

Mathematical Methods for Physics

October 7, 2023

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Lecture 1

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1 Introduction

The course is about group theory and explaining where it appears in theoretical physics. Group theory is motivated by the fact that the current understanding of Nature is based on symmetries. Symmetries are properties that are invariant under some transformations. Utilizing Noether's theorem, one can link the conservation of charges to transformations and invariants. Symmetries play an important role in physics and are described by groups. There are several classes of symmetries.

Continuous symmetries. Symmetries can be parameterized by continuous variables. Some examples of continuous symmetries are:

- (space) translation, equivalent to the assumption that space is homogeneous: one can obtain the conservation of momentum;
- time translation, equivalent to the assumption that time is homogeneous: conservation of energy;
- space rotation, equivalent to the assumption of the isotropy of space: conservation of angular momentum;
- Lorentz and Poincaré transformations: conservation of the energy–momentum tensor.
- Local gauge symmetry: it is a symmetry of an internal degree of freedom (i.e. not related to temporal nor spacial degrees of freedom) and the transformation depends on the space-time coordinates

$$V_{ab}(\vec{x}, t)\phi(\vec{x}, t)$$

These kinds of symmetries describe the dynamics of quantum field theory and the properties of fundamental interactions.

- Internal, global symmetry, for example isospin: swapping the up and down quarks does not change the physics.

Discrete symmetries. A few examples of discrete symmetries are:

- parity $\vec{x} \rightarrow -\vec{x}$: parity is conserved in quantum electrodynamics and in quantum chromodynamics, but not in electroweak theory.
- Time reversal $t \rightarrow -t$;
- charge conjugation;
- discrete lattice: no more continuous translation symmetries, because there is only a subset of them. Lattices are used for the study of QCD in the non-perturbative regime.

This course will be dedicated to the classification and study of groups and their representations.

Definition 1.1. A group G is a set endowed with a binary operation \circ (called group multiplication) that has the following properties:

- closure: $\forall g_1, g_2 \in G, \exists! g_3 \in G$ such that $g_3 = g_1 \circ g_2$.
- associativity: $(g_1 \circ g_2) \circ g_3 = g_1 \circ (g_2 \circ g_3), \forall g_1, g_2, g_3 \in G$.
- identity element: $\exists e \in G$ such that $g \circ e = e \circ g = g, \forall g \in G$.
- inverse element: $\forall g \in G, \exists g^{-1} \in G$ such that $g \circ g^{-1} = g^{-1} \circ g = e$.

Example 1.2. A few examples:

- The set \mathbb{R} of the real numbers endowed with summation is a group $(\mathbb{R}, +)$ with identity element 0 and inverse $-g$.
- The whole numbers with summation $(\mathbb{Z}, +)$ is a group.
- The positive integers with summation $(\mathbb{N}, +)$ are not a group: there does not exist the inverse.
- The real numbers with multiplication (\mathbb{R}, \cdot) has identity element 1, but is not a group because 0 does not have an inverse. To obtain a group, one can consider $\mathbb{R} \setminus \{0\}$.
- Consider the set of square matrices of size n with either real entries $\text{Mat}(n, \mathbb{R})$ or complex entries $\text{Mat}(n, \mathbb{C})$. Taking the operation to be matrix multiplication, the identity to be $I = \text{diag}(1, 1, 1, \dots)$, the set is not a group because the inverse element, inverse matrices, does not exist for matrices with null determinant.

Definition 1.3. The general linear group is defined as $\text{Gl}(n, \mathbb{R}) \equiv \{M \in \text{Mat}(n, \mathbb{R}) \mid \det M \neq 0\}$ and is the largest and most general group of matrices. The definition is equivalent for matrices with complex entries.

Definition 1.4. The cyclic group \mathbb{Z}_n is discrete and defined by

$$\mathbb{Z}_n \equiv \{e, a, a^2, a^3, \dots, a^{n-1}\}, \quad a^n \equiv e$$

with generic operation \circ where the notation implies $a^2 \equiv a \circ a$.

