

# Foundations & applications of generalised symmetries

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## 1 Foundations

### 1.1 Conventional symmetries \*

Most parts of this section are adopted from the materials below.

[1] M. E. Peskin and D. V. Schroeder, “An Introduction to quantum field theory”

[2] M. Srednicki, “Quantum field theory”

[3] P. R. S. Gomes, “An introduction to higher-form symmetries”, Section 3

#### 1.1.1 Schwinger-Dyson equation & conversation laws

**Proposition<sup>(ph)</sup> 1.1.** We have following relation, which is well-known as Schwinger-Dyson equation.

$$\left\langle \frac{\partial S[\varphi]}{\partial \varphi(x)} \varphi(x_1) \cdots \varphi(x_n) \right\rangle = i \sum_{i=1}^n \left\langle \varphi(x_1) \cdots \delta^{(D)}(x - x_i) \cdots \varphi(x_n) \right\rangle. \quad (1.1)$$

*Proof.* First of all, we prove the general relation

$$\int \mathcal{D}\varphi \frac{\delta}{\delta \varphi(x)} \left( F[\varphi] e^{iS[\varphi]} \right) = 0. \quad (1.2)$$

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<sup>1</sup>The sections with asterisk “\*” are materials that is not directly related to generalised symmetries but supplemental.

We start from the obvious relation

$$\int \mathcal{D}\varphi F[\varphi] e^{iS[\varphi]} = \int \mathcal{D}\varphi' F[\varphi'] e^{iS[\varphi']}, \quad (1.3)$$

which is just a renaming of a dummy variable of the integration. Now we perform a change of variables  $\varphi'(x) \mapsto \varphi(x) + \varepsilon(x)$ . Then we have

$$\begin{aligned} \int \mathcal{D}\varphi F[\varphi] e^{iS[\varphi]} &= \int \mathcal{D}\varphi F[\varphi + \varepsilon] e^{iS[\varphi + \varepsilon]} \\ &= \int \mathcal{D}\varphi \left\{ F[\varphi] + \int d^D x \frac{\delta F[\varphi]}{\delta \varphi(x)} \varepsilon(x) \right\} \exp \left\{ iS[\varphi] + i \int d^D x \frac{\delta S[\varphi]}{\delta \varphi(x)} \varepsilon(x) \right\} \\ &= \int \mathcal{D}\varphi \left\{ F[\varphi] + \int d^D x \frac{\delta F[\varphi]}{\delta \varphi(x)} \varepsilon(x) \right\} \left\{ 1 + i \int d^D x \frac{\delta S[\varphi]}{\delta \varphi(x)} \varepsilon(x) \right\} e^{iS[\varphi]} \\ &= \int \mathcal{D}\varphi F[\varphi] e^{iS[\varphi]} + \int \mathcal{D}\varphi \int d^D x \left\{ \frac{\delta F[\varphi]}{\delta \varphi(x)} e^{iS[\varphi]} + F[\varphi] i \frac{\delta S[\varphi]}{\delta \varphi(x)} e^{iS[\varphi]} \right\} \varepsilon(x), \quad \forall \varepsilon(x), \end{aligned} \quad (1.4)$$

which leads us to the identity

$$\int \mathcal{D}\varphi \left\{ \frac{\delta F[\varphi]}{\delta \varphi(x)} e^{iS[\varphi]} + F[\varphi] i \frac{\delta S[\varphi]}{\delta \varphi(x)} e^{iS[\varphi]} \right\} = 0. \quad (1.5)$$

Now, by substituting  $F[\varphi]$  with  $\varphi(x_1) \cdots \varphi(x_n)$  we get

$$i \int \mathcal{D}\varphi \frac{\delta S[\varphi]}{\delta \varphi(x)} \varphi(x_1) \cdots \varphi(x_n) e^{iS[\varphi]} = - \sum_{i=1}^n \int \mathcal{D}\varphi \varphi(x_1) \cdots \delta^{(D)}(x - x_i) \cdots \varphi(x_n) e^{iS[\varphi]}, \quad (1.6)$$

which we simply denote

$$\left\langle \frac{\delta S[\varphi]}{\delta \varphi(x)} \varphi(x_1) \cdots \varphi(x_n) \right\rangle = i \sum_{i=1}^n \left\langle \varphi(x_1) \cdots \delta^{(D)}(x - x_i) \cdots \varphi(x_n) \right\rangle. \quad (1.7)$$

