)] \\ & + (ie_0)^2 \int d^4w d^4w' \frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} [S_F(x - w) \gamma^0 S_F(w - w') \gamma^0 S_F(w' - y)]_{ab} \\ & + \frac{1}{2} (ie_0)^2 S_F(x - y)_{ab} \int d^4w d^4w' \frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} \text{Tr}[\gamma^0 S_F(w - w)] \text{Tr}[\gamma^0 S_F(w' - w')] \\ & - \frac{1}{2} (ie_0)^2 S_F(x - y)_{ab} \int d^4w d^4w' \frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} \text{Tr}[\gamma^0 S_F(w - w') \gamma^0 S_F(w' - w)] \end{aligned}$$

It can be represented by the following Feynman diagram.



**Figure 14.2:** Feynman diagram representation of perturbation expansion

Before we write down Feymann rules, we notice that the offending non-local interaction comes from the  $A_0$  component of the gauge field, we could try to redefine the propagator to include a  $G_F(x - y)_{00}$  piece which will capture this term. We can verify that

$$\frac{i\delta(w^0 - w'^0)}{4\pi |\mathbf{w} - \mathbf{w}'|} = \int \frac{d^4p}{(2\pi)^4} \frac{ie^{ip(w-w')}}{|\mathbf{p}|^2}$$

So we can combine the non-local interaction with the transverse photon propagator by defining a new photon propagator

$$G_F(p)_{\mu\nu} \equiv \begin{cases} \frac{i}{|\mathbf{p}|^2} & \mu, \nu = 0 \\ \frac{-i}{p^2 - i\epsilon} \left( \delta_{ij} - \frac{p_i p_j}{|\mathbf{p}|^2} \right) & \mu = i \neq 0, \nu = j \neq 0 \\ 0 & \text{otherwise} \end{cases}$$



With this propagator, the wavy photon line now carries a  $\mu\nu = 0, 1, 2, 3$  index, with the extra  $\mu = 0$  component taking care of the instantaneous interaction.

The Feynman rules for QED are:

1. For each Fermion propagator from  $y$  to  $x$ ,  $P = S_F(x - y)$
2. For each vector propagator,  $P = G_F(x - y)$
3. For each vertex,  $V = (ie_0\gamma^\mu) \int d^4w$
4. For each external point,  $E = 1$
5. Divided by the symmetry factor

### 14.4.3 Lorentz Gauge

In Lorentz gauge,

$$\mathcal{H}_{int} = -e_0 \bar{\Psi} \gamma^\mu \Psi A_\mu$$

The Feynman rules for QED in Lorentz gauge will be the same as that in Coulomb gauge expect for that the vector propagator will be

$$G_F(p)_{\mu\nu} = \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon} + i(1 - \xi) \frac{p_\mu p_\nu}{(p^2 - i\epsilon)^2}$$

Especially, for Feynman gauge  $\xi = 1$ , we have

$$G_F(p)_{\mu\nu} = \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon}$$

## 14.5 Path integral quantization

### 14.5.1 Path integral formulation for free EM field

The correlation function is given by

$$\langle \Omega | T A_H(x_1) A_H(x_2) | \Omega \rangle = \lim_{T \rightarrow \infty(1-i\epsilon)} \frac{\int \mathcal{D}A \exp \left[ i \int_{-T}^T d^4x \left( -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right) \right] A(x_1) A(x_2)}{\int \mathcal{D}A \exp \left[ i \int_{-T}^T d^4x \left( -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right) \right]}$$

The generating function is

$$Z[J] = \int \mathcal{D}A \exp \left[ i \int d^4x \left( -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right) + J^\mu A_\mu \right]$$

We can verify that

$$S = \int d^4x \left( -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right) = \frac{1}{2} \int d^4x A_\mu(x) (\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu) A_\nu(x)$$



Notice that  $(\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu)$  is singular, since for any  $\alpha(x)$ ,

$$(\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu) \partial_\mu \alpha(x) = 0$$

This difficulty is due to gauge invariance:  $\alpha(x)$  is gauge equivalent to 0. The functional is badly defined because we are redundantly integrating over a continuous infinity of physically equivalent field configurations. To fix the problem, we would like to isolate the interesting part of the functional integral, which counts each physical configuration only once.

Let  $G(A)$  be some function that we wish to set equal zero as a gauge-fixing condition. We could constrain the functional integral to cover only the configurations with  $G(A) = 0$  by inserting a functional delta function,  $\delta(G(A))$ . To do so, we insert 1 in the path integral:

$$1 = \int \mathcal{D}\alpha(x) \delta(G(A(\alpha))) \det \left( \frac{\delta G}{\delta \alpha} \right)$$

where,

$$A_\mu(\alpha(x)) = A_\mu(x) + \frac{1}{e_0} \partial_\mu \alpha(x)$$

We set the gauge fixing function as  $G(A) = \partial^\mu A_\mu - \omega(x)$ , so  $G(A(\alpha)) = \partial^\mu A_\mu + \frac{1}{e_0} \partial^2 \alpha - \omega(x)$ . It is obvious that  $\det \left( \frac{\delta G}{\delta \alpha} \right)$  is equivalent to  $\det(\partial^2)/e_0$ , which is independent of  $A$ . So,

$$Z_0[A] = \det \left( \frac{\delta G}{\delta \alpha} \right) \int \mathcal{D}\alpha \int \mathcal{D}A e^{iS[A]} \delta(G(A(\alpha)))$$

Now change variables from  $A$  to  $A(\alpha)$ . This is a simple shift, so  $\mathcal{D}A = \mathcal{D}A(\alpha)$ . Also, by gauge invariance,  $S[A] = S[A(\alpha)]$ . Since  $A(\alpha)$  is now just a dummy integration variable, we can rename it back to  $A$ , so

$$Z_0[A] = \det \left( \frac{\delta G}{\delta \alpha} \right) \int \mathcal{D}\alpha \int \mathcal{D}A e^{iS[A]} \delta(\partial^\mu A_\mu - \omega(x))$$