Example 1.5. Some examples are:

- $\mathbb{Z}_2 = \{0, 1\}$ with summation mod 2,
- the group $G = \{1, -1\}$ with multiplication,
- endowing the integers \mathbb{Z} with summation mod n , one can split the set into equivalence classes that are the elements of the cyclic group. For example, if $n = 2$ then the sets

$$\{0\} = \{0, 2, 4, \dots\}, \quad \{1\} = \{1, 3, 5, \dots\}$$

are the elements of the cyclic group \mathbb{Z}_2 . This group is important in particle physics.

Definition 1.6. The order of a group G , denoted by $|G|$, is given by the number of elements of the group.

Definition 1.7. A group G is finite if its order is finite. Otherwise it is infinite.

Definition 1.8. A group G is discrete if it is a countable set.

Definition 1.9. A group G is abelian if its operation is commutative $g_1 \circ g_2 = g_2 \circ g_1, \forall g_1, g_2$.

Example 1.10. A few examples of abelian and non-abelian groups:

- Some abelian groups are $(\mathbb{R}, +)$, $(\mathbb{Z}, +)$ which are also infinite. Though, the first is not countable, while the second is and as such it is a discrete group.
- All cyclic groups \mathbb{Z}_n are abelian: $a^2 \circ a^3 = a^3 \circ a^2$.
- The general linear group $\text{Gl}(n, \mathbb{R})$ is not abelian: the order of matrix multiplication matters.

Definition 1.11. A ring R is an abelian group with composition $+$, endowed with a second operation $\cdot : R \times R \rightarrow R$ with the properties:

- associativity $(r_1 \cdot r_2) \cdot r_3 = r_1 \cdot (r_2 \cdot r_3), \forall r_1, r_2, r_3 \in R$;
- distributivity with respect to the first composition: $r_1 \cdot (r_2 + r_3) = r_1 \cdot r_2 + r_1 \cdot r_3$ and equivalently for right multiplication.

Remark 1.12. The identity element of the relation $+$ is 0, while the inverse is $-r$. The second relation need not an identity nor an inverse.

Definition 1.13. A field \mathbb{F} is a ring such that $\mathbb{F} \setminus \{0\}$ is an abelian group with respect to the ring's second operation.

Example 1.14. Some examples and counterexamples of fields are the following.

- Consider the integers with summation $(\mathbb{Z}, +)$: it is an abelian group. It is also a ring with the multiplication $n_1 \cdot n_2 \in \mathbb{Z}$. However, (\mathbb{Z}, \cdot) is not a group because $n^{-1} \notin \mathbb{Z}$, therefore the set of integers is not a field.
- The real numbers with summation and multiplication is a field.
- The complex numbers are also a field.
- The cyclic group \mathbb{Z}_n with summation is an abelian group. Adding the multiplication $\{n_1\} \cdot \{n_2\} \equiv \{n_1 \cdot n_2\}$, the cyclic group is a field only for n prime. See the following theorem.

The fact that real numbers and complex numbers are fields implies one can define sets of matrices with entries from those fields.

Theorem 1.15. If n is prime, then the cyclic group \mathbb{Z}_n is a field (and vice versa).

Example 1.16. Some more examples:

- Consider the cyclic group \mathbb{Z}_5 . It is an abelian group with respect to summation. One can study if $(\mathbb{Z}_5 \setminus \{0\}, \cdot)$ is an abelian group:

$$\{2\} \cdot \{3\} = \{6\} = \{1\}$$

This means that $\{3\}$ is the inverse of $\{2\}$. Continuing, one gets

$$\{4\} \cdot \{4\} = \{1 + 5 \cdot 3\} = \{1\}$$

So $\{4\}$ is its own inverse. Since the remaining elements are the additive identity $\{0\}$ and multiplicative identity $\{1\}$, the set \mathbb{Z}_5 is a field.

- The group $(\mathbb{Z}_4 \setminus \{0\}, \cdot)$ is not abelian because

$$\{2\} \cdot \{2\} = \{4\} = \{0\}$$

the set is not closed under multiplication. Therefore \mathbb{Z}_4 is not a field.

