BAYESUVIUS QUANTICO

A VISUAL DICTIONARY OF QUANTUM BAYESIAN NETWORKS

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Bayesuvius Quantico,
a visual dictionary of Quantum Bayesian Networks

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This book is constantly being expanded and improved. To download the latest version, go to
`https://github.com/rrtucci/bayes-quantico`

Bayesuvius Quantico
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Appendices

Appendix A

Notational Conventions and Preliminaries

This book is a sequel to my book entitled "Bayesuvius" (see Ref.[5]). For consistency, I have tried to follow in this book the same notational conventions used in the prior book. If any notation is not defined in this book, check in the prior book. It might be defined there.

A.1 Set notation

Definitions

$|S|$ = the number of elements in a set S. (known as its **order, size, length, cardinality**)

$\mathbb{Z}$ = integers

$\mathbb{Z}_{>0}$ = positive integers

$\mathbb{Z}_{[a,b]} = a, a+1, \ldots, b$ for some integers a, b such that $a \leq b$

$\mathbb{R}$ = reals

$\mathbb{Q}$= rationals

$\mathbb{C}$ = complex numbers

$\mathbb{C}^{n\times m} = n \times m$ matrices of complex numbers

A.2 Commutator and Anti-commutator

Let

commutator of A and B

$$[A, B] = AB - BA \tag{A.1}$$

Anti-commutator of A and B

$$[A, B]_+ = AB + BA \tag{A.2}$$

A.3 Equivalence Relation

An **equivalence relation** R on a set X is a subset of $X \times X$ that satisfies the 3 axioms given below. One writes $a \sim b$ or aRb instead of $(a, b) \in R$. For all $a, b, c \in X$, R must satisfy:

1. reflexive: $a \sim a$
2. symmetric: if $a \sim b$ then $b \sim a$
3. transitive: if $a \sim b$ and $b \sim c$ then $a \sim c$.

An **equivalence class** of R is a set $C(a) = \{x \sim a \mid x \in X\}$. All possible equivalence classes of R constitute a disjoint partition of X:

$$X = \bigcup_{a \in X} C(a) \tag{A.3}$$

$$C(a) \cap C(b) = \emptyset \text{ iff } C(a) \neq C(b) \tag{A.4}$$

A.4 Direct Sum and Tensor Product of Matrices

The **Cartesian product** $A \times B$ of two sets A and B (or of two groups or of two vector spaces, if they are being treated as sets) is defined as a set of ordered pairs

$$A \times B = \{(a, b) \mid a \in A, b \in B\} \tag{A.5}$$

Sometimes we want to indicate that $A \times B$ is endowed with an operation that is bilinear. In those cases, instead of the **times symbol** $\times$, we use the **otimes (a.k.a., tensor product) symbol** $\otimes$.

For any square matrices A, B, C (not necessarily of the same dimension)

$$A \oplus B \oplus C = \begin{pmatrix} A & 0 & 0 \\ 0 & B & 0 \\ 0 & 0 & C \end{pmatrix} \tag{A.6}$$

If A_i for $i = 1, 2, \ldots, n$ are square matrices, $A_1 \oplus A_2 \oplus \ldots \oplus A_n$ is called a **block diagonal matrix**. This is also called the **direct sum** of matrices A_i.

The **tensor product or direct product** of two rectangular matrices A and B of arbitrary size is defined as the generalization of the following example to rectangular

matrices A and B of any dimensions:

$$A \otimes B = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \otimes \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} = \begin{pmatrix} a_{11} \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} & a_{12} \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} \\ a_{21} \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} & a_{22} \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} \end{pmatrix} \tag{A.7}$$

Note that if matrices A, A', B, B' have suitable dimensions, then

$$(A \otimes B)(A' \otimes B') = (AA') \otimes (BB') \tag{A.8}$$

If A and B are square matrices, then

$$\mathrm{tr}(A \otimes B) = \mathrm{tr}(A)\mathrm{tr}(B) \tag{A.9}$$

Besides $A \otimes B$ being used to denote the tensor product of two matrices A and B, it is used to denote the tensor product of two operators or two vector spaces. In all cases, there is a bilinear tensor operation at play. But note that[1]

$$A \times B \cong A \otimes B \tag{A.10}$$

so they are often used indistinguishably.

A.5 Baker-Campbell-Hausdorff (BCH) formula

Claim 1 *(Baker-Campbell-Hausdorff (BCH) formula)*

$$e^{tX} e^{tY} = e^{tX + tY + \frac{t^2}{2}[X,Y] + \mathcal{O}(t^3)} \tag{A.11}$$

proof:

To prove this, just expands the exponentials on both sides, neglecting terms of order t^3.

Let

LHS = Left Hand Side of Eq.(A.11)

RHS = Right Hand Side of Eq.(A.11)

Then

$$\begin{aligned} LHS &= (1 + tX + \frac{1}{2}t^2X^2)(1 + tY + \frac{1}{2}t^2Y^2) && \text{(A.12)} \\ &= 1 + t(X+Y) + t^2XY + \frac{t^2}{2}(X^2 + Y^2) + \mathcal{O}(t^3) && \text{(A.13)} \end{aligned}$$

[1] $\cong$ means there is a 1-1 onto map between them.

$$RHS = 1 + t(X+Y) + \frac{t^2}{2}[X,Y] + \frac{t^2}{2}(X+Y)^2 + \mathcal{O}(t^3) \tag{A.14}$$

$$= 1 + t(X+Y) + \frac{t^2}{2}(X^2 + 2XY + Y^2) + \mathcal{O}(t^3) \tag{A.15}$$

QED

The commutator identity of a Lie algebra

$$[X_i, X_j] = f_{ijk} X_k \tag{A.16}$$

is a consequence of the BCH formula. Here is how.

Suppose $\rho : \mathcal{G} \to \mathbb{C}^{n\times n}$ is a rep of group $\mathcal{G}$ and $a_i, b_i, c_i, c_i' \in \mathbb{R}$. Let

$$A = a_i X_i, \quad B = b_i X_i, \quad C = c_i X_i, \quad C' = c_i' X_i \tag{A.17}$$

and

$$\rho(g_1) = e^{sA}, \quad \rho(g_2) = e^{tB}, \quad \rho(g_1 g_2) = e^{tsC}, \quad \rho(g_1 g_2) = e^{tsC'} \tag{A.18}$$

Then

$$\rho(g)\rho(g') = \rho(gg') \tag{A.19}$$

for all $g, g' \in \mathcal{G}$ implies

$$[\rho(g_1), \rho(g_2)] = \rho(g_1 g_2) - \rho(g_2 g_1) \tag{A.20}$$

Substituting the exponential values of $\rho(g)$ for various $g \in \mathcal{G}$ gives

$$[e^{sA}, e^{tB}] = e^{tsC} - e^{tsC'} \tag{A.21}$$

By the BCH formula

$$[e^{sA}, e^{tB}] = \left[1 + sA + tB + \frac{1}{2}ts[A,B]\right] - \left[1 + sA + tB + \frac{1}{2}ts[B,A]\right] + \mathcal{O}(3) \tag{A.22}$$

$$= ts[A,B] + \mathcal{O}(t^i s^j \mid i + j \geq 3) \tag{A.23}$$

Hence

$$ts[A,B] = ts(C - C') + \frac{(ts)^2}{2}\left[C^2 - (C')^2\right] + \mathcal{O}(t^i s^j \mid i + j \geq 3) \tag{A.24}$$

Hence, we must have

$$C = -C', \qquad \underbrace{[A,B]}_{a_i b_j [X_i, X_j]} = 2\underbrace{C}_{c_k X_k} \tag{A.25}$$

Hence, $[X_i, X_j]$ must be a sum of X_k.

A.6 Jacobi identity

The **Jacobi identity** (JI) is

$$[X,[Y,Z]] = [[X,Y],Z] + [Y,[X,Z]] \tag{A.26}$$

The JI can be easily proven by expanding both sides. In this form, the JI says that $[X,\cdot]$ acts like a derivative operator on product $[Y,Z]$.

The JI can be rewritten as

$$[X,[Y,Z]] + [Y[Z,X]] + [Z[X,Y]] = 0 \tag{A.27}$$

In this form, it says that all cyclic permutations of $[X,[Y,Z]]$ add up to zero.

A.7 Group Theory References

Much of this book deals with Group Theory (GT).

GT is a vast subject. Who would have thought that the simple definition of a group would generate so many elegant and useful results.

GT books by mathematicians are very different from GT books by physicists, even though, of course, they agree on the definitions. Mathematicians are, as to be expected, more rigorous and abstract. But it goes much further than that. Physicists are much more interested in applications to physical systems, especially Quantum Mechanics (QM). Soon after QM was invented, it was realized that Linear Algebra (LA) and GT (especially Group Representation Theory, which combines GT and LA) are extremely relevant and useful in QM. Hermann Weyl, Eugene Wigner, Hans Bethe, Linus Pauling, etc. combined QM and GT to understand the spectra and chemistry of atoms and molecules, and later GT was heavily used in Quantum Field Theory and Particle Physics to devise the Standard Model. Condensed Matter physicists have also used it to understand crystalline solids and to predict quasi particles that can be detected in the lab.

My PhD is in physics so in this book I cover GT topics that are mainly of interests to physicists and engineers. Furthermore, I am nowhere as abstract and rigorous as mathematicians usually are.

My favorite books about GT for physicists are Predrag Cvitanovic's Birdtracks book Ref.[1], the Elliott & Dawber's (ED) 2 volume series Ref. [2] and Joshi's book Ref.[3]. I highly recommend all 3 of these references.

The Birdtracks book explains key concepts in GT representation theory using network diagrams (Cvitanovic calls such diagrams birdtracks) The ED books, on the other hand, do not use birdtracks. They use algebra instead. In fact, most GT books don't use birdtracks either. But since this is a book about visualization using network diagrams (quantum bnets), we use birdtracks. In fact, many of the chapters in this

book were heavily influenced by Ref.[1] by Cvitanovic. I hope he doesn't mind. I really love his book.

A.8 Group

A **group** $\mathcal{G}$ is a set of elements with a multiplication map $\mathcal{G} \times \mathcal{G} \to \mathcal{G}$ such that

1. the multiplication is **associative** ; i.e.,

$$(ab)c = a(bc) \tag{A.28}$$

   for $a, b, c \in \mathcal{G}$.

2. there exists an **identity element** $e \in \mathcal{G}$ such that

$$ea = ae = a \tag{A.29}$$

   for all $a \in \mathcal{G}$

3. for any $a \in \mathcal{G}$, there exists an **inverse** $a^{-1} \in \mathcal{G}$ such that

$$aa^{-1} = a^{-1}a = e \tag{A.30}$$

$|\mathcal{G}|$ (i.e., number of elements in $\mathcal{G}$) is called the **order** of the group.

If multiplication is **commutative** (i.e., $ab = ba$ for all $a, b \in \mathcal{G}$), the group is said to be **abelian**.

A **subgroup** $\mathcal{H}$ of $\mathcal{G}$ is a subset of $\mathcal{G}$ ($\mathcal{H} \subset \mathcal{G}$) which is also a group. It's easy to show that any $\mathcal{H} \subset \mathcal{G}$ is a group if it contains the identity and is **closed under multiplication** (i.e., $ab \in \mathcal{H}$ for all $a, b \in \mathcal{H}$)

A.9 Group Representation

A **representation (rep) of a group** $\mathcal{G}$ is a pair (V, ρ) of a vector space V and a map $\rho : \mathcal{G} \to \mathbb{C}^{n\times n}$[2] such that for all $a, b \in \mathcal{G}$,

$$\rho(a)\rho(b) = \rho(ab), \quad \rho(e) = I \tag{A.31}$$

where e is the identity of the group and I is the identity matrix. Such a map is called a homomorphism (because it preserves an operation). [3] The map ρ partitions $\mathcal{G}$ into

[2] More generally, the $\mathbb{C}^{n\times n}$ can be replaced by $\mathbb{R}^{n\times n}$ or by $\mathbb{F}^{n\times n}$ for any field $\mathbb{F}$

[3] In general, any map $\phi : X \to Y$ such that $\phi(x_1x_2) = \phi(x_1)\phi(x_2)$ is called a **homomorphism**. This assumes the product of two elements x_1 and x_2 of X is defined. A homomorphism that is 1-1 and onto is called an **isomorphism**.

disjoints subsets (equivalence classes), such that all elements of $\mathcal{G}$ in each disjoint subset are represented by the same matrix.

Given a vector space V, let

$L(V) = End(V) =$ the **endomorphisms of** V, i.e., the set of all linear maps from V to V,

$GL(V) = \{f \in L(V) \mid f \text{ is invertible}\} =$ **General Linear set on** V.

For a fixed basis of V, there is clearly a 1-1 relationship between elements of $L(V)$ and the matrices in $\mathbb{C}^{n\times n}$ where $n = dim(V)$.

An equivalent but more abstract definition of a rep is: A **representation (rep) of group** $\mathcal{G}$ is a map $\Omega : \mathcal{G} \to L(V)$ such that for all $a, b \in \mathcal{G}$,

$$\Omega(a) \circ \Omega(b) = \Omega(ab), \quad \Omega(e) = I \tag{A.32}$$

A linear map automatically yields a matrix once you choose a basis. That's the entire bridge between the two definitions of a rep.

A linear map in $L(V)$ is called a "linear operator" in Physics. Neither has a particular basis or matrix attached to it. We will henceforth refer to the two definitions of a rep as the **matrix definition and operator definition of a rep**.

Two reps $\rho_1()$ and $\rho_2()$ of a group $\mathcal{G}$ are **equivalent reps** if they are equal up to a **similarity transformation**; i.e., if there is a non-singular matrix M such that

$$\rho_1(g) = M\rho_2(g)M^{-1} \tag{A.33}$$

for all $g \in \mathcal{G}$. In that case, we will write $\rho_1 \equiv \rho_2$.

The vector space V with basis $|i\rangle$ satisfies

$$\Omega(a)|i\rangle = \sum_j |j\rangle \underbrace{\langle j|\Omega(a)|i\rangle}_{\rho(a)_{ji}} \tag{A.34}$$

for all $a \in \mathcal{G}$. This situation is often described by saying that the group $\mathcal{G}$ "acts on" the vector space V. One way to specify a representation is to give the effect of each group element $a \in \mathcal{G}$ on a basis of vectors $\{|1\rangle, |2\rangle, \ldots, |n\rangle\}$.

In this book, we will usually label reps by a Greek letter such as λ, and we will refer to $\rho(g) = G_\lambda(g) = G_\lambda$ as the **representation matrix** (rep-matrix) of $g \in \mathcal{G}$.

If the map $\rho : G \to C^{n\times n}$ is 1-1, we call it a **faithful representation**.

Irreducible representations (irreps) are defined in Ch. 17.

A **singlet (or invariant or conserved) quantity of group** $\mathcal{G}$ is a quantity that is invariant under the group transformations $g \in \mathcal{G}$. The **trivial or singlet representation** is the rep with $\rho(g) = 1 = [1]^{1\times 1}$ for all $g \in \mathcal{G}$. The dimension of this rep is $d_\lambda = 1$. If $\rho(g) = diag(1, 1)$, this is referred to as two identical copies of a singlet rep. The **singlet projection operator** $\delta^b_a \delta^d_c$ when acting on ${z_c}^d$ gives a $\mathrm{tr}(z)diag(1, 1, \ldots, 1)$ where $\mathrm{tr}(z) = {z_c}^c$, so it projects to out a singlet quantity. A singlet projection operator P_λ is associated with a singlet rep λ with rep-matrices

$G_\lambda(g) = 1$. For example, $P_\lambda = \delta_a^b \delta_c^d$ is associated with a rep λ with rep-matrices $G_\lambda \otimes G_\lambda^\dagger = 1$

A **1-dimensional (1-D or 1dim) representation** assigns a complex number to each $g \in \mathcal{G}$.[4] For example, the rep with $\rho(g) = e^{i\beta(g)} = [e^{i\beta(g)}]^{1\times 1}$ for all $g \in \mathcal{G}$, where $\beta(g) \in \mathbb{R}$. The the trivial/singlet rep is a special 1-dim rep. The dimension of this rep is $d_\lambda = 1$.

When a group is defined using matrices, those matrices are called the **defining representation** (def-rep). For example, the group of **General Linear Transformations** is defined by

$$GL(n;\mathbb{C}) = \{M \in \mathbb{C}^{n\times n} : \det M \neq 0\} \tag{A.35}$$

The **adjoint representation** (adj-rep) is defined in Section A.10.

The **fundamental representation** (fun-rep) is defined as the smallest irrep. The def-rep equals the fun-rep for $SU(n), SO(n), Sp(n)$, but not for E_8.

The **regular representation** is defined in Chapter 17 for any finite group and in Chapter 27 for the symmetric group on n_b letters (or n_b boxes), S_{n_b}.

A.10 Adjoint Representation

Let $L(V)$ denote the set of all linear operators on a vector space V. In this section, we will assume the group $\mathcal{G}$ and its Lie algebra $\mathfrak{g}$ are subsets of $L(V)$.

Note that

$$\exp : \mathfrak{g} \to \mathcal{G}, \quad \exp(X) = g \tag{A.36}$$

$$D : \mathcal{G} \to \mathfrak{g}, \quad \underbrace{Dg}_{X} = \lim_{t\to 0} \frac{d}{dt} \underbrace{g(t)}_{e^{tX}} \tag{A.37}$$

($Dg = \ln g$ also)

Define the adjoint function adj by

$$adj : \mathfrak{g} \times l9v \to L(V), \quad ad\{X\}(Y) = [X, Y] \tag{A.38}$$

Note that $ad\{X\}$ can be thought of as half a commutator bracket:

$$ad\{X\} = [X, \cdot\,] \tag{A.39}$$

Claim 2

$$[ad\{X_1\}, ad\{X_2\}] = ad\{[X_1, X_2]\} \tag{A.40}$$

[4]Note that a 1-dim rep and a tensor with one index x_a, where $a = 1, 2, \ldots, n$ are not the same thing. x_a is not even a rep. x_a is often referred to as an n-dim vector. x_a might transform as the n-dim rep with rep-matrices ${G_b}^a$ where $b = 1, 2, \ldots, n$. Always associate the dim of a rep with the matrix dimension of a square matrix.

proof:

$$
\begin{aligned}
[ad\{X_1\}, ad\{X_2\}]\,(Y) &= ad\{X_1\}ad\{X_2\}Y - ad\{X_2\}ad\{X_1\}Y && \text{(A.41)}\\
&= [X_1, [X_2, Y]] - [X_2, [X_1, Y]] && \text{(A.42)}\\
&= [X_1, [X_2, Y]] + [[X_1, Y], X_2] && \text{(A.43)}\\
&= [[X_1, X_2], Y] && \text{(A.44)}\\
&= ad\{[X_1, X_2]\}(Y) && \text{(A.45)}
\end{aligned}
$$

QED

We can also define the Adjoint (capital "A") function Adj by

$$
Adj : \mathcal{G} \times L(V) \to L(V), \quad Ad\{g\}(h) = ghg^{-1} \tag{A.46}
$$

Note that adj and Adj are related as follows

$$
\begin{aligned}
\left[\frac{d}{d\lambda} Ad\{e^{\lambda X}\}(Y)\right]_{\lambda=0} &= \left[e^{\lambda X} X Y e^{-\lambda X} - e^{\lambda X} Y X e^{-\lambda X}\right]_{\lambda=0} && \text{(A.47)}\\
&= [X, Y] && \text{(A.48)}\\
&= ad\{X\}(Y) && \text{(A.49)}
\end{aligned}
$$

Claim 3

$$
Ad\{g_1\}Ad\{g_2\} = Ad\{g_1 g_2\} \tag{A.50}
$$

proof:

$$
\begin{aligned}
Ad\{g_1\}Ad\{g_2\}(X) &= g_1 g_2 X g_2^{-1} g_1^{-1} && \text{(A.51)}\\
&= g_1 g_2 X (g_1 g_2)^{-1} && \text{(A.52)}\\
&= Ad\{g_1 g_2\}(X) && \text{(A.53)}
\end{aligned}
$$

QED

Claim 4 *If the generators* $\{T^i \in \mathbb{C}^{n\times n} \mid i = 1, 2, \ldots N\}$ *of a group* $\mathcal{G}$ *satisfy*

$$[T^i, T^j] = i \sum_k f_{ijk} T^k$$

(A.54)

for $i, j, k = 1, 2, \ldots, N$. *and*

$$(F^i)_{jk} = -if_{ijk} \tag{A.55}$$

Then

$$[F^i, F^j] = i \sum_k f_{ijk} F^k$$

(A.56)

proof:

Suppose

$$F^i = ad\{T^i\} \tag{A.57}$$

Then

$$\begin{aligned} F^i T^j &= ad\{T^i\}(T^j) && \text{(A.58)} \\ &= [T^i, T^j] && \text{(A.59)} \\ &= i \sum_k f_{ijk} T^k && \text{(A.60)} \\ &= \sum_k T^k (F^i)_{kj} && \text{(A.61)} \end{aligned}$$

and

$$\mathrm{tr}(T^{k\dagger} F_j F^j) = (F^i)_{kj} \tag{A.62}$$

Hence

$$\begin{aligned}
[F^i, F^j] &= [ad\{T^i\}, ad\{T^j\}] && \text{(A.63)}\\
&= ad\{[T^i, T^j]\} && \text{(A.64)}\\
&= i\sum_k f_{ijk} ad\{T^k\} && \text{(A.65)}\\
&= i\sum_k f_{ijk} F^k && \text{(A.66)}
\end{aligned}$$

QED

The matrices $\{F^i \in \mathbb{C}^{N\times N} \mid i = 1, 2, \ldots, N\}$ generate what is called the **adjoint representation** of the Lie algebra $\mathfrak{g}$ of group $\mathcal{G}$.

A.11 Dimensions

In Physics/Math, the term "dimension" can mean various things. For example, it might mean

1. vector space dimension: the number of vectors in a basis of a vector space
2. matrix row or column dimensions: the number of rows or columns in a square matrix $M_{a,b}$.
3. vector dimension: the number of components of a vector x_a

These 3 uses of the term "dimension" are all closely related but not the same. Sometimes, there are several dimensions at play in the same conversation.

Let MD stand for matrix dimension. A rep λ of group $\mathcal{G}$ with rep-matrices G_λ has 2 MDs associated with it that we must distinguish:

1. adjoint rep MD: the number N of generators T_i, where $i = 1, 2, \ldots, N$, the dimension of the Lie algebra (considered as a vector space spanned by the generators) of $\mathcal{G}$.
2. def rep MD: the number of rows and columns of the square rep-matrix G_λ

For example, the Pauli matrices are 3 2×2 matrices.

For $SU(n)$ and $U(n)$

$n = d_{def}$ = MD of rep-matrices G_λ in defining rep of $U(n)$ or $SU(n)$. This MD equals n for both $U(n)$ and $SU(n)$.

$N = d_{adj}$ = MD of rep-matrices G_λ in adjoint rep of $U(n)$ or $SU(n)$. As we shall prove in Chapter 24, $N = n^2$ for $U(n)$ but $N = n^2 - 1$ for $SU(n)$.

A.12 Vector Space and Algebra Over a Field $\mathbb{F}$

A **vector space (a.k.a. linear space) $\mathcal{V}$ over a field $\mathbb{F}$** is defined as a set $\mathcal{V}$ endowed with two operations: vector addition $+ : \mathcal{V} \times \mathcal{V} \to \mathcal{V}$, and scalar multiplication $\mathbb{F} \times \mathcal{V} \to \mathcal{V}$, such that

- $\mathcal{V}$ is an abelian group under $+$ with identity 0 and inverse of $x \in \mathcal{V}$ equal to $-x \in \mathcal{V}$
- For $\alpha, \beta \in \mathbb{F}$ and $x, y \in \mathcal{V}$

$$\alpha(x+y) = \alpha x + \alpha y \tag{A.67}$$
$$(\alpha+\beta)x = \alpha x + \beta x \tag{A.68}$$
$$\alpha(\beta x) = (\alpha\beta)x \tag{A.69}$$
$$1x = x \tag{A.70}$$
$$0x = 0 \tag{A.71}$$

In this book, we will always use either $\mathbb{C}$ or $\mathbb{R}$ for $\mathbb{F}$. Both of these fields are infinite but some fields are finite.

An **algebra $\mathcal{A}$** is a vector space which, besides being endowed with vector addition and scalar multiplication as all vector spaces are, it has a **bilinear vector product**. A bilinear vector product is a product that is linear on both sides; i.e.,

$$(\alpha x + \beta y) \cdot z = \alpha x \cdot z + \beta y \cdot z \tag{A.72}$$

and

$$z \cdot (\alpha x + \beta y) = \alpha z \cdot x + \beta z \cdot y \tag{A.73}$$

for $x, y, z \in \mathcal{A}$ and $\alpha, \beta \in \mathbb{C}$. The cross product (but not the dot product) for vectors in $\mathbb{R}^3$, the multiplication of 2 complex numbers, the matrix product or matrix commutator of 2 square matrices, are all good examples of bilinear vector products.

Let $B = \{\tau_i : i = 1, 2, \ldots, r\}$ be a basis for the vector space $\mathcal{A}$. Then note that $\mathcal{A}$ is closed under vector multiplication.

$$\tau_i \cdot \tau_j = \sum_k {c_{ij}}^k \tau_k \tag{A.74}$$

where ${c_{ij}}^k \in \mathbb{C}$. The ${c_{ij}}^k$ are called **structure constants** of $\mathcal{A}$. In Dirac notation

$$\tau_i|\tau_j\rangle = |\tau_i \cdot \tau_j\rangle = \sum_k {c_{ij}}^k |\tau_k\rangle \tag{A.75}$$

$$\langle\tau_k|\tau_i|\tau_j\rangle = {c_{ij}}^k \tag{A.76}$$

An **associative algebra** satisfies $(x \cdot y) \cdot z = x \cdot (y \cdot z)$ for $x, y, z \in \mathcal{A}$.

- Not associative: cross product for vectors in $\mathbb{R}^3$.
- Associative: the matrix product or matrix commutator of 2 square matrices and the product of complex numbers

A.13 Tensors

Let

$(x_a) = (x_1, x_2, \ldots, x_n) = x^{:n} \in V^n = \mathbb{C}^{n\times 1}$

Reverse of vector $rev(x_1, x_2, \ldots, x_n) = (x_n, x_{n-1}, \ldots, x_1)$

$x^b = \sum_a g^{ba} x_a$, g^{ab} is the **metric tensor**

$(y^b) = (y^1, y^2, \ldots, y^n) = y^{\dagger:n} \in V^{\dagger n} = \mathbb{C}^{n\times 1}$. V^n is the lower indices vector space and $V^{\dagger n}$ is its **dual vector space** (i.e., with upper indices).

${M_a}^b \in \mathbb{C}^{n\times n}$, $a, b \in \mathbb{Z}_{[1,n]}$

Implicit Summation Convention

$$ {M_a}^b x_b = \sum_{b=1}^{n} {M_a}^b x_b \tag{A.77} $$

The **Hermitian conjugate** $\dagger$ equals $*T$ where $*$ is complex conjugation and T is transpose. Hence

$$ \boxed{{(M^T)_a}^b = {M_b}^a} \qquad a \longleftarrow M^T \longleftarrow b \;=\; b \longleftarrow M \longleftarrow a \tag{A.78} $$

$$ \boxed{{(M^\dagger)_a}^b = ({M_b}^a)^*} \qquad a \longleftarrow M^\dagger \longleftarrow b \;=\; b \longleftarrow M^* \longleftarrow a \tag{A.79} $$

To avoid confusion, follow the golden rule: <u>write $\dagger$ and T only before declaring the indices; and write the $*$ only after declaring the indices.</u> Note that $\dagger$ does 3 things:

1. reverse the horizontal order of the indices
2. reverse vertical positions of the indices; i.e., lower upper indices and raise lower indices.
3. replace the tensor components by their complex conjugates

Transposing only does items 1 and 2.

If M is a Hermitian matrix (i.e., $M^\dagger = M$), then

$$ \boxed{{M_a}^b = ({M_b}^a)^*} \qquad a \longleftarrow M \longleftarrow b \;=\; b \longleftarrow M^* \longleftarrow a \tag{A.80} $$

Suppose $a_i, b_i, c_i, d_i \in \mathbb{Z}_{[1,n]}$. From Fig.A.1

Figure A.1: Index labels for Mx where $M \in \mathbb{C}^{n^{p+q} \times n^{p+q}}$ and $x \in V^{n^p} \otimes V^{\dagger n^q}$. Note that we list indices in counterclockwise (CC) direction, starting at the top.