Since the above equation holds for any  $\omega(x)$ , so we have

$$\begin{aligned} Z_0[A] &= N(\xi) \int \mathcal{D}\omega \exp \left[ -i \int d^4x \frac{\omega^2}{2\xi} \right] \det(\partial^2) \int \mathcal{D}\alpha \int \mathcal{D}A e^{iS[A]} \delta(\partial^\mu A_\mu - \omega(x)) \\ &= N(\xi) \frac{\det(\partial^2)}{e_0} \int \mathcal{D}\alpha \int \mathcal{D}A e^{iS[A]} \exp \left[ -i \int d^4x \frac{1}{2\xi} (\partial^\mu A_\mu)^2 \right] \\ &= W(\xi) \int \mathcal{D}A \exp \left[ \frac{i}{2} \int d^4x A_\mu (\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu + \frac{1}{\xi} \partial^\mu \partial^\nu) A_\nu \right] \end{aligned}$$

And we rewrite the generating function as

$$Z[J] = W(\xi) \int \mathcal{D}A \exp \left[ \frac{i}{2} \int d^4x A_\mu (\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu + \frac{1}{\xi} \partial^\mu \partial^\nu) A_\nu + J^\mu A_\mu \right]$$

Define

$$A'(x) = A(x) - i \int d^4y G_F(x-y) J(y)$$

Recall that

$$(\partial^2 \eta^{\mu\nu} - \partial^\mu \partial^\nu + \frac{1}{\xi} \partial^\mu \partial^\nu) G_F(x-y)_{\nu\rho} = i \delta_\rho^\mu \delta(x-y)$$





We can derive that

$$Z[J] = Z_0[A] \exp \left[ -\frac{1}{2} \int d^4x d^4y J^\mu(x) G_F(x-y)_{\mu\nu} J^\nu(y) \right]$$

The two point correlation functions are

$$\langle 0 | T A_H(x_1) A_H(x_2) | 0 \rangle = Z_0^{-1} \left( -i \frac{\delta}{\delta J(x_1)} \right) \left( -i \frac{\delta}{\delta J(x_2)} \right) Z[J] \Big|_{J=0} = G_F(x_1 - x_2)$$

### 14.5.2 Perturbation theory for path integral quantization

We use QED theory as an example.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\not{\partial} - m_0)\Psi + e_0 \bar{\Psi} \gamma^\mu \Psi A_\mu$$

As we stated in section 4.1, the Lagrangian of QED is also invariant under a general gauge transformation. And we also notice that the measure  $\mathcal{D}\Psi \mathcal{D}\bar{\Psi}$  is invariant under gauge transformation. By the similar method, we can show that

$$Z_0 \equiv \int \mathcal{D}A \mathcal{D}\Psi \mathcal{D}\bar{\Psi} e^{iS[A, \Psi, \bar{\Psi}]} = W(\xi) \int \mathcal{D}A \mathcal{D}\Psi \mathcal{D}\bar{\Psi} e^{iS[A, \Psi, \bar{\Psi}]} \exp \left[ -i \int d^4x \frac{1}{2\xi} (\partial^\mu A_\mu)^2 \right]$$

So, define

$$\mathcal{L}_0 \equiv -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2\xi} (\partial^\mu A_\mu)^2 + \bar{\Psi}(i\not{\partial} - m_0)\Psi \quad \mathcal{L}_1 \equiv e_0 \bar{\Psi} \gamma^\mu \Psi A_\mu$$

$$\begin{aligned} Z[J] &= W(\xi) \int \mathcal{D}A \mathcal{D}\bar{\Psi} \mathcal{D}\Psi e^{i \int d^4x [\mathcal{L}_0 + \mathcal{L}_1 + JA + \bar{\eta}\Psi + \bar{\Psi}\eta]} \\ &= W(\xi) e^{i \int d^4x \mathcal{L}_1(\frac{1}{i} \frac{\delta}{\delta J(x)}, \frac{1}{i} \frac{\delta}{\delta \bar{\eta}(x)}, -\frac{1}{i} \frac{\delta}{\delta \eta(x)})} \int \mathcal{D}\phi \mathcal{D}\bar{\Psi} \mathcal{D}A e^{i \int d^4y [\mathcal{L}_0 + JA + \bar{\eta}\Psi + \bar{\Psi}\eta]} \\ &\propto e^{i \int d^4x \mathcal{L}_1(\frac{1}{i} \frac{\delta}{\delta J(x)}, \frac{1}{i} \frac{\delta}{\delta \bar{\eta}(x)}, -\frac{1}{i} \frac{\delta}{\delta \eta(x)})} \exp \left[ - \int d^4y d^4z \frac{1}{2} J(y) G_F(y-z) J(z) + \bar{\eta}(y) S_F(y-z) \eta(z) \right] \\ &= \sum_{V=0}^{\infty} \frac{1}{V!} [i e_0 \int d^4x (\frac{1}{i} \frac{\delta}{\delta J^\mu(x)} \cdot -\frac{1}{i} \frac{\delta}{\delta \eta(x)} \cdot \gamma^\mu \cdot \frac{1}{i} \frac{\delta}{\delta \bar{\eta}(x)})]^V \\ &\times \sum_{P_1=0}^{\infty} \frac{1}{P_1!} \left[ -\frac{1}{2} \int d^4y_1 d^4z_1 J(y_1) G_F(y_1 - z_1) J(z_1) \right]^{P_1} \\ &\times \sum_{P_2=0}^{\infty} \frac{1}{P_2!} \left[ - \int d^4y_2 d^4z_2 \bar{\eta}(y_2) S_F(y_2 - z_2) \eta(z_2) \right]^{P_2} \end{aligned}$$