□

**Remark 1.1.** Schwinger-Dyson equation is the generalisation of Ward-Takahashi identity.

**Proposition<sup>(ph)</sup> 1.2.** We have following relation, which is a correlation function representation of the conservation law of Noether current.

$$\langle \{ \partial_\mu j^\mu(x) \} \varphi_{a_1}(x_1) \cdots \varphi_{a_n}(x_n) \rangle = -i \sum_{i=0}^n \left\langle \varphi_{a_1}(x_1) \cdots \delta^{(D)}(x - x_i) \delta \varphi_{a_i}(x_i) \cdots \varphi_{a_n}(x_n) \right\rangle. \quad (1.8)$$

*Proof.* Now, we consider the transformation

$$\varphi_a(x) \mapsto \varphi'_a(x) = \varphi_a(x) + \delta_{\varepsilon(x)} \varphi_a(x) = \varphi_a(x) + \varepsilon(x) g_a(x). \quad (1.9)$$

We first prove the relation

$$\delta_{\varepsilon(x)} S[\varphi] = - \int d^D x \varepsilon(x) \partial_\mu \left\{ \sum_{a=1}^N g_a(x) \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi_a(x))} - K^\mu[\varphi] \right\} = - \int d^D x \varepsilon(x) \partial_\mu j^\mu(x) \quad (1.10)$$

where we defined  $j^\mu(x)$  as

$$j^\mu(x) = \sum_{a=1}^N g_a(x) \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi_a(x))} - K^\mu[\varphi]. \quad (1.11)$$

The direct calculation of  $\delta_{\varepsilon(x)}S[\varphi]$  is as follows.

$$\begin{aligned}
\delta_{\varepsilon(x)}S[\varphi] &= \int d^Dx \delta_{\varepsilon(x)}\mathcal{L}[\varphi, \partial_\mu\varphi] = \int d^Dx \{\mathcal{L}[\varphi(x) + \varepsilon(x)\varphi(x), \partial_\mu\{\varphi(x) + \varepsilon(x)g(x)\}] - \mathcal{L}[\varphi(x), \partial_\mu\varphi(x)]\} \\
&= \int d^Dx \{\mathcal{L}[\varphi(x) + \varepsilon(x)\varphi(x), \partial_\mu\varphi(x) + \partial_\mu\varepsilon(x)g(x) + \varepsilon(x)\partial_\mu g(x)] - \mathcal{L}[\varphi(x), \partial_\mu\varphi(x)]\} \\
&= \int d^Dx \left\{ \varepsilon(x) \sum_{a=1}^N g_a(x) \frac{\partial \mathcal{L}}{\partial \varphi_a(x)} + \varepsilon(x) \sum_{a=1}^N \partial_\mu g_a(x) \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi_a(x))} + \partial_\mu \varepsilon(x) \sum_{a=1}^N g_a(x) \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi_a(x))} \right\} \\
&= \int d^Dx \varepsilon(x) \partial_\mu K^\mu(x) + \int d^Dx \partial_\mu \varepsilon(x) \sum_{a=1}^N g_a(x) \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi_a(x))} \tag{1.12}
\end{aligned}$$

Here, we assumed

$$\sum_{a=1}^N g_a(x) \frac{\partial \mathcal{L}}{\partial \varphi_a(x)} + \sum_{a=1}^N \partial_\mu g_a(x) \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi_a(x))} = \partial_\mu K^\mu[\varphi(x)], \quad \exists K^\mu[\varphi(x)]. \tag{1.13}$$