Figure A.2: Index labels for $x^\dagger M^\dagger$ corresponding to Fig.A.2. Note that we list indices in counterclockwise (CC) direction, starting at the top.

$$y_{a^{:p}}{}^{b^{:q}} = M_{a^{:p}}{}^{b^{:q}}{}_{rev(c^{:q})}{}^{rev(d^{:p})} x_{d^{:p}}{}^{c^{:q}} \tag{A.81}$$

If we define x_α and x^α by

$$x_\alpha = x_{a^{:p}}{}^{b^{:q}}, \quad x^\alpha = x_{rev(b^{:q})}{}^{rev(a^{:p})} \tag{A.82}$$

then

$$x_\alpha = M_\alpha{}^\beta x_\beta \tag{A.83}$$

Hermitian conjugation (see Fig.A.2)

$$\begin{cases} (M^\dagger)_a{}^d = (M_d{}^a)^* \\ (M^\dagger)_\alpha{}^\delta = (M_{rev(\delta)}{}^{rev(\alpha)})^* \end{cases} \qquad \alpha \longleftarrow M^\dagger \longleftarrow \delta \;=\; rev(\delta) \longleftarrow M^* \longleftarrow rev(\alpha) \tag{A.84}$$

Note that † does 3 things to the birdtrack:

1. It flips the horizontal axis of the figure. (In the algebraic expression of the tensor, this corresponds to reversing the horizontal order of the indices.)

2. For each node, it changes incoming arrows to outgoing ones and vice versa. (In the algebraic expression of the tensor, this corresponds reversing the vertical positions of the indices; i.e., lowering upper indices and raising lower ones.)

3. It replaces the tensor component by its complex conjugate

Hermitian matrix

$$M^\dagger = M, \quad \begin{cases} M_a{}^d = (M_d{}^a)^* \\ M_\alpha{}^\delta = (M_{rev(\delta)}{}^{rev(\alpha)})^* \end{cases} \tag{A.85}$$

Unitary matrix

$$M^\dagger M = 1, \quad \begin{cases} (M_b{}^a)^* M_a{}^c = \delta_b^c \\ (M_{rev(\beta)}{}^{rev(\alpha)})^* M_\alpha{}^\gamma = \delta^\gamma_{rev(\beta)} \end{cases} \tag{A.86}$$

Note that for $x \in V^n$, $y \in V^{\dagger n}$, and $G \in \mathcal{G} \subset GL(n;\mathbb{C})$,

$$(x')_a (y')^b = G^b{}_c G_a{}^d x_d y^c \tag{A.87}$$

If $x \in V^{n^p} \otimes V^{\dagger n^q}$, $\mathbb{G} \in \mathcal{G} \subset GL(n^{p+q};\mathbb{C})$,

$$(x')_{a^{\cdot p}}{}^{b^{\cdot q}} = \mathbb{G}_{a^{\cdot p}}{}^{b^{\cdot q}}{}_{rev(c^{\cdot q})}{}^{rev(d^{\cdot p})} x_{d^{\cdot p}}{}^{c^{\cdot q}}, \quad (x'_\alpha = \mathbb{G}_\alpha{}^\beta x_\beta) \tag{A.88}$$

where we define

$$\mathbb{G}_{a^{\cdot p}}{}^{b^{\cdot q}}{}_{rev(c^{\cdot q})}{}^{rev(d^{\cdot p})} \stackrel{\text{def}}{=} \prod_{i=1}^p G_{a_i}{}^{d_i} \prod_{i=1}^q G^\dagger{}^{b_i}{}_{c_i} \tag{A.89}$$

An issue that arises with tensors is this: When is it permissible to represent a tensor by M^{cd}_{ab}? If we define M^{cd}_{ab} by

$$M^{cd}_{ab} = M_{ab}{}^{cd} \tag{A.90}$$

then it's always permissible. Then one can define tensors like $M_a{}^{bcd}$ as

$$M_a{}^{bcd} = g^{bb'} M_{ab'}{}^{cd} = g^{bb'} M^{cd}_{ab'} \tag{A.91}$$

One drawback of using the notation M^{cd}_{ab} is that if one is interested in using several versions of M^{cd}_{ab} with some indices raised or lowered, one has to write down explicitly the metric tensors that do the lowering and raising. Instead of writing $M_a{}^{bcd}$, you'll have to write $g^{bb'} M^{cd}_{ab'}$. This is not very onerous when explaining a topic in which not much lowering and raising of indices is done. But in topics like General Relativity that do use a lot of raising and lowering of indices, it might not be too succinct.

A.14 Permutations

Some well known notation and results about permutations are these.

$(1,2)$ stands for a **transposition**; i.e., a map that swaps 1 and 2:

$$\begin{pmatrix} 1 & 2 & 3 & \dots & p \\ & \swarrow\!\!\searrow & \downarrow & & \downarrow \\ 1 & 2 & 3 & \dots & p \end{pmatrix} \tag{A.92}$$

$(3, 2, 1)$ stands for a **permutation**; i.e., a map that maps $3 \to 2 \to 1 \to 3$.

$$\begin{tikzcd}[column sep=small] \left(\begin{array}{cccccc} 1 & 2 & 3 & 4 & \dots & p \\ 1 & 2 & 3 & 4 & \dots & p \end{array} \right) \end{tikzcd} \tag{A.93}$$

Any reordering of $(1, 2, 3, \dots, p)$ is a permutation of p letters (or numbers or elements).

The set S_p of all permutation of p letters is called the **symmetric group in p letters**. It has $p!$ elements (i.e., $|S_p| = p!$) and is a group, where the group's product is map composition and the group's identity element is the identity map.

Any permutation can be expressed as a product of transpositions, For example, $(3, 2, 1) = (3, 2)(2, 1)$.

An **even permutation** such as $(3, 2, 1)$ can be expressed as a product of an even number of transpositions. An **odd permutation** can be expressed as a product of an odd number of transpositions.

Appendix B

Birdtracks

This chapter is based on Cvitanovic's Birdtracks book Ref. [1] and my paper Ref. [6]

The tensor notation discussed in Sec.A.13 is succinct and straightforward, but it's not visually illuminating. The birdtrack notation that we shall discuss in this chapter, is not as succinct as the tensor notation, and can lead to sign errors if you are careless, but it is very visually illuminating. Thus, the tensor and birdtrack notations complement each other well. We will often display results using both, side by side.

B.1 Classical Bayesian Networks and their Instantiations

Classical Bayesian Networks (bnets) are discussed exhaustively in the first book of this series, Ref.[5]. This is a brief section to remind the reader of how they are defined.

Let PD stand for probability distribution.

We call $P_{\underline{y}|\underline{x}} : val(\underline{y}) \times val(\underline{x}) \to [0,1]$ a **Transition Probability Matrix** (TPM)[1] if

$$\sum_{y \in val(\underline{y})} P_{\underline{y}|\underline{x}}(y|x) = 1 \tag{B.1}$$

In other words, a TPM is a conditional PD. A TPM of the form

$$P(y|x) = \delta(y, f(x)) \tag{B.2}$$

for some function $f : val(\underline{x}) \to val(\underline{y})$ is said to be **deterministic**.

A bnet is a **Directed Acyclic Graph** (DAG) with the nodes labelled by random variables[2]. Each bnet stands for a full PD of the node random variables expressed as a product of a TPM for each node. For example, the bnet

[1] A TPM is also known as a Conditional Probability Table (CPT).

[2] As in the first volume of this series, we indicate random variables by underlined letters

$$\mathcal{C} = \begin{tikzcd} & \underline{b} \arrow[dl] & \\ \underline{c} & & \underline{a} \arrow[ul] \arrow[ll] \end{tikzcd} \tag{B.3}$$

stands for the full PD

$$P(a,b,c) = P(c|b,a)P(b|a)P(a) \tag{B.4}$$

Bnets do not have free indices because their nodes are labelled by random variables. It is convenient to draw the DAG for a bnet but with the underlining removed from the random variables, and then to assign a numerical value to this new DAG. The resultant DAG now has free indices. We call it an **instantiation of the bnet**. For example, from the bnet $\mathcal{C}$ of Eq.(B.3), we get the instantiation[3]

$$P(a,b,c) = P(c|b,a)P(b|a)P(a) = \begin{tikzcd} & b \arrow[dl] & \\ c & & a \arrow[ul] \arrow[ll] \end{tikzcd} \quad P(a) \tag{B.5}$$

Let $a^{:2} = (a_1, a_2)$. Based on the bnet $\mathcal{C}$ of Eq.(B.3), define a new bnet $\mathcal{C}'$ as follows

$$\mathcal{C}' = \begin{tikzcd} & \underline{b} \arrow[dl] & \\ \underline{c} & & \underline{a}^{:2} \arrow[ul, "\underline{a}_1"'] \arrow[ll, "\underline{a}_2"] \end{tikzcd} \tag{B.6}$$

$\mathcal{C}'$ represents the the full PD

$$P(a^{:2}, b, c) = P(c|b, a_2)P(a_2|a^{:2})P(b|a_1)P(a_1|a^{:2})P(a^{:2}) \tag{B.7}$$

The 2 new nodes $\underline{a}_1$ and $\underline{a}_2$ of bnet $\mathcal{C}'$ are called **marginalizer nodes**. We assign to them the following TPMs (printed in blue):

$$P[a'_i|\underline{a}^{:2} = (a_1, a_2)] = \delta(a'_i, a_i) \tag{B.8}$$

for $i = 1, 2$. We can also define an instantiation of $\mathcal{C}'$ as follows:

$$P'(a^{:2}, b, c) = \begin{tikzcd} & b \arrow[dl] & \\ c & & a^{:2} \arrow[ul, "a_1"'] \arrow[ll, "a_2"] \end{tikzcd} \quad P(a^{:2}) \tag{B.9}$$

[3]Note that we don't include the root node probabilities as part of the graph value. Thus, $P(a,b) = \underbrace{b \longleftarrow a}_{P(b|a)} P(a)$

B.2 Quantum Bayesian Networks and their Instantiations

As far as I know, Quantum Bayesian Networks (qbnets) were invented by me in Ref.[6].

qbnets are closely analogous to classical bnets, but the TPM are replaced by **Transition Amplitude Matrices (TAM)**.

Let PA stand for probability amplitude.

We call $A_{\underline{y}|\underline{x}} : val(\underline{y}) \times val(\underline{x}) \to \mathbb{C}$ a TAM if

$$\sum_{y \in val(\underline{y})} |A(y|x)|^2 = 1 \tag{B.10}$$

Note that if A is the matrix with entries $\langle y|A|x\rangle = A(y|x)$, then

$$\left\langle x|A^\dagger A|x\right\rangle = \sum_{y \in val(\underline{y})} |A(y|x)|^2 = 1 \tag{B.11}$$

If A is a unitary matrix, then $A^\dagger A = AA^\dagger = 1$ so "half" ($A^\dagger A = 1$) of the definition of unitary matrix is satisfied by a TAM. If both halves were satisfied, A would have to be a square matrix.

A qbnet is a DAG with the nodes labelled by random variables. Each qbnet stands for a full PA of the node random variables expressed as a product of a TAM for each node. For example, the qbnet

$$\mathcal{Q} = \tag{B.12}$$

stands for the full PA

$$A(a,b,c) = A(c|b,a)A(b|a)A(a) \tag{B.13}$$

Qbnets do not have free indices because their nodes are labelled by random variables. It is convenient to draw the DAG for a qbnet but with the underlining removed from the random variables, and then to assign a numerical value to this new DAG. The resultant DAG now has free indices. We call it an **instantiation of the qbnet**. For example, from the bnet $\mathcal{Q}$ of Eq.(B.12), we get the instantiation

$$A(a,b,c) = A(c|b,a)A(b|a)A(a) = \tag{B.14}$$

$$A(a)$$

Let $a^{:2} = (a_1, a_2)$. Based on the qbnet $\mathcal{Q}$ of Eq.(B.12), define a new qbnet $\mathcal{Q}'$ as follows

$$\mathcal{Q}' = \quad \begin{tikzcd} & \underline{b} \arrow[dl] & \\ \underline{c} & & \underline{a}^{:2} \arrow[ul, "\underline{a}_1"'] \arrow[ll, "\underline{a}_2"'] \end{tikzcd} \tag{B.15}$$

$\mathcal{Q}'$ represents the the full PA

$$A(a^{:2}, b, c) = A(c|b, a_2)A(a_2|a^{:2})A(b|a_1)A(a_1|a^{:2})A(a^{:2}) \tag{B.16}$$

The 2 new nodes $\underline{a}_1$ and $\underline{a}_2$ of qbnet $\mathcal{Q}'$ are called **marginalizer nodes**. We assign to them the following TAMs (printed in blue):

$$A[a'_i|\underline{a}^{:2} = (a_1, a_2)] = \delta(a'_i, a_i) \tag{B.17}$$

for $i = 1, 2$. We can also define an instantiation of $\mathcal{Q}'$ as follows:

$$A(a^{:2}, b, c) = \quad \begin{tikzcd} & b \arrow[dl] & \\ c & & a^{:2} \arrow[ul, "a_1"'] \arrow[ll, "a_2"'] \end{tikzcd} \quad A(a^{:2}) \tag{B.18}$$

B.3 Birdtracks

Tensors written in **algebraic notation** such as $T_a{}^{bc}$ were already discussed in Section A.13

Birdtracks are a DAG used to represent algebraic tensor equations. The nodes of the DAG are labelled by tensors and the arrows are labeled by the indices of the tensors: upper indices of a tensor are pictured as incoming arrows of the node, and lower indices as outgoing arrows.

We've already discussed in Section A.13 what we will call the **Counter Clockwise (CC) convention** of drawing birdtrack nodes. Now that we have discussed classical and quantum bnets, we would like to introduce an equivalent, more bnet like, convention that we will call the **Fully Label (FL) convention**. Cvitanovic's birdtracks book Ref.[1] uses the CC convention. We will use both. No confusion will arise, as long as it is clear from context which convention is being used.

Next we review the CC convention and then describe the FL convention for the first time.

---

1. **CC convention**

   In the CC convention, we must specify for each the node, which arrow is first, and then the CC order in which the arrows enter or leave the node is drawn so that it reproduces the horizontal order of the indices in the algebraic notation for the tensor. We shall often indicate the first arrow by coloring it green.

   For example,

$$\delta(b, a) = \mathbb{1}(a = b) = \delta^b_a = \; a \leftarrow\!\bullet\!\!- b \tag{B.19}$$

$$X_{ab}{}^{c} =$$

(B.20)

In this picture, the green arrow indicates which tensor index is first horizontally in the algebraic representation of the tensor.

Sometimes there is no need to indicate which arrow is first by drawing it in green, because all choices give the same number. For example, in the birdtracks for δ_a^b, starting with the incoming arrow or the outgoing arrow leads to the same number. Likewise, with the totally symmetric tensor d_{ijk} (doesn't change sign under swap of any two indices) and the totally antisymmetric tensor f_{ijk} (changes sign under swap of any two indices), it doesn't matter if one starts at i, j or k. This is shown below.

(B.21)

(B.22)

Note that for a totally antisymmetic tensor with an even number of indices, the beginning arrow can change the sign. Indeed,

(B.23)

2. **FL convention**

   In the FL convention, the arrows must be labelled by random (underlined) variables, and the names of the nodes must also indicate by underlined variables what is the the order of the indices

For example,

$$\delta(b,a) = \mathbb{1}(a=b) = \delta^b_a = \; a \longleftarrow\!\bullet\!\longleftarrow b \tag{B.24}$$

$$\langle a,b|X_{\underline{ab}}{}^{\underline{c}}|c\rangle = X_{ab}{}^{c} = \tag{B.25}$$

Sometimes, we will denote this node simply by X. This is okay as long as we state that $X = X_{\underline{ab}}{}^{\underline{cd}}$, and we don't start using X to represent a different version of $X_{\underline{ab}}{}^{\underline{cd}}$ with some of the indices raised or lowered or their horizontal order changed.

Often, we will write simply a instead of $\underline{a} = a$. This is similar to the shorthand $P(\underline{a} = a) = P(a)$.

Note that, unlike in the CC convention, in the FL convention, the CC order in which the arrows enter or leave the node, is meaningless. All orders are equivalent. This is akin to the notation for bnets and qbnets.

If we don't follow either convention CC or FL, we won't be able to distinguish between the graphical representations of $T^{1,2,3}$ and $T^{2,1,3}$, for example.

Two other features of the CC and FL conventions that we would like to discuss before ending this section are how to indicate

- **noncyclic index contractions**; i.e., index contractions (i.e., summations) that do not introduce cycles, and
- **traces**; i.e., index contractions that do introduce cycles.

Noncyclic index contractions will be indicated by an arrow connecting two nodes, with the symbol $\sum a$ midway in the arrow if the index a is being contracted. For simplicity, we often omit writing the $\sum a$ altogether.

For example (in CC convention),

$$X_{ab}{}^{c} = \quad , \quad (X^\dagger)_c{}^{ba} = \tag{B.26}$$

$$(X^\dagger)_c{}^{ba} X_{ab}{}^c \quad =$$

(B.27)

$$=$$

(B.28)

Birdtracks are DAGs until we are asked to take a trace of one of their indices. Tracing ruins their acyclicity. The acyclicity of DAGs is mandated by causality. The acyclicity of tracing hints to its acausal (or feedback) nature.

In this book, we will indicate tracing with a red undirected arrow. For example, in the CC convention,

$$\mathrm{tr}_{\underline{b}} X_{a\underline{b}}{}^{\underline{b}} = \sum_b X_{ab}{}^b =$$

(B.29)

If

$$R^x{}_{b_3}{}^{a_3}{}_{a_2}{}^{b_2} S_{x' b_2}{}^{a_2}{}_{a_1}{}^{b_1} =$$

(B.30)

then

$$\mathrm{tr}_{\underline{x}} R^{\underline{x}}{}_{b_3}{}^{a_3}{}_{a_2}{}^{b_2} S_{\underline{x} b_2}{}^{a_2}{}_{a_1}{}^{b_1} =$$

(B.31)

When using the FL convention, it becomes clear that birdtracks can be understood as instantiations of qbnets, provided that we weaken slightly the definition

of qbnets, by not requiring that the unitarity condition Eq.(B.10) be satisfied. Also, the outgoing arrows of the nodes of a birdtrack must be understood as the result of marginalizer nodes. For example, if the arrows leaving a node are labelled a_1 and a_2, then these two arrows must be understood as the result of marginalizing an arrow $a^{:2} = (a_1, a_2)$.

Appendix C

Clebsch-Gordan Series Tables

In this Appendix, we present jpgs of some interesting tables from the Birdtracks book Ref.[1] by Cvitanovic. The tables give Clebsch-Gordan series (tensor product decompositions) of $SU(n)$ and $SO(n)$

A black (white) filled rectangle with p incoming and p outgoing legs represents the anti-symmetrizer $\mathcal{A}_p$ (symmetrizer $\mathcal{S}_p$).

Thick lines represent particles in the defining representation. These lines range over $1, 2, \ldots, n$.

Thin lines represent particles in the adjoint rep. (In this book we represent such particles by a wavy line $\sim\sim\sim$.)

Y_a	$\mathbf{P}_{Y_a}$	d_{Y_a}
$\begin{array}{\|c\|c\|c\|}\hline 1 & 2 & 3 \\ \hline\end{array}$		$\frac{n(n+1)(n+2)}{6}$
$\begin{array}{\|c\|c\|}\hline 1 & 2 \\ \hline 3 \\ \cline{1-1}\end{array}$		$\frac{n(n^2-1)}{3}$
$\begin{array}{\|c\|c\|}\hline 1 & 3 \\ \hline 2 \\ \cline{1-1}\end{array}$		
$\begin{array}{\|c\|}\hline 1 \\ \hline 2 \\ \hline 3 \\ \hline\end{array}$		$\frac{(n-2)(n-1)n}{6}$
$\boxed{1} \otimes \boxed{2} \otimes \boxed{3}$		n^3

Table 9.1 Reduction of 3-index tensor. The last row shows the direct sum of the Young tableaux, the sum of the dimensions of the irreps adding up to n^3, and the sum of the projection operators adding up to the identity as verification of completeness (3.51).

Young tableaux	$\square \times \square$	$=$	$\bullet$	$+$	$\begin{array}{\|c\|}\hline \\ \hline \\ \hline\end{array}$	$+$	$\square\square$
Dynkin labels	$(10\ldots) \times (10\ldots)$	$=$	$(00\ldots)$	$+$	$(010\ldots)$	$+$	$(20\ldots)$
Dimensions	n^2	$=$	1	$+$	$\frac{n(n-1)}{2}$	$+$	$\frac{(n+2)(n-1)}{2}$
Dynkin indices	$2n\frac{1}{n-2}$	$=$	0	$+$	1	$+$	$\frac{n+2}{n-2}$
Projectors		$=$	$\frac{1}{n}$	$+$		$+$	$\left\{ \right.$ $-\frac{1}{n}$ $\left. \right\}$

Table 10.1 $SO(n)$ Clebsch-Gordan series for $V \otimes V$.

	$\underline{A} \otimes \underline{q}$	$=$	$\underline{V_1}$	$\oplus$	$\underline{V_2}$	$\oplus$	$\underline{V_3}$
Dynkin labels	$(10\ldots1) \otimes (10\ldots)$	$=$	$(10\ldots)$	$\oplus$	$(200\ldots01)$	$\oplus$	$(010\ldots01)$
Dimensions:	$(n^2-1)n$	$=$	n	$+$	$\frac{n(n-1)(n+2)}{2}$	$+$	$\frac{n(n+1)(n-2)}{2}$
Indices:	$n+\frac{n^2-1}{2n}$	$=$	$\frac{1}{2n}$	$+$	$\frac{(n+2)(3n-1)}{4n}$	$+$	$\frac{(n-2)(3n+1)}{4n}$
SU(3) example:							
Dimensions:	$8 \cdot 3$	$=$	3	$+$	15	$+$	6
Indices:	$13/3$	$=$	$1/6$	$+$	$10/3$	$+$	$5/6$
SU(4) example:							
Dimensions:	$15 \cdot 4$	$=$	4	$+$	36	$+$	20
Indices:	$47/8$	$=$	$1/8$	$+$	$33/8$	$+$	$13/8$
Projection operators:							
$\mathbf{P}_1 = \frac{n}{n^2-1}$							
$\mathbf{P}_2 = \frac{1}{2}\Big\{$							
$\mathbf{P}_2 = \frac{1}{2}\Big\{$							

Table 9.3 $SU(n)$ $V \otimes A$ Clebsch-Gordan series.

Young tableaux		=		+		+	
Dynkin labels	$(010\ldots) \times (100\ldots)$	=	$(100\ldots)$	+	$(0010\ldots)$	+	$(110\ldots)$
Dimensions	$\frac{n^2(n-1)}{2}$	=	n	+	$\frac{n(n-1)(n-2)}{6}$	+	$\frac{n(n^2-4)}{3}$
$SO(3)$	$\underline{9}$	=	$\underline{3}$	+	$\underline{1}$	+	$\underline{5}$
$SO(4)$	$\underline{24}$	=	$\underline{4}$	+	$\underline{4}$	+	$\underline{16}$
Projectors		=	$\frac{2}{n-1}$	+	$\frac{1}{3}\Big\{$ -2	+	$\frac{2}{3}\Big\{$ $-\frac{3}{n-1}$

Table 10.2 $SO(n)$ $A \otimes V$ Clebsch-Gordan series.

Chapter 1

Branching Rules and Symmetry Breaking

1.1 Block diagonalization

Figure 1.1: Pictorial representation of Clebsch-Gordan series

For any square matrices A, B, C (not necessarily of the same dimension)

$$A \oplus B \oplus C = \begin{pmatrix} A & 0 & 0 \\ 0 & B & 0 \\ 0 & 0 & C \end{pmatrix} \tag{1.1}$$

If A_i for $i = 1, 2, \ldots, n$ are square matrices, $A_1 \oplus A_2 \oplus \ldots \oplus A_n$ is called a **block diagonal matrix**.

An intuitive way of discussing branching rules is via block diagonalization (BD) of matrices.

Before discussing branching rules via BD, it is a good idea to discuss Clebsch-Gordan series via BD. When we discuss later on the branching rules via BD, we shall point out the difference between the two. The two are different applications of BD that are often confused.

Clebsch-Gordan series (see Chapter 4) via BD is illustrated in Fig.1.1. The figure shows a chain of BD steps. The first BD step is

$$\rho(g) \xrightarrow[BD]{} \rho_1(g) \oplus \rho_2(g) \oplus \ldots \oplus \rho_n(g) \tag{1.2}$$

where $\rho(), \rho_i()$ are reps of G. The second BD step, each $\rho_i(g)$ is block diagonalized to produce

$$\bigoplus_{i=1}^{n} \rho_i(g) \xrightarrow[BD]{} \bigoplus_{i=1}^{n} \bigoplus_{j=1}^{m} \rho_{i,j}(g) \tag{1.3}$$

where the $\rho_{ij}()$ are reps of G. In general, we can have any number of BD steps, not just 2.

Usually, the beginning of the chain of BDs is

$$\rho(g) = \rho'(g) \otimes \rho''(g) \tag{1.4}$$

and at the end of chain, the reps $\rho_{i,j,\ldots}(g)$ are all irreducible.

Figure 1.2: Pictorial representation of Branching Rules.

Given a map $f : X \to Y$, $x \mapsto f(x)$, a restriction $f \downarrow X_1$ of the map to $X_1 \subset X$ is the same assignment rule but the domain restricted to X_1. Hence, $f \downarrow X_1 : X_1 \to Y$, $x \mapsto f(x)$.

Branching rules via BD are illustrated in Fig.1.2. Assume G, H_1, H_2 are groups and $G \supset H_1 \supset H_2$. The first BD step takes

$$\{\rho(g) \mid g \in G\} \xrightarrow[BD]{} \{\rho_1(h_1) \oplus \rho_2(h_1) \oplus \ldots \oplus \rho_n(h_1) \mid h_1 \in H_1\} \tag{1.5}$$

where $\rho()$ is an irrep of G and $\rho_i()$ for $i = 1, 2, \ldots, n$ are irreps of H_1. $\rho_i()$ can be obtained by block diagonalizing the restriction $\rho \downarrow H_1(h_1)$ for each $h_1 \in H_1$.

In the second BD step,

$$\left\{\bigoplus_{i=1}^{n} \rho_i(h_1) \mid h_1 \in H_1\right\} \xrightarrow[BD]{} \left\{\bigoplus_{i=1}^{n}\bigoplus_{j=1}^{m} \rho_{i,j}(h_2) \mid h \in H_2\right\} \tag{1.6}$$

where the $\rho_{ij}()$ are irreps of H_2. $\rho_{ij}()$ can be obtained by block diagonalizing the restriction $\rho \downarrow H_2(h_2)$ for each $h_2 \in H_2$. In general, we can have any number of BD steps, not just 2.

Note that both Clebsch-Gordan series and branching rules can be described in terms of vector spaces, by the following equation, but the meaning of the vector spaces is different for the 2.

$$V \xrightarrow[BD]{} \bigoplus_{i=1}^{n} V_i \xrightarrow[BD]{} \bigoplus_{i=1}^{n}\bigoplus_{j=1}^{m} V_{ij} \tag{1.7}$$

Now that we have clarified the difference between Clebsch-Gordan series and branching rules, let's say more about the topic of this chapter, branching rules.

Define a **tree of reps (TOR)** as a tree wherein each node represents an irrep of H_j and arrows point from an irrep of H_j to a direct sum of irreps of H_{j+1} where $H_j \supset H_{j+1}$ and H_j, H_{j+1} are subgroups of G.

As the tree branches out more and more, we get

- less symmetry, fewer conserved quantities, fewer unbroken generators, smaller multiplets, less degeneracy, lower energy scale
- more broken generators.

If the root node irrep of a TOR is the adjoint representation of G, then the dimension of each irrep in the tree is also the number of generators for that irrep. Hence, we will call the TOR for the adjoint rep of G, a **tree of generators (TOG)**. For example, the octet ($\underline{8}$) irrep of $SU(3)$ is the adjoint irrep of $SU(3)$, and $SU(3)$ has 8 generators. If we draw the weight diagram[1] for $\underline{8}\mid_{SU(3)}$, it contains 6 weights of multiplicity 1 and one weight of multiplicity 2. Hence, if a weight of multiplicity m is thought of as m dots, then there is a 1–1 correspondence between the dots of a weight diagram of the adjoint rep of G, and the generators of G.

[1]Weight diagrams are discussed in Chapter 25

1.2 Symmetry Breaking

- **Explicit symmetry breaking**:

  $\mathfrak{g}$ = Lie algebra of symmetry group G.

  In explicit symmetry breaking, we add a small perturbation $\delta\mathcal{H}$ to the Hamiltonian $\mathcal{H}$ so that

$$[\mathfrak{g}, \mathcal{H}] = 0, \quad [\mathfrak{g}, \mathcal{H} + \delta\mathcal{H}] \neq 0 \tag{1.8}$$

- **Spontaneous symmetry breaking**

  $\{Q_u \mid u = 1, 2, \ldots, n_u\}$ = unbroken generators. $Q_u|vac_0\rangle = 0$ for all u. If $h = e^{i\sum_u r_u Q_u}$ where $r_u \in \mathbb{R}$, then $h|vac_0\rangle = |vac_0\rangle$

  $\{X_b \mid b = 1, 2, \ldots n_b\}$ = broken generators. $X_b|vac_0\rangle \neq 0$ for all b.