If we focus on a term with particular values of  $V$ ,  $P_1$  and  $P_2$ , then the number of surviving scalar sources is  $E_1 = 2P_1 - V$ , the number of surviving fermion sources is  $E_2 = 2P_2 - 2V$ . We can introduce Feynman diagrams as in the  $\phi^4$  theory. In these diagrams, a wavy line segment stands for a vector propagator  $G_F(x-y)$ , a line with an arrow pointing from  $y$  to  $x$  for a fermion propagator  $S_F(x-y)$ , a filled circle at one end of a wavy line segment for a vector source  $i \int d^4x J(x)$ , a filled circle at the start of a line with an arrow for a fermion source  $i \int d^4x \eta(x)$ , a filled circle at the end of a line with an arrow for an anti-fermion source  $i \int d^4x \bar{\eta}(x)$ , a vertex joining three line segments for  $i e_0 \gamma^\mu \int d^4x$ .



### 14.5.3 Ward-Takahashi identity (1)

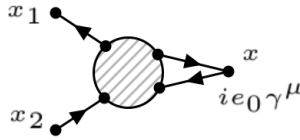
The Noether current of the symmetry  $\Psi \rightarrow e^{i\alpha}\Psi$  is  $j^\mu = \bar{\Psi}\gamma^\mu\Psi$ . Recall the conservation law in functional formalism

$$\langle \partial_\mu j^\mu(x) \phi(x_1) \cdots \phi(x_n) \rangle = \sum_{i=1}^n \langle \phi(x_1) \cdots (i\Delta\phi(x_i)\delta(x-x_i)) \cdots \phi(x_n) \rangle$$

So, we can write the charge conservation law as

$$ie_0\partial_\mu \langle \Omega | T j^\mu \Psi(x_1) \bar{\Psi}(x_2) | \Omega \rangle = -ie_0\delta(x-x_1) \langle \Omega | T \Psi(x_1) \bar{\Psi}(x_2) | \Omega \rangle + ie_0\delta(x-x_2) \langle \Omega | T \Psi(x_1) \bar{\Psi}(x_2) | \Omega \rangle$$

Notice that  $i\langle \Omega | T j^\mu \psi(x_1) \bar{\Psi}(x_2) | \Omega \rangle$  can be represented by



**Figure 14.3:** Feynman diagram representation of correlation function

From the diagram, we have

$$\langle A_\nu(y) \rangle = \int d^4x G_F(x-y)_{\mu\nu} ie \langle j^\mu(x) \rangle = \int \frac{d^4p}{(2\pi)^4} e^{-ipy} G_F(p)_{\mu\nu} \int d^4x e^{ipx} ie \langle j^\mu(x) \rangle$$

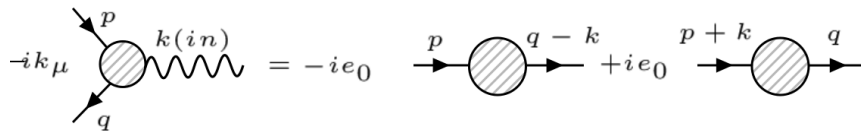
So,

$$\int d^4x \langle A_\nu(x) \rangle e^{ikx} = G_F(p)_{\mu\nu} \int d^4x e^{ikx} ie \langle j^\mu(x) \rangle$$

Compute the Fourier transformation of the equation of charge conservation by integrating

$$\int d^4x e^{ikx} \int d^4x_1 e^{-iqx_1} \int d^4x_2 e^{ipx_2}$$

We can get



**Figure 14.4:** Feynman diagram representation of Ward identity

Note that in the diagram above, the external leg of photon will be cut-off, but external leg of fermion will remain. The above equation can be generated to the diagram with  $n$  external fermions. Another proof of Ward-Takahashi identity by calculating the Feynman diagram directly can be found in chapter 7.4 of *An introduction to quantum field theory* (M.E.Peskin & D.V.Schroeder)



## 14.6 Exact propagator of photon

### 14.6.1 Photon self-energy

The exact propagator of photon is

$$\mathcal{G}(x)_{\mu\nu} = \langle \Omega | T \{ A_\mu(x) A_\nu(0) | \Omega \rangle_C$$

Its Fourier transformation can be represented by the following diagram.



**Figure 14.5:** Feynman diagram representation of exact propagator of photon

Let us define  $i\Pi^{\mu\nu}$  to be the sum of all 1-particle-irreducible insertions into the photon propagator. So, we have

$$\mathcal{G}(k) = G_F(k) + G_F(k)(i\Pi(k))G_F(k) + \cdots = G_F(k) \frac{1}{1 - i\Pi(k)G_F(k)}$$

Hence,

$$(i\mathcal{G})^{-1} = (iG_F)^{-1} - \Pi$$

Recall that

$$iG_F(p)_{\mu\nu} = \frac{\eta_{\mu\nu}}{k^2 - i\epsilon} - (1 - \xi) \frac{k_\mu k_\nu}{(k^2 - i\epsilon)^2} = \frac{1}{k^2 - i\epsilon} (P_{\mu\nu}^T + \xi P_{\mu\nu}^L)$$

Here,

$$P_{\mu\nu}^T \equiv \eta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} \quad P_{\mu\nu}^L \equiv \frac{k_\mu k_\nu}{k^2}$$

We can derive that

$$(iG_F)^{-1}(k)_{\mu\nu} = k^2 (P_{\mu\nu}^T + \frac{1}{\xi} P_{\mu\nu}^L)$$

We may also expand  $i\Pi^{\mu\nu}$  as

$$\Pi^{\mu\nu} = P_T^{\mu\nu} f_T(k^2) + P_L^{\mu\nu} f_L(k^2) = \eta^{\mu\nu} f_T + \frac{k^\mu k^\nu}{k^2} (f_L - f_T)$$