Integrating the second term by parts, we get

$$\delta_{\varepsilon(x)}S[\varphi] = \int d^Dx \varepsilon(x) \partial_\mu K^\mu(x) - \int d^Dx \varepsilon(x) \partial_\mu \left\{ g_a(x) \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi_a(x))} \right\} = - \int d^Dx \varepsilon(x) \partial_\mu j^\mu(x). \tag{1.14}$$

Now, we move on to the proof of the relation in consider. We start from the trivial relation

$$\int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \varphi_{a_n}(x_n) e^{iS[\varphi]} = \int \left( \prod_{a=1}^N \mathcal{D}\varphi'_a \right) \varphi'_{a_1}(x_1) \cdots \varphi'_{a_n}(x_n) e^{iS[\varphi]}. \tag{1.15}$$

Here, we perform the change of variable  $\varphi'_a(x) = \varphi_a(x) + \varepsilon(x)g_a(x)$  and we get

$$\begin{aligned}
\int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \varphi_{a_n}(x_n) e^{iS[\varphi]} &= \int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \varphi_{a_n}(x_n) e^{iS[\varphi]} \\
&\quad + i \int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \varphi_{a_n}(x_n) \left\{ - \int d^Dx \varepsilon(x) \partial_\mu j^\mu(x) \right\} e^{iS[\varphi]} \\
&\quad + \sum_{i=1}^n \int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \varepsilon(x_i) g_{a_i}(x_i) \cdots \varphi_{a_n}(x_n) e^{iS[\varphi]}, \tag{1.16}
\end{aligned}$$

which leads us to

$$\begin{aligned}
&- i \int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \varphi_{a_n}(x_n) \left\{ \int d^Dx \varepsilon(x) \partial_\mu j^\mu(x) \right\} e^{iS[\varphi]} \\
&= \sum_{i=1}^n \int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \varepsilon(x_i) g_{a_i}(x_i) \cdots \varphi_{a_n}(x_n) e^{iS[\varphi]} = 0. \tag{1.17}
\end{aligned}$$

Now, we substitute  $\varepsilon(x_i)$  in RHS with a trivial relation  $\varepsilon(x_i) = \int d^Dx \varepsilon(x) \delta^{(D)}(x - x_i)$ , we get

$$\begin{aligned}
&- i \int d^Dx \varepsilon(x) \int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \varphi_{a_n}(x_n) \{ \partial_\mu j^\mu(x) \} e^{iS[\varphi]} \\
&= \int d^Dx \varepsilon(x) \sum_{i=1}^n \int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \delta^{(D)}(x - x_i) g_{a_i}(x_i) \cdots \varphi_{a_n}(x_n) e^{iS[\varphi]}, \quad \forall \varepsilon(x). \tag{1.18}
\end{aligned}$$

Then we get

$$i \int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \varphi_{a_n}(x_n) \{ \partial_\mu j^\mu(x) \} e^{iS[\varphi]} = \sum_{i=1}^n \int \left( \prod_{a=1}^N \mathcal{D}\varphi_a \right) \varphi_{a_1}(x_1) \cdots \delta^{(D)}(x - x_i) g_{a_i}(x_i) \cdots \varphi_{a_n}(x_n) e^{iS[\varphi]}, \quad (1.19)$$

which means that

$$\langle \varphi_{a_1}(x_1) \cdots \varphi_{a_n}(x_n) \{ \partial_\mu j^\mu(x) \} \rangle = -i \sum_{i=0}^n \left\langle \varphi_{a_1}(x_1) \cdots \delta^{(D)}(x - x_i) g_{a_i}(x_i) \cdots \varphi_{a_n}(x_n) \right\rangle. \quad (1.20)$$