Definition 1.17. A **module** M with respect to a **ring** R is an abelian group endowed with an action $\cdot : R \times M \rightarrow M$ such that the following properties hold for every $r \in R$ and $m \in M$:

- associativity $(r_1 \cdot r_2) \cdot m = r_1 \cdot (r_2 \cdot m)$
- distributivity $r_1 \cdot (m_1 + m_2) = r_1 \cdot m_1 + r_1 \cdot m_2$ and $(r_1 + r_2) \cdot m = r_1 \cdot m + r_2 \cdot m$

Pay attention to whom the operations apply: operations in different sets have the same notation.

Definition 1.18. A vector space V with respect to a field \mathbb{F} is a module over \mathbb{F} such that the multiplicative identity of \mathbb{F} acts as the identity on V : $1 \cdot v = v \cdot 1 = v, \forall v \in V$.

Definition 1.19. An associative algebra A over a ring R is a ring and also a module with respect to R such that the action of R on A is bilinear

$$r \cdot (a_1 \cdot a_2) = (r \cdot a_1) \cdot a_2 = a_1 \cdot (r \cdot a_2)$$

Again, pay attention to whom the operations apply.

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Example 1.20. The set of square matrices of size n , $\text{Mat}(n, \mathbb{F})$, with summation, matrix multiplication and scalar product forms an algebra over the field \mathbb{F} .

Lecture 2

Definition 1.21. The set of vectors $\{|e_i\rangle\}$ is a basis of a vector space V if and only if $|v\rangle = v^i |e_i\rangle$, $v^i \in \mathbb{F}$ for all $|v\rangle \in V$.

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Definition 1.22. The action of an inner product on a basis defines a metric $g^i_j = \langle e^i | e_j \rangle$. The metric g is hermitian and if $g^i_j = \delta^i_j$ then the basis is orthonormal.

Lemma 1.23. Linear operators over V form an algebra called $\text{End}(V)$:

$$A : |v\rangle \mapsto |Av\rangle \in V, \quad A : |w\rangle = \alpha |v_1\rangle + \beta |v_2\rangle \mapsto |Aw\rangle = \alpha |Av_1\rangle + \beta |Av_2\rangle$$

Proposition 1.24. Linear operators follow these properties:

- composition: $(A \circ B) |v\rangle = A |Bv\rangle = |ABv\rangle$;
- given a basis $\{|e_i\rangle\}$, the operator A is a matrix $n \times n$ over a field \mathbb{F} ;
- a basis rotation S is a linear operator which is invertible ($\det S \neq 0$):

$$|e'_i\rangle = S^j_i |e_j\rangle \implies \langle e'^i | e'_j \rangle = (S^\dagger)^i_k \langle e^k | e_l \rangle S^l_j \implies g' = S^\dagger g S$$

Definition 1.25. A linear operator A is idempotent if $A^2 = A$ (and $A \neq I$). Given a basis $\{|e_i\rangle\}$, an example of idempotent linear operator the projector $A = |e_i\rangle\langle e^i|$:

$$A |v\rangle = |e_i\rangle\langle e^i | v^k |e_k\rangle = v^i |e_i\rangle$$

Definition 1.26. A linear operator A is nilpotent if $\exists n \in \mathbb{N}$ such that $A^n = 0$ where 0 is the null operator. For example

$$A = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

One wants to categorize type of transformations to be able to study symmetries.

1.1 Classical groups of matrices

Linear group. The general linear group $\text{Gl}(n, \mathbb{C})$ is the largest group in the endomorphism algebra $\text{End}(V)$. The group is parametrized by $2n^2$ real elements. The dimension of the group is given by the number of free parameters.

The special linear group is defined by

$$\text{Sl}(n, \mathbb{C}) \equiv \{M \in \text{Gl}(n, \mathbb{C}) \mid \det M = 1\} \subset \text{Gl}(n, \mathbb{C})$$

This set is also a group, not just a subset of matrices. The number of free parameters is $2n^2 - 1$ because of the condition on the determinant. The definition is analogous for $\text{Sl}(n, \mathbb{R})$. The set $\text{Sl}(n, \mathbb{Z})$ is also a group.