Therefore,

$$(i\mathcal{G})^{-1}(k)_{\mu\nu} = (k^2 - f_T(k^2)) P_{\mu\nu}^T + (\frac{k^2}{\xi} - f_L(k^2)) P_{\mu\nu}^L$$

$$\mathcal{G}(k)_{\mu\nu} = \frac{-i}{k^2 - f_T(k^2)} P_{\mu\nu}^T + \frac{-i}{\frac{k^2}{\xi} - f_L(k^2)} P_{\mu\nu}^L$$

We observe that if  $f_{T,L}(k^2 = 0) \neq 0$ , a mass will be generated for the photon. Because  $\Pi(k)$  comes from 1PI diagrams, it should not be singular at  $k^2 = 0$ , and so  $f_L - f_T = O(k^2)$ , as  $k \rightarrow 0$ . We will show that gauge invariance ensures that no mass is generated from the loop corrections



### 14.6.2 Ward identities(2)

We define the generating functional for connected diagrams

$$Z[J, \eta, \bar{\eta}] = e^{-iE[J, \eta, \bar{\eta}]}$$

For example,

$$\mathcal{G}(x - y)_{\mu\nu} = -i \frac{\delta^2 E[J, \eta, \bar{\eta}]}{\delta J^\mu(x) \delta J^\nu(y)} \Big|_{J, \eta, \bar{\eta} = 0}$$

Recall, for infinitesimal gauge transformations,  $\delta A_\mu = \partial_\mu \lambda$ ,  $\delta \Psi = ie_0 \lambda \Psi$  and  $\delta \bar{\Psi} = -ie_0 \lambda \bar{\Psi}$ . For a change of variables in the path integral,  $Z[J, \eta, \bar{\eta}]$  will remain the same. Recall that

$$Z[J, \eta, \bar{\eta}] = W(\xi) \int \mathcal{D}A \mathcal{D}\bar{\Psi} \mathcal{D}\Psi e^{i \int d^4x [\mathcal{L}_0 + \mathcal{L}_1 + JA + \bar{\eta}\Psi + \bar{\Psi}\eta]}$$

The change of action is

$$\delta S = -\frac{1}{\xi} \int d^4x \partial_\mu A^\mu \partial^2 \lambda + \int d^4x J^\mu \partial_\mu \lambda + ie_0 \bar{\eta} \Psi \lambda - ie_0 \bar{\Psi} \eta \lambda$$

Hence, we must have

$$\int d^4x \lambda(x) W(\xi) \int \mathcal{D}A \mathcal{D}\bar{\Psi} \mathcal{D}\Psi e^{iS} \left[ -\frac{1}{\xi} \partial^2 \partial_\mu A^\mu - \partial_\mu J^\mu + ie_0 (\bar{\eta} \Psi - \bar{\Psi} \eta) \right]$$

Since

$$\langle A_\mu(x) \rangle_{J, \eta, \bar{\eta}} = -\frac{\delta E}{\delta J^\mu} \quad \langle \Psi(x) \rangle_{J, \eta, \bar{\eta}} = -\frac{\delta E}{\delta \bar{\eta}} \quad \langle \bar{\Psi}(x) \rangle_{J, \eta, \bar{\eta}} = \frac{\delta E}{\delta \eta}$$

The above equation can be written as

$$\frac{1}{\xi} \partial^2 \partial^\mu \frac{\delta E}{\delta J^\mu} - \partial_\mu J^\mu - ie_0 \left[ \bar{\eta} \frac{\delta E}{\delta \bar{\eta}} + \frac{\delta E}{\delta \eta} \eta \right] = 0$$

We can derive that

$$\frac{1}{\xi} \partial^2 \partial^\mu \frac{\delta^2 E[J, \eta, \bar{\eta}]}{\delta J^\mu(x) \delta J^\nu(y)} \Big|_{J, \eta, \bar{\eta} = 0} - \partial_\nu \delta(x - y) = 0$$

that is,

$$\frac{i}{\xi} \partial^2 \partial^\mu \mathcal{G}(x - y)_{\mu\nu} + \partial_\nu \delta(x - y) = 0$$

or, written in momentum-space,

$$-\frac{i}{\xi} k^2 k^\mu \mathcal{G}(k)_{\mu\nu} + k_\nu = 0$$

So

$$-\frac{k^2}{k^2 - \xi f_L(k^2)} k_\nu + k_\nu = 0$$

Which means  $f_L(k^2) = 0$  and so, we have  $f_T(k^2) \rightarrow O(k^2)$  as  $k^2 \rightarrow 0$ . The exact propagator of photon is

$$\mathcal{G}(k)_{\mu\nu} = \frac{-i}{k^2(1 - \pi(k^2))} P_{\mu\nu}^T + \frac{-i\xi}{k^2} P_{\mu\nu}^L$$

where  $\pi(k^2) \equiv \frac{f_T(k^2)}{k^2}$



## 14.7 LSZ reduction formula

### 14.7.1 LSZ reduction formula and Feynman rules

Suppose that the probability for the quantum field to create or annihilate an exact one-particle eigenstate of  $H$  is  $Z_3$ , i.e.

$$\langle \Omega | A(0) | p, \lambda \rangle = \sqrt{Z_3} \epsilon_\lambda(p)$$

In Feynman gauge, because the norm of  $|p, 0\rangle$  is negative, the expansion of orthogonal complete set will be written as

$$\frac{d^3 q}{(2\pi)^3} \frac{1}{2E_q} \eta^{\lambda\lambda'} |p, \lambda\rangle \langle p, \lambda'|$$