□

### 1.1.2 Reformulation in the language of differential forms

**Fact<sup>(ph)</sup> 1.1.** Mathematically speaking, Noether current  $j^\mu(x)$  are coefficients of a vector field on the space-time manifold  $\mathcal{M}$ , which is a section of the tangent bundle  $T\mathcal{M}$ . And equivalently  $j_\mu(x)$  are coefficients of a covector field of a section of the cotangent bundle  $T^*\mathcal{M}$ . Let us stick to the representation on cotangent bundle in this notes, then we can write

$$j = j_\mu(x) dx^\mu. \quad (1.21)$$

And obviously, we have the Hodge dual of it.

$$*j = \frac{1}{(D-1)!} j_{\mu_0}(x) \epsilon^{\mu_0}_{\mu_1 \cdots \mu_{D-1}} dx^{\mu_1} \wedge \cdots \wedge dx^{\mu_{D-1}}. \quad (1.22)$$

**Proposition<sup>(ph)</sup> 1.3.** The conservation law  $\partial_\mu j^\mu(x) = 0$  can be written as

$$d * j = 0. \quad (1.23)$$

*Proof.* We will see the equivalence of the two representations  $\partial_\mu j^\mu = \partial^\mu j_\mu = 0$  and  $d * j = 0$ . We start from

$$\begin{aligned} d * j &= \frac{1}{(D-1)!} \partial_\alpha j_{\mu_0}(x) \epsilon^{\mu_0}_{\mu_1 \cdots \mu_{D-1}} dx^\alpha \wedge dx^{\mu_1} \wedge \cdots \wedge dx^{\mu_{D-1}} = \frac{1}{(D-1)!} \partial_\alpha j_{\mu_0}(x) \epsilon^{\mu_0}_{\mu_1 \cdots \mu_{D-1}} \epsilon^{\alpha \mu_1 \cdots \mu_{D-1}} \\ &= (-1)^{D-1} \partial_\alpha j_{\mu_0}(x) \eta^{\mu_0 \alpha} dx^0 \wedge \cdots \wedge dx^{D-1} = (-1)^{D-1} \partial^\mu j_\mu(x) dx^0 \wedge \cdots \wedge dx^{D-1}. \end{aligned} \quad (1.24)$$

Now, if we assume  $d * j = 0$ , obviously  $\partial_\mu j^\mu(x) = 0$  because  $dx^0 \wedge \cdots \wedge dx^{D-1} \neq 0$ . Also if we assume  $\partial_\mu j^\mu(x) = 0$ , obviously  $d * j = 0$  from the relation we just derived. □

**Remark 1.2.** In the Euclidean theory, which we will be using so often in this note, we simply have

$$d * j = \partial_\mu j^\mu(x) dx^0 \wedge \cdots \wedge dx^{D-1}. \quad (1.25)$$

**Proposition<sup>(ph)</sup> 1.4.** The definition of Noether charge  $Q = \int d^{D-1}x j_0(x)$  is translated to differential forms as follows.

$$Q = \int_\Sigma *j, \quad (1.26)$$

where,  $\Sigma$  is the spatial submanifold of the spacetime manifold  $\mathcal{M}$ .

*Proof.* We start by rewriting the integral.

$$\begin{aligned} Q &= \int_{\Sigma} *j = \int_{\Sigma} \frac{1}{(D-1)!} j_{\mu_0}(x) \epsilon^{\mu_0}_{\mu_1 \dots \mu_{D-1}} dx^{\mu_1} \wedge \dots \wedge dx^{\mu_{D-1}} \\ &= \int_{\Sigma} \frac{1}{(D-1)!} j_{\mu_0}(x) \epsilon^{\mu_0}_{\mu_1 \dots \mu_{D-1}} \epsilon^{0\mu_1 \dots \mu_{D-1}} dx^1 \wedge \dots \wedge dx^{D-1} = \int_{\Sigma} j_{\mu_0}(x) (-1)^{D-1} \eta^{\mu_0 0} dx^1 \wedge \dots \wedge dx^{D-1}. \end{aligned} \quad (1.27)$$