Consider a change of coordinates from x^i to $\bar{x}^j = S^j_i x^i$ with the intention to perform an integral over space-time. The measures of the two coordinate systems are related by the Jacobian

$$d^n \bar{x} = |\partial_x \bar{x}| d^n x = \det S d^n x$$

Matrices in the special linear group preserve the volume.

Unitary group. Consider the groups that preserve the metric of V over \mathbb{C} :

$$|\bar{e}_i\rangle = U^j_i |e_j\rangle \implies \delta^i_j = \langle \bar{e}^i | \bar{e}_j \rangle = \langle e^k | (U^\dagger)^i_k U^l_j |e_l\rangle = (U^\dagger)^i_k U^l_j \delta^k_l \implies U^\dagger U = I$$

Unitary matrices belong to the unitary group $\text{U}(n, \mathbb{C})$ which is defined as

$$\text{U}(n, \mathbb{C}) \equiv \{M \in \text{Gl}(n, \mathbb{C}) \mid M^\dagger M = MM^\dagger = I\}$$

The number of free parameters is $2n^2 - n - n(n-1) = n^2$:

- the unitary condition $U^\dagger U$ imposes n conditions corresponding to the elements on the diagonal, $[U^\dagger U]^i_i = 1$ (no sum);
- the upper and lower triangular parts of the matrix provide $\frac{n(n-1)}{2}$ conditions each.

The unitary group $\text{U}(1)$ describes quantum electrodynamics. The determinant of a unitary matrix is

$$\det(U^\dagger U) = |\det U|^2 = 1 \implies \det U = e^{i\varphi}, \quad \varphi \in \mathbb{R}$$

One can define the special unitary group as

$$\text{SU}(n, \mathbb{C}) \equiv \{M \in \text{U}(n, \mathbb{C}) \mid \det M = 1\}$$

The number of free parameters is $n^2 - 1$. The strong and weak interactions are described by special unitary groups.

Orthogonal group. Consider the groups that preserve the metric of V over \mathbb{R} . The orthogonal group is

$$\text{O}(n, \mathbb{R}) \equiv \{M \in \text{Gl}(n, \mathbb{R}) \mid M^\top M = MM^\top = I\}$$

The number of free parameters is $n^2 - n - \frac{n(n-1)}{2} = \frac{n(n-1)}{2}$. The determinant of the orthogonal matrices is

$$\det(O^\top O) = (\det O)^2 = 1 \implies \det O = \pm 1$$

The special orthogonal group is

$$\text{SO}(n, \mathbb{R}) \equiv \{M \in \text{O}(n, \mathbb{R}) \mid \det M = 1\}$$

For the unitary group and orthogonal group, the field is not usually specified, but rather understood to be \mathbb{C} and \mathbb{R} respectively.

Indefinite orthogonal group. Consider the groups that preserve the metrics of V over \mathbb{R} with signature (p, q) . Consider the metric to be

$$g^i_j = \eta^i_j = \text{diag}(\underbrace{1, \dots, 1}_p, \underbrace{-1, \dots, -1}_q)$$

Then

$$|\bar{e}'_i\rangle = R^j_i |e_j\rangle \implies \bar{\eta} = R^\top \eta R$$

The indefinite orthogonal group is

$$O(p, q, \mathbb{R}) \equiv \{R \in \text{Gl}(n, \mathbb{R}) \mid \eta = R^\top \eta R\}$$

The indefinite special orthogonal group is

$$SO(p, q, \mathbb{R}) \equiv \{R \in O(p, q, \mathbb{R}) \mid \det R = 1\}$$

The Lorentz group is $SO(1, 3)$. The group $SO(p, q)$ contains both ordinary rotations $SO(p)$ and $SO(q)$ subgroups.