We have demonstrated that photon will remain massless when interacting with charged fermions. And recall that  $\sum_\lambda \xi_\lambda(p) \xi_\lambda^*(p) = \eta_{\mu\nu}$ . So, we can derive by the similar method in  $\phi^4$  theory that

$$\int d^4 x e^{-ipx} \langle \Omega | T A_\mu(x) A_\nu(0) | \Omega \rangle_C = \frac{-i Z_3 \eta_{\mu\nu}}{p^2 - i\epsilon} + \dots$$

The LSZ reduction formula for fermions would take the form as

#### Theorem 14.1 LSZ reduction formula

$$\begin{aligned} & \langle p_1 \cdots p_n | S | k_1 \cdots k_m \rangle \\ &= \prod_1^n \int d^4 x_i e^{-ip_i x_i} \prod_1^m \int d^4 y_j e^{ik_j y_j} \\ &\times \left( \frac{i}{\sqrt{Z_3}} \right)^{m+n} [p_1^2 \epsilon_{\lambda_1}^{*\mu_1}(p_1)] \cdots [p_n^2 \epsilon_{\lambda_n}^{*\mu_n}(p_n)] [k_1^2 \epsilon_{\lambda'_1}^{\nu_1}(k_1)] \cdots [k_m^2 \epsilon_{\lambda'_m}^{\nu_m}(k_m)] \\ &\times \langle \Omega | T \{ A_{\mu_1}(x_1) \cdots A_{\mu_n}(x_n) A_{\nu_1}(y_1) \cdots A_{\nu_m}(y_m) \} | \Omega \rangle \end{aligned}$$

The LSZ reduction formula in other gauge would give similar procedure for calculating scattering amplitude: Fourier transform the Green function in position space to momentum space, cut-off the external legs and multiply the polarization vector of asymptotic states. (Note there is still an extra factor  $\sqrt{Z_3}^{m+n}$  to multiply, similar to the  $\phi^4$  theory).

Finally, we list the Feynmann rules of QED in momentum space as follows:

1. For each incoming electron, draw a solid line with an arrow pointed towards the vertex, and label it with the electron's four-momentum,  $p_i$ .
2. For each outgoing electron, draw a solid line with an arrow pointed away from the vertex, and label it with the electron's four-momentum,  $p'_i$ .
3. For each incoming positron, draw a solid line with an arrow pointed away from the vertex, and label it with minus the positron's four-momentum,  $-p_i$ .
4. For each outgoing positron, draw a solid line with an arrow pointed towards the vertex, and label it with minus the positron's four-momentum,  $-p'_i$ .



5. For each incoming photon, draw a wavy line with an arrow pointed towards the vertex, and label it with the photon's four-momentum,  $k_i$ .
6. For each outgoing photon, draw a wavy line with an arrow pointed away from the vertex, and label it with the photon's four-momentum,  $k'_i$ .
7. The only allowed vertex joins two solid lines, one with an arrow pointing towards it and one with an arrow pointing away from it, and one wavy line. Using this vertex, join up all the external lines, including extra internal lines as needed. In this way, draw all possible diagrams that are topologically inequivalent.
8. Assign each internal line its own four-momentum. Think of the four-momenta as flowing along the arrows, and conserve four-momentum at each vertex.
9. The value of a diagram consists of the following factors:
  - for each incoming photon,  $\epsilon^\mu_\lambda(k)$ ; for each outgoing photon,  $\epsilon^{*\mu}_\lambda(k)$ ;
  - for each incoming electron,  $u_r(\mathbf{k})$ ; for each outgoing electron,  $\bar{u}_s(\mathbf{p})$ ;
  - for each incoming positron,  $\bar{v}_r(\mathbf{k})$ ; for each outgoing positron,  $v_s(\mathbf{p})$ ;
  - for each vertex,  $ie_0\gamma^\mu$ ; for each internal photon,  $G_F(p)$ ; for each internal fermion,  $S_F(p)$ .
10. Spinor indices are contracted by starting at one end of a fermion line: specifically, the end that has the arrow pointing away from the vertex. The factor associated with the external line is either  $\bar{u}$  or  $\bar{v}$ . Go along the complete fermion line, following the arrows backwards, and write down (in order from left to right) the factors associated with the vertices and propagators that you encounter. The last factor is either a  $u$  or  $v$ . Repeat this procedure for the other fermion lines, if any. The vector index on each vertex is contracted with the vector index on either the photon propagator (if the attached photon line is internal) or the photon polarization vector (if the attached photon line is external).
11. The overall sign of a tree diagram is determined by drawing all contributing diagrams in a standard form: all fermion lines horizontal, with their arrows pointing from left to right, and with the left endpoints labeled in the same fixed order (from top to bottom); if the ordering of the labels on the right endpoints of the fermion lines in a given diagram is an even (odd) permutation of an arbitrarily chosen fixed ordering, then the sign of that diagram is positive (negative)
12. Each closed fermion loop contributes an extra minus sign.
13. Value of  $i\mathcal{M}$  is given by a sum over the values of the contributing diagrams.
14.  $\langle f|S|i\rangle = (Z_2)^{\frac{n_f}{2}}(Z_3)^{\frac{n_p}{2}}i\mathcal{M}\delta(\sum p_f - \sum p_i)$