  $\mathfrak{h}$ = stabilizer subalgebra. Algebra spanned by the Q_u

  $\mathfrak{g}/\mathfrak{h}$ = orbit subalgebra. Algebra spanned by the X_b.

  $\pi_b \in \mathbb{R}$, Goldstone (Go) boson modes, one Go-boson mode per broken generator X_b

  $|vac_\pi\rangle = e^{i\sum_b \pi_b X_b}|vac_0\rangle$= vacuum state, n_b dimensional manifold.

  $K.E.$ = Kinetic Energy

  V = Potential Energy

  $\mathcal{H} = K.E. + V$ = Hamiltonian (total energy)

$$\begin{cases} \text{for all } u, & [Q_u, \mathcal{H}] = 0, \quad Q_u|vac_0\rangle = 0 \\ \text{for all } b, & [X_b, \mathcal{H}] = 0, \quad X_b|vac_0\rangle \neq 0 \end{cases} \tag{1.9}$$

$$[\mathfrak{g}, \mathcal{H}] = 0, \quad \mathfrak{h}|vac_0\rangle = 0, \quad \mathfrak{g}/\mathfrak{h}|vac_0\rangle \neq 0 \tag{1.10}$$

  Each Q_u corresponds to a massless boson.

  Each X_b corresponds to a massive boson.

  Example (Higgs Mechanism):

  Suppose $\phi \in \mathbb{C}$ (Later on we discuss electroweak symmetry breaking where $\phi \in \mathbb{C}^2$).

$$\mathcal{H} = K.E. + \underbrace{\lambda(|\phi|^2 - v^2)^2}_{V(\phi)} \tag{1.11}$$

where $\lambda, v > 0$. The order parameter v is called the **vacuum expected value (VEV)**. This potential V is plotted in Fig.1.3. Note that its minimum is when $|\phi| = v$ and that $V(e^{i\theta}\phi) = V(\phi)$ for $\theta \in \mathbb{R}$. Consider

$$\underbrace{U(1)}_{G} \supset \underbrace{\{e\}}_{H} \tag{1.12}$$

$$\mathfrak{g} = \{1\}, \quad \mathfrak{g}/\mathfrak{h} = \{1\}, \quad \mathfrak{h} = \emptyset \tag{1.13}$$

$$\begin{aligned} &\text{extremum that does not violate symmetry:} && \phi = 0 \\ &\text{extremum that breaks } U(1) \text{ symmetry:} && \phi = \underbrace{\langle\phi\rangle}_{v} + \tilde{\phi} \end{aligned} \tag{1.14}$$

$$V = \lambda(2v\tilde{\phi} + \tilde{\phi}^2)^2 \tag{1.15}$$

Go-boson manifold

$$|vac_\theta\rangle = e^{i\theta}|vac_0\rangle \tag{1.16}$$

for $\theta \in \mathbb{R}$.

Figure 1.3: Mexican Hat potential for Higgs Mechanism.

For Mexican hat potential:

- The circular valley = degenerate vacua
- Motion around the circle = Go-boson mode (massless)
- Motion radially = Higgs mode (massive)

1.3 Examples

gen=generator, X =broken gen, ✓ =unbroken gen, degen.=degeneracy

1. $SU(3)$ triplet (Explicit Symmetry Breaking)

$$\begin{cases} SU(3) \supset & SU(2) \times U(1) \\ 8 \text{ gen} & 3+1 \text{ gen} \end{cases} \tag{1.17}$$

$\underline{3}$, 3 degen
- $\underline{2}$, 2 degen
- $\underline{1}$, 1 degen

---

2. $SU(3)$ octet (Spontaneous Symmetry Breaking)

$$\begin{cases} SU(3) \supset & SU(2) \times U(1) \supset & U(1) \\ 8 \text{ gen} & 3+1 \text{ gen} & 1 \text{ gen} \end{cases} \tag{1.18}$$

Assume symmetry is broken spontaneously instead of explicitly. Note that octet is adjoint rep of $SU(3)$ so TOR is TOG too.

$\underline{8}$, 8 gen ✓
- $\underline{2}$, 2 gen X
  - $\underline{1}$ 1 gen X
  - $\underline{1}$ 1 gen X
- $\underline{3}$, 3 gen ✓
  - $\underline{1}$, 1 gen X
  - $\underline{1}$, 1 gen X
  - $\underline{1}$, 1 gen X
- $\underline{1}$, 1 gen ✓
- $\underline{2}$, 2 gen X
  - $\underline{1}$, 1 gen X
  - $\underline{1}$, 1 gen X

---

3. Zeeman splitting without electron spin (Explicit Symmetry Breaking)

$$\begin{cases} SU(2) \supset & SO(2) \\ 3 \text{ gen} & 1 \text{ gen} \end{cases} \tag{1.19}$$

$L = \ell$, $(2\ell+1)$ degen
- $L_z = -\ell$, 1 degen
- $L_z = -\ell + 1$, 1 degen
- $\cdots$
- $L_z = \ell$, 1 degen

---

4. Zeeman splitting with electron spin (Explicit Symmetry Breaking)

   $L_z = \ell_z \in \{-\ell, -\ell+1, \ldots, \ell-1, \ell\} = \mathbb{Z}_{[-\ell,\ell]}$

   $S_z = s_z \in \{-\frac{1}{2}, +\frac{1}{2}\}$

   $J_z = j_z = \ell_z + s_z \in \mathbb{Z}_{[-\ell,\ell]} \pm \frac{1}{2}$

$$\begin{cases} SU(2)_{\text{orbital } \ell} \times SU(2)_{\text{spin } 1/2} \supset & U(1)_{\text{orbital } \ell} \times SU(2)_{\text{spin } 1/2} \\ 3+3 \text{ gen} & 1+3 \text{ gen} \end{cases} \tag{1.20}$$

   $L = \ell, S = \frac{1}{2}$, $(2\ell+1)2$ `degen`
   - $L_z = -\ell$, $S = \frac{1}{2}$, `2 degen`
   - $L_z = -\ell+1$, $S = \frac{1}{2}$, `2 degen`
   - $\ldots$
   - $L_z = \ell$, $S = \frac{1}{2}$, `2 degen`

5. $SO(n)$ $\underline{n}$ rep (Explicit Symmetry Breaking)

   Let $n = p + q$[2]

$$\begin{cases} SO(n) & \supset & SO(p) \times SO(q) \\ \mathfrak{so}(n) & \supset & \mathfrak{so}(p) \oplus \mathfrak{so}(q) \\ \frac{1}{2}n(n-1) \text{ gen} & & \frac{1}{2}p(p-1) + \frac{1}{2}q(q-1) \text{ gen} \end{cases} \tag{1.21}$$

   $\underline{n}$, n `degen`
   - $\underline{p}$, p `degen`
   - $\underline{q}$, q `degen`

6. $SO(n)$ $\underline{n}$ rep (Explicit Symmetry Breaking)

$$\begin{cases} SO(n) & \supset & SO(n-1) \\ \frac{1}{2}n(n-1) \text{ gen} & & \frac{1}{2}(n-1)(n-2) \text{ gen} \end{cases} \tag{1.22}$$

   $\underline{n}$, n `degen`
   - $\underline{1}$, `1 degen`
   - $\underline{n-1}$, $n-1$ `degen`

---

7. Electroweak symmetry breaking (Spontaneous Symmetry Breaking)

$$\begin{cases} SU(2)_Y \times U(1)_Y \supset & U(1)_{em} \\ 3+1 \text{ gen} & 1 \text{ gen} \end{cases} \tag{1.23}$$

[2]Note that given two groups G_1, G_2, their Cartesian product $G_1 \times G_2$ is defined, but not their direct sum $G_1 \oplus G_2$ or direct (Kronecker) product $G_1 \otimes G_2$. Direct sums and products are defined for vectors (and vector spaces) and matrices (and matrix reps).

$\underline{3} \times \underline{1}$, 3+1 gen ✓
- $\underline{1}$, 1 gen ✓ , photon A_μ
- $\underline{1}$, 1 gen X , W^+
- $\underline{1}$, 1 gen X , W^-
- $\underline{1}$, 1 gen X , Z^0

- 1 unbroken generator (electric charge $Q = T_3 + \frac{1}{2}Y$) yields massless photons.
- 3 broken generators $(T_1, T_2, T_3 - \sin(\theta_W)Q)$ yield 3 Goldstone (Go) modes (massless). The 3 Go modes become the longitudinal modes of the 3 gauge bosons W^+, W^-, Z^0. Massless particles like the photon have 2 transverse polarizations, and no longitudinal one. Only massive particles have 3 polarization (2 transverse and one longitudinal). So the 3 Go-bosons are "eaten up" by the 3 initially (i.e., when $v = 0$) massless gauge bosons to produce finally (i.e., when $v \neq 0$) 3 massive gauge bosons.

Higgs field $\phi(x) \in \mathbb{C}^2$.

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \tag{1.24}$$

	$VEV = 0$	$VEV \neq 0$
massive gauge bosons		3 (9 dofs)
massless gauge bosons	4 (8 dofs)	1 (2 dofs)
massive Higgs (real scalar field)		1 (1 dof)
massless Higgs (complex doublet)	1 (4 dofs)	

Table 1.1: For electroweak symmetry breaking, number of degrees of freedom (dofs) before and after VEV

Table 1.1 and Fig.1.4 gives an inventory of the number of (real) degrees of freedom (dofs) before and after VEV. In both cases, it's 12, so the number of dofs is conserved. Massless gauge bosons have 2 dofs (2 polarizations) and massive ones have 3 dofs (3 polarizations). The Higgs field initially has 4 (real) dofs because it's a $\mathbb{C}^2$ vector. The Higgs field finally is reduced to a real number.

It might sound paradoxical that a massless Go-boson + a massless gauge boson can yield a massive gauge boson. This is explained intuitively by the following analogy: when light (massless gauge boson) goes through a medium (Go-bosons), it slows down to speeds less than speed of light, so the photons acquire a mass. The Go-bosons are massless but they have kinetic energy.

Figure 1.4: Pictorial representation of info in Table 1.1. Each arrow represents one dof (i.e., one polarization).

Chapter 2

Casimir Operators

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

The term **Casimir operator** will be used to refer to 2 types of operators: a Casimir matrix or a Casimir sun

---

Casimir matrix

Examples:

$M_2 =$

(2.1)

$M_4 =$

(2.2)

Casimir matrices are invariant matrices so they satisfy

$0 = [T_r, M_4]$

$0 =$

(2.3)

Because Casimir matrices are invariant matrices, they commute with each other. For example,

$$M_2 M_4 = M_4 M_2 \tag{2.4}$$

Casimir sun. By this we mean a tensor consisting of a loop of fundamental particles with gluons (rays) emanating from it; i.e., this:

$\mathrm{tr}(T_i T_j \ldots T_l) =$

(2.5)

Note that the Lie Algebra commutation relations can be applies to a Casimir sun:

(2.6)

Note also that we can define a symmetrized version of a Casimir sun:

$$h_{i_1 i_2 \ldots i_p} = \frac{1}{p!} \sum_{\sigma \in \mathcal{S}_p} \mathrm{tr}(T_{\sigma(i_1)} T_{\sigma(i_2)} \ldots T_{\sigma(i_p)}) =$$

(2.7)

2.1 Independent Casimirs of Simple Lie Groups

So as not to have any gluon free indices, it is convenient to contract with a matrix M, all the outgoing gluons of a Casimir sun . Let

$$\boxed{M = \sum_i T_i x_i} \qquad \longleftarrow M \longleftarrow \; = \sum_i x_i$$

(2.8)

Then

$$\mathrm{tr}(M^k) = \leftarrow M \leftarrow M \quad \ldots \leftarrow M \leftarrow \tag{2.9}$$

$$= \sum_{i_1 i_2 \ldots i_k} \leftarrow T_{i_1} \leftarrow T_{i_2} \quad \ldots \leftarrow T_{i_k} \leftarrow \quad x_{i_1} x_{i_2} \ldots x_{i_k} \tag{2.10}$$

$$= \sum_{i_1 i_2 \ldots i_k} \underbrace{\begin{array}{c} \leftarrow T_{i'_1} \leftarrow T_{i'_2} \quad \ldots \leftarrow T_{i'_k} \leftarrow \\ \mathcal{S}_k \\ i_1 \quad i_2 \quad i_k \end{array}}_{h_{i_1 i_2 \ldots i_k}} \quad x_{i_1} x_{i_2} \ldots x_{i_k} \tag{2.11}$$

Recall Eq.(3.22) for the general characteristic equation of a matrix M

$$0 = \sum_{k=0}^{n} (-1)^k \left(\mathrm{tr}_{1\ldots n-k} \mathcal{A}_{n-k} M^{\otimes n-k} \right) M^k \tag{2.12}$$

$$= \begin{cases} M^n \\ -M^{n-1}(\mathrm{tr} M) \\ +M^{n-2}(\mathrm{tr}_{1\ldots 2} \mathcal{A}_2 M^{\otimes 2}) \\ \ldots \\ (-1)^n det(M) \end{cases} \tag{2.13}$$

Note that that $\mathrm{tr}_{12} \mathcal{A}_2 M^{\otimes 2}$ can be expressed in terms of $\mathrm{tr}(M)$ and $\mathrm{tr}(M^2)$. Likewise, $\mathrm{tr}_{123} \mathcal{A}_3 M^{\otimes 3}$ can be expressed in terms of $\mathrm{tr}(M)$, $\mathrm{tr}(M^2)$ and $\mathrm{tr}(M^3)$. If we take the trace of the above equation, we get an equation constraining $\mathrm{tr}(M^k)$ for $k = 1, 2, \ldots n$.

The **Betti number** of the Casimir $\mathrm{tr}(M^k) \neq 0$ is the integer k. Table 2.1 gives all the Betti numbers for the simple Lie Algebras. Note that the Betti numbers in Table 2.1 are all even except for $SU(n)$.

For all simple Lie Groups except for $SU(n)$, there is a invertible symmetric or skew-symmetric bilinear invariant matrix g_{ab} satisfying $g_{ab} g^{bc} = \delta_a^c$. Hence

$A_r = \mathfrak{su}(r+1)$	$2, 3, \ldots, r+1$
$B_r = \mathfrak{so}(2r+1)$	$2, 4, 6, \ldots, 2r$
$C_r = \mathfrak{sp}(2r)$	$2, 4, 6, \ldots, 2r$
$D_r = \mathfrak{so}(2r)$	$2, 4, \ldots, 2r-2, 2r$
G_2	$2, 6$
F_4	$2, 6, 8, 12$
E_6	$2, 5, 6, 8, 9, 12$
E_7	$6, 8, 10, 12, 14, 18$
E_8	$8, 12, 14, 18, 20, 24, 30$

Table 2.1: Betti numbers for the simple Lie Algebras

(2.14)

As illustrated in Eq.(2.14), if such a g^{ab} exists, a Casimir $\mathrm{tr}(M^k)$ equals itself times $(-1)^k$. Hence, only Casimirs with even k are non-zero.

Claim 5 *The following are a complete set of Casimir operators for the given groups*

$GL(n;\mathbb{C})$:

(2.15)

$SU(n)$:

(2.16)

$SO(2r+1)$ *and* $Sp(2r)$:

(2.17)

$SO(2r)$:

(2.18)

proof:

Define

$$I_r(x) = \quad (2.19)$$

where $\mathcal{A}^{\frac{1}{2}}$ is the Levi Civita tensor.(see Chapter 23). Then an expansion of $I_r^2(x)$ contains $\mathrm{tr}(M^{2r})$ among its summands.

$$I_r^2(x) = \quad = \mathrm{tr}(M^{2r}) + \dots \quad (2.20)$$

QED

2.2 Casimir Matrix Expressed in Terms of $6j$ Coefficients

Define the Casimir matrix I_p as

$$(I_p)_a{}^b = \mathrm{tr}(T_\lambda^{i_1} T_\lambda^{i_2} \dots T_\lambda^{i_p})(T_\mu^{i_1} T_\mu^{i_2} \dots T_\mu^{i_p})_a{}^b \tag{2.21}$$

$$= \tag{2.22}$$

The goal of this section is to express I_p in terms of $6j$ coefficients.

Let

$$M = \tag{2.23}$$

We will first decompose M in terms of $6j$ coefficients, and then use that result to decompose I_p for $p = 1, 2, 3, \dots$. Note that

$$M = \sum_{\rho,\rho'} \tag{2.24}$$

$$= \sum_\rho A(\lambda, \rho, \mu) \tag{2.25}$$

where

$$A(\lambda, \rho, \mu) = \frac{1}{d_\rho} \tag{2.26}$$

Claim 6 *If*

$$\Gamma_2(\rho) = \tag{2.27}$$

then

$$A(\lambda,\mu,\rho) = -\frac{1}{2}\left[\Gamma_2(\rho) - \Gamma_2(\lambda) - \Gamma_2(\mu)\right] \tag{2.28}$$

proof:

Recall Eq.(10.22). Square both sides of the equation.

(2.29)

(2.30)

(2.31)

$$= -\frac{1}{2}\left[\Gamma_2(\rho) - \Gamma_2(\lambda) - \Gamma_2(\mu)\right] \tag{2.32}$$

This is similar to assuming

$$\vec{J} = \vec{L} + \vec{S} \tag{2.33}$$

where $\vec{J}, \vec{L}, \vec{S}$ are the total, orbital and spin angular momentum. Then

$$\vec{L} \cdot \vec{S} = \frac{1}{2}\left[J^2 - L^2 - S^2\right] \tag{2.34}$$

QED Next note that

$$\begin{aligned}
(I_p)_a{}^b &= (M^p)^c{}_a{}^b{}_c && (2.35)\\
&= \sum_{\rho \in irreps} [A(\lambda,\mu,\rho)]^p \quad a \xleftarrow{\rho} C_\rho \quad C_\rho^\dagger \xleftarrow{\rho} b && (2.36)
\end{aligned}$$

If μ is an irrep,

$$\xleftarrow{\rho} C_\rho \quad C_\rho^\dagger \xleftarrow{\rho} \quad = \quad \frac{T_\rho \xleftarrow{\lambda} T_\rho}{d_\mu} \xleftarrow{\mu} \tag{2.37}$$

$$= \quad \frac{d_\rho}{d_\lambda} \xleftarrow{\mu} \text{(because } \rho \text{ is an irrep)} \tag{2.38}$$

2.3 $\mathrm{tr}(M^2)$ and $\mathrm{tr}(M^3)$

There are 3 quadratic Casimir ($\mathrm{tr}(M^2)$) matrices:

1. $$\boxed{(T_iT_i)_a{}^b = \Gamma_{fun}\delta_a^b} \quad \longleftarrow T_i \longleftarrow T_i \longleftarrow \quad = \Gamma_{fun} \longleftarrow \tag{2.39}$$

2. $$\boxed{\mathrm{tr}(T_iT_j) = \kappa\delta_i^j} \quad \sim\sim T_i \quad T_j \sim\sim \quad = \kappa \sim\sim \tag{2.40}$$

3. $$\boxed{f_{ijk}f_{kji'} = \Gamma_{adj}\delta_i^{i'}} \quad \sim\sim f \quad f \sim\sim \quad = \Gamma_{adj} \sim\sim \tag{2.41}$$

Note that

$$T_i \sim\sim T_i \quad = n\Gamma_{fun} = N\kappa \tag{2.42}$$

Claim 7

$$\longleftarrow T_i \longleftarrow T_k \longleftarrow T_i \longleftarrow \quad = \left(\frac{\kappa N}{n} - \frac{\Gamma_{adj}}{2}\right) \quad \longleftarrow T_k \longleftarrow \tag{2.43}$$

(2.44)

(2.45)

proof:
QED

2.4 Dynkin Index

$$DI_\lambda = \frac{\mathrm{tr}(T^i_\lambda T^i_\lambda)}{f^i_{jk} f^i_{kj}} =$$

(2.46)

Chapter 3

Characteristic Equations

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

Let

$$M_a{}^b = \; a \longleftarrow M \longleftarrow b \tag{3.1}$$

for $a, b = 1, 2, \ldots, n$.

The goal of this chapter is to express the coefficients of the characteristic equation (i.e., $det(M - \lambda) = 0$) of M as traces.

For starters, note the difference between birdtracks for a matrix power and a tensor power of M.

$$M^2 = \; \longleftarrow M^2 \longleftarrow \; = \; \longleftarrow M \longleftarrow M \longleftarrow \tag{3.2}$$

$$M \otimes M = M^{\otimes 2} = \begin{array}{c} \longleftarrow M \longleftarrow \\ \\ \longleftarrow M \longleftarrow \end{array} \tag{3.3}$$

In general, $M^{\otimes p}$ is defined by

$$(M^{\otimes p})_\alpha{}^\beta = (M^{\otimes p})_{a^{:p}}{}^{rev(b^p)} = M_{a_1}{}^{b_1} M_{a_2}{}^{b_2} \ldots M_{a_p}{}^{b_p}$$

$$\begin{array}{c} \longleftarrow M^{\otimes p} \longleftarrow \\ \longleftarrow \quad \longleftarrow \\ \vdots \qquad \vdots \\ \longleftarrow \quad \longleftarrow \end{array} \quad = \quad \begin{array}{c} \longleftarrow M \longleftarrow \\ \longleftarrow M \longleftarrow \\ \vdots \qquad \vdots \\ \longleftarrow M \longleftarrow \end{array} \tag{3.4}$$

where $a_i, b_i \in \mathbb{Z}_{[1,n]}$, and we define the anti-symmetrized trace of $M^{\otimes p}$ by

$$\mathrm{tr}_{1\ldots p}\mathcal{A}[M^{\otimes p}] \;=\; \mathcal{A}_{a^{\cdot p}}{}^{rev(b^{\cdot p})} \prod_{i=1}^{p} M_{b_i}{}^{a_i} \tag{3.5}$$

$=$

(Cvitanovic Drawing Style) (3.6)

$=$

(This book's drawing style) (3.7)

Note that the determinant of M is one of those traces

$$detM = \mathrm{tr}_{1\ldots n}\mathcal{A}[M^{\otimes n}] \tag{3.8}$$

Claim 8

(3.9)

proof:

See Chapter 23.

QED

Consider the above claim for $p = 2, 3$.

(3.10)

If we multiply from the right, by M^d for $d = 1, 2$, the first row of Eq.(3.10) and then take the trace of that row, we get

(3.11)

Let

$$\tau = \mathrm{tr}(M) \tag{3.12}$$

Then Eqs.(3.11) can be expressed algebraically by

$$\mathrm{tr}_{1,2,3}\mathcal{A}_3(M^{\otimes 3}) = \frac{1}{3}\left[\tau \mathrm{tr}_{1,2}\mathcal{A}_2(M^{\otimes 2}) - \mathrm{tr}(M^2)\tau + \mathrm{tr}M^3\right] \tag{3.13}$$

and

$$\mathrm{tr}_{1,2}\mathcal{A}_2 M^{\otimes 2} = \frac{1}{2}\left[\tau^2 - \mathrm{tr}(M^2)\right] \tag{3.14}$$

Therefore,

$$\mathrm{tr}_{1,2,3}\mathcal{A}_3(M^{\otimes 3}) = \frac{1}{3}\left[\frac{1}{2}\tau^3 - \frac{3}{2}\mathrm{tr}(M^2)\tau + \mathrm{tr}M^3\right] \tag{3.15}$$

$$= \frac{1}{3!}\left[\tau^3 - 3\mathrm{tr}(M^2)\tau + 2\mathrm{tr}M^3\right] \tag{3.16}$$

In general,

$$\mathrm{tr}_{1\ldots p}\mathcal{A}_p M = \frac{1}{p}\sum_{k=1}^{p}(-1)^{k-1}\left(\mathrm{tr}_{1\ldots p-k}\mathcal{A}_{p-k}M^{\otimes p-k}\right)\mathrm{tr}(M^k) \tag{3.17}$$

Next note that

$$\mathcal{A}_p = 0 \quad \text{if } p > n \tag{3.18}$$

This follows because the Levi Civita tensor with more than n indices is zero.; i.e.,

$$\epsilon_{a_1,a_2,\ldots,a_{n+1}} = 0 \tag{3.19}$$

Indeed, two of the a_i must be equal, so that element of the ϵ tensor is zero

Let I be the $n \times n$ identity matrix. Then, since $\mathcal{A}_{n+1} = 0$, the following is true

$$0 = \mathrm{tr}_{2\ldots n+1}\mathcal{A}_{n+1} I \otimes M^{\otimes n} \qquad 0 = \tag{3.20}$$

We can now expand the right hand side of Eq.(3.20) using identity Eq.(3.17)

$$0 = \sum_{k=0}^{n}(-1)^k\left(\mathrm{tr}_{1\ldots n-k}\mathcal{A}_{n-k}M^{\otimes n-k}\right)M^k \tag{3.21}$$

$$= \begin{cases} M^n \\ -M^{n-1}(\mathrm{tr}M) \\ +M^{n-2}(\mathrm{tr}_{1\ldots 2}\mathcal{A}_2 M^{\otimes 2}) \\ \ldots \\ (-1)^n det(M) \end{cases} \tag{3.22}$$

Viola. The last equation is none other than the characteristic equation of M. As promised, the coefficients of this polynomial in M, are expressed as traces.

Chapter 4

Clebsch-Gordan Coefficients

This chapter is based on Cvitanovic's Birdtracks book Ref.[1].

Recall that if $|x\rangle$ for $x \in val(\underline{x})$ is a complete, orthonormal basis in Quantum Mechanics, then

$$\langle x|y\rangle = \delta(x,y) \quad \text{(orthonormality)} \tag{4.1}$$

and

$$\sum_x |x\rangle\langle x| = 1 \quad \text{(completeness)} \tag{4.2}$$

Furthermore, if we define

$$\pi_x = |x\rangle\langle x| \tag{4.3}$$

then π_x is a is a projection operator so

$$\pi_x \pi_x = \pi_x \tag{4.4}$$

and

$$\pi_x|y\rangle = |y\rangle\delta(x,y), \quad \langle y|\pi_x = \langle y|\delta(x,y) \tag{4.5}$$

Below, we will define matrices $C_\lambda = \langle\lambda|$ and $C_\lambda^\dagger = |\lambda\rangle$. If we identify $\langle\lambda|$ with $\langle x|$, and $|\lambda\rangle$ with $|x\rangle$, then $\langle\lambda|$ and $|\lambda\rangle$ satisfy identities similar to those satisfied by $\langle x|$ and $|x\rangle$. We will show this in this chapter.

4.1 CB Coefficients as Matrices

Suppose that $M \in \mathbb{C}^{d\times d}$ is a Hermitian matrix. Then we have

$$M = C^\dagger \Lambda C \tag{4.6}$$

where $C \in \mathbb{C}^{d\times d}$ is a unitary matrix, and Λ is a diagonal matrix.

One can partition C into rectangular submatrices $\langle\lambda|$ that have d_λ rows with $d_\lambda < d$, such that we have one $\langle\lambda|$ for each eigenvalue λ of C. Likewise, we can partition $C^\dagger$ into rectangular submatrices $C_\lambda^\dagger$ that have d_λ columns with $d_\lambda < d$, such that we have one $|\lambda\rangle$ for each eigenvalue λ of C. Thus, if $I^{d_\lambda \times d_\lambda}$ is the $d_\lambda \times d_\lambda$ identity matrix,

$$\begin{bmatrix} 0 \\ C_\lambda^{d_\lambda \times d} \\ 0 \end{bmatrix}^{d\times d} = \underbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & I^{d_\lambda \times d_\lambda} & 0 \\ 0 & 0 & 0 \end{bmatrix}^{d\times d}}_{\pi_\lambda} C^{d\times d} \tag{4.7}$$

$$\begin{bmatrix} 0 & (C_\lambda^\dagger)^{d\times d_\lambda} & 0 \end{bmatrix}^{d\times d} = (C^\dagger)^{d\times d} \underbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & I^{d_\lambda \times d_\lambda} & 0 \\ 0 & 0 & 0 \end{bmatrix}^{d\times d}}_{\pi_\lambda} \tag{4.8}$$

Henceforth in this chapter, we will use C_λ and $\langle\lambda|$ interchangeably. Likewise, we will use $C_\lambda^\dagger$ and $|\lambda\rangle$ interchangeably The matrices $C_\lambda = \langle\lambda|$ are called the **Clebsch-Gordan (CG) coefficients** for M.