Obviously, (1.27) = 0 for  $\mu_0 \neq 0$ . Then we have

$$Q = Q(\Sigma) = (-1)^{D-1} \int_{\Sigma} j_0(x) dx^1 \wedge \dots \wedge dx^{D-1}, \quad (1.28)$$

which has the same meaning as  $\int d^{D-1}x j_0(x)$ .<sup>2</sup>  $\square$

**Proposition<sup>(ph)</sup> 1.5.** The conversation law in a correlation function representation is interpreted as follows.

$$\langle (d * j) \varphi_{a_1}(x_1) \dots \varphi_{a_n}(x_n) \rangle = -i \sum_{i=0}^n \left\langle \varphi_{a_1}(x_1) \dots \delta^{(D)}(x - x_i) g_{a_i}(x_i) \dots \varphi_{a_n}(x_n) \right\rangle dx^0 \wedge \dots \wedge dx^{D-1}. \quad (1.29)$$

*Proof.* By simply putting  $dx^0 \wedge \dots \wedge dx^{D-1}$  on both sides of (1.8), we get (1.29).  $\square$

**Definition<sup>(ph)</sup> 1.1.** We say that, in the case of conventional symmetries, the operator  $\mathcal{O}(\mathcal{M})$  defined on some manifold  $\mathcal{M}$  is topological if  $\langle \mathcal{O}(\mathcal{M}) \varphi(x_1) \dots \varphi(x_n) \rangle$  is invariant under the deformation of  $\mathcal{M}$ .

**Proposition<sup>(ph)</sup> 1.6.** We have the following relation.

$$\langle Q(\Sigma) \varphi_{a_1}(x_1) \dots \varphi_{a_n}(x_n) \rangle = -i \sum_{i=0}^n \text{Link}(\Sigma, x_i) \langle \varphi_{a_1}(x_1) \dots g_{a_i}(x_i) \dots \varphi_{a_n}(x_n) \rangle, \quad (1.30)$$

where we defined the link number as

$$\text{Link}(\Sigma, x_i) = \int_{\Omega_{\Sigma}} dx^0 \wedge \dots \wedge dx^{D-1} \delta^{(D)}(x - x_i), \quad \partial \Omega_{\Sigma} = \Sigma. \quad (1.31)$$

*Proof.* We just integrate the both sides of (1.29) in terms of  $x$  on  $\Omega_{\Sigma}$ .

$$\begin{aligned} \text{LHS of (1.29)} &= \int_{\Omega_{\Sigma}} \langle (d * j) \varphi_{a_1}(x_1) \dots \varphi_{a_n}(x_n) \rangle \\ &= \left\langle \int_{\Omega_{\Sigma}} (d * j) \varphi_{a_1}(x_1) \dots \varphi_{a_n}(x_n) \right\rangle \stackrel{\text{Stokes's theorem}}{=} \left\langle \int_{\Sigma} *j \varphi_{a_1}(x_1) \dots \varphi_{a_n}(x_n) \right\rangle \\ &\stackrel{(1.27)}{=} \left\langle \int_{\Sigma} Q(\Sigma) \varphi_{a_1}(x_1) \dots \varphi_{a_n}(x_n) \right\rangle \end{aligned} \quad (1.32)$$

$$\begin{aligned} \text{RHS of (1.29)} &= -i \sum_{i=0}^n \int_{\Omega_{\Sigma}} \delta^{(D)}(x - x_i) \langle \varphi_{a_1}(x_1) \dots g_{a_i}(x_i) \dots \varphi_{a_n}(x_n) \rangle dx^0 \wedge \dots \wedge dx^{D-1} \\ &= -i \sum_{i=0}^n \int_{\Omega_{\Sigma}} \delta^{(D)}(x - x_i) \langle \varphi_{a_1}(x_1) \dots g_{a_i}(x_i) \dots \varphi_{a_n}(x_n) \rangle dx^0 \wedge \dots \wedge dx^{D-1} \\ &= -i \sum_{i=0}^n \text{Link}(\Sigma, x_i) \langle \varphi_{a_1}(x_1) \dots g_{a_i}(x_i) \dots \varphi_{a_n}(x_n) \rangle \end{aligned} \quad (1.33)$$

This proves the proposition.  $\square$

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<sup>2</sup>Here, we ignore the factor  $(-1)^{D-1}$  because it does not affect the physical invariant.