### 14.7.2 Ward Takahashi identity (3)

Suppose the invariant matrix element for a process is  $\mathcal{M}$ , if we replace the polarization state vector  $\epsilon_\lambda^\mu$  (or  $\epsilon_\lambda^{*\mu}$ ) of one incoming (or outgoing) photon with its momentum vector  $k^\mu$ , we have

$$k^\mu \mathcal{M}_\mu = 0$$

**Proof:** Without losing generality, we can consider a physical process with a single incoming and outgoing fermion lines respectively. So, the ward identities states that

$$-ik_\mu F^\mu(k; p, q) = ie_0 [F_0(p + k, q) - F_0(p, q - k)]$$

Here,  $F$  keeps the external fermion legs but cuts external photon lines. According to the LSZ reduction formula, from each diagram a contribution to an S matrix element by taking the coefficient of the product of poles

$$\left( \frac{-i}{\not{p} + m} \right) \left( \frac{-i}{\not{q} + m} \right)$$

But the terms on the right hand side contain one of these poles, but neither contains both poles. So they contribute nothing to S-matrix. So, we can have

$$k^\mu \mathcal{M}_\mu = 0$$

□

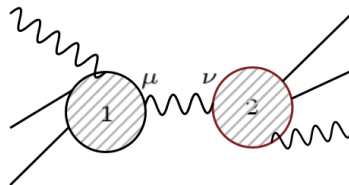
We also note that when calculating invariant matrix element, the main difference between different gauge are photon propagator. In Coulomb gauge, we have

$$G_F(p)_{\mu\nu} \equiv \begin{cases} \frac{i}{|\mathbf{p}|^2} & \mu, \nu = 0 \\ \frac{-i}{p^2 - i\epsilon} \left( \delta_{ij} - \frac{p_i p_j}{|\mathbf{p}|^2} \right) & \mu = i \neq 0, \nu = j \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

In Lorentz gauge, we have

$$G_F(p)_{\mu\nu} = \frac{-i\eta_{\mu\nu}}{p^2 - i\epsilon} + i(1 - \xi) \frac{p_\mu p_\nu}{(p^2 - i\epsilon)^2}$$

We now argue that the lead to the same  $\mathcal{M}$  element. For a general process, it can be represented as follows.



**Figure 14.6:** Feynman diagram representation of a QED process

The value of the diagram is

$$\mathcal{M}_1^\mu G_F(k)_{\mu\nu} \mathcal{M}_2^\nu$$



and  $k_\mu \mathcal{M}_1^\mu = 0$ ,  $k_\nu \mathcal{M}_2^\nu = 0$ . So the factor  $\xi$  in Lorentz gauge is irrelevant to the value of  $\mathcal{M}$ . As for Coulomb gauge, denote  $\mathcal{M}_1^\mu$  as  $\alpha^\mu$ ,  $\mathcal{M}_2^\mu$  as  $\beta^\mu$ , so

$$\alpha^\mu G_F(k)_{\mu\nu} \beta^\nu = i \left( -\frac{\alpha \cdot \beta}{k^2} + \frac{(\alpha \cdot \mathbf{k})(\beta \cdot \mathbf{k})}{k^2 \mathbf{k}^2} + \frac{\alpha^0 \beta^0}{\mathbf{k}^2} \right)$$

Using the fact that  $\alpha \cdot \mathbf{k} + \alpha^0 k_0 = 0$ , we can verify that

$$\alpha^\mu G_F(k)_{\mu\nu} \beta^\nu = \alpha^\mu \left( -\frac{i\eta_{\mu\nu}}{k^2} \right) \beta^\nu$$

So, the invariant matrix element is gauge invariant.

## 14.8 Renormalization

### 14.8.1 Renormalized quantum electrodynamics

The Lagrangian of QED is

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\not{\partial} - m_0)\Psi + e_0 j^\mu A_\mu,$$

Suppose the number of external photons is  $N_\gamma$ , the number of external fermions is  $N_e$ , the number of photon propagator (after amputation) is  $P_\gamma$ , the number of fermion propagator is  $P_e$ , the number of vertex is  $V$ . So we know the number of loops is

$$L = P_\gamma + P_e - V + 1$$

We also know that

$$V = 2P_\gamma + N_\gamma \quad 2V = 2P_e + N_e$$

So, the superficial divergence is

$$D = 4L - 2P_\gamma - P_e = 4 - N_\gamma - \frac{3}{2}N_e$$

Recall that  $C$  is a symmetry of QED, so  $C|\Omega\rangle = |\Omega\rangle$ . But  $j^\mu$  changes sign under charge conjugation,  $Cj^\mu(x)C^\dagger = -j^\mu(x)$ , so its vacuum expectation value must vanish:

$$\langle\Omega|Tj^\mu(x)|\Omega\rangle = \langle\Omega|TC^\dagger Cj^\mu(x)C^\dagger C|\Omega\rangle = -\langle\Omega|Tj^\mu(x)|\Omega\rangle = 0$$

So, the amplitude with  $N_\gamma = 1$ ,  $N_e = 0$  will vanish. Similarly, we can verify that the diagram with  $N_\gamma = 3$ ,  $N_e = 0$  will also vanish.

As for the amplitude with  $N_\gamma = 4$ , the superficial divergence  $D = 0$ . So the only divergence must be of the form  $\log \Lambda$ . But the ward identity implies that

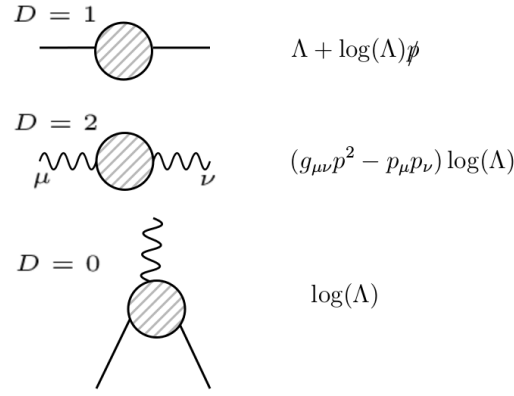
$$K^\mu \mathcal{M}_{\mu\nu\sigma\rho} = 0$$

So, the divergent terms must vanish.

If we neglect the vacuum term with  $N_\gamma = 0$ ,  $N_e = 0$ , there are only three divergent amplitude terms left.