The matrices π_λ obviously form a complete orthogonal set of projection operators:

$$\sum_\lambda \pi_\lambda = 1, \quad \pi_\lambda \pi_\mu = \pi_\lambda \delta(\lambda, \mu) \tag{4.9}$$

We now have

$$\pi_\lambda C = \langle\lambda|, \quad C^\dagger \pi_\lambda = |\lambda\rangle \tag{4.10}$$

$$\begin{aligned} \langle\lambda||\lambda\rangle &= \pi_\lambda C C^\dagger \pi_\lambda && (4.11) \\ &= \pi_\lambda && (4.12) \end{aligned}$$

$$\begin{aligned} M &= C^\dagger \Lambda C && (4.13) \\ &= C^\dagger \left(\sum_\lambda \lambda \pi_\lambda \right) C && (4.14) \\ &= \sum_\lambda \lambda |\lambda\rangle\langle\lambda| && (4.15) \end{aligned}$$

$$\begin{aligned} I^{d\times d} &= C^\dagger C && (4.16) \\ &= \sum_\lambda C^\dagger \pi_\lambda C && (4.17) \\ &= \sum_\lambda \underbrace{|\lambda\rangle\langle\lambda|}_{P_\lambda} && (4.18) \end{aligned}$$

We will call Eq.(4.18) a **Clebsch-Gordan (CG) series or decomposition** either in that form, or after multiplying by a vector space V, as in

$$V = \sum_\lambda P_\lambda V \tag{4.19}$$

A simple example of a CG series is

$$\vec{r} = \hat{x} \oplus \hat{y} \oplus \hat{z} \tag{4.20}$$

for a vector $\vec{r} \in \mathbb{R}^3$. In this expression, the vectors $\hat{x}, \hat{y}, \hat{z}$ constitute a complete (i.e., basis) orthonormal set for the vectors acted upon by $SO(3)$. Any generic vector $\vec{r} \in \mathbb{R}^3$ can be expressed as[1]

$$\vec{r} = a\hat{x} + b\hat{y} + c\hat{z} \tag{4.21}$$

for some $a, b, c \in \mathbb{R}$.

So far, we have established that

$$\begin{aligned} P_\lambda &= |\lambda\rangle\langle\lambda| = C^\dagger \pi_\lambda C, && (4.22)\\ \pi_\lambda &= \langle\lambda||\lambda\rangle && (4.23)\\ 1 &= \sum_\lambda \underbrace{|\lambda\rangle\langle\lambda|}_{P_\lambda} = \sum_\lambda \underbrace{\langle\lambda||\lambda\rangle}_{\pi_\lambda} && (4.24) \end{aligned}$$

In fact, the P_λ form a complete orthogonal set of projection operators, just like the π_λ.

$$\sum_\lambda P_\lambda = 1, \quad P_\lambda P_\mu = P_\lambda \delta(\mu, \nu) \tag{4.25}$$

Whereas the π_λ satisfy

$$\pi_\lambda C = \langle\lambda|, \quad C^\dagger \pi_\lambda = |\lambda\rangle \tag{4.26}$$

the P_λ satisfy

$$C P_\lambda = \langle\lambda|, \quad P_\lambda C^\dagger = |\lambda\rangle \tag{4.27}$$

Since we are assuming M is Hermitian, its eigenvalues are real. Thus, we can absorb the eigenvalue λ into the CG coefficients by defining

$$\mathcal{C}_\lambda = \sqrt{\lambda}\langle\lambda| \tag{4.28}$$

and writing

$$M = \sum_\lambda \mathcal{C}_\lambda^\dagger \mathcal{C}_\lambda \tag{4.29}$$

[1]Recall that a direct sum of two vector spaces $V = V_1 \oplus V_2$ means $V_1 \cap V_2 = \{0\}$

Here is an example of a CG series. One can decompose $V^n \otimes V^{\dagger n} = \sum_\lambda V_\lambda$ as follows

$$
\begin{aligned}
&1 = \frac{1}{n} P_S + P_{adj} + \sum_{\lambda \neq Adj} P_\lambda, \\
&\delta^a_d \delta^c_d = \frac{1}{n} \delta^a_b \delta^c_d + (P_{adj})_a{}^b{}_c{}^d + \sum_{\lambda \neq Adj} (P_\lambda)_a{}^b{}_c{}^d
\end{aligned}
\tag{4.30}
$$

4.2 Generalization From Matrices to Tensors

Let $b^{:nb} = (b_1, b_2, \ldots, b_{nb})$ where $b_i \in Z_{[0,d_{\mu_i}]}$ and $a \in Z_{[1,d_\lambda]}$. Assume that

$$
d_\lambda = \prod_{i=1}^{:nb} d_{\mu_i} \tag{4.31}
$$

Now define the birdtracks

(4.32)

and

(4.33)

We will assume there is no difference between when a Greek letter is lowered and when it is raised. Also, all summations over a Greek letter will be stated explicitly; i.e., no implicit summations over repeated Greek letters.

On the other hand, the Latin letter indices b_i, a of $\langle\lambda|$ and $|\lambda\rangle$ may be lowered or raised and their arrows changed from outgoing to incoming or vice versa. Furthermore, we will use implicit summation over repeated Latin letters.

The Greek letters label representation of the group (not necessarily irreps). Each b_i labels a member of μ_i, and each a labels a member of λ.

$$(\langle\lambda|)_a{}^{rev((b')^{:nb})}(P_\mu)_{(b')^{:nb}}{}^{rev(b^{:nb})} = \delta(\mu,\lambda)(\langle\mu|)_a{}^{rev(b^{:nb})}, \quad \langle\lambda|P_\mu = \delta(\mu,\lambda)\langle\mu|$$

(4.34)

$$(P_\mu)_{b^{:nb}}{}^{rev((b')^{:nb})}(|\lambda\rangle)^a{}_{(b')^{:nb}} = \delta(\mu,\lambda)(|\mu\rangle)^a{}_{b^{:nb}}, \quad P_\mu|\lambda\rangle = \delta(\mu,\lambda)|\mu\rangle$$

(4.35)

$$(\langle\lambda|)_a{}^{rev(b^{:nb})}(|\mu\rangle)^{a'}{}_{b^{:nb}} = \delta(\lambda,\mu)\delta^{a'}_a, \quad \langle\lambda||\mu\rangle = \delta(\mu,\lambda)$$

(4.36)

$$\sum_\lambda (|\lambda\rangle)^a{}_{b^{:nb}}(\langle\lambda|)_a{}^{rev((b')^{:nb})} = \delta^{rev((b')^{:nb})}_{b^{:nb}}, \quad \sum_\lambda |\lambda\rangle\langle\lambda| = 1$$

(4.37)

Chapter 5

Dynkin Diagrams

This chapter is based on Ref.[2], section 20.4.

This chapter is an overview of the classification of simple Lie algebras, a classification that was invented mainly by Killing, Cartan and Dynkin, in that historical order. The classification is valid for Lie algebras over $\mathbb{C}$[1] This caveat is important because there are more simple Lie algebras over $\mathbb{R}$ than over $\mathbb{C}$. When defining the generators of Lie algebras in other chapters, we defined a real Lie algebra $\mathfrak{g}_{\mathbb{R}}$ (a vector space over $\mathbb{R}$) which exponentiates to a group $\mathcal{G}_{\mathbb{R}} = \exp(\mathfrak{g}_{\mathbb{R}})$. This chapter refers to the complexification $\mathfrak{g}_{\mathbb{C}}$ (a vector space over $\mathbb{C}$) of $\mathfrak{g}_{\mathbb{R}}$ and to the group $\mathcal{G}_{\mathbb{C}} = \exp(\mathfrak{g}_{\mathbb{C}})$

Suppose $\mathfrak{g}_{\mathbb{C}}$ has generators X_s for $s \in S = \{1, 2, \ldots \mathcal{D}\}$ where

$\mathcal{D} = \frac{1}{2} \dim_{\mathbb{R}} \mathfrak{g}_{\mathbb{C}} = \dim_{\mathbb{C}} \mathfrak{g}_{\mathbb{C}} =$ half the number of real degrees of freedom of the Lie algebra.

By definition, the generators X_s are closed under commutation so

$$[X_q, X_p] = \sum_t f_{qp}{}^t X_t \tag{5.1}$$

for some $f_{qp}{}^t \in \mathbb{C}$.

Define

$$g_{qs} = \sum_{p,t} f_{qp}{}^t f_{st}{}^p = \quad q \sim\sim f \sim\sim f \sim\sim s \tag{5.2}$$

If $\det g = 0$, we can find disjoint sets S_1, S_2 so that $S = S_1 \cup S_2$ and

$$[X_a, X_b] = 0 \quad \text{for } a, b \in S_1 \tag{5.3}$$

and

$$[X_q, X_p] = \sum_t f_{qp}{}^t X_t \quad \text{for } p, q, t \in S_2 \tag{5.4}$$

Cartan Criterion: $\det g \neq 0$

[1] More generally, Cartan's classification is valid for Lie algebras over $\mathbb{F}$, where $\mathbb{F}$ is an algebraically closed field of characteristic zero. $\mathbb{C}$ satisfies both of these constraints. $\mathbb{R}$ has characteristic zero but is not algebraically closed.

We will assume that the CC is satisfied. This implies that the Lie algebra is semi-simple and that we can and will assume that g_{st} is diagonal.

$$g_{st} = \delta(s,t) = \quad \sim\sim\sim \tag{5.5}$$

$$f_{qp}{}^{t} = f_{qpt} \tag{5.6}$$

Will not, however, assume that f_{qpt} is totally antisymmetric, as is often assumed.

Cartan-Weyl commutators for $\mathfrak{su}(2)$

$$E_- = \frac{1}{\sqrt{2}}|2\rangle\langle 1|, \quad E_+ = \frac{1}{\sqrt{2}}|1\rangle\langle 2|, \quad H = \frac{1}{2}[|1\rangle\langle 1| - |2\rangle\langle 2|] \tag{5.7}$$

$$\begin{tikzcd} & H \arrow[dl, "-E_-"'] \arrow[dr, "E_+"] & \\ E_- & & E_+ \arrow[ll, "H"] \end{tikzcd} \qquad \begin{cases} [E_+, E_-] = H \\ [H, E_+] = E_+ \\ [H, , E_-] = -E_- \end{cases} \tag{5.8}$$

Cartan-Weyl commutators for any semi-simple Lie algebra

For any lower case latin letter q and Greek letter α, let

$q_- = 1, 2, \ldots, \mathcal{R}$

$\vec{\alpha} = \mathcal{R}+1, \mathcal{R}+2, \ldots, \mathcal{D}$

$q =$ either q_- or $\vec{\alpha}$ but not both.

Let $\{H_{i_-}\}_{i_-=1}^{\mathcal{R}}$ be the largest possible set of mutually commuting X_p. $\mathcal{R}$ is called the **rank** of the group.

$$\boxed{[H_{i_-}, H_{j_-}] = 0} \tag{5.9}$$

Let $E_{\vec{\alpha}}$ be eigenvectors of H_{i_-} for a commutator "product" instead of a matrix multiplication product

$$\boxed{[H_{i_-}, E_{\vec{\alpha}}] = \alpha_{i_-} E_{\vec{\alpha}}} \tag{5.10}$$

The vectors $\vec{\alpha} \in \mathbb{R}^{\mathcal{R}}$ of eigenvalues are called **root vectors**.

From the properties of a commutator bracket[2]

$$\begin{aligned} [H_{i_-}, [E_{\vec{\alpha}}, E_{\vec{\beta}}]] &= [[H_{i_-}, E_{\vec{\alpha}}], E_{\vec{\beta}}] + [E_{\vec{\alpha}}, [H_{i_-}, E_{\vec{\beta}}]] && (5.11) \\ &= (\alpha_{i_-} + \beta_{i_-})[E_{\vec{\alpha}}, E_{\vec{\beta}}] && (5.12) \end{aligned}$$

If $\vec{\alpha} + \vec{\beta} = 0$, $[H_{i_-}, [E_{\vec{\alpha}}, E_{\vec{\beta}}]] = 0$ so

$$\boxed{[E_{\vec{\alpha}}, E_{-\vec{\alpha}}] = \sum_{i_-} \xi_{i_-} H_{i_-}} \tag{5.13}$$

[2]The commutator $[x,y] = xy - yx$ acts like a derivative operator: $[x[a,b]] = [[x,a],b] + [a,[x,b]]$

Claim 9 *If we assume the normalization of $\mathfrak{su}(2)$ operators used in Eq.(5.7), then*

$$\xi_{i_-} = \frac{\alpha_{i_-}}{\vec{\alpha} \cdot \vec{\alpha}} \tag{5.14}$$

proof:

Applying $[E_{\vec{\alpha}}, \cdot]$ to both sides of Eq.(5.13)

$$[E_{\vec{\alpha}}, [E_{\vec{\alpha}}, E_{-\vec{\alpha}}]] = -\vec{\xi} \cdot \vec{\alpha} E_{\vec{\alpha}} \tag{5.15}$$

But for $\mathfrak{su}(2)$

$$[E_+, [E_+, E_-]] = [E_+, H] = -E_+ \tag{5.16}$$

If set $E_{\vec{\alpha}} = E_+$, $E_{-\vec{\alpha}} = E_-$, then

$$\vec{\xi} \cdot \vec{\alpha} = 1 \tag{5.17}$$

QED

If $\vec{\alpha} + \vec{\beta} \neq 0$,

$$\boxed{[E_{\vec{\alpha}}, E_{\vec{\beta}}] = N_{\vec{\alpha},\vec{\beta}} E_{\vec{\alpha}+\vec{\beta}} \quad \text{if } \vec{\alpha} + \vec{\beta} \neq 0} \tag{5.18}$$

for some $N_{\vec{\alpha},\vec{\beta}} \in \mathbb{C}$.

The roots (**root system**) of a semisimple Lie algebra form a real $\mathcal{R}$ dimensional vector space.

A **positive/negative (P/N) root** $\vec{\alpha}$ is a root for which the first component α_1 is positive/negative. If the first component of $\vec{\alpha}$ is zero, then decide the root's sign from its second component α_2. And so on. Note that the definition of P/N root is basis dependent.

A P root $\vec{\alpha}$ is a **simple positive (SP) root** if there are no P roots $\vec{\rho}$ and $\vec{\sigma}$ such that $\vec{\alpha} = \vec{\rho} + \vec{\sigma}$. Hence, SP roots are like the atoms or indivisible constituents of the root system.

Properties of root vectors $\vec{\alpha}, \vec{\beta}, \ldots \in \mathbb{R}^{\mathcal{R}}$

1. If $\vec{\alpha}$ is a root, then $-\vec{\alpha}$ is too.

2. We can find a basis of SP roots for the root space.

3. **Claim 10** *If $\vec{\alpha}$ and $\vec{\rho}$ are SP roots, then $\vec{\alpha} - \vec{\rho}$ is not a root of any kind.*

   proof:

   Assume $\vec{\alpha} - \vec{\rho}$ is either a P root or an N root.

   If $\vec{\alpha} - \vec{\rho}$ is a P root $\vec{\sigma}$, then $\vec{\alpha} = \vec{\rho} + \vec{\sigma}$ so $\vec{\alpha}$ is not a SP root.

   Likewise, if $\vec{\alpha} - \vec{\rho}$ is an N root $\vec{\sigma}$, then $-\vec{\sigma}$ is a P root and $\vec{\alpha} = \vec{\rho} + (-\vec{\sigma})$.
   QED

4. If $\vec{\alpha}$ and $\vec{\beta}$ are SP, then there can be roots

$$\{\vec{\beta} + n\vec{\alpha} | i = 0, 1, 2, \ldots, n\} \tag{5.19}$$

for some terminal integer $n \geq 0$ defined by (see Fig.5.1)

$$n = \frac{-2\vec{\alpha} \cdot \vec{\beta}}{\vec{\alpha} \cdot \vec{\alpha}} \tag{5.20}$$

The following roots are also possible

$$\{\vec{\alpha} + p\vec{\beta} | i = 0, 1, 2, \ldots, p\} \tag{5.21}$$

for some terminal integer $p \geq 0$ defined by (see Fig.5.1)

$$p = \frac{-2\vec{\alpha} \cdot \vec{\beta}}{\vec{\beta} \cdot \vec{\beta}} \tag{5.22}$$

5. angle constraint

Multiplying Eqs.(5.20) and (5.22), we get

$$-\sqrt{\frac{np}{4}} = \hat{\alpha} \cdot \hat{\beta} \in [-1, 0] \tag{5.23}$$

This angle constraint implies that the angle between the two SP roots $\vec{\alpha}$ and $\vec{\beta}$ can only have one of the 4 possible values listed in Table 5.1.

6. length ratio constraint

Dividing Eqs.(5.20) and (5.22), we get

$$\sqrt{\frac{n}{p}} = \frac{|\vec{\beta}|}{|\vec{\alpha}|} \tag{5.24}$$

Table 5.2 gives the possible length ratios implied by Eq.(5.24).

Figure 5.1: Pictorial representation of Eqs.(5.20) and (5.22).

np	$\sqrt{np/4}$	$\angle(\vec{\alpha},\vec{\beta}) = \arccos\left(-\sqrt{np/4}\right)$
0	0	$\frac{\pi}{2} = 90^o$
1	$\frac{1}{2}$	$\frac{2\pi}{3} = 120^o$
2	$\frac{1}{\sqrt{2}}$	$\frac{3\pi}{4} = 135^o$
3	$\frac{\sqrt{3}}{2}$	$\frac{5\pi}{6} = 150^o$

Table 5.1: The 4 possible angles between two PS roots, as dictated by the angle constraint Eq.(5.23).

np	(n,p)	$\lvert\vec{\beta}\rvert/\lvert\vec{\alpha}\rvert$
0	(0, 1) or (1,0)	0 or ∞
1	(1,1)	1
2	(1,2) or (2,1)	$1/\sqrt{2}$ or $\sqrt{2}$
3	(1,3) or (3,1)	$1/\sqrt{3}$ or $\sqrt{3}$

Table 5.2: Possible length ratios between two PS roots, as dictated by the length ratio constraint Eq.(5.24).

Using the definition of SP roots, and the angle and length constraints on SP roots, one can show that all possible simple Lie algebras have one of the root systems given by Fig.5.2. In that figure, the parameters of a root system are specified via Dynkin diagrams.

Rules for drawing **Dynkin Diagrams (DD)**

1. One dot for each SP root. k subscript in A_k, B_k, C_k, D_k is number of dots
2. Dots connected by np number of lines
3. If $np > 1$, draw arrowhead (i.e., greater-than sign $>$) pointing from bigger to smaller root.
4. Draw one connected diagram (CD) for a simple Lie algebra. Draw multiple disconnected CDs for a semisimple Lie algebra.

   This follows because the Lie algebra of a semisimple Lie algebra $\mathfrak{g}$ is a direct sum $\mathfrak{g} = \mathfrak{g}_1 \oplus \mathfrak{g}_2 \oplus \ldots \mathfrak{g}_t$ of simple Lie algebras $\mathfrak{g}_i$ and the root vectors of any two of those Lie algebras $\mathfrak{g}_1$ and $\mathfrak{g}_2$ are orthogonal so $np = 0$ and there is no line connecting the roots of $\mathfrak{g}_1$ and $\mathfrak{g}_2$.

5.1 Examples

- DD for $SO(3)$ and its double cover $SU(2)$ is a single dot

Figure 5.2: Dynkin diagrams for the simple Lie groups. n subscript in A_k, B_k, C_k, D_k is the number of dots, which equals the number of SP roots.

- $SO(4) \cong SO(3) \times SO(3)$ is not a simple Lie algebra. Its DD is two disconnected dots
- For $SU(3)$, the DD is $\bullet$ —— $\bullet$

$$H_1 = T_z, \quad H_2 = \frac{\sqrt{3}}{2} Y \tag{5.25}$$

$$E_{\vec{\alpha}} = \frac{1}{\sqrt{2}} T_+, \quad E_{\vec{\beta}} = \frac{1}{\sqrt{2}} U_+, \quad E_{\vec{\alpha}+\vec{\beta}} = \frac{1}{\sqrt{2}} V_- \tag{5.26}$$

Figure 5.3: Root system for $SU(3)$

Chapter 6

General Relativity Nets: COMING SOON

T.his chapter is based on Cvitanovic's Birdtracks book Ref. [1]

Chapter 7

Integrals over a Group

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

For a group $\mathcal{G}$, let

SR = set of singlet reps, and SR^c = set of nonsinglet reps,

Let g be an element of $\mathcal{G}$ with a rep-matrix G. The goal of this chapter is to show how to evaluate integrals over a group $\mathcal{G}$, of the form:

$$\int dg\, G_a{}^b G_c{}^d \ldots (G^\dagger)_e{}^f (G^\dagger)_g{}^h \tag{7.1}$$

subject to the constraints that:

$$\int dg = 1 \tag{7.2}$$

and

$$\int dg\, G_\lambda = 0 \quad \text{if } \lambda \in SR^c \tag{7.3}$$

We will represent the rep-matrix G by

$$G_a{}^b = \; a \longleftarrow G \longleftarrow b\,, \quad (G^\dagger)_b{}^a = \; b \longleftarrow G^\dagger \longleftarrow a \tag{7.4}$$

Note that we will always take the out arrow (green) as the first one.

We will assume that G is a unitary matrix

$$\boxed{G^\dagger G = G G^\dagger = 1} \qquad \longleftarrow G^\dagger \longleftarrow G \longleftarrow \;=\; \longleftarrow G \longleftarrow G^\dagger \longleftarrow \;=\; \longleftarrow \bullet \longleftarrow \tag{7.5}$$

Tensor products of G's will be represented thus

$$G \otimes G \otimes G^\dagger = \begin{array}{c} \longleftarrow G \longleftarrow \\ \longleftarrow G \longleftarrow \\ \longleftarrow G^\dagger \longleftarrow \end{array} \tag{7.6}$$

7.1 $\int dg\, G$

To evaluate $\int dg\, G$, we expand G in its Clebsch-Gordan series. Such series and the Clebsch-Gordan coefficients C_λ are discussed in Chapter 4.

$$\int dg\, G = \sum_\lambda C_\lambda^\dagger \left[\int dg\, G_\lambda\right] C_\lambda \tag{7.7}$$

$$= \sum_{\lambda\in SR} C_\lambda^\dagger C_\lambda \tag{7.8}$$

$$= \sum_{\lambda\in SR} P_\lambda \tag{7.9}$$

This result is valid for any group $\mathcal{G}$ and any rep-matrix G of that group.

7.2 $\int dg\, G\otimes G^\dagger$

Claim 11 *For $G \in SU(n) \subset \mathbb{C}^{n\times n}$,*

(7.10)

proof: Recall that

$$\delta_a^d\delta_c^b = \frac{1}{n}\delta_a^b\delta_c^d + \frac{1}{\kappa}(T^i)_a{}^b(T^i)_c{}^d$$

(7.11)

Will set $\kappa = 1$ from here on. Multiplying both sides from the left by $G \otimes G^\dagger$, we get

$$G_a{}^d(G^\dagger)_c{}^b = \frac{1}{n}\delta_a^b\delta_c^d + (G^\dagger T^i G)_a{}^b(T^i)_c{}^d$$

(7.12)

Since the generators T^i are invariant tensors,

$$G_a{}^{a'}(G^\dagger)_{b'}{}^b(T^{i'})_{a'}{}^{b'}G_{i'i} = (T^i)_a{}^b$$

(7.13)

Hence,

$$G_a{}^{a'}(G^\dagger)_{b'}{}^b(T^i)_{a'}{}^{b'} = (T^i)_a{}^b G_{ii'}$$

(7.14)

QED

Claim 12 *For $G \in SU(n) \subset \mathbb{C}^{n\times n}$,*

$$\int dg\, G_a{}^d(G^\dagger)_b{}^c = \frac{1}{n}\delta_a^b\delta_c^d$$

(7.15)

proof:

This claim follows immediately from the previous one.

QED

Claim 12 can be extended to any group $\mathcal{G}$ that has a single singlet rep. For such groups, we have, if $G \in \mathbb{C}^{d_{def}\times d_{def}}$ is the defining rep so that $a, b, c, d \in \{1, 2, \ldots d_{def}\}$,

$$\delta_a^d\delta_c^b = \frac{1}{d_{def}}\delta_a^b\delta_c^d + \sum_{\lambda\in SR^c}\frac{1}{\kappa}(T^i_\lambda)_a{}^b(T^i_\lambda)_c{}^d$$

(7.16)

so Eq.(7.15) is valid with n replaced by d_{def}.

Claim 13 *For any group $\mathcal{G}$ with rep-matrices G_μ and G_ν (μ, ν are not necessarily irreps)*

$$\int dg\ (G_\mu)_{ab}(G_\nu)^{cd} = \sum_{\lambda \in SR} (P_\lambda)_{ab}{}^{cd} \tag{7.17}$$

proof:

Let

$(C^\dagger_{\lambda i})_{ac} =$

(7.18)

represent the Clebsch-Gordan coefficients for the Clebsch-Gordan series $V_\mu \otimes V_\nu = \sum_\lambda V_\lambda$.

Since the C_λ are invariant tensors:

$$(G_\mu)_a{}^{a'}(G_\nu)_{b'}{}^{b}(C^\dagger_{\lambda i})_{a'}{}^{b'} = (C^\dagger_{\lambda i'})_a{}^{b}(G_\lambda)_{i'i}$$

(7.19)

Therefore,

$\int dg$

(7.20)

$$= \sum_{ij} \sum_\lambda (C^\dagger_{\lambda i})_{ab}(C_{\lambda j})^{cd} \int dg (G_\lambda)_{ij} \tag{7.21}$$

$$= \sum_i \sum_{\lambda \in SR} (C^\dagger_{\lambda i})_{ab}(C_{\lambda i})^{cd} \tag{7.22}$$

$$= \sum_{\lambda \in SR} (P_\lambda)_{ab}{}^{cd} \tag{7.23}$$

QED

7.3 Character Orthonormality Relation

For any rep-matrix G_λ in rep λ such that G_λ represents the group element g in the Group $\mathcal{G}$, define the **character of g in rep λ** by

$$\chi_\lambda(g) = \chi_\lambda(G_\lambda) \stackrel{\text{def}}{=} \text{tr}G_\lambda = (G_\lambda)_a{}^a \tag{7.24}$$

Note that

$$\text{tr}G_\lambda^\dagger = (G_a{}^a)^* = \chi_\lambda(g)^* \tag{7.25}$$

Claim 14 *Suppose G_λ and G_μ are rep-matrices in irreps λ and μ, respectively. Suppose $h, G_\lambda \in \mathbb{C}^{d_\lambda \times d_\lambda}$ and $f, G_\mu \in \mathbb{C}^{d_\mu \times d_\mu}$. Then*

$$\boxed{\int dg\ \chi_\lambda(h^\dagger G_\lambda)\chi_\mu^*(G_\mu^\dagger f) = \delta(\mu,\lambda)\frac{1}{d_\mu}\chi_\lambda(h^\dagger f)}$$

(7.26)

proof:

This claim follows from Eq.(7.16 once we prove that the left hand side of Eq.(7.26) is zero if $\lambda \neq \mu$. Because λ and μ are both irreps, there can be no matrix connecting G_μ and G_λ when $\lambda \neq \mu$, so the left hand side of Eq.(7.26) is indeed zero. Even when $\lambda = \mu$, there can only be one matrix, namely a Kronecker delta, connecting G_λ and G_μ, so the group must have only one singlet rep.

QED

Note that since the matrices $h, f \in \mathbb{C}^{d_\mu \times d_\mu}$ are arbitrary, differentiation can be used to retrieve G_μ from its character with various h:

$$G_a{}^b = \frac{d}{d(h^\dagger)_b{}^a}\underbrace{\chi_\mu(h^\dagger G)}_{(h^\dagger)_b{}^a G_a{}^b} \tag{7.27}$$

7.4 $SU(n)$ Examples

In $SU(n)$, $n = d_{def}$, where d_{def} is the dimension of the defining rep. ($\mathcal{G} \subset \mathbb{C}^{n\times n}$). In this section, all matrices G are elements of $\mathbb{C}^{n\times n}$.