**Remark 1.3.** The link number (1.31) is topological under the deformation that does not cross the point  $x_i$ .

For simplicity, we will be considering  $n = 1$  case only for the present. (1.29) and (1.30) are

$$\langle \{d * j(x)\} \varphi(y) \rangle = -i\delta^{(D)}(x - y) \langle g(y) \rangle dx^0 \wedge \dots \wedge dx^{D-1}, \quad \langle Q(\Sigma) \varphi(y) \rangle = -i \text{Link}(\Sigma, y) \langle g(y) \rangle. \quad (1.34)$$

**Theorem<sup>(ph)</sup> 1.1.** Noether charge is topological under the deformation  $\Omega_\Sigma \mapsto \Omega'_\Sigma = \Omega_\Sigma \cup \Omega_0$  such that  $y$  does not belong to  $\Omega_0$ . This is the topological expression of the conversation law of Noether charge.

*Proof.* Under the defirmation  $\Omega_\Sigma \mapsto \Omega'_\Sigma = \Omega_\Sigma \cup \Omega_0$ , Nother charge transforms as follows.

$$\langle Q(\Sigma + \partial\Omega_0) \varphi(y) \rangle = \int_{\Omega_\Sigma \cup \Omega_0} \langle \{d * j(x)\} \varphi(y) \rangle = \underbrace{\int_{\Omega_\Sigma} \langle \{d * j(x)\} \varphi(y) \rangle}_{\langle Q(\Sigma) \varphi(y) \rangle} + \int_{\Omega_0} \langle \{d * j(x)\} \varphi(y) \rangle. \quad (1.35)$$

Here, since  $\Omega_0$  does not include the point  $y$  and  $d * j(x) = 0$ , the second term vanishes. Then we get

$$\langle Q(\Sigma + \partial\Omega_0) \varphi(y) \rangle = \langle Q(\Sigma) \varphi(y) \rangle. \quad (1.36)$$

This proves the theorem.  $\square$

**Proposition<sup>(ph)</sup> 1.7.** We have the following relation.

$$\langle U(\Sigma) \varphi(y) \rangle = R \langle \varphi(y) \rangle \quad (1.37)$$

Here, we defined

$$U(\Sigma) = e^{i\epsilon Q}, \quad R = e^{i\epsilon T}, \quad (1.38)$$

where  $\epsilon$  is the arbitrary real number and  $T$  is the representation on the vector space spanned by the field  $\varphi(y)$  of the generator of the symmetry we are considering.

*Proof.*  $\square$

**Remark 1.4.**  $Q(\Sigma)$  is the representation on the Hilbert space of the generator of the symmetry.

### 1.1.3 New perspective on symmetries

**Observation<sup>(ph)</sup> 1.1.** It may be possible to generalise symmetries as

$$\text{symmetry generator} = \text{topological operator}. \quad (1.39)$$

## 1.2 Definition of higher-form symmetries

Most parts of this section are adopted from the materials below.

[3] P. R. S. Gomes, “An introduction to higher-form symmetries”

## 2 Applications

### 2.1 Ginzburg-Landau theory \*

#### References

- [1] M. E. Peskin and D. V. Schroeder, Addison-Wesley, 1995, ISBN 978-0-201-50397-5, 978-0-429-50355-9, 978-0-429-49417-8 doi:10.1201/9780429503559
- [2] M. Srednicki, Cambridge University Press, 2007, ISBN 978-0-521-86449-7, 978-0-511-26720-8 doi:10.1017/CBO9780511813917
- [3] P. R. S. Gomes, SciPost Phys. Lect. Notes **74** (2023), 1 doi:10.21468/SciPostPhysLectNotes.74 [arXiv:2303.01817 [hep-th]].