**Figure 14.7:** Feynman diagram representation of divergent amplitude in QED

We need four counter terms to eliminate all the divergence. The Lagrangian can be written as

$$\mathcal{L} = \mathcal{L}_1 + \mathcal{L}_{ct}$$

Here,

$$\begin{aligned}\mathcal{L}_1 &= -\frac{1}{4}F_r^{\mu\nu}F_{r\mu\nu} + i\bar{\Psi}_r\gamma^\mu\partial_\mu\Psi_r - m\bar{\Psi}_r\Psi_r + e\bar{\Psi}_r\gamma^\mu\Psi_r A_{r\mu} \\ \mathcal{L}_{ct} &= -\frac{1}{4}\delta_3 F_r^{\mu\nu}F_{r\mu\nu} + i\delta_2\bar{\Psi}_r\gamma^\mu\partial_\mu\Psi_r - \delta_m\bar{\Psi}_r\Psi_r + e\delta_1\bar{\Psi}_r\gamma^\mu\Psi_r A_{r\mu} \\ A &= \sqrt{Z_3}A_r \quad \Phi = \sqrt{Z_2}\Phi_r \quad \delta_3 = Z_3 - 1 \quad \delta_2 = Z_2 - 1 \\ \delta_m &= Z_2 m_0 - m \quad \delta_1 = Z_1 - 1 = (e_0/e)Z_2 Z_3^{\frac{1}{2}} - 1\end{aligned}$$

The Feynman rules of counter terms are:

$$\begin{aligned}-\frac{1}{4}\delta_3 F_r^{\mu\nu}F_{r\mu\nu} &\quad -i(\eta^{\mu\nu}q^2 - q^\mu q^\nu)\delta_3 \\ i\bar{\Psi}_r(\delta_2\not{\partial} - \delta_m)\Psi_r &\quad -i(\delta_2\not{p} + \delta_m) \\ e\delta_1\bar{\Psi}_r\gamma^\mu\Psi_r A_{r\mu} &\quad ie\gamma^\mu\delta_1\end{aligned}$$

We also denote the renormalized 1PI component of exact propagator of photon as  $i(\eta^{\mu\nu}q^2 - q^\mu q^\nu)\Pi_r(q^2)$ , the renormalized 1PI component of exact propagator of fermion as  $-i\Sigma_r(\not{p})$ , the renormalized exact amputated photon-fermion-antifermion vertex as  $ie\Gamma_r^\mu(p, p')$ .

So, renormalized exact propagator of photon is

$$\mathcal{G}_r(q)_{\mu\nu} = \frac{-i}{q^2(1 - \Pi_r(q^2))}P_{\mu\nu}^T$$

renormalized exact propagator of fermion is

$$\mathcal{S}_r(p) = \frac{-i}{\not{p} + m + \Sigma_r(\not{p})}$$



The on-shell renormalization conditions are

$$\begin{aligned}\Sigma_r(\not{p} = -m) &= 0 \\ \frac{d}{d\not{p}}\Sigma_r(\not{p})\Big|_{\not{p}=-m} &= 0 \\ \Pi_r(q^2 = 0) &= 0 \\ ie\Gamma_r^\mu(p = p', p^2 = -m^2) &= ie\gamma^\mu\end{aligned}$$

Recall the ward identity, we have

$$ie\sqrt{Z_2}\partial_\mu\langle\Omega|Tj_r^\mu\Psi_r(x_1)\bar{\Psi}_r(x_2)|\Omega\rangle = -ie\delta(x-x_1)\langle\Omega|T\Psi_r(x_1)\bar{\Psi}_r(x_2)|\Omega\rangle + ie\delta(x-x_2)\langle\Omega|T\Psi_r(x_1)\bar{\Psi}_r(x_2)|\Omega\rangle$$

In momentum space, we have

$$-k_\mu Z_2 Z_1^{-1} \mathcal{S}_r(p+k)[ie\Gamma_r^\mu(p+k, p)]\mathcal{S}_r(p) \frac{1}{1-\Pi_r(k^2)} = e(\mathcal{S}_r(p+k) - \mathcal{S}_r(p))$$

So,

$$Z_2 Z_1^{-1} k_\mu [\Gamma_r^\mu(p+k, p)] \frac{1}{1-\Pi_r(k^2)} = \not{k} + \Sigma_r(\not{k} + \not{p}) - \Sigma_r(\not{p})$$

Since  $\Gamma_r$ ,  $\Pi_r$  and  $\Sigma_r$  are all finite by renormalization, so  $Z_1/Z_2$  must be finite. In  $\overline{MS}$  renormalization scheme, we immediately get

$$Z_1 = Z_2$$

In on-shell renormalization scheme, taking the limit of  $k \rightarrow 0$ , we can also get that

$$Z_1 = Z_2$$

So, we know

$$e = \sqrt{Z_3}e_0$$

This means that the relation between the bare and renormalized electric charge depends only on the photon field strength renormalization, not on quantities particular to the fermions, leading to a universal electric charge which has the same value for all species.

In the following subsection, we would omit the subscript  $r$  unless it is necessary to emphasis the difference of bare field and renormalized fields.

## 14.8.2 One loop structure of QED

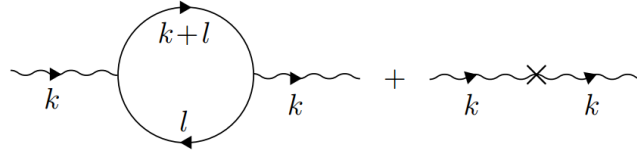
### Photon propagator

$$\Pi(k^2) = -\frac{e^2}{\pi^2} \int_0^1 dx x(1-x) \left[ \frac{1}{\epsilon} - \frac{1}{2} \ln\left(\frac{D}{\mu^2}\right) \right] - \delta_3 + O(e^4)$$

where  $D = x(1-x)k^2 + m^2 - i\epsilon$  and  $\mu^2 = 4\pi e^{-\gamma} \tilde{\mu}^2$ . Impose the OS renormalization condition  $\Pi(0) = 0$ , we have

$$\begin{aligned}\delta_3 &= -\frac{e^2}{6\pi^2} \left[ \frac{1}{\epsilon} - \ln\left(\frac{m}{\mu}\right) \right] + O(e^4) \\ \Pi(k^2) &= \frac{e^2}{2\pi^2} \int_0^1 dx x(1-x) \ln\left(\frac{D}{m^2}\right) + O(e^4)\end{aligned}$$