7.4.1 $\int dg\, G{\otimes}G$

Consider $V \otimes V$. We have

(7.28)

because

(7.29)

and

(7.30)

Thus

(7.31)

$$= \frac{n(n+1)}{2} \tag{7.32}$$

and

(7.33)

$$= \frac{n(n-1)}{2} \tag{7.34}$$

Note that $d_{\mathcal{S}} = 1$ iff $n = 1$, and $d_{\mathcal{A}} = 1$ iff $n = 2$. Therefore, for $SU(n)$

$$\int dg\, G \otimes G = 0 \quad \text{if } n > 2 \tag{7.35}$$

7.4.2 $\int dg\, G^\dagger{\otimes}G^\dagger{\otimes}G{\otimes}G$

Consider $V^\dagger \otimes V^\dagger \otimes V \otimes V$. We have

(7.36)

(7.37)

(7.38)

Let

$P_1 = \frac{1}{n^2}$

(7.39)

and

$P_2 = \frac{1}{n^2}$

$= \frac{1}{n^2}$

(7.40)

Then

$$P_1^2 = P_1, \quad P_2^2 = P_2, \quad P_1 P_2 \neq 0 \tag{7.41}$$

$$dim(P_1) = dim(P_2) = 1 \tag{7.42}$$

This hints to the possibility of two orthogonal projectors, if only we include terms where there is a single swap on either the right or the left side, but not on both sides as in Eq.(7.40). So define

$$\pi_{\mathcal{S}} = \frac{1}{d_{\mathcal{S}}}$$

$$\text{where } d_{\mathcal{S}} = \frac{n(n+1)}{2} \tag{7.43}$$

and

$$\pi_{\mathcal{A}} = \frac{1}{d_{\mathcal{A}}}$$

$$\text{where } d_{\mathcal{A}} = \frac{n(n-1)}{2} \tag{7.44}$$

Then

$$\pi_{\mathcal{A}}^2 = \pi_{\mathcal{A}}, \quad \pi_{\mathcal{S}}^2 = \pi_{\mathcal{S}}, \quad \pi_{\mathcal{A}}\pi_{\mathcal{S}} = 0 \tag{7.45}$$

$$dim(\pi_{\mathcal{S}}) = \mathrm{tr}\pi_{\mathcal{S}} = \frac{1}{d_{\mathcal{S}}}$$

$$= 1 \tag{7.46}$$

$$dim(\pi_{\mathcal{A}}) = 1 \tag{7.47}$$

Thus

$$= \pi_{\mathcal{S}} + \pi_{\mathcal{A}} + \text{ non-singlet projectors} \tag{7.48}$$

Hence

$$\int dg$$

$$= \pi_{\mathcal{S}} + \pi_{\mathcal{A}} \tag{7.49}$$

Chapter 8

Invariant Tensors

This chapter is based on Cvitanovic's Birdtracks book Ref.[1].

A **bilinear form** is a linear function $m : V^{\dagger n} \times V^n \to \mathbb{C}$ usually with $V^{\dagger n}, V^n = \mathbb{C}^n$. For example,

$$m(x^{\dagger :n}, y^{:n}) = x^{\dagger a} M_a{}^b y_b \qquad \begin{tikzcd} & M \arrow[dl] & \\ a & & b \arrow[ul] \end{tikzcd} \tag{8.1}$$

$m()$ is said to be invariant if

$$m(x^{\dagger :n}, y^{:n}) = m(x^{\dagger :n} G^\dagger, G y^{:n}) \tag{8.2}$$

$m()$ is invariant iff matrix M is an **invariant matrix**; i.e., iff

$$\boxed{M_a{}^b = (G^\dagger)_a{}^{a'} G_{b'}{}^b M_{a'}{}^{b'}} \qquad \begin{tikzcd} & M \arrow[dl] & \\ a & & b \arrow[ul] \end{tikzcd} \quad = \quad \begin{tikzcd} & M \arrow[dl, "G^\dagger"] & & \\ a & & & b \arrow[ul, "G"'] \end{tikzcd} \tag{8.3}$$

$$M = G^\dagger M G \tag{8.4}$$

If G is unitary,

$$GM = MG, \quad [G, M] = 0 \tag{8.5}$$

A **multilinear form** is a linear function $h : V^{\dagger n^p} \times V^{n^q} \to \mathbb{C}$, usually with $V^\dagger, V = \mathbb{C}$. For example,

$$h(w^\dagger, x^\dagger, y, z) = h_{ab}{}^{cd} w^{\dagger a} x^{\dagger b} y_c z_d \qquad \begin{tikzcd} h \arrow[d] \arrow[dr] \arrow[drr] \arrow[drrr] & & & \\ a & b & c & d \end{tikzcd} \tag{8.6}$$

$h()$ is said to be invariant if

$$h(w^\dagger, x^\dagger, y, z) = h(w^\dagger G^\dagger, x^\dagger G^\dagger, Gy, Gz) \tag{8.7}$$

$h()$ is invariant iff tensor ${h_{ab}}^{cd}$ is a **invariant tensor** (IT); i.e., iff

$$\boxed{{h_{ab}}^{cd} = {(G^\dagger)_a}^{a'}{(G^\dagger)_b}^{b'}{h_{a'b'}}^{c'd'}{G_{c'}}^{c}{G_{d'}}^{d}}$$

(8.8)

A **composed IT** is an IT that can be written as a product or contraction of ITs.

A **tree IT** is a composed IT without any loops.

A **primitive IT** is an IT that can be expressed as a linear combination of a finite number of tree ITs.

The **primitiveness assumption**: All IT are primitive.

Examples. Suppose $x, y, z \in \mathbb{R}^3$ and $i, j, k \in \{1, 2, 3\}$.

- Primitive ITs

$$length(x) = \delta_{ij} x_i x_i \quad volume(x, y, z) = \epsilon_{ijk} x_i y_j z_k \tag{8.9}$$

$\delta_{ij} =$

, $\epsilon_{ijk} =$

(8.10)

- Tree ITs

$\delta_{ij}\epsilon_{klm} =$

(8.11)

$\epsilon_{ijm}\delta_{mn}\epsilon_{nkl} =$

(8.12)

- Non-tree IT

$\epsilon_{ims}\epsilon_{jnm}\epsilon_{krn}\epsilon_{lsr} =$

(8.13)

$$\epsilon_{ims}\epsilon_{jnm}\epsilon_{krn}\epsilon_{lsr} = \delta_{ij}\delta_{kl} + \delta_{il}\delta_{jk}$$

(8.14)

- Primitiveness Assumption

  Suppose $\mathcal{P} = \{\delta_{ij}, f_{ijk}\}$ where f_{ijk} is not ϵ_{ijk}. For some $A, B, C, \ldots H \in \mathbb{C}$, one has

(8.15)

(8.16)

(8.17)

Let $\mathcal{P} = (p_1, p_2, \ldots, p_k)$ be a **full set of primitive ITs**. By "full", we mean no others exist. $\mathcal{P}$ is a basis for an **algebra of invariants**.[1]

An **invariance group** $\mathcal{G}$ with a full set of primitive ITs $\mathcal{P} = \{p_1, p_2, \ldots, p_k\}$ is the set of all linear transformation $G \in \mathcal{G}$ such that

$$p_1(x^\dagger, y) = p_1(x^\dagger G^\dagger, Gy) \tag{8.18}$$

$$p_2(w^\dagger, x^\dagger, y, z) = p_2(w^\dagger G^\dagger, x^\dagger G^\dagger, Gy, Gz) \tag{8.19}$$

$$\text{etc.} \tag{8.20}$$

Example. Consider an invariance group with a single primitive IT $p()$ defined by

$$p(x^\dagger, y) = \delta^b_a {x^\dagger}^a y_b = {x^\dagger}^b y_b \tag{8.21}$$

Then

$$(x')^{\dagger a}(y')_a = {x^\dagger}^b (G^\dagger G)_b{}^c y_c = {x^\dagger}^b y_b \tag{8.22}$$

[1] An algebra over a field is defined in Sec.A.12

so G must be unitary

$$G^\dagger G = 1 \tag{8.23}$$

The group of n dimensional unitary matrices is called $U(n)$

Chapter 9

Lagrange's Theorem and Orbit-Stabilizer Theorem

9.1 Lagrange's Theorem

Let H be a subgroup of a finite group G (i.e., $H \leq G$)

$gH = \{gh|h \in H\}$ = **left coset** with coset representative g

$G/H = \{gH|g \in G\} = \{gH|g \in G : H\}$

$G : H$ = set of **coset representatives**

The **Lagrange table** is a table with rows labelled by $g \in G : H$, columns labelled by $h \in H$, and table entries equal to gh.

Claim 15 *Every element of G appears exactly once in the Lagrange Table. Therefore*[1]

$$|G| = |G : H| \, |H| \tag{9.1}$$

proof:

If $x \in G$, then $x \in xH = gH$ for some $g \in G : H$. So every $x \in G$ appears at least in one coset.

Suppose x appears in 2 cosets g_1H and g_2H.

$$g_1h_1 = g_2h_2 \tag{9.2}$$

so

$$g_2^{-1}g_1 = h_2h_1^{-1} \in H \tag{9.3}$$

Hence,

$$g_2^{-1}g_1H = H \implies g_2H = g_1H \tag{9.4}$$

QED

[1] Eq.(9.1) is for finite groups. For infinite Lie groups, the order of each group is replace by the dimension of the Lie algebra vector space: $dim(\mathfrak{g}) = dim(\mathfrak{g}/\mathfrak{h}) \; dim(\mathfrak{h})$, where $\mathfrak{g} = \mathfrak{g}/\mathfrak{h} + \mathfrak{h}$

A group G is **abelian** if $g_1 g_2 = g_2 g_1$ for all $g_1, g_2 \in G$.

H is a **normal** subgroup of G (i.e., $H \trianglelefteq G$) iff $gH = Hg$ (i.e., $gHg^{-1} = H$) for all $g \in G$. All subgroups H of an abelian group G are normal subgroups.

$G =$ all symmetries.

$H =$ symmetries for a given reference state

$G : H =$ a set of reference states that yield all distinct left cosets, often called the **index set**

$G/H =$ set of left cosets, often called a **quotient space or coset space**. Also called **quotient group or coset group** if H is a normal subgroup

Examples:

---

1. (H not normal subgroup)

   $G = S_3 = \{e,\ (12),\ (13),\ (23),\ (123),\ (132)\}$ The symmetric group on 3 letters,

   $H = \{e, (12)\}$

   Cosets

$$\begin{cases} eH & = \{e, (12)\} \\ (13)H & = \{(13), (123)\} \\ (23)H & = \{(23), (132)\} \end{cases} \tag{9.5}$$

   $G : H = \{e,\ (13),\ (23)\}$ coset representatives.

$$|G| = 6, \quad |G : H| = 3, \quad |H| = 2 \tag{9.6}$$

   In this example, H is not a normal subgroup of G because

$$(13)H = \{(13), \underbrace{(13)(12)}_{(123)}\} \tag{9.7}$$

   and

$$H(13) = \{(13), \underbrace{(12)(13)}_{(213)}\} \tag{9.8}$$

   are not equal.

---

2. (H normal because G is abelian)

   $G = Z_6 = \{0, 1, 2, 3, 4, 5\}$ under addition mod 6.

   $H = \{0, 3\}$

   G is abelian so every subgroup of G is normal

   $G : H = \{0, 1, 2\}$, coset representatives

Cosets

$$\begin{cases} 0+H=\{0,3\} \\ 1+H=\{1,4\} \\ 2+H=\{2,5\} \end{cases} \tag{9.9}$$

---

3. (H is normal subgroup even though G is not abelian)

   $S_3^e = \{e, (123), (132)\}$, even number of cycles

   $S_3^o = \{(12), (13), (23)\}$, odd number of cycles

   $G = S_3 = S_3^o \cup S_3^e$

   $H = S_3^e$.

   $S_3^e \trianglelefteq S_3$ because $\sigma S_3^e = S_3^e \sigma = S_3^o$ for all $\sigma \in S_3$

   $G : H = \{e, (12)\}$ coset representatives

   Cosets

$$\begin{cases} eH & = S_3^e \\ (12)H & = S_3^o \end{cases} \tag{9.10}$$

$$S_3/S_3^e \cong Z_2 \tag{9.11}$$

9.2 Orbit-Stabilizer Theorem

Let a group G act on a set X by an action $\odot$. This means that $\odot : G \times X \to X$ and $(g, x) \mapsto g \odot x$. Usually the **action** $\odot$ is **group conjugation**. $g \odot x = gxg^{-1}$. In the special case of Lagrange's theorem, $X = G$ and $g \odot x = gx$.

$Stab(x) = \{g \in G | g \odot x = x\}$= **Stabilizer of** x, the symmetries of x, group operations that keep x fixed or "stabilized".

$O(x) = \{g \odot x | g \in G\}$ = **Orbit of** x, all possible projections of x via $g \in G$.

Fig.9.1 represents $O(x)$ and $Stab(x)$ pictorially.

Claim 16 *(Orbit-Stabilizer theorem for single point $x \in X$)*

$$|G| = |O(x)|\,|Stab(x)| \tag{9.12}$$

proof:
QED

$Z(G) = \{z \in G | gzg^{-1} = z \text{ for all } g \in G\}$ = **center of** G

Suppose H is a subgroup of G (i.e., $H \leq G$) and the action is group conjugation. There are two ways of generalizing $Stab(x)$, to define it for a subgroup H, instead of a single point x

Figure 9.1: Pictorial representation of $O(x)$ and $Stab(x)$

$$\begin{cases} \cup_{h\in H} Stab(h) = \cup_{h\in H}\{g \in G | ghg^{-1} = h\} = C_G(H) & \textbf{centralizer (a.k.a. commutant)} \\ Stab(H) = \{g \in G | gHg^{-1} = H\}) = N_G(H) & \textbf{normalizer} \end{cases} \tag{9.13}$$

Both $C_G(H)$ and $N_G(H)$ are subgroups of G. Furthermore, $C_G(H)$ is a subgroup of $N_G(H)$ so

$$Z(G) \leq C_G(H) \leq N_G(H) \leq G \tag{9.14}$$

$C_G(H)$ contains elements of G that commute with every element of H. That's why commutant is a good name for it. The elements of a normalizer, on the other hand, may not commute with some elements of H.

$N_G(H)$ is the biggest subset of G that leaves the subgroup H fixed under conjugation. If H is a normal subgroup of G, then $N_G(H) = G$.

$O(H) = \cup_{h\in H} O(h) =$ projections (orbits) of structure(subgroup) H instead of single point H

Claim 17 *(Orbit-Stabilizer theorem for subgroup $H \leq G$)*

$$|G| = |O(H)| \, |\underbrace{Stab(H)}_{N_G(H)}| \tag{9.15}$$

proof:
QED

Suppose G is a group and H is a subgroup of G.

For any two $a, b \in G$, define $a \sim b$ if $a = gbg^{-1}$ for some $g \in G$. This is an equivalence relation that partitions G into disjoint classes. Now define

$CC(x) = \{gxg^{-1} | g \in G\} =$ **conjugacy class (CC) of** $x \in G$.

$CC(H) = \{gHg^{-1} | g \in G\} = \bigcup_{h\in H} CC(h) =$ **union of CCs of** $H \leq G$.

The orbit (for conjugacy action) and the conjugacy class are the same thing.

$$CC(x) = O(x) = G : Stab(x) \tag{9.16}$$

$$CC(H) = O(H) = G : Stab(H) \tag{9.17}$$

A normal subgroup H of G satisfies $gHg^{-1} = H$ for all $g \in G$, so it equals a union of CCs.

$$H = \bigcup_{x \in X} CC(x) = CC(X) \tag{9.18}$$

where $X \subset H$. So conjugacy classes are the "atoms" from which normal subgroups are built.

A **central conjugacy class** is a $CC(x)$ such that $CC(x) \subset Z(G)$. Hence, we must have $CC(x) = \{x\}$. So central CCs are precisely the singleton sets $\{x\}$ for all $x \in Z(G)$.

Claim 18 *(sum of class orders)*

$$|G| = |Z(G)| + \sum_{x \in X} \underbrace{|G : Stab(x)|}_{|O(x)|} \tag{9.19}$$

where X contains representatives of non-central CCs (i.e., CCs with more than one element)

proof:
QED

Examples:

1. $G = S_3$

   $x = (12)$

   $Stab(x) = \{e, (12)\}$

   $O(x) = \{(12), (13)(12)(13), (23)(12)(23)\} = \{(12), (23), (13)\}$

$$|G| = 6, |O(x)| = 3, |Stab(x)| = 2 \implies |G| = |O(x)|\ |Stab(x)| \tag{9.20}$$

---

2. (sum of class orders)

   $G = S_3$

   conjugacy classes:

   $CC_0 = \{e\}$, (0 cycles)

   $CC_1 = \{(12), (23), (13)\}$, (1 cycle)

   $CC_2 = \{(123), (132)\}$, (2 cycles)

$$|G| = 6, |CC_0| = 1, |CC_1| = 3, |CC_2| = 2 \implies |G| = |CC_0| + |CC_1| + |CC_2| \tag{9.21}$$

$$Z(G) = \{e\} \tag{9.22}$$

$$Stab((12)) = \{e, (12)\} \implies |S_3 : Stab((12))| = 6/2 = 3 \tag{9.23}$$

$$Stab((123)) = \{(12), (23), (13)\} \implies |S_3 : Stab((123))| = 6/3 = 2 \tag{9.24}$$

Applications:

- Quantum Error Correction

  Pauli group $=\{1, \sigma_x, \sigma_y, \sigma_z\} \times \{\pm 1, \pm i\}$. Has 16 elements.

  Clifford group =group generated by $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$ and $S = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$. Has 24 elements

  $G =$ Pauli or Clifford group

  x= code state

  $O(x)$= orbit (i.e., projections) of code state x

  $Stab(x)$ = subgroup of G that preserves (doesn't change, stabilizes, fixes) code state x

  H = code space, subgroup of G

  $Stab(H)$ = subgroup of G that fixes code space H

- Thermodynamics

  G= group

  x= single microstate

  $O(x)$= set of equivalent microstates=single macrostate

  $\ln |O(x)|$= entropy

  $Stab(x)$ = subgroup of G that preserves (doesn't change, stabilizes, fixes) microstate x, residual symmetry group

- Lie groups

  G= Lie group

  H= stabilizer, principal fibre

  $G : H =$ base space

  $\pi(g) = gH =$ projection, fibre

  $\pi : G \to G/H = \{gH : g \in G\}$ fibre bundle

  Example

  $G = SU(2)$

  $H = U(1)$ fibre

  $G : H = S^2$= two sphere, base space

Chapter 10

Lie Algebras

This chapter is based on Ref.[1].

10.1 Generators of Infinitesimal Transformations

For some group $\mathcal{G}$, assume that any group element $G \in \mathcal{G}$ that is infinitesimal close to the identity 1 can be parametrized by

$$G = 1 + i \sum_i \epsilon_i T_i \tag{10.1}$$

where $T_i \in \mathbb{C}^{n\times n}$ for $i = 1, 2, \ldots, N$, $\epsilon_i \in \mathbb{R}$ and $|\epsilon_i| << 1$ [1].

The T_i matrices are called the **generators of infinitesimal transformations** for group $\mathcal{G}$. The generators of a group $\mathcal{G}$ span a vector space called a Lie algebra $\mathfrak{g}$.[2] For example, the generators of the group SU(2) span the **Lie algebra** $\mathfrak{su}(2)$.

The tensor

$$g_{ij} = \mathrm{tr}(T_i^\dagger T_j) \tag{10.2}$$

is called the **Cartan-Killing form**. This tensor can be used to raise and lower the the adjoint rep indices i, j, k in a tensor such as M_{ijk}:

$$M^i{}_{jk} = g^{ii'} M_{i'jk} \tag{10.3}$$

Assume that the T_i matrices are Hermitian and that they satisfy

$$g_{ij} = \mathrm{tr}(T_i T_j) = \kappa\delta(i, j) \tag{10.4}$$

A Lie algebra that satisfies Eq.(10.4) is called a **simple Lie algebra**.

A **semi-simple Lie algebra** is a direct sum of simple Lie algebras.

[1] Note that the ϵ_i are real, not complex.

[2] See Sec.A.12 for the definition of an algebra over a field.

It's customary to choose generators so that $\kappa = \frac{1}{2}$.[3] However, we will often set $\kappa = 1$ for intermediate calculations and restore $\kappa \neq 1$ at the end by dimensional analysis. Just remember that each T^j scales as $\sqrt{\kappa}$. For example, given the equation $\mathrm{tr}(T^i T^j) = \delta(i,j)$, we know that when $\kappa \neq 1$, $\mathrm{tr}(T^i T^j) = \kappa\delta(i,j)$ so both sides of the equation scale as κ.

We will use the following scaled version of T^j as a birdtrack. Define

$$(C^i_{adj})_b{}^a = \frac{1}{\sqrt{\kappa}}(T^i)_b{}^a = \frac{1}{\sqrt{\kappa}}$$

(10.5)

In the CC convention, we will always start reading the indices of this node at the wavy undirected green leg. *adj* stands the adjoint. In this node (vertex), an adj-rep particle (wavy line, gluon) is generated (released) by a def-rep particle (straight solid line, arrow).

In terms of birdtracks, Eq.(10.4) becomes

$$(T^i)^b{}_a (T^j)^a{}_b = \mathrm{tr}(T^i T^j) = \delta(i,j)$$

(10.6)

We can now define the projection operator for the adj-rep. This projection operator represent a gluon exchange between 2 def-rep particles.

$$(P_{adj})_b{}^a{}_d{}^c = \sum_i (T^i)_b{}^a (T^i)_d{}^c$$

(10.7)

The green arrow is the first index in the CC convention.

Note that if $x \in V^n \otimes V^{\dagger n}$, then

$$(P_{adj})_b{}^a{}_d{}^c x_c{}^d = \sum_i (T^i)_b{}^a \underbrace{\left[(T^i)_d{}^c x_c{}^d\right]}_{\epsilon_i \in \mathbb{R}} \tag{10.8}$$

[3]For $SU(2)$, it is customary to choose $T^i = \frac{1}{2}\sigma_i$, where σ_i for $i = 1,2,3$ are the Pauli matrices. For $SU(3)$, it is customary to choose $T^i = \frac{1}{2}\lambda_i$ where λ_i for $i = 1,2,\ldots,8$ are the Gell-Mann matrices. For both of these choices, $\kappa = \frac{1}{2}$.

10.2 Tensor Invariance Conditions

Recall Eq.(A.88). If $x \in V^{n^p} \otimes V^{\dagger n^q}$, and $\mathbb{G} \in \mathcal{G} \subset GL(n^{p+q}; \mathbb{C})$,

$$(x')_{a^{:p}}{}^{b^{:q}} = \mathbb{G}_{a^{:p}}{}^{b^{:q}}{}_{rev(c^{:q})}{}^{rev(d^{:p})} x_{d^{:p}}{}^{c^{:q}}, \quad x'_\alpha = \mathbb{G}_\alpha{}^\beta x_\beta \tag{10.9}$$

where we define

$$\mathbb{G}_\alpha{}^\beta \stackrel{\text{def}}{=} \prod_{i=1}^{p} G_{a_i}{}^{d_i} \prod_{i=1}^{q} G^{\dagger b_i}{}_{c_i} \tag{10.10}$$

If $\mathbb{G}$ is infinitesimally close to the identity, then we can parametrize it as

$$\mathbb{G}_\alpha{}^\beta = 1 + i \sum_j \epsilon_j (M^j)_\alpha{}^\beta \tag{10.11}$$

$$G_{a_i}{}^{d_i} = 1 + i \sum_j \epsilon_j (T^j)_{a_i}{}^{d_i} \tag{10.12}$$

$$G^{\dagger b_i}{}_{c_i} = 1 - i \sum_j \epsilon_j (T^j)^{b_i}{}_{c_i} \tag{10.13}$$

Define

$$(M^j)_\alpha{}^\beta = \left[(T^j)_{a_i}{}^{d_i} \frac{1}{\delta^{d_i}_{a_i}} - (T^j)^{b_i}{}_{c_i} \frac{1}{\delta^{b_i}_{c_i}} \right] \delta^{d^{:p}}_{a^{:p}} \delta^{b^{:q}}_{c^{:q}} \tag{10.14}$$

When $x'_\alpha = x_\alpha$, to first order in ϵ_i,

$$0 = (M^j)_\alpha{}^\beta x_\beta = \left[(T^j)_{a_i}{}^{d_i} \frac{1}{\delta^{d_i}_{a_i}} - (T^j)^{b_i}{}_{c_i} \frac{1}{\delta^{b_i}_{c_i}} \right] \delta^{d^{:p}}_{a^{:p}} \delta^{b^{:q}}_{c^{:q}} x_{d^{:p}}{}^{c^{:q}} \tag{10.15}$$

For example, if we define

$$(M^j)_{a_1 a_2}{}^{b_1}{}_{c_1}{}^{d_2 d_1} = (T^j)_{a_1}{}^{d_1} \delta^{d_2}_{a_2} \delta^{b_1}_{c_1} + \delta^{d_1}_{a_1} (T^j)_{a_2}{}^{d_2} \delta^{b_1}_{c_1} - \delta^{d_1}_{a_1} \delta^{d_2}_{a_2} (T^j)^{b_1}{}_{c_1}$$

(10.16)

then

$$0 = (M^j x)_{a_1 a_2}{}^{b_1} = \left[(T^j)_{a_1}{}^{d_1} \delta^{d_2}_{a_2} \delta^{b_1}_{c_1} + \delta^{d_1}_{a_1} (T^j)_{a_2}{}^{d_2} \delta^{b_1}_{c_1} - \delta^{d_1}_{a_1} \delta^{d_2}_{a_2} (T^j)^{b_1}{}_{c_1} \right] x_{d_1 d_2}{}^{c_1}$$

(10.17)

We will refer to identities such as Eq.(10.16) and (10.17) as **tensor invariance conditions**.

10.3 Clebsch-Gordan Coefficients

The Clebsch Gordan (CG) coefficients are introduced in Ch.4. Note that the generators $(T^i)_a{}^b$ are a simple kind of CG coefficient, one with

- a gluon (adj-rep) particle instead of a general λ rep particle emanating from the i index,
- a particle of the def-rep entering and another leaving the node, instead of any number of def-rep particles entering and leaving.

Since $\mathbb{G} = 1 + i \sum_j \epsilon_j M^j$, generators decompose in the same way as the group elements

$$M^j = \sum_\lambda C^\dagger_\lambda T^j_\lambda C_\lambda$$

(10.18)

The CG coefficients are invariant tensors.

$$C_\lambda = G^\dagger_\lambda C_\lambda G \tag{10.19}$$

Hence,

$$0 = -T^j_\lambda C_\lambda + C_\lambda T^j \tag{10.20}$$

Note that in the last equation, T^j_λ and T^j are different. In terms of birdtracks, we might have, for example,

$$0 = \left\{ \begin{array}{l}
- \; a \leftarrow T^j_\lambda \leftarrow C_\lambda \begin{array}{l} \leftarrow c_1 \\ \leftarrow c_2 \\ \rightarrow b_1 \end{array} \; + \; a \leftarrow C_\lambda \begin{array}{l} \leftarrow T^j \leftarrow c_1 \\ \leftarrow c_2 \\ \rightarrow b_1 \end{array} \\[2em]
+ \; a \leftarrow C_\lambda \begin{array}{l} \leftarrow c_1 \\ \leftarrow T^j \leftarrow c_2 \\ \rightarrow b_1 \end{array} \; - \; a \leftarrow C_\lambda \begin{array}{l} \leftarrow c_1 \\ \leftarrow c_2 \\ \rightarrow T^j \rightarrow b_1 \end{array}
\end{array} \right\} \tag{10.21}$$

Multiplying Eq.(10.21) on the left by $C^\dagger_\lambda$, and moving the first tem to the right side, we obtain an expression for the generator T^i_λ in term the generators T^j (and C_λ CG coefficients).

$$a \leftarrow T^j_\lambda \leftarrow a' = \underbrace{a \leftarrow T_j \leftarrow C_\lambda \leftarrow \leftarrow C^\dagger_\lambda \leftarrow a' \; - \; a \leftarrow C_\lambda \leftarrow \leftarrow C^\dagger_\lambda \leftarrow T_j \leftarrow a'}_{=0}$$

$$+ \; a \leftarrow C_\lambda \begin{array}{l} \leftarrow T^j \\ \leftarrow \leftarrow \\ \rightarrow \rightarrow \end{array} C^\dagger_\lambda \leftarrow a' \; + \; a \leftarrow C_\lambda \begin{array}{l} \leftarrow T^j \leftarrow \\ \rightarrow \rightarrow \end{array} C^\dagger_\lambda \leftarrow a' \; - \; a \leftarrow C_\lambda \begin{array}{l} \leftarrow \leftarrow \\ \rightarrow T^j \rightarrow \end{array} C^\dagger_\lambda \leftarrow a' \tag{10.22}$$

The term with the underbrace in Eq.(10.22) does not come from Eq.(10.21). I included it to demonstrate to the reader that Eq.(10.22) is just another tensor invariance condition that touches all the incoming and outgoing arrows.

10.4 Structure Constants (3 gluon vertex)

A **Lie Algebra** is an algebra over the field $\mathbb{C}$ such that its vector product is the matrix commutator (see Section A.12). Simply put, a Lie Algebra is a set of square Hermitian matrices $\{T^i\}_{i=1}^N$ that satisfy

$$\underbrace{T^iT^j - T^jT^i}_{[T^i,T^j]} = if_{ijk}T^k \quad \textbf{(Lie Algebra commutation relations)}$$

(10.23)

The f_{ijk} tensors are called the **structure constants** of the Lie Algebra. They define a 3 gluon vertex in term of the generators T^i.[4]

If $(T^j)_a{}^b$ are the rep-matrices (in the def-rep) of the generators of a group $\mathcal{G}$, then Eq.(10.23) shows that the matrices $(M^k)_{ij} = if_{ijk}$ are also a rep-matrix (in the adj-rep) of the generators of $\mathcal{G}$.