1.1.1 Symplectic forms

Definition 1.27. A symplectic vector space V is a vector space over a field \mathbb{F} equipped with a bilinear form $\Omega : V \times V \rightarrow \mathbb{F}$. The bilinear form is:

- anti-symmetric: $\Omega(\vec{v}, \vec{w}) = -\Omega(\vec{w}, \vec{v})$;
- non-singular: $\Omega(\vec{v}, \vec{w}) = 0, \forall \vec{w} \implies \vec{v} = \vec{0}$,

Theorem 1.28. Given a square matrix A of size n and a constant c , then

$$\det(cA) = c^n \det A$$

Proof. From the hypotheses, it follows

$$\det(cA) = \det(cI) \det A = c^n \det A$$

□

Given a vector space V over \mathbb{R} , one of its bases $\{|e_i\rangle\}$ and a bilinear form $\Omega_{ij} = \Omega(|e_i\rangle, |e_j\rangle)$, the aim is to represent the form Ω as a linear operator acting on the basis of V . Using anti-symmetry and the theorem above, it follows

$$\det \Omega = \det(-\Omega^\top) = (-1)^n \det \Omega$$

Because of non-singularity, the dimension n can only be even. Using anti-symmetry and setting $\vec{w} = \vec{v}$ then

$$\Omega(\vec{v}, \vec{v}) = -\Omega(\vec{v}, \vec{v}) \implies \Omega_{ii} = 0, \quad \Omega_{ij} = -\Omega_{ji}$$

Fixing i , if $\Omega_{ij} = 0$ for all j then $|e_i\rangle = 0$. Negating this statement means if all basis' vectors are non-zero (which must hold for a vector to be part of a basis) then, for at least one j , it must be true that $\Omega_{ij} \neq 0$. One can choose $\Omega_{ij} = 0$ for all $j \neq i+1$ and $\Omega_{i,i+1} = \lambda_i$. With this choice, one can obtain the canonical form

$$\Omega = \begin{pmatrix} 0 & 1 & & \\ -1 & 0 & 1 & \\ & -1 & 0 & 1 \\ & & -1 & 0 & 1 \end{pmatrix}$$

Another canonical form obtained by change of basis from the previous is

$$\Omega = \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix}$$

given by the conditions

$$\Omega_{i, \frac{n}{2}+i} = 1, \quad \Omega_{ij} = 0, \quad \forall j \neq \frac{n}{2} + i, \quad i < \frac{n}{2}$$

These two forms amount to a decomposition of the vector space $V = V_1 \oplus V_1^*$ — where V_1^* is the dual space of V_1 — such that a basis of V can be written as

$$\{|e_1\rangle, \dots, |e_m\rangle, |f_1\rangle, \dots, |f_m\rangle\}, \quad |e_i\rangle \leftrightarrow V_1, \quad |f_i\rangle \leftrightarrow V_1^*$$

As such the dimension is always even

$$n = \dim V = \dim V_1 + \dim V_1^* = 2 \dim V_1 = 2m$$

A generic transformation of a symplectic form

$$\Omega' = A\Omega B$$

needs to preserve the form's properties:

$$\begin{aligned} (\Omega')^\top &= B^\top \Omega^\top A^\top = -B^\top \Omega A^\top \\ &= -\Omega' = -A\Omega B \implies A = B^\top \end{aligned}$$

Symplectic group. The symplectic group is

$$\mathrm{Sp}(2n, \mathbb{F}) \equiv \{M \in \mathrm{Mat}(2n, \mathbb{F}) \mid M^\top \Omega M = \Omega\}, \quad (\det M)^2 = 1$$

This group also preserves the pfaffian

$$[\mathrm{Pf}(N)]^2 = \det N$$

1.2 Morphisms

Definition 1.29. A morphism ϕ is a map from a group G to another group G' , $\phi : G \rightarrow G'$, $\phi(g) = g'$ with $g \in G$ and $g' \in G'$.

Definition 1.30. A homomorphism is a morphism that respects the composition law of G and G' : $\forall g_1, g_2 \in G$, $\phi(g_1 \cdot g_2) = \phi(g_1) \cdot \phi(g_2)$. The first composition is in G , the second is in G' .

Definition 1.31. An isomorphism is an invertible homomorphism. It is a bijective map: $\forall g \in G$, $\phi(g) = g' \in G'$ and $\exists \phi^{-1} : G' \rightarrow G$ such that $\phi^{-1}(g') = \phi^{-1}(\phi(g)) = g$.

Definition 1.32. An automorphism is an isomorphism with $G' = G$.