**Figure 14.8:** The one-loop and counterterm corrections to the photon propagator

### Fermion propagator

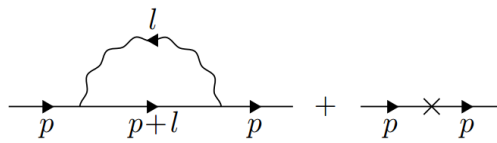
The exact renormalized fermion propagator in OS renormalization can be written in Lehmann–Kallen form as

$$iS(\not{p}) = \frac{1}{\not{p} + m - i\epsilon} + \int_{m_{th}}^{\infty} ds \frac{\rho_{\Psi}(s)}{\not{p} + \sqrt{s} - i\epsilon}$$

We see that the first term has a pole at  $\not{p} = -m$  with residue one. This residue corresponds to the field normalization that is needed for the validity of the LSZ formula.

There is a problem, however: in quantum electrodynamics, the threshold mass  $m_{th}$  is  $m$ , corresponding to the contribution of a fermion and a zero energy photon. Thus the second term has a branch point at  $\not{p} = -m$ . The pole in the first term is therefore not isolated, and its residue is ill defined.

This is a reflection of an underlying infrared divergence, associated with the massless photon. To deal with it, we must impose an infrared cutoff that moves the branch point away from the pole. The most direct method is to change the denominator of the photon propagator from  $k^2$  to  $k^2 + m_{\gamma}^2$ , where  $m_{\gamma}$  is a fictitious photon mass. Ultimately, we must deal with this issue by computing cross sections that take into account detector inefficiencies. In quantum electrodynamics, we must specify the lowest photon energy  $\omega_{min}$  that can be detected. Only after computing cross sections with extra undetectable photons, and then summing over them, is it safe to take the limit  $m_{\gamma} \rightarrow 0$ .



**Figure 14.9:** The one-loop and counterterm corrections to the fermion propagator

$$\Sigma(\not{p}) = \frac{e^2}{8\pi^2} \int_0^1 dx \left( (2 - \epsilon)(1 - x)\not{p} + (4 - \epsilon)m \right) \left[ \frac{1}{\epsilon} - \frac{1}{2} \ln\left(\frac{D}{\mu^2}\right) \right] + \delta_2 \not{p} + \delta_m + O(e^4)$$

where  $D = x(1 - x)p^2 + xm^2 + (1 - x)m_{\gamma}^2$ . The fitness of  $\Sigma(\not{p})$  requires that

$$\delta_2 = -\frac{e^2}{8\pi^2} \left( \frac{1}{\epsilon} + \text{finite} \right) + O(e^4)$$

$$\delta_m/m = -\frac{e^2}{2\pi^2} \left( \frac{1}{\epsilon} + \text{finite} \right) + O(e^4)$$

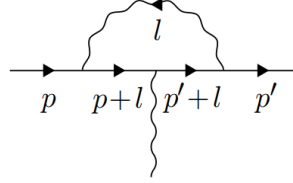


Impose the OS renormalization condition  $\Sigma(-m) = 0$  and  $\Sigma'(-m) = 0$ , we have

$$\Sigma(\not{p}) = -\frac{e^2}{8\pi^2} \int_0^1 dx ((1-x)\not{p} + 2m) \ln\left(\frac{D}{D_0}\right) + \kappa_2(\not{p} + m) + O(e^4)$$

where  $D_0 = x^2 m^2 + (1-x)m_\gamma^2$  and  $\kappa_2 = -2 \ln(m/m_\gamma) + 1$ .

### Vertex



**Figure 14.10:** The one-loop correction to the photon-fermion-fermion vertex

$$\Gamma^\mu(p, p') = (1 + \delta_1)\gamma^\mu + \frac{e^2}{8\pi^2} \left[ \left( \frac{1}{\epsilon} - 1 - \frac{1}{2} \int dF_3 \ln(D/\mu^2) \right) \gamma^\mu + \frac{1}{4} \int dF_3 \frac{\tilde{N}^\mu}{D} \right] + O(e^4)$$

where

$$\int dF_3 = 2 \int_0^1 dx_1 dx_2 dx_3 \delta(x_1 + x_2 + x_3 - 1)$$

$$D = x_1(1-x_1)p^2 + x_2(1-x_2)p'^2 - 2x_1x_2p \cdot p' + (x_1+x_2)m^2 + x_3m_\gamma^2$$

$$\tilde{N}^\mu = \gamma_\nu [x_1\not{p} - (1-x_2)\not{p}' + m] \gamma^\mu [-(1-x_1)\not{p} + x_2\not{p}' + m] \gamma^\nu$$

Fitness of  $\Gamma^\mu$  requires that

$$\delta_1 = -\frac{e^2}{8\pi^2} \left( \frac{1}{\epsilon} + \text{finite} \right) + O(e^4)$$

Impose the OS renormalization condition  $\Gamma_r^\mu(p = p', p^2 = -m^2) = \gamma^\mu$ , we have

$$\Gamma^\mu(p, p') = \gamma^\mu - \frac{e^2}{16\pi^2} \int dF_3 \left[ (\ln(D/D_0) + 2\kappa_1) \gamma^\mu - \frac{\tilde{N}^\mu}{2D} \right] + O(e^4)$$

where

$$D_0 = (1-x_3)^2 m^2 + x_3 m_\gamma^2 \quad \kappa_1 = -2 \ln(m/m_\gamma) + \frac{5}{2}$$