Since $\mathrm{tr}(T^kT^{k'}) = \delta(k,k')$, Eq.(10.23) implies

$$if_{ijk} = \mathrm{tr}([T^i,T^j]T^k) = (T^i)_a{}^c(T^k)_c{}^b(T^j)_b{}^a - (T^i)_a{}^c(T^j)_c{}^b(T^k)_b{}^a$$

(10.24)

Note that

[4] It's possible to distinguish between upper and lower gluon indices (i.e., to give the gluon arrows a direction. In that case, the Lie Algebra commutation relations would be $[T^i,T^j] = f^{ij}{}_kT^k$ and the gluon indices could be lowered and raised using the metric (called the **Cartan-Killing form**) $g_{ij} = \mathrm{tr}((T^i)^\dagger T^j)$. But since we are assuming $g_{ij} = \kappa\delta_i^j$, there is no need to do this.

$f_{ijk} = -f_{jik}$

(10.25)

In fact, the tensor f_{ijk} is **totally antisymmetric** (i.e., it changes sign under a transposition of any two indices).

Claim 19 *f_{ijk} is a real number.*

proof:

$$\left[i\mathrm{tr}([T^i, T^j]T^k)\right]^\dagger = (-i)\mathrm{tr}(T^k[T^j, T^i]) \tag{10.26}$$

$$= (-i)\mathrm{tr}([T^j, T^i]T^k) \tag{10.27}$$

$$= i\mathrm{tr}([T^i, T^j]T^k) \tag{10.28}$$

QED

Note that the birdtrack for the Lie Algebra commutation relations Eq.(10.23) can be understood as the statement that the generators T^j are invariant matrices. Below we restate Eq.(10.23) to make that obvious

(10.29)

Claim 20

$$f_{ijm}f_{mkl} - f_{ljm}f_{mki} = f_{iml}f_{jkm} \quad \textbf{(Jacobi identity)}$$

(10.30)

proof:

Note that

$$\begin{aligned}
\mathrm{tr}\left([[T^i,T^j],T^k]T^l\right) &= \mathrm{tr}\left(f_{ijm}[T^m,T^k]T^l\right) && (10.31)\\
&= \mathrm{tr}\left(f_{ijm}f_{mkl'}T^{l'}T^l\right) && (10.32)\\
&= f_{ijm}f_{mkl} && (10.33)
\end{aligned}$$

so the Jacobi identity can be restated as

$$\mathrm{tr}\left(\left\{[[T^i,T^j],T^k] + [[T^j,T^k],T^i] + [[T^k,T^i],T^j]\right\}T^l\right) = 0 \tag{10.34}$$

Hence, the claim follows if we can prove that

$$\underbrace{[[T^i,T^j],T^k] + [[T^j,T^k],T^i] + [[T^k,T^i],T^j]}_{\text{cyclic permutations of } ijk} = 0 \tag{10.35}$$

If we expand the left hand side on Eq.(10.35), we find 6 terms that cancel in pairs.
QED

Note Claim 20 can be undertood as the Lie Algebra commutation relations Eq.(10.23), but stated in the adj-rep instead of the def-rep. Indeed, if

$$M^i_{jk} = if_{ijk} \tag{10.36}$$

then Claim 20 becomes

$$(M^iM^l - M^lM^i)_{jk} = if_{ilm}(M^m)_{jk} \tag{10.37}$$

Note that Claim 20 can be understood as a statement of the fact that f_{ijk} is an invariant tensor.

$$0 = f_{ijm} f_{mkl} - f_{ljm} f_{mki} - f_{iml} f_{jkm}$$

(10.38)

10.5 Other Forms of Lie Algebra Commutators

Consider the following two gluon exchange operators. Note that $\mathbb{P}^2 = \mathbb{P}$, but $\mathbb{Q}^2 \neq \mathbb{Q}$, so $\mathbb{P}$ is a bonafide projection operator but $\mathbb{Q}$ isn't. $\mathbb{Q}\mathbb{Q}^\dagger = \mathbb{P}$ so $\mathbb{Q}$ behaves like half of a projection operator.

$$\mathbb{P}_a{}^b{}_c{}^d = \sum_i (T^i)_a{}^b (T^i)_c{}^d$$

(10.39)

$$\mathbb{Q}_a{}^b{}_Y{}^X = \sum_i (T^i)_a{}^b (T^i_\lambda)_Y{}^X$$

(10.40)

Claim 21 *If $\mathbb{Q}_b{}^a$ is the matrix with (Z, X) entries $\mathbb{Q}_b{}^a{}_Z{}^X$, then*

$$[\mathbb{Q}_b{}^a, \mathbb{Q}_d{}^c] = \mathbb{P}_{c'}{}^{ca}{}_b \mathbb{Q}_d{}^{c'} - \mathbb{Q}_{d'}{}^c \mathbb{P}_d{}^{d'a}{}_b \tag{10.41}$$

proof:

This claim can be visualized as follows. $\mathbb{Q}$ is an invariant tensor so

$$0 = \left\{ \begin{tikzcd}[column sep=small] c \arrow[dr] & & & & d \\ i \arrow[dr, squiggly] & & & & \\ Y & T^i_\lambda \arrow[l, Rightarrow] & \mathbb{Q} \arrow[l, Rightarrow] \arrow[uur] & X \arrow[l, Rightarrow] & \\ & c \arrow[r] & T^i \arrow[r] \arrow[d, squiggly] & \mathbb{Q} \arrow[r] \arrow[dl, Rightarrow] & d \\ - & i & & & \\ & Y & & X \arrow[ul, Rightarrow] & \end{tikzcd} - \begin{tikzcd}[column sep=small] c \arrow[dr] & & & & d \\ i \arrow[dr, squiggly] & & & & \\ Y & \mathbb{Q} \arrow[l, Rightarrow] \arrow[uur] & T^i_\lambda \arrow[l, Rightarrow] & X \arrow[l, Rightarrow] & \\ & c \arrow[r] & \mathbb{Q} \arrow[r] \arrow[d, squiggly] & T^i \arrow[r] & d \\ + & i & & & \\ & Y & & X \arrow[ul, Rightarrow] & \end{tikzcd} \right\} \tag{10.42}$$

Now multiplying by $(T^i)_a{}^b$, we get

$$\mathbb{Q}_b{}^a{}_Y{}^Z \mathbb{Q}_d{}^c{}_Z{}^X - \mathbb{Q}_d{}^c{}_Y{}^Z \mathbb{Q}_b{}^a{}_Z{}^X = \mathbb{P}_{c'}{}^{ca}{}_b \mathbb{Q}_d{}^{c'}{}_Y{}^X - \mathbb{Q}_{d'}{}^c{}_Y{}^X \mathbb{P}_d{}^{d'a}{}_b$$

$$\begin{tikzcd}[column sep=small] c \arrow[dr] & & & & d \\ a \arrow[dr] & & & & b \\ Y & \mathbb{Q} \arrow[l, Rightarrow] \arrow[uur] & \mathbb{Q} \arrow[l, Rightarrow] \arrow[uur] & X \arrow[l, Rightarrow] & \\ & c \arrow[r] & T^i \arrow[r] \arrow[d, squiggly] & \mathbb{Q} \arrow[r] \arrow[dl, Rightarrow] & d \\ & a \arrow[r] & T^i \arrow[r] & b & \\ & Y & & X \arrow[ul, Rightarrow] & \end{tikzcd} - \begin{tikzcd}[column sep=small] c \arrow[dr] & & & & d \\ a \arrow[dr] & & & & b \\ Y & \mathbb{Q} \arrow[l, Rightarrow] \arrow[uur] & \mathbb{Q} \arrow[l, Rightarrow] \arrow[uur] & X \arrow[l, Rightarrow] & \\ & c \arrow[r] & \mathbb{Q} \arrow[r] \arrow[d, squiggly] & T^j \arrow[r] & d \\ & a \arrow[r] & T^j \arrow[r] & b & \\ & Y & & X \arrow[ul, Rightarrow] & \end{tikzcd} = \tag{10.43}$$

Finally, if we hide the capital letter indices to obtain a statement about matrices with capital letter indices, we get

$$\mathbb{Q}_b{}^a \mathbb{Q}_d{}^c - \mathbb{Q}_d{}^c \mathbb{Q}_b{}^a = \mathbb{P}_{c'}{}^{ca}{}_b \mathbb{Q}_d{}^{c'} - \mathbb{Q}_{d'}{}^c \mathbb{P}_d{}^{d'a}{}_b \tag{10.44}$$

QED

Chapter 11

Lie Algebras of Classical Groups

In this chapter, we present an overview of the Lie algebras for the classical simple Lie groups.

Recall from Chapter 5 that the Lie algebras of the simple Lie groups can be divided into two classes: the Classical and the Exceptional. The Lie algebras of the classical simple Lie groups are

- $A_k = \mathfrak{su}(k+1)$
- $B_k = \mathfrak{so}(2k+1)$
- $C_k = \mathfrak{sp}(2k)$
- $D_k = \mathfrak{so}(2k)$

and the Lie algebras of Exceptional simple Lie groups are:

- E_6, E_7, E_8
- F_4
- G_2

11.1 $SU(n)$

$$SU(n) = \{U \in \mathbb{C}^{n\times n} : U^\dagger U = I,\ \det U = 1\} \tag{11.1}$$

Note that

$$1 = U^\dagger U = e^{X^\dagger} e^X \implies X^\dagger = -X \tag{11.2}$$

$$1 = \det U = \det e^X = e^{\mathrm{tr}X} \implies \mathrm{tr}X = 0 \tag{11.3}$$

Thus:

$$\mathfrak{su}(n) = \{X \in \mathbb{C}^{n\times n} : X^\dagger = -X, \quad \mathrm{tr}X = 0\} \tag{11.4}$$

Claim 22 *(Real dimension)*

$$\dim_{\mathbb{R}} \mathfrak{su}(n) = n^2 - 1 \tag{11.5}$$

proof:

Real parameter count:

- $+1$ for each diagonal entry
- $+1$ for the real part of each entry above the diagonal
- $+1$ for the imaginary part of each entry below the diagonal
- -1 for the zero trace constraint.

This adds up to $n^2 - 1$.

QED

Let X_j be the generators of the Lie algebra, and set

$$X_j = -iT_j. \tag{11.6}$$

By definition, the generators X_j are closed under commutation

$$[X_i, X_j] = f_{ijk} X_k \implies [T_i, T_j] = i f_{ijk} T_k \tag{11.7}$$

where f_{ijk} are the real structure constants of $\mathfrak{su}(n)$

$$X^\dagger = -X, \quad \mathrm{tr} X = 0 \implies (T_i)^\dagger = T_i, \quad \mathrm{tr}(T_i) = 0 \tag{11.8}$$

It's also possible to assume

$$\mathrm{tr}(T_i T_j) = \frac{1}{2}\delta_{ij} \tag{11.9}$$

For $SU(2)$, $T^i = \frac{1}{2}\sigma_i$ (Pauli matrices)
For $SU(3)$, $T^i = \frac{1}{2}\lambda_i$ (Gel-Mann matrices)

11.2 $SO(n)$

$$SO(n) = \{G \in \mathbb{R}^{n\times n} : G^T G = 1, \quad \det G = 1\} \tag{11.10}$$

$$\mathfrak{so}(n) = \{X \in \mathbb{R}^{n\times n} | X^T = -X\} \tag{11.11}$$

Note that $X^T = -X$ implies that the diagonal of X is zero, so $\mathrm{tr} X = 0$ automatically.

Claim 23

$$\dim_{\mathbb{R}} \mathfrak{so}(n) = \frac{n(n-1)}{2} \tag{11.12}$$

proof:

Real parameter count

- +1 for each entry above the diagonal

This adds up to $\frac{(n^2-n)}{2} = \frac{n(n-1)}{2}$.

QED

Define the generator basis $\{L_{ij} | i < j\}$, where

$$(L_{ij})_{ab} = \delta_{ia}\delta_{jb} - \delta_{ja}\delta_{ib} =$$

(11.13)

Note that $L_{ij}^T = L_{ji} = -L_{ij}$ and $L_{ii} = 0$. Hence these generators satisfy $X^T = -X$. Physicists often define generators $T_{ij} = iL_{ij}$ that are Hermitian.

Claim 24

$$[L_{ij}, L_{kl}] = \delta_{jk}L_{il} - \delta_{ik}L_{jl} - \delta_{jl}L_{ik} + \delta_{il}L_{jk}$$

(11.14)

proof:

Just calculate the commutator $[L_{ij}, L_{kl}]$ using the definition Eq.(11.13) of L_{ij}

(11.15)

(11.16)

(11.17)

(11.18)

$$(i \quad j \frown k \quad l) - (k \overset{\frown}{l \quad i} j) = \{ i \quad j \frown k \quad l \} = \delta_{jk} L_{il} \tag{11.19}$$

$$[L_{ij}, L_{kl}] = \{ i \quad j \frown k \quad l \} + \{ i \overset{\frown}{j \quad k} l \} - \{ i \overset{\frown}{j} k \quad l \} - \{ i \quad j \overset{\frown}{k} l \} \tag{11.20}$$

QED

11.3 $Sp(n)$

Assume n is even. Then

$$Sp(n) = \{U \in \mathbb{C}^{n \times n} : U^\dagger U = I, \quad U^T J U = J\} \tag{11.21}$$

where

$$J = \begin{pmatrix} 0 & I_{n/2} \\ -I_{n/2} & 0 \end{pmatrix} \tag{11.22}$$

Note that J satisfies

$$J^T = -J, \quad J^T J = 1 \tag{11.23}$$

Note that

$$1 = U^\dagger U = e^{X^\dagger} e^X \implies X^\dagger = -X. \tag{11.24}$$

$$U^T J U = J \implies 1 = J^T U^T J U = e^{J^T X^T J} e^X \implies J^T X^T J = -X \tag{11.25}$$

Hence

$$\mathfrak{sp}(n) = \{X \in \mathbb{C}^{n \times n} : X^\dagger = -X, \quad J^T X^T J = -X\} \tag{11.26}$$

Claim 25 *$X^\dagger = -X$ and $J^T X^T J = -X$ iff X has the* **A-B form**

$$X = \begin{pmatrix} A & B \\ -B^* & A^* \end{pmatrix} \tag{11.27}$$

where

$$A^\dagger = -A, \quad B^T = B \tag{11.28}$$

proof:

Let

$$X = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \tag{11.29}$$

Then

$$\begin{aligned} J^T X^T J &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} A^T & C^T \\ B^T & D^T \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} && (11.30) \\ &= \begin{pmatrix} -B^T & -D^T \\ A^T & C^T \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} && (11.31) \\ &= \begin{pmatrix} D^T & -B^T \\ -C^T & A^T \end{pmatrix} && (11.32) \end{aligned}$$

$$J^T X^T J + X = \begin{pmatrix} D^T + A & -B^T + B \\ -C^T + C & A^T + D \end{pmatrix} = 0 \tag{11.33}$$

Hence

$$\boxed{B^T = B, \quad C^T = C, \quad A^T = -D} \tag{11.34}$$

Also

$$X^\dagger + X = \begin{pmatrix} A^\dagger + A & C^\dagger + B \\ B^\dagger + C & D^\dagger + D \end{pmatrix} = 0 \tag{11.35}$$

Hence

$$\boxed{A^\dagger = -A, \quad D^\dagger = -D, \quad C^\dagger = -B} \tag{11.36}$$

Combining Eqs.(11.34) and (11.36), we get

$$C = -B^*, \quad D = A^* \tag{11.37}$$

QED

Let

$$X = X_A + \epsilon_B \tag{11.38}$$

where

$$X_A = \begin{pmatrix} A & 0 \\ 0 & A^* \end{pmatrix}, \qquad X_A^\dagger = -X_A \tag{11.39}$$

and

$$\epsilon_B = \begin{pmatrix} 0 & B \\ -B^* & 0 \end{pmatrix}, \quad \epsilon_B^\dagger = -\epsilon_B \tag{11.40}$$

Note that

$$J^T \epsilon_B^\dagger J = -\epsilon_B, \quad J^T X_A^\dagger J = -X_A \tag{11.41}$$

Claim 26 *(Lie Algebra is closed)*

$$[X_1, X_2] \in \mathfrak{sp}(n), \tag{11.42}$$

proof:

If $X, Y \in \mathfrak{sp}(n)$,

$$[X, Y]^\dagger = [Y^\dagger, X^\dagger] = [-Y, -X] = -[X, Y] \tag{11.43}$$

$$\begin{aligned} X_A \epsilon_B &= \begin{pmatrix} A & 0 \\ 0 & A^* \end{pmatrix} \begin{pmatrix} 0 & B \\ -B^* & 0 \end{pmatrix} && (11.44) \\ &= \begin{pmatrix} 0 & AB \\ -(AB)^* & 0 \end{pmatrix} && (11.45) \\ &= \epsilon_{AB} && (11.46) \end{aligned}$$

$$\begin{aligned} \epsilon_B X_A &= \begin{pmatrix} 0 & B \\ -B^* & 0 \end{pmatrix} \begin{pmatrix} A & 0 \\ 0 & A^* \end{pmatrix} && (11.47) \\ &= \begin{pmatrix} 0 & BA^* \\ -B^* A & 0 \end{pmatrix} && (11.48) \\ &= \epsilon_{BA^*} && (11.49) \end{aligned}$$

$$X_{A_1} X_{A_2} = X_{A_1 A_2} \tag{11.50}$$

$$\begin{aligned} \epsilon_{B_1} \epsilon_{B_2} &= \begin{pmatrix} 0 & B_1 \\ -B_1^* & 0 \end{pmatrix} \begin{pmatrix} 0 & B_2 \\ -B_2^* & 0 \end{pmatrix} && (11.51) \\ &= \begin{pmatrix} -B_1 B_2^* & 0 \\ 0 & -B_1^* B_2 \end{pmatrix} && (11.52) \\ &= X_{-B_1 B_2^*} && (11.53) \end{aligned}$$

$$[X_A, \epsilon_B] = \epsilon_{AB - BA^*} \tag{11.54}$$

$$[X_{A_1}, X_{A_2}] = X_{[A_1, A_2]} \tag{11.55}$$

$$[\epsilon_{B_1}, \epsilon_{B_2}] = X_{-B_1 B_2^* - B_2 B_1^*} \tag{11.56}$$

QED

Claim 27 *(Real dimension)*

$$\dim_{\mathbb{R}} \mathfrak{sp}(n) = n(2n+1) \tag{11.57}$$

proof:

$A^\dagger = -A$ so A contributes n^2 real parameters.

$B^T = B$ so B contributes

$$\frac{(n^2-n)}{2} + n = \frac{(n^2+n)}{2} = \frac{n(n+1)}{2} \tag{11.58}$$

complex parameters.

This adds up to

$$n^2 + n(n+1) = n(2n+1) \tag{11.59}$$

real parameters.

QED

Chapter 12

Orthogonal Groups

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

$O(n)$ and $SO(n)$ are defined as the following groups of real matrices:

$$O(n) = \{G \in \mathbb{R}^{n\times n} : G^T G = 1\} \tag{12.1}$$

$$SO(n) = \{G \in O(n) : \det G = 1\} \tag{12.2}$$

$O(n)$ contains orthogonal matrices G ($G^T G = GG^T = 1$) with $\det G \in Z_2 = \{-1, 1\}$. $SO(n)$ only contains those with $\det G = 1$. $O(n) \cong Z_2 \times SO(n)$ where $Z_2 = \{-1, 1\}$ corresponds to the sign of $\det G$. Hence, $O(n)$ is a **double cover** of $SO(n)$. $O(n)$ consists of 2 **connected components** (CC), whereas $SO(n)$ has only one CC.

An example of a $G \in O(n)$ that is not in $SO(n)$ is a reflection $Gx = -x$ for odd n. Another example for $O(2)$ is

$$\text{rotation:} \quad G = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \quad \det G = 1 \tag{12.3}$$

$$\text{improper rotation:} \quad G = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix}, \quad \det G = -1 \tag{12.4}$$

The irreps of $SO(n)$ depend on whether n is even or odd, and whether the rep is spinor or non-spinor. This chapter deals with **non-spinor reps** (with either even or odd n.). Chapter 19 deals with the **spinor reps**.

We assume that the **metric tensor** $g_{\mu\nu}$ is a primitive invariant that satisfies:

$$g_{\mu\nu} = g_{\nu\mu} = [g]_{\mu\nu}, \quad g^{\mu\nu} = g^{\nu\mu} = [g]_{\mu\nu}, \quad g_\mu{}^\nu = g_\nu{}^\mu = \delta_\mu^\nu \tag{12.5}$$

$$g_{\nu\mu} x^\mu = x_\nu, \quad g^{\rho\nu} x_\nu = x^\rho \quad (\text{so } g_{\nu\mu} g^{\rho\nu} = \delta_\mu^\rho) \tag{12.6}$$

where $\mu, \nu, \rho \in \{1, 2, \ldots, n\}$ and x_μ is any tensor.

In this section, we will call **orthogonal groups** the group of matrices under which the following symmetric quadratic form is invariant

$$h(x) = g_{\mu\nu} x^\mu x^\nu \tag{12.7}$$

where $\mu, \nu \in \{1, \ldots, n\}$. Thus

$$h(Gx) = h(x) \tag{12.8}$$

$$g_{\mu\nu} G^\mu{}_\alpha G^\nu{}_\beta x^\alpha x^\beta = g_{\alpha\beta} x^\alpha x^\beta \implies g_{\mu\nu} G^\mu{}_\alpha G^\nu{}_\beta = g_{\alpha\beta} \implies G^T g G = g \tag{12.9}$$

This condition guarantees that $G \in O(n)$ is orthogonal for $g_{\mu\nu} = \delta^\nu_\mu$ but not that $\det G = 1$. When $g_{\mu\nu}$ is not the Kronecker delta function, we get a different group. For example, if $g_{\mu\nu} = diag(1, -1, -1, -1)$ and $\det G = 1$, we get the **Lorentz group** $SO(1, 3)$ used in Special Relativity.

In this chapter (and in this book), we will point the arrows in a birdtrack so that the birdtrack is a DAG. Cycles that make the birdtrack not acyclic will have a segment in red. Without that red segment, the birdtrack becomes acyclic. The reason we follow this arrow convention is that it promotes acyclic birdtracks which are more akin to bnets. We will eschew undirected birdtracks for the same reason: bnets are directed.

Let

$$\boxed{g_\mu{}^\nu = \delta^\nu_\mu}, \quad \longleftarrow g \longleftarrow \; = \; \longleftarrow \tag{12.10}$$

$$\boxed{g^\mu{}_\nu = \delta^\mu_\nu}, \quad \longrightarrow g \longrightarrow \; = \; \longrightarrow \tag{12.11}$$

$$\boxed{g_{\mu\sigma} g^{\sigma\nu} = \delta^\nu_\mu} \quad \longleftarrow \underline{g} \longrightarrow \overline{g} \longleftarrow \; = \; \longleftarrow \tag{12.12}$$

Note that we used

$$\underline{g} = [g_{\mu\nu}], \quad \overline{g} = [g^{\mu\nu}] \tag{12.13}$$

We could write Eq.(12.12) without the overline and underline on g. Those g-decorations are redundant as omitting them would not introduce any ambiguity. However, we will use them because they make spotting errors in the arrow directions easier.

The generators of orthogonal groups will be represented by:

$$(T_i)_\mu{}^\nu = \quad \longleftarrow T_i \longleftarrow \tag{12.14}$$

We will also use

$(T_i)^\mu{}_\nu =$

$(T_i)_{\mu\nu} =$

$(T_i)^{\mu\nu} =$

(12.15)

For $G \in O(n)$, $G^T G = 1$ with $G = e^{iT_i\epsilon_i}$ where $\epsilon_i \in \mathbb{R}$. Hence, the generators T_i must be anti-symmetric ($T_i^T = -T_i$).

$$\boxed{(T_i)_{\mu\nu} = -(T_i)_{\nu\mu}}$$

(12.16)

$g^\nu_\mu = \delta^\nu_\mu$ is obviously an invariant matrix. $g_{\mu\nu}$ must be invariant too, so

$$\boxed{\underbrace{(T_i)_\mu{}^\sigma g_{\sigma\nu} + (T_i)_\nu{}^\sigma g_{\mu\sigma} = 0}_{(T_i)_{\mu\nu}=-(T_i)_{\nu\mu}}}$$

(12.17)

Hence, the invariance condition Eq.(12.17) reduces to to the statement that $(T_i)_{\mu\nu}$ is antisymmetric.

The anti-symmetrizer $\mathcal{A}_2$ is an invariant tensor (see Section 23.3). Other projectors of the $V \otimes V$ are not invariant tensors. Therefore, we must have

(12.18)

For $SO(n)$ and $O(n)$, the dimension N of the adjoint rep (= number of generators) is

$$N = \frac{n(n-1)}{2} =$$

(12.19)

If you take an $n \times n$ matrix and remove its diagonal, this N is the number of entries in the upper (or lower) triangular sector of the matrix. Recall that for $U(n)$, $N = n^2$, and for $SU(n)$, $N = n^2 - 1$. So for $U(n)$ (or $SU(n)$), there is a generator for each entry (or each entry minus one) of an $n \times n$ matrix.

Claim 28

$$\Gamma_{fun}\delta^{\nu}_{\mu} = \sum_i (T_i T_i)_{\mu}{}^{\nu} = \frac{n-1}{2}\delta^{\nu}_{\mu} \tag{12.20}$$

$\sum_i$

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

proof:

$(T_i T_i)_{\mu}{}^{\nu} =$

(12.21)

$=$

(12.22)

$= \frac{1}{2}\Bigg[$

$\Bigg]$ (12.23)

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

(12.24)

QED

12.1 $V_{def} \otimes V_{def}$ Decomposition

Let

$V_{def} = V =$ vector space in defining representation $\{|\mu\rangle\}_{\mu=1}^{n}$.

Note that the symmetrizer $\mathcal{S}_2$ originaly has two upper anf two lower indices. Its two upper indices can be lowered using the metric tensor:

$$(\mathcal{S}_2)_{\mu\nu,\rho\sigma} = g_{\rho\rho'} g_{\sigma\sigma'} (\mathcal{S}_2)_{\mu\nu}{}^{\rho'\sigma'} \tag{12.25}$$

$$= \frac{1}{2}\left(g_{\mu\nu} g_{\nu\rho} + g_{\mu,\rho} g_{\mu\sigma}\right) \tag{12.26}$$

$=$

(12.27)

$=$

(12.28)

Likewise

(12.29)

Define tensor M by

$$M_{\mu\nu}{}^{\rho\sigma} = g_{\mu\nu} g^{\rho\sigma} =$$

(12.30)

Note that

$$M^2 =$$

$$= nM$$

(12.31)

Hence, $(M-n)M = 0$ so M has two eigenvalues $\lambda = 0, n$.

Next we will use the following equation from Chapter 18 [1] to obtain a projection (PO) operator for each eigenvalue

$$P_i = \sum_{j \neq i} \frac{M - \lambda_j}{\lambda_i - \lambda_j} \tag{12.32}$$

1. Singlet PO

$$(P_S)_{\mu\nu}{}^{\rho\sigma} = \frac{1}{n}$$

(12.33)

$$dim(P_S) = \frac{1}{n}$$

(12.34)

$$= 1 \tag{12.35}$$

2. Traceless Symmetric PO[2]

[1] Note that this equation projects to zero all eigenvalues except one.

[2] Traceless here refers to $P_a{}^a{}_c{}^d V_d{}^c = (PV)_a{}^a = 0$ for any vector $V_d{}^c$. It does not refer to $P_a{}^b{}_b{}^a = 0$

$$(P_{TS})_{\mu\nu}{}^{\rho\sigma} =$$ (12.36)

$$dim(P_{TS}) =$$ (12.37)

$$= \frac{1}{2}(n^2+n) - 1 \tag{12.38}$$

$$= \frac{1}{2}(n+2)(n-1) \tag{12.39}$$

3. Anti-symmetric PO

$$(P_A)_{\mu\nu}{}^{\rho\sigma} =$$ (12.40)

$$dim(P_A) =$$ (12.41)

$$= \frac{1}{2}(n^2-n) \tag{12.42}$$

$$= \frac{1}{2}n(n-1) \tag{12.43}$$

Claim 29 *The Clebsch-Gordan series for $V \otimes V$ (i.e., decomposition of $V \otimes V$) is*

$$\begin{array}{ccccccc} \overbrace{V \otimes V}^{\mathcal{V}} & = & P_S\mathcal{V} & \oplus & P_{TS}\mathcal{V} & \oplus & P_A\mathcal{V} \\ \square \otimes \square & = & \bullet & \oplus & \square\square & \oplus & \begin{smallmatrix}\square\\ \square\end{smallmatrix} \\ n^2 & = & 1 & + & \frac{1}{2}(n+2)(n-1) & + & \frac{1}{2}n(n-1) \end{array} \tag{12.44}$$

The projection operator tree is

where $P_{SYM} = \mathcal{S}_2$.

proof:
QED

12.2 $V_{adj} \otimes V_{def}$ Decomposition

Let

$V_{def} = V =$ vector space in defining representation $\{|\mu\rangle\}_{\mu=1}^{n}$.
$V_{adj} =$ vector space in adjoint representation $\{|i\rangle\}_{i=1}^{N}$.
$V_{adj} \otimes V \cong (V \otimes V^{\dagger}) \otimes V$

$e =$

(12.45)

$R =$

(12.46)

$Q =$

(12.47)

Recall that for $SO(n)$ and $O(n)$, the dimension N of the adjoint rep is

$$N = \frac{n(n-1)}{2} =$$ (12.48)

For example, for $SO(3)$, $N = 3$.

Note that

$\mathrm{tr}(e) =$ $= Nn$ (12.49)

$\mathrm{tr}(R) =$

$= N$ (12.50)

$\mathrm{tr}(Q) =$

$= N$ (12.51)

Claim 30

$$R^2 = \frac{n-1}{2} R \tag{12.52}$$

$$QR = RQ = \frac{1}{2}R \tag{12.53}$$

$$Q^2 = \frac{e - Q}{2} \tag{12.54}$$

proof:

$R^2 \;=$

(12.55)

$$= \frac{n-1}{2}R \quad \text{(by Eq.(12.20))} \tag{12.56}$$

$QR \;=$

(12.57)

Define

$X =$

(12.58)

$$X \;=\;$$

(12.59)

$$= \frac{1}{2}\Bigg[$$

$$\Bigg]$$

(12.60)

$$= \frac{1}{2}$$

(12.61)

so

$$QR = RQ = \frac{1}{2}R \tag{12.62}$$

$$Q^2 =$$

(12.63)

$$=$$

(12.64)

$$= \frac{1}{2}\Bigg[$$

$$-$$

$$\Bigg]$$

(12.65)

$$= \frac{1}{2}\Bigg[$$

$$-$$

$$\Bigg]$$

(12.66)

$$= \frac{e-Q}{2}$$

(12.67)

QED

Claim 31

$$P_1 = \frac{2}{n-1}R \tag{12.68}$$

$$P_2 = \frac{1}{3}P_4(1-2Q) = \frac{1}{3}\left[e-2Q\right] \tag{12.69}$$

$$P_3 = \frac{2}{3}P_4(1+Q) = \frac{2}{3}\left[e+Q-\frac{3}{n-1}R\right] \tag{12.70}$$

$$P_4 = e - P_1 \tag{12.71}$$

are projectors for $O(n)$ and $SO(n)$. The $V_{adj} \otimes V = \sum_\lambda V_\lambda$ Clebsch-Gordan series is given by

$$\overbrace{V_{adj} \otimes V}^{\mathcal{V}} = P_1\mathcal{V} \oplus P_2\mathcal{V} \oplus P_3\mathcal{V}$$

(12.72)

$\frac{1}{2}n^2(n-1)$	$=$	n	$+$	$\frac{1}{6}n(n-1)(n-2)$	$+$	$\frac{1}{3}n(n+2)(n-2)$
$SO(3):9$	$=$	3	$+$	1	$+$	5
$SO(4):24$	$=$	4	$+$	4	$+$	16

The projection operator tree is

proof:

$$\begin{aligned} \mathrm{tr}(P_1) &= \frac{2}{n-1}N && (12.73)\\ &= \frac{1}{n-1}n(n-1) && (12.74)\\ &= n && (12.75) \end{aligned}$$

$$\begin{aligned} \mathrm{tr}(P_2) &= \frac{N}{3}(n-2) && (12.76)\\ &= \frac{n(n-1)}{6}(n-2) && (12.77) \end{aligned}$$

$$\begin{aligned} \mathrm{tr}(P_3) &= \frac{2N}{3}\left(n+1-\frac{3}{n-1}\right) && (12.78)\\ &= \frac{n}{3}\left(n^2-4\right) && (12.79) \end{aligned}$$

From $R^2 = \frac{2}{n-1}R$,

$$P_1 = \frac{2}{n-1}R \qquad (12.80)$$

Define

$$P_4 = e - P_1 \tag{12.81}$$

From $Q^2 = \frac{1}{2}(1-Q)$, we get

$$2Q^2 + Q - 1 = (2Q-1)(Q+1) = 0 \tag{12.82}$$

Let

$$P_2 = \frac{1}{3}P_4(1-2Q) \quad P_3 = \frac{2}{3}P_4(1+Q) \tag{12.83}$$

and

$$a = \frac{2}{n-1} \tag{12.84}$$

Then

$$\begin{aligned}
P_3 &= \frac{2}{3}P_4(1+Q) && (12.85)\\
&= \frac{2}{3}(e-aR)(1+Q) && (12.86)\\
&= \frac{2}{3}(e-aR+Q-aRQ) && (12.87)\\
&= \frac{2}{3}\left(e-\frac{3}{2}aR+Q\right) \quad (\text{use } QR = \frac{1}{2}R) && (12.88)\\
&= \frac{2}{3}\left(e-\frac{3}{n-1}R+Q\right) && (12.89)
\end{aligned}$$

Furthermore

$$\begin{aligned}
P_2 &= \frac{1}{3}P_4(1-2Q) && (12.90)\\
&= \frac{1}{3}(e-aR)(1-2Q) && (12.91)\\
&= \frac{1}{3}(e-aR-2Q+2aRQ) && (12.92)\\
&= \frac{1}{3}(e-2Q) \quad (\text{use } QR = \frac{1}{2}R) && (12.93)
\end{aligned}$$

QED

Chapter 13

Paulions and Gammions

13.1 Paulions

Let

$\vec{a} \in \mathbb{R}^3$, $\hat{a} = \frac{\vec{a}}{|\vec{a}|}$
$i = 1, 2, 3$, $\mu = 0, 1, 2, 3$
The Pauli matrices are defined by

$$\sigma_x = \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{13.1}$$

Note that they are Hermitian

$$\sigma_i^\dagger = \sigma_i \tag{13.2}$$

and their multiplication table is given by

$$\sigma_i \sigma_j = \delta_{ij} I_2 + i\epsilon_{ijk}\sigma_k \tag{13.3}$$

This multiplication table implies

- Square is 1 (unitary too because Hermitian)

$$\sigma_i^2 = 1 \tag{13.4}$$

- Different ones anticommute and proportional to third

$$\sigma_x \sigma_y = -\sigma_y \sigma_x \tag{13.5}$$

$$\sigma_x \sigma_y = i\sigma_z \tag{13.6}$$

It's common to write

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3) \tag{13.7}$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \sigma_\mu = (\sigma_0, \vec{\sigma}) \tag{13.8}$$

Suppose $\vec{x} = (x_1, x_2, x_3) \in \mathbb{R}^3$. We define the **Paulion** $\sigma_{\vec{x}}$ by[1]

$$\sigma_{\vec{x}} = \sigma \cdot \vec{x} = x_1\sigma_1 + x_2\sigma_2 + x_3\sigma_3 \tag{13.9}$$

Claim 32

$$\sigma_{\vec{a}}\sigma_{\vec{b}} = \vec{a} \cdot \vec{b} + i\sigma_{\vec{a}\times\vec{b}} \tag{13.10}$$

As a consequence,

$$(\sigma_{\vec{a}})^2 = |\vec{a}|^2 \tag{13.11}$$

$$(\sigma_{\hat{a}})^2 = 1 \tag{13.12}$$

$$[\sigma_{\vec{a}}, \sigma_{\vec{b}}]_+ = 2(\vec{a} \cdot \vec{b}) \tag{13.13}$$

$$[\sigma_{\vec{a}}, \sigma_{\vec{b}}] = 2i\sigma_{\vec{a}\times\vec{b}} \tag{13.14}$$

proof: This follows directly from Eq.(13.3).
QED

Claim 33 *If $\vec{a} \in \mathbb{R}^3$ then*

$$e^{i\sigma_{\vec{a}}} = \cos|\vec{a}| + i\sigma_{\hat{a}} \sin|\vec{a}| \tag{13.15}$$

and

$$e^{i\beta\sigma_{\hat{a}}} = \cos(\beta) + i\sigma_{\hat{a}} \sin(\beta) \tag{13.16}$$

proof:

First show by Taylor expansion of the exponential that the following equation is true.

$$e^{i\beta\sigma_i} = \cos\beta + i\sigma_i \sin\beta \tag{13.17}$$

Then replace σ_i by $\sigma_{\hat{a}}$.
QED

[1]The term Paulion is my own. As far as I know, the construct $\sigma_{\vec{a}}$, although often used, doesn't have a common name.

Figure 13.1: Reflection about plane with normal vector $\hat{a}$

Figure 13.2: Geometry of $R_{\hat{a}}(\Theta)x$, where $\Theta = 2\theta$

Define

$$\left\langle \sigma_{\underline{\hat{a}}} \right\rangle (\vec{x}) = -\sigma_{\hat{a}}\sigma_{\vec{x}}\sigma_{\hat{a}} \tag{13.18}$$

Fig.13.1 illustrates reflection about plane with normal vector $\hat{a}$

Claim 34 *(Reflection)*

$$-\sigma_{\hat{a}}\sigma_{\vec{x}}\sigma_{\hat{a}} = \sigma_{\rho_{\hat{a}}\vec{x}} \tag{13.19}$$

where

$$\rho_{\hat{a}}\vec{x} = \vec{x} - 2(\hat{a}\cdot\vec{x})\hat{a} \tag{13.20}$$

proof:

$$\begin{aligned}
\sigma_{\hat{a}}\sigma_{\vec{x}}\sigma_{\hat{a}} &= \left[\hat{a}\cdot\vec{x} + i\sigma_{\hat{a}\times\vec{x}}\right]\sigma_{\hat{a}} && (13.21)\\
&= \hat{a}\cdot\vec{x}\sigma_{\hat{a}} + i\underbrace{(\hat{a}\times\vec{x})\cdot\hat{a}}_{=0} - \sigma\cdot\underbrace{(\hat{a}\times\vec{x})\times\hat{a}}_{\vec{x}-(\vec{x}\cdot\hat{a})\hat{a}} && (13.22)\\
&= -\sigma\cdot\left[\vec{x} - 2(\hat{a}\cdot\vec{x})\hat{a}\right] && (13.23)
\end{aligned}$$

QED

Claim 35 *(Rotation, Rodrigues formula)*

If

$$U = e^{-i\frac{\Theta}{2}\sigma_{\hat{a}}}, \quad \Theta = 2\theta \tag{13.24}$$

then

$$U\sigma_{\vec{x}}U^\dagger = \sigma_{R_{\hat{a}}(\Theta)\vec{x}} \tag{13.25}$$

where

$$\begin{aligned} R_{\hat{a}}(\Theta)\vec{x} &= \vec{x} + (2|\vec{x}|\sin\beta\sin\theta)(-\sin\theta\hat{r} + \cos\theta\hat{\theta}) && (13.26)\\ &= \vec{x} + (2\sin\theta)(-\sin\theta\vec{r} + \cos\theta\vec{\theta}) && (13.27) \end{aligned}$$

where (see Fig.13.2)

$$\beta = \angle(\vec{x}, \vec{a}), \quad \hat{\theta} = \frac{1}{|\vec{x}|\sin\beta}\overbrace{(\hat{a}\times\vec{x})}^{\vec{\theta}}, \quad \hat{r} = \frac{1}{|\vec{x}|\sin\beta}\overbrace{[\vec{x} - \hat{a}(\hat{a}\cdot\vec{x})]}^{\vec{r}} \tag{13.28}$$

This immediately implies that $SU(2)_{\mathbb{R}}$ is a double cover of $SO(3)$.

$$SU(2)_{\mathbb{R}} \xrightarrow[2\ to\ 1\ map]{} SO(3), \quad SU(2)_{\mathbb{R}}/\{1,-1\} \cong SO(3) \tag{13.29}$$

proof:

Let $C = \cos\theta$, $S = \sin\theta$. Then

$$\begin{aligned} U\sigma_{\vec{x}}U^\dagger &= (C - iS\sigma_{\hat{a}})\sigma_{\vec{x}}(C + iS\sigma_{\hat{a}}) && (13.30)\\ &= C^2\sigma_{\vec{x}} - iSC[\sigma_{\hat{a}}, \sigma_{\vec{x}}] + S^2\sigma_{\hat{a}}\sigma_{\vec{x}}\sigma_{\hat{a}} && (13.31)\\ &= \sigma\cdot\left\{C^2\vec{x} + 2SC(\hat{a}\times\vec{x}) - S^2[\vec{x} - 2(\hat{a}\cdot\vec{x})\hat{a}]\right\} && (13.32)\\ &= \sigma\cdot\left\{\vec{x} + 2SC\vec{\theta} - 2S^2\vec{r}\right\} && (13.33) \end{aligned}$$

If U produces rotation R, then $-U$ gives the same rotation so 2 to 1 map:

$$(-U)\sigma_{\vec{x}}(-U)^\dagger = U\sigma_{\vec{x}}U^\dagger. \tag{13.34}$$

QED

13.2 Gammions

Suppose

$n_- = n$ for n even and $n_- = n - 1$ for n odd.
$int(x)$ = integer part of $x \in \mathbb{R}$. $int(n/2) = n_-/2$
$\mu = 1, 2, \ldots, n$
$a_\mu, b_\mu \in \mathbb{R}$ for each μ,
$\gamma_\mu \in \mathbb{C}^{d\times d}$ where $d = int(n/2)$.

$$a \cdot b = a_\mu b^\mu \tag{13.35}$$

We define the **Gammion** $\gamma_{\underline{a}}$ by[2]

$$\gamma \cdot a = \gamma_{\underline{a}} = \gamma_\mu a^\mu \tag{13.36}$$

We will use an underline in $\gamma_{\underline{a}}$ to distinguish a from an index.

The Clifford anticommutation relation is

$$[\gamma_\mu, \gamma_\nu]_+ = 2\eta_{\mu\nu} \tag{13.37}$$

where $\eta_{\mu\nu}$ is real valued[3] For $n = 4$, it equals the Euclidean metric $(1, 1, 1, 1)$ or the Lorentzian metric $(1, -1, -1, -1)$. The Clifford anticommutation relation can be expressed in terms of gammions thus:

$$\gamma_{\underline{a}}\gamma_{\underline{b}} = a \cdot b + \gamma_{\mu\nu} a^\mu b^\nu, \tag{13.38}$$

where bivector

$$\gamma_{\mu\nu} = \frac{1}{2}[\gamma_\mu, \gamma_\nu] \tag{13.39}$$

is the generator of $\mathfrak{so}(n)_\mathbb{R}$ or $\mathfrak{so}(p, q)$.

Define

$$\left\langle \gamma_{\underline{\hat{a}}} \right\rangle (x) = -\gamma_{\underline{\hat{a}}}\gamma_{\underline{x}}\gamma_{\underline{\hat{a}}} \tag{13.40}$$

Claim 36 *(Reflection)*

$$-\gamma_{\underline{\hat{a}}}\gamma_{\underline{x}}\gamma_{\underline{\hat{a}}} = \gamma_{\underline{\rho_{\hat{a}} x}} \tag{13.41}$$

where

$$\rho_{\hat{a}} x = x - 2(\hat{a} \cdot x)\hat{a} \tag{13.42}$$

[2]The term Gammion, like the term Paulion, is my own. As far as I know, the construct $\gamma_{\underline{a}}$, although often used, doesn't have a common name.

[3]Since $\eta_{\mu\nu}$ is real, we consider later on in this chapter, the Clifford algebra $Cl(n)_\mathbb{R}$ instead of its complexification $Cl(n)_\mathbb{C}$

proof:
QED

Claim 37 *(Rotation)*
If

$$S(\omega) = e^{\omega^{\mu\nu}\gamma_{\mu\nu}} \tag{13.43}$$

for some $\omega_{\mu\nu} \in \mathbb{R}$*, then*

$$S(\omega)\gamma_{\underline{x}}S^{\dagger}(\omega) = \gamma_{Rx} \tag{13.44}$$

where $R \in SO(n)$ *(or* $SO(p,q)$*).*

proof:
QED

13.3 $Spin(n)_{\mathbb{R}}$

If $\gamma_\mu^\dagger = \gamma_\mu$ for $\mu = 1, 2, \ldots, n$ (this assumes the Euclidean metric which is $g_{\mu\nu} = diag(1,1,1,1)$ for $n = 4$)

$$Spin(n)_{\mathbb{R}} = \{e^{\omega^{\mu\nu}\gamma_{\mu\nu}} | \omega_{\mu\nu} = -\omega_{\nu\mu} \in \mathbb{R}\}\} \tag{13.45}$$

If $\gamma_0^\dagger = \gamma_0$, and $\gamma_i^\dagger = -\gamma_i$ (this assumes the mostly-minus metric which is $g_{\mu\nu} = diag(1,-1,-1,-1)$ for $n = 4$)

$$Spin(1,3)_{\mathbb{R}} = \{e^{-i\omega^{\mu\nu}\gamma_{\mu\nu}} | \omega_{\mu\nu} = -\omega_{\nu\mu}, \omega_{0,i} \in \mathbb{R}, \omega_{i,j} \in i\mathbb{R}\} \tag{13.46}$$

Spinors are the vectors in the vector space upon which the group $Spin(n)_{\mathbb{R}}$ acts.

Suppose $e_i \in \mathbb{R}^n$ for $i = 1, 2, \ldots n$, and all components of e_i are zero except the ith one. Define

$$\gamma_i = \gamma_{\underline{e}_i} \tag{13.47}$$

Consider the Clifford anticommutator in the Euclidean metric:

$$[\gamma_i, \gamma_j]_+ = 2\delta_{i,j} \tag{13.48}$$

Define the Clifford algebra $Cl(n)_{\mathbb{R}}$ by

$$\Pi_0 = \{1\}, \quad |\Pi_0| = \binom{n}{0} = 1 \tag{13.49}$$

$$\Pi_1 = \{\gamma_i | i = 1, 2, \ldots, n\} \quad |\Pi_1| = \binom{n}{1} = n \tag{13.50}$$

$$\Pi_2 = \{\gamma_{i_1}\gamma_{i_2}|i_1 < i_2\}, \quad |\Pi_2| = \binom{n}{2} \tag{13.51}$$

$$\Pi_3 = \{\gamma_{i_1}\gamma_{i_2}\gamma_{i_3}|i_1 < i_2 < i_3\}, \quad |\Pi_3| = \binom{n}{3} \tag{13.52}$$

$$\Pi_n = \{\gamma_1\gamma_2 \ldots \gamma_n\}, \quad |\Pi_n| = \binom{n}{n} = 1 \tag{13.53}$$

$$\sum_{k=0}^{n} |\Pi_k| = \sum_{k=0}^{n} \binom{n}{k} = (1+1)^n = 2^n \tag{13.54}$$

$$Cl(n)_{\mathbb{R}} = span_{\mathbb{R}} \left(\bigcup_{k=0,1,2,\ldots,n} \Pi_k \right) \tag{13.55}$$

$$Cl^0(n)_{\mathbb{R}} = span_{\mathbb{R}} \left(\bigcup_{k=0,2,4,\ldots,n_-} \Pi_k \right) \tag{13.56}$$

$$Cl^1(n)_{\mathbb{R}} = span_{\mathbb{R}} \left(\bigcup_{k=1,3,5,\ldots,n_-} \Pi_k \right) \tag{13.57}$$

$$Cl(n)_{\mathbb{R}} = Cl^0(n)_{\mathbb{R}} \oplus Cl^1(n)_{\mathbb{R}} \tag{13.58}$$

Since $e^{\omega^{\mu\nu}\gamma_{\mu\nu}}$ is the exponentiation of a bivector, its Taylor expansion only contains summands with an even number of gammas. Hence,

$$Spin(n)_{\mathbb{R}} \subset Cl^0(n)_{\mathbb{R}} \tag{13.59}$$

Define thee unit sphere in n dimensions by

$$S^n = \{\hat{a} \in \mathbb{R}^n | \hat{a}^2 = 1\} \tag{13.60}$$

Pin stands for "Product of involutions" An involution in this case is a unit vector (i.e., $\hat{a} \in \mathbb{R}^n$ such that $\hat{a} \cdot \hat{a} = \hat{a}^2 = 1$) The $Pin(n)_{\mathbb{R}}$ group is defined by

$$Pin(n)_{\mathbb{R}} \quad = \quad \cup_{k=1}^{\infty} \{\gamma_{\underline{\hat{a}}_1}\gamma_{\underline{\hat{a}}_1} \ldots \gamma_{\underline{\hat{a}}_k} | \hat{a}_i \in S^n \text{ for all } i\} \tag{13.61}$$

Note that

- One refection

$$det[\left\langle \gamma_{\underline{\hat{a}}} \right\rangle (x)] = -det(\gamma_{\underline{x}}\gamma_{\underline{\hat{a}}}^2) = -\det(\gamma_{\underline{x}}) \tag{13.62}$$

- Two reflections = a rotation

$$det[\left\langle \gamma_{\underline{\hat{a}}_1}\gamma_{\underline{\hat{a}}_2} \right\rangle (x)] = +\det(\gamma_{\underline{x}}) \tag{13.63}$$

Hence, $Pin(n)_{\mathbb{R}}$ is a double cover of $O(n)$ (because $det = \pm 1$)

$$Pin(n)_{\mathbb{R}} \xrightarrow[\text{2 to 1 map}]{} O(n), \quad Pin(n)_{\mathbb{R}}/\{1,-1\} \cong O(n) \tag{13.64}$$

Previously, we defined $Spin(n)_{\mathbb{R}}$ by exponentiating its generators. $Spin(n)_{\mathbb{R}}$ can also be defined as follows, in terms of products of gammions instead of exponentiating generators:

$$Spin(n)_{\mathbb{R}} = \cup_{k=1}^{\infty}\{\gamma_{\underline{\hat{a}}_1}\gamma_{\underline{\hat{a}}_1}\dots\gamma_{\underline{\hat{a}}_{2k}}|\hat{a}_i \in S^n \text{ for all } i\} \tag{13.65}$$

$Spin(n)_{\mathbb{R}}$ is a double cover of $SO(n)$ (because $\left\langle \gamma_{\underline{\hat{a}}} \right\rangle = \langle \gamma_{-\hat{a}} \rangle$)

$$Spin(n)_{\mathbb{R}} \xrightarrow[\text{2 to 1 map}]{} SO(n), \quad Spin(n)_{\mathbb{R}}/\{1,-1\} \cong SO(n) \tag{13.66}$$

Define $Cl(n)_{\mathbb{F}}$ as a span over $\mathbb{F} = \mathbb{R}, \mathbb{C}$ and $Spin(n)_{\mathbb{F}} \subset Cl^0(n)_{\mathbb{F}}$.

When you go from a vector space

$$V_{\mathbb{R}} = span_{\mathbb{R}}(e_1, e_2, \dots, e_n) \tag{13.67}$$

to

$$V_{\mathbb{C}} = span_{\mathbb{C}}(e_1, e_2, \dots, e_n), \tag{13.68}$$

this is called a **complexification** of the vector space. Lie algebras over $\mathbb{R}$ can be complexified. $Cl(n)_{\mathbb{C}}$ is the complexification of $Cl(n)_{\mathbb{R}}$.

$Spin(n)_{\mathbb{R}} \xrightarrow[\text{2 to 1 map}]{} SO(n;\mathbb{R})$ and $Spin(n)_{\mathbb{C}} \xrightarrow[\text{2 to 1 map}]{} SO(n;\mathbb{C})$. Rotations by a complex angle as in $SO(n)_{\mathbb{C}}$ are meaningless, even in Quantum Mechanics. Only group $Spin(n)_{\mathbb{R}}$ describes symmetries in physical systems. However, in Quantum Mechanics, we use complex representations of $Spin(n)_{\mathbb{R}}$ and a complex spinor space. The complex rep of $Spin(n)_{\mathbb{R}}$ and its complexification $Spin(n)_{\mathbb{C}}$ are isomorphic.

Careful. The following possibilities are not equivalent

1. representation of $Spin(n)_{\mathbb{F}}$ is real or complex
2. Spinor space on which $Spin(n)_{\mathbb{F}}$ acts is real or complex
3. γ matrices are real or complex

$n =$	0	1	2	3	4	5	6	7
$Cl(n)_{\mathbb{R}} \cong$	$\mathbb{R}$	$\mathbb{R} \oplus \mathbb{R}$	$M_2(\mathbb{R})$	$M_2(\mathbb{C})$	$M_2(\mathbb{H})$	$M_2(\mathbb{H}) \oplus M_2(\mathbb{H})$	$M_4(\mathbb{H})$	$M_8(\mathbb{C})$

Table 13.1: Sets isomorphic ($\cong$) to $Cl(n)_{\mathbb{R}}$. In this figure, $M_n(\mathbb{F}) = \mathbb{F}^{n\times n}$ for $\mathbb{F} = \mathbb{R}, \mathbb{C}, \mathbb{H}$ where $\mathbb{H}$ are the quaternions.

$n =$	$2k$	$2k+1$
$Cl(n)_{\mathbb{C}} \cong$	$M_{2^k}(\mathbb{C}) \oplus M_{2^k}(\mathbb{C})$	$M_{2^k}(\mathbb{C})$

Table 13.2: Sets isomorphic ($\cong$) to $Cl(n)_{\mathbb{C}}$. Table 13.1 collapses to this table when $Cl(n)_{\mathbb{R}}$ is complexified.

13.4 $Cl(n)_{\mathbb{R}}$ representations

Consider Table 13.1 which gives sets isomorphic to $Cl(n)_{\mathbb{R}}$ for all n.

Notes on Table 13.1

- Dimension check: the real dimension for the two isomorphic sets is equal to 2^n in every column. For example[4], $\dim_{\mathbb{R}} M_2(\mathbb{C}) = 8 = 2^3$.
- The pattern repeats with period 8 (**Bott Periodicity**).

$$Cl(n+8)_{\mathbb{R}} \cong Cl(n)_{\mathbb{R}} \otimes M_{16}(\mathbb{R}) \tag{13.69}$$

Rather than depending on n, the pattern depends on[5] $n \mod 8$. For example

$$Cl(8)_{\mathbb{R}} \cong \underbrace{Cl(0)}_{\mathbb{R}} \otimes M_{16}(\mathbb{R}) \cong M_{16}(\mathbb{C}) \tag{13.70}$$

$$Cl(9)_{\mathbb{R}} \cong \underbrace{Cl(1)}_{\mathbb{R}\oplus\mathbb{R}} \otimes M_{16}(\mathbb{R}) \cong M_{16}(\mathbb{C}) \oplus M_{16}(\mathbb{C}) \tag{13.71}$$

$M_{16}(\mathbb{C})$ are $2^{int(n/2)} \times 2^{int(n/2)}$ complex matrices where $n = 8$.

- The exact same table is valid for $Cl(p,q)_{\mathbb{R}}$, except with n replaced by $(p-q)\%8$. Note, however, that according to this, $Cl(1,3)_{\mathbb{R}}$ is congruent to column $(1-3)\%8 = 6$ of Table 13.1, whereas $Cl(3,1)_{\mathbb{R}}$ is congruent to column $(3-1)\%8 = 2$ and columns 2 and 6 are not isomorphic. Hence

$$Cl(p,q)_{\mathbb{R}} \ncong Cl(q,p)_{\mathbb{R}} \tag{13.72}$$

However, one can show that

$$Cl(p,q)_{\mathbb{C}} \cong Cl(q,p)_{\mathbb{C}} \tag{13.73}$$

and

[4] $dim_{\mathbb{R}}$= number of real degrees of freedom (dofs). $dim_{\mathbb{C}} = 2dim_{\mathbb{R}}$. For example, $dim_{\mathbb{R}}(\mathbb{H}) = 4$, where $\mathbb{H}$ are the quaternions.

[5] In Python $n \mod 8$ is denoted by $n\%8$, the remainder after dividing n by 8.

$$Spin(p,q)_{\mathbb{R}} \cong Spin(q,p)_{\mathbb{R}}, \quad \mathfrak{spin}(p,q)_{\mathbb{R}} \cong \mathfrak{spin}(q,p)_{\mathbb{R}} \tag{13.74}$$

$$SO(p,q)_{\mathbb{R}} \cong SO(q,p)_{\mathbb{R}}, \quad \mathfrak{so}(p,q)_{\mathbb{R}} \cong \mathfrak{so}(q,p)_{\mathbb{R}} \tag{13.75}$$

13.5 $Cl(n)_{\mathbb{C}}$ representations

Upon complexification, Table 13.1 collapses to Table 13.2. In fact, the representations of $Cl(n)_{\mathbb{C}}$ are all complex.

For $n = 2k$,

$$Cl(2k)_{\mathbb{C}} \cong M_{2^k}(\mathbb{C}) \oplus M_{2^k}(\mathbb{C}) \supset Spin(2k)_{\mathbb{C}} \tag{13.76}$$

and for $n = 2k+1$,

$$Cl(2k+1)_{\mathbb{C}} \cong M_{2^k}(\mathbb{C}) \supset Spin(2k+1)_{\mathbb{C}} \tag{13.77}$$

Assuming complexification, if n is even, we can define a nontrivial chirality operator:

$$\Gamma_5 = i^{n/2}\gamma_1\gamma_2\cdots\gamma_n. \tag{13.78}$$

Γ_5 satisfies:

- anticommutes with all the γ_μ
- commutes with the elements of group $Spin(n)_{\mathbb{R}}$ (because this group consists of products of even number of gammions)
- $\Gamma_5^2 = 1$. Therefore, Γ_5 has eigenvalues $1, -1$.

Assuming complexification, if n is even, and $V = \mathbb{C}^{n/2}$, then

$$V = V_+ \oplus V_-, \tag{13.79}$$

where:

$$V_\pm = \{\psi \in V \mid \Gamma_5\psi = \pm\psi\} \tag{13.80}$$

Thus, there are the two Weyl (or chiral) spinors when n is even.

Assuming complexification, if n is odd, the expression $\gamma^1\cdots\gamma^n$ is proportional to the identity. Hence, there is no new operator that commutes with all the elements of $Spin(n)_{\mathbb{R}}$ and there is no chiral decomposition of vector space V. The space V is irreducible.

13.6 Examples

$Spin(2)_{\mathbb{R}}$

$$Cl(2)_{\mathbb{R}} = span_{\mathbb{R}}\{1, \sigma_1, \sigma_2, \underbrace{\sigma_1\sigma_2}_{i\sigma_3}\} \tag{13.81}$$

$$Cl^0(2)_{\mathbb{R}} = span_{\mathbb{R}}\{1, \underbrace{\sigma_1\sigma_2}_{i\sigma_3}\} = \{Ae^{i\theta\sigma_3} : \theta, A \in \mathbb{R}\} \cong \mathbb{C} \tag{13.82}$$

$$Cl^1(2)_{\mathbb{R}} = span_{\mathbb{R}}\{\sigma_1, \sigma_2\} \tag{13.83}$$

$$Cl(2)_{\mathbb{R}} = Cl^0(2)_{\mathbb{R}} \oplus Cl^1(2)_{\mathbb{R}} \tag{13.84}$$

$$Spin(2)_{\mathbb{R}} = \{e^{i\theta\sigma_3} : \theta \in \mathbb{R}\} \cong U(1) \tag{13.85}$$

Claim 38 *(Double Cover)*
$Spin(2)_{\mathbb{R}} \xrightarrow[2\ to\ 1\ map]{} SO(2)$.

proof:
If $U = e^{i\theta\sigma_3}$ and $\vec{x} = (x_1, x_2)$, then

$$U\sigma_{\vec{x}}U^\dagger = \begin{pmatrix} e^{i\theta} & 0 \\ 0 & e^{-i\theta} \end{pmatrix} \begin{pmatrix} 0 & x_1 - ix_2 \\ x_1 + ix_2 & 0 \end{pmatrix} \begin{pmatrix} e^{-i\theta} & 0 \\ 0 & e^{i\theta} \end{pmatrix} \tag{13.86}$$

$$= \begin{pmatrix} 0 & z^* e^{i2\theta} \\ ze^{-i2\theta} & 0 \end{pmatrix} \quad (z = x_1 + ix_2) \tag{13.87}$$

$$= \begin{pmatrix} 0 & x_1' - ix_2' \\ x_1' + ix_2' & 0 \end{pmatrix} \tag{13.88}$$

$$x_1' = \mathrm{Re}(ze^{-i2\theta}) = x_1 \cos 2\theta + x_2 \sin\theta \tag{13.89}$$

$$x_2' = \mathrm{Im}(ze^{-i2\theta}) = -x_1 \sin 2\theta + x_2 \cos 2\theta \tag{13.90}$$

$$R_z(2\theta) = \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{pmatrix} \tag{13.91}$$

$$\vec{x} = (x_1, x_2)^T, \quad \vec{x'} = (x_1', x_2')^T \tag{13.92}$$

$$\vec{x'} = R_z(2\theta)\vec{x} \tag{13.93}$$

The 2 to 1 map:

$$e^{i\theta\sigma_3} \mapsto R_z(2\theta) \tag{13.94}$$

QED

$Spin(3)_{\mathbb{R}}$

$$Cl(3)_{\mathbb{R}} = span_{\mathbb{R}}\{1, \sigma_1, \sigma_2, \sigma_3, \underbrace{\sigma_1\sigma_2}_{i\sigma_3}, \underbrace{\sigma_2\sigma_3}_{i\sigma_1}, \underbrace{\sigma_3\sigma_1}_{i\sigma_2}, \underbrace{\sigma_1\sigma_2\sigma_3}_{i}\} \cong \mathbb{C}^{2\times 2} \tag{13.95}$$

$$Cl^0(3)_{\mathbb{R}} = span_{\mathbb{R}}\{1, i\sigma_1, i\sigma_2, i\sigma_3\} \cong \mathbb{H} \tag{13.96}$$

$$Cl^1(3)_{\mathbb{R}} = span_{\mathbb{R}}\{\sigma_1, \sigma_2, \sigma_3, i\} \cong -i\mathbb{H} \tag{13.97}$$

$$Cl(3)_{\mathbb{R}} = Cl^0(3)_{\mathbb{R}} \oplus Cl^1(3)_{\mathbb{R}} \cong \mathbb{H} \oplus -i\mathbb{H} \tag{13.98}$$

$$Spin(3)_{\mathbb{R}} = \{e^{i\sigma_{\vec{a}}} | \vec{a} \in \mathbb{R}^3\} \cong SU(2) \tag{13.99}$$

Claim 39

$$SL(2;\mathbb{C}) \supset SU(2) \cong Spin(3)_{\mathbb{R}} \xrightarrow[2\ to\ 1\ map]{} SO(3) \tag{13.100}$$

proof:

QED

Quaternions

The set of quaternions is called $\mathbb{H}$ in honor of Hamilton. ($\mathbb{Q}$ is used for the rationals). A **quaternion** q is an expression of the form

$$q = a + x\mathbf{i} + y\mathbf{j} + z\mathbf{k} \tag{13.101}$$

where $a, x, y, z \in \mathbb{R}$. The multiplication table for quaternions is the same as that for Pauli matrices, if we map

$$i\sigma_1 \leftrightarrow \mathbf{i}, \qquad i\sigma_2 \leftrightarrow \mathbf{j}, \qquad i\sigma_3 \leftrightarrow \mathbf{k} \tag{13.102}$$

Quaternion multiplication rules:

$$(i\sigma_i)(i\sigma_j) = -(\delta_{ij} + \epsilon_{ijk} i\sigma_k) \tag{13.103}$$

Chapter 14

Quantum Shannon Information Theory: COMING SOON

Chapter 15

Recoupling Identities

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

In this chapter, we will refer to the following 2 birdtracks as s and t channels.[1]

s-channel t-channel (15.1)

This terminology comes from High Energy Physics, where these birdtracks are used to define the so called Mandelstam variables. The Mandelstam variables measure the energy of particles in various birdtracks.

15.1 Parallel Channels to Sum of t-channels

Clebsch-Gordan (CG) coefficients were introduced in Chapter 4. Define the CG coefficients node

$C_{\lambda a}{}^{\nu b \mu c} =$

(15.2)

Note that

[1] My mnemonic to remember which is which: **s-channel**: particle synergy, energy from particles coming together, **t-channel**: particle trade.

(15.3)

Note that we are defining the CG coefficient C_λ so that the λ rep particle is created in an s-channel by converging μ and ν rep particles. When we define the generators T^i_λ, the i (gluon, adj-rep particle) is in a t-channel emanating from incoming and outgoing def-rep particles. Another big difference between C_λ and T^i_λ is that T^i_λ is assumed to be Hermitian, whereas C_λ is not Hermitian in general. C_λ is not even a square matrix in general.

In this chapter, we won't use implicit summation over Greek indices.

In this section, sometimes instead of labelling arrows by a lower case Greek letter denoting its rep, we will disclose an arrow's rep by a color, according to the following rep-to-color code.

$$\lambda : red, \quad \mu : green, \quad \nu : blue \tag{15.4}$$

According to Chapter 4, the CG coefficient C_λ satisfies

$$C_\lambda C^\dagger_\lambda = P_\lambda \tag{15.5}$$

$$\mathrm{tr}(P_\lambda) = d_\lambda \tag{15.6}$$

where P_λ is the projection operator onto the vector space of the rep λ and d_λ is the dimension of that vector space.

Note that if we divide C_λ by $\sqrt{d_\lambda}$, then

$$\mathrm{tr}\left(\frac{C_\lambda}{\sqrt{d_\lambda}}\frac{C^\dagger_\lambda}{\sqrt{d_\lambda}}\right) = 1 \tag{15.7}$$

Define

$P_\lambda =$

(15.8)

$P_\mu = \frac{d_\mu}{d_\lambda}$

(15.9)

$P_\nu = \frac{d_\nu}{d_\lambda}$

(15.10)

One can check that these operators are projection operators normalized to the dimennsion of their rep; i.e., for $\Omega \in \{\lambda, \mu, \nu\}$,

$$P_\Omega^2 = P_\Omega \tag{15.11}$$

and

$$\mathrm{tr}(P_\Omega) = d_\Omega \tag{15.12}$$

The normalization of the projectors P_Ω can be remembered if one takes the denominator d_λ and splits it into two factors of $\sqrt{d_\lambda}$ and puts one $\sqrt{d_\lambda}$ under C_λ and the other under $C_\lambda^\dagger$. Then one "trades" $\frac{C_\lambda}{\sqrt{d_\lambda}}$ by $\frac{C_\mu}{\sqrt{d_\mu}}$ or $\frac{C_\nu}{\sqrt{d_\nu}}$.

Next we define a scaled version of the CG coefficients C_λ as follows

(15.13)

The **scaled CG coefficients** $\mathfrak{C}_\lambda$ satisfy

(15.14)

Therefore

$$\mathfrak{C}^\dagger_\lambda \xleftarrow{\lambda} \mathfrak{C}_\lambda \;=\; \kappa_\lambda{}^{\nu\mu} d_\lambda \tag{15.15}$$

The projection operators P_Ω for $\Omega \in \{\lambda, \mu, \nu\}$ can be expressed in a more symmetrical form using nodes for the scaled CG coefficients as follows

$$P_\lambda = \frac{1}{\kappa_\lambda{}^{\nu\mu}} \tag{15.16}$$

$$P_\mu = \frac{1}{\kappa_\mu{}^{\lambda\nu}} \tag{15.17}$$

$$P_\nu = \frac{1}{\kappa_\nu{}^{\mu\lambda}} \tag{15.18}$$

The CG series for $V_\mu \otimes V_\nu = \sum_\lambda V_\lambda$ can be expressed in terms of birdtracks as follows

$$= \sum_\lambda P_\lambda = \sum_\lambda \frac{d_\lambda}{\mathfrak{C}^\dagger_\lambda \xleftarrow{\lambda} \mathfrak{C}_\lambda} \tag{15.19}$$

This CG series expresses two **parallel channels** as a sum of s-channels.

The CG series for $N > 2$ parallel channels $V_{\mu_1} \otimes V_{\mu_2} \otimes \ldots \otimes V_{\mu_N} = \sum_\lambda V_\lambda$ is obtained by combining pairs of vector spaces recursively. The series depends on what vector space pairs are chosen in what order. For example, we can use[2]

[2]For succinctness, we are dropping the rep labels μ, λ from $\kappa_\nu{}^{\mu\lambda}$, but the κ_ν still depends on them.

(15.20)

Another possibility is

(15.21)

15.2 t-channel to Sum of s-channels

We can express a t-channel as a sum over s-channels as follows

$$
\begin{tikzcd}
 & \mathfrak{C}^\dagger_\mu \arrow[d, "\omega"] & \\
 & \mathfrak{C}_\rho &
\end{tikzcd}
= \sum_\lambda
\left[
\begin{tikzcd}
\frac{d_\lambda}{\mathfrak{C}^\dagger_\lambda \underset{\rho}{\overset{\sigma}{\leftleftarrows}} \mathfrak{C}_\lambda} \; \frac{d_\lambda}{\mathfrak{C}^\dagger_\lambda \underset{\nu}{\overset{\mu}{\leftleftarrows}} \mathfrak{C}_\lambda} & & \\
 & \mathfrak{C}^\dagger_\mu \arrow[dl, "\sigma"'] \arrow[dr, "\mu"] \arrow[dd, "\omega"] & \\
* \quad \mathfrak{C}^\dagger_\lambda \arrow[ur, "\sigma"] \arrow[dr, "\rho"'] & \mathfrak{C}_\lambda \arrow[l, "\lambda"'] & \mathfrak{C}^\dagger_\lambda \arrow[l, "\lambda"'] \arrow[dl, "\nu"] \quad \mathfrak{C}_\lambda \arrow[ul, "\mu"'] \\
 & \mathfrak{C}_\rho \arrow[ul, "\rho"] \arrow[ur, "\nu"'] &
\end{tikzcd}
\right]
\tag{15.22}
$$

$$
= \sum_\lambda \Phi_\lambda
\begin{tikzcd}
 & \mathfrak{C}^\dagger_\lambda \arrow[ul, "\sigma"] \arrow[dl, "\rho"'] & \mathfrak{C}_\lambda \arrow[l, "\lambda"'] \arrow[ul, "\mu"'] \arrow[dl, "\nu"]
\end{tikzcd}
\tag{15.23}
$$

where

$$
\Phi_\lambda = \frac{d_\lambda}{\mathfrak{C}^\dagger_\lambda \underset{\rho}{\overset{\sigma}{\leftleftarrows}} \mathfrak{C}_\lambda} \; \frac{d_\lambda}{\mathfrak{C}^\dagger_\lambda \underset{\nu}{\overset{\mu}{\leftleftarrows}} \mathfrak{C}_\lambda} \; \frac{\begin{tikzcd}
 & \mathfrak{C}^\dagger_\mu \arrow[d, "\omega"] \arrow[ddl, bend right, "\sigma"'] \arrow[ddr, bend left, "\mu"] & \\
 & \mathfrak{C}_\rho \arrow[dl, "\rho"'] & \\
\mathfrak{C}_\lambda \arrow[rr, "\lambda"] & & \mathfrak{C}^\dagger_\lambda \arrow[ul, "\nu"]
\end{tikzcd}}{d_\lambda}
\tag{15.24}
$$

$$
= d_\lambda \frac{\begin{tikzcd}
 & \mathfrak{C}^\dagger_\mu \arrow[d, "\omega"] \arrow[ddl, bend right, "\sigma"'] \arrow[ddr, bend left, "\mu"] & \\
 & \mathfrak{C}_\rho \arrow[dl, "\rho"'] & \\
\mathfrak{C}_\lambda \arrow[rr, "\lambda"] & & \mathfrak{C}^\dagger_\lambda \arrow[ul, "\nu"]
\end{tikzcd}}{\mathfrak{C}^\dagger_\lambda \underset{\rho}{\overset{\sigma}{\leftleftarrows}} \mathfrak{C}_\lambda \quad \mathfrak{C}^\dagger_\lambda \underset{\nu}{\overset{\mu}{\leftleftarrows}} \mathfrak{C}_\lambda}
\tag{15.25}
$$

15.3 Wigner $3n - j$ Coefficients/DAGs

A DAG with no incoming or outgoing arrows is called an **isolated DAG**. Physicists sometimes call it a **vacuum bubble** also. On the right hand side of Eq.(15.25), the isolated DAG with two $\mathfrak{C}$ is called a $3j$ **coefficient/DAG**, and the one with 4 $\mathfrak{C}$ is called a $6j$ **coefficient/DAG**. So far we seen $3j$ and $6j$ coefficients/DAGs. Atomic physicists define **Wigner** $3n - j$ **coefficients/DAGs**, for $n = 1, 2, 3, \ldots$. They are called that because they describe how to "add" $3n$ angular momenta j. There is only one topological distinct $3j$ DAG but two $6j$ DAGs, five $9j$ DAGs, and so on.

In Chapter 2, we discussed Casimir suns. Next we show that they can always be expressed in terms of $3j$ and $6j$ coefficients and CG coefficients. We proceed as we did in Eq.(15.20) but here we use the most general t-channel to sum of s-channels conversion Eq.(15.23).

(15.26)

(15.27)

(15.28)

Chapter 16

Recoupling Identities for $U(n)$

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

For $U(n)$ (as opposed to $SU(n)$), there are no antiparticles (i.e., one can use only lowered indices). A consequence of this is that for proper operators in $U(n)$, the total particle number is conserved.

Young Tableaux are discussed in Chapter 27.

Clebsh-Gordan series for $U(n)$ can be written in terms of Standard Young Tableaux (SYT). For example, the tensor decomposition of $V^{\otimes 5}$ is:[1]

(16.1)

(16.2)

where $\leftarrow\!\!p\!\!-$ means p parallel arrows superimposed on each other.

[1] $x(h.c.) = xx^\dagger$.

It's always true that

(16.3)

for some $K_\sigma \in \{-1, 0, 1\}$. More generally,

(16.4)

for some $K \in \mathbb{R}$ that is independent of n.

16.1 $3j$ Coefficients

Recall that $|\mathcal{Y}_\alpha|$ or $|\alpha|$ is the number of boxes (or number of outgoing legs in its birdtrack) in the YT $\mathcal{Y}_\alpha$.

Clebsch-Gordan (CG) coefficients are discussed in Chapter 4. One can define a CG coefficient $\mathfrak{C}_\beta$ in terms of Young Tableaux as follows:

(16.5)

where $|\beta| = |\alpha| + |\gamma|$

Claim 40 *(3j coefficient for $U(n)$ in terms of YT)*[2]

$$\mathrm{tr}(\mathfrak{C}^\dagger_\beta \mathfrak{C}_\beta) = \quad = \tag{16.6}$$

$$= dim(\mathcal{Y}_\beta) \tag{16.7}$$

proof:

(16.8)

$$= K dim(\mathcal{Y}_\beta) \tag{16.9}$$

Ref. [1] shows that for this example, $K = 1$.

QED

16.2 $6j$ Coefficients

Claim 41 *(6j coefficient for $U(n)$ in terms of YT)*[3]

(16.10)

$$= K dim(\mathcal{Y}_\omega) \tag{16.11}$$

where K is independent of n

[2]Ref.[1], on which this claim is based, uses different labels for the Young projectors. Their labels and ours are related as follows:
$\mathcal{Y}_\alpha \to X$, $\mathcal{Y}_\beta \to Y$, $\mathcal{Y}_\gamma \to Z$.

[3]Ref.[1], on which this claim is based, uses different labels for the Young projectors. Their labels and ours are related as follows:
$\mathcal{Y}_\sigma \to X$, $\mathcal{Y}_\omega \to Y$, $\mathcal{Y}_\rho \to U$, $\mathcal{Y}_\lambda \to W$, $\mathcal{Y}_\nu \to V$, $\mathcal{Y}_\mu \to Z$.

proof: Replace each of the 6 Young projectors $\mathcal{Y}_\alpha$ of the right hand side (RHS) by its square. That gives 12 Young projectors on the RHS. Each of the 4 generators $\mathfrak{C}_\lambda$ on the left hand side (LHS) is composed of 3 Young projectors so there are 12 Young projectors on the LHS too.

(16.12)

$$= K dim(\mathcal{Y}_\omega) \tag{16.13}$$

QED

For example, Ref.[1] shows that if

$$\mathcal{Y}_\rho = \begin{array}{|c|c|}\hline 2 & 3 \\ \hline 4 \\ \cline{1-1}\end{array}, \qquad \mathcal{Y}_\nu = \boxed{1}, \qquad \mathcal{Y}_\lambda = \boxed{2} \tag{16.14}$$

$$\mathcal{Y}_\sigma = \begin{array}{|c|}\hline 3 \\ \hline 4 \\ \hline\end{array}, \qquad \mathcal{Y}_\omega = \begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 \\ \cline{1-1} 4 \\ \cline{1-1}\end{array}, \qquad \mathcal{Y}_\mu = \begin{array}{|c|}\hline 1 \\ \hline 2 \\ \hline\end{array} \tag{16.15}$$

then

$$K = \frac{1}{3}, \quad dim\mathcal{Y}_\omega = \frac{n(n^2-1)(n^2-2)}{8} \tag{16.16}$$

16.3 Sum Rules

Let

$SYT(n_b)$ = set of SYT with n_b boxes
$SYT = \bigcup_{n_b=1}^{\infty} SYT(n_b)$

Claim 42

$$\sum_{\alpha',\gamma' \in SYT} \mathbb{1}(|\alpha'| + |\gamma'| = |\beta|)\, \mathfrak{C}^\dagger_\beta \overset{\alpha'}{\underset{\gamma'}{\leftarrow\beta\leftarrow}} \mathfrak{C}_\beta = (|\beta| - 1) dim(\mathcal{Y}_\beta) \tag{16.17}$$

proof:

$$\sum_{\alpha' \in SYT(|\alpha|)} \mathcal{Y}_{\alpha'} = 1, \qquad \sum_{\gamma' \in SYT(|\gamma|)} \mathcal{Y}_{\gamma'} = 1 \tag{16.18}$$

$$\sum_{\alpha',\gamma' \in SYT} \mathbb{1}(|\alpha'| + |\gamma'| = |\beta|)\ \mathfrak{C}^\dagger_\beta \xleftarrow{\alpha'}\xleftarrow{\beta}\xleftarrow{\gamma'} \mathfrak{C}_\beta = \sum_{|\alpha'|=1}^{|\beta|-1} \sum_{\substack{\alpha' \in SYT(|\alpha'|) \\ \gamma' \in SYT(|\beta|-|\alpha'|)}}$$

(16.19)

$$= \sum_{|\alpha'|=1}^{|\beta|-1}$$

(16.20)

$$= (|\beta| - 1) dim(\mathcal{Y}_\beta) \tag{16.21}$$

QED

Let

$$A = \{\rho, \nu, \lambda, \sigma, \omega, \mu\}, \quad B = A - \{\omega\} \tag{16.22}$$

$$A' = \{\rho', \nu', \lambda', \sigma', \omega', \mu'\}, \quad B' = A' - \{\omega'\} \tag{16.23}$$

$$J(A) = \mathbb{1} \begin{pmatrix} |\sigma| + |\mu| = |\omega|, \\ |\nu| + |\rho| = |\omega|, \\ |\sigma| + |\lambda| = |\rho|, \\ |\lambda| + |\nu| = |\mu| \end{pmatrix} \tag{16.24}$$

Claim 43

$$\prod_{\alpha' \in B'} \left[\sum_{\alpha' \in SYT} \right] J(B', \omega)$$

$$\begin{tikzcd}
 & \mathfrak{C}^\dagger_{\rho'} \arrow[d, "\lambda'"] \arrow[ddl, bend right, "\sigma'"'] \arrow[ddr, bend left, "\rho'"] & \\
 & \mathfrak{C}_{\mu'} \arrow[dl, "\mu'"] & \\
\mathfrak{C}_\omega \arrow[rr, "\omega"] & & \mathfrak{C}^\dagger_\omega \arrow[ul, "\nu'"']
\end{tikzcd}$$

$$= \frac{1}{2}(|\omega| - 1)(|\omega| - 2) dim \mathcal{Y}_\omega \tag{16.25}$$

proof:

See Ref.[1] for proof.

QED

Chapter 17

Reducibility of Representations, I

This chapter is based on Joshi's book Ref.[3].

Representations (reps) of groups are defined in Section A.9. In this chapter, we will discuss reps of finite groups in more detail.

17.1 Symmetries of a Square

Figure 17.1: Elements of order 8 group Sq_8 that describes symmetries of a square.

	E	$\substack{C_4\\N_1S_{12}}$	$\substack{C_4^3\\N_2S_{12}}$	$\substack{C_4^2\\N_1N_2}$	N_2	N_1	$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$	$\substack{\sigma_{y=x}\\S_{12}}$
E	E	$\substack{C_4\\N_1S_{12}}$	$\substack{C_4^3\\N_2S_{12}}$	$\substack{C_4^2\\N_1N_2}$	N_2	N_1	$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$	$\substack{\sigma_{y=x}\\S_{12}}$
$\substack{C_4\\N_1S_{12}}$	$\substack{C_4\\N_1S_{12}}$	$\substack{C_4^2\\N_1N_2}$	E	$\substack{C_4^3\\N_2S_{12}}$	$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$	$\substack{\sigma_{y=x}\\S_{12}}$	N_1	N_2
$\substack{C_4^3\\N_2S_{12}}$	$\substack{C_4^3\\N_2S_{12}}$	E	$\substack{C_4^2\\N_1N_2}$	$\substack{C_4\\N_1S_{12}}$	$\substack{\sigma_{y=x}\\S_{12}}$	$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$	N_2	N_1
$\substack{C_4^2\\N_1N_2}$	$\substack{C_4^2\\N_1N_2}$	$\substack{C_4^3\\N_2S_{12}}$	$\substack{C_4\\N_1S_{12}}$	E	N_1	N_2	$\substack{\sigma_{y=x}\\S_{12}}$	$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$
N_2	N_2	$\substack{\sigma_{y=x}\\S_{12}}$	$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$	N_1	E	$\substack{C_4^2\\N_1N_2}$	$\substack{C_4^3\\N_2S_{12}}$	$\substack{C_4\\N_1S_{12}}$
N_1	N_1	$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$	$\substack{\sigma_{y=x}\\S_{12}}$	N_2	$\substack{C_4^2\\N_1N_2}$	E	$\substack{C_4\\N_1S_{12}}$	$\substack{C_4^3\\N_2S_{12}}$
$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$	$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$	N_2	N_1	$\substack{\sigma_{y=x}\\S_{12}}$	$\substack{C_4\\N_1S_{12}}$	$\substack{C_4^3\\N_2S_{12}}$	E	$\substack{C_4^2\\N_1N_2}$
$\substack{\sigma_{y=x}\\S_{12}}$	$\substack{\sigma_{y=x}\\S_{12}}$	N_1	N_2	$\substack{\sigma_{y=-x}\\N_1N_2S_{12}}$	$\substack{C_4^3\\N_2S_{12}}$	$\substack{C_4\\N_1S_{12}}$	$\substack{C_4^2\\N_1N_2}$	E

Table 17.1: Multiplication Table for group Sq_8

Fig.17.1 shows an order 8 group that we shall call Sq_8 [1] that describes symmetries of a square. The group is generated by the 3 generators N_1, N_2 and S_{12}. (i.e., every group element is of the form $N_1^a N_2^b S_{12}^c$, for $a, b, c \in \mathbb{Z}_{>0}$). The operators N_i for $i = 1, 2$ replace the i'th component by its negative. The operator S_{12} swaps components 1 and 2. Ref.[3] uses $m_x = N_2$, $m_y = N_1$, $\sigma_u = \sigma_{y=-x}$ (reflection about line $y = -x$), $\sigma_v = \sigma_{y=x}$ (reflection about line $y = x$). Note that

$$[N_1, N_2] = 0, \quad \begin{pmatrix} N_1 \\ N_2 \end{pmatrix} S_{12} = S_{12} \begin{pmatrix} N_2 \\ N_1 \end{pmatrix}, \quad N_1^2 = N_2^2 = S_{12}^2 = 1 \tag{17.1}$$

A **group multiplication table (MT)** contains all the elements of the group as column and row labels, and the product ab as entry for row a and column b. Using the identities given by Eq.(17.1), one can easily calculate the MT for Sq_8. Table 17.1 is the result. Note that all elements in a row and all elements in a column of the MT are distinct. This is called the **Rearrangement Theorem**; i.e., any group $\mathcal{G}$ satisfies $a\mathcal{G} = \mathcal{G}$ for all $a \in \mathcal{G}$.

Fig.17.2 shows the conjugacy classes (CCs) of Sq_8.

Table 17.2 shows the irreps of Sq_8.

Table 17.3 shows the characters of Sq_8.

17.2 Block Diagonalization

Suppose S (smaller) and L (larger) are two vector spaces and $S \subset L$, with $L \neq S$ (i.e., proper subspace). Suppose $\mathcal{G}$ is a group. Suppose $\mathcal{G}S \subset S$ and $\mathcal{G}L \subset L$. Then

[1] Joshi Ref.[3] calls this group $C_{4\nu}$

$CC_1 = (E)$
$CC_2 = (N_1S_{12}, N_2S_{12})$ (rotations by 90 and 270 degrees)
$CC_3 = (N_1N_2)$ (rotation by 180 degrees)
$CC_4 = (N_1, N_2)$ (refection about x or y axis)
$CC_5 = (S_{12}, N_1N_2S_{12})$ (reflection about $y = x$ or $y = -x$ diagonal lines)

Figure 17.2: CCs for Sq_8. Conjugacy classes (CC) are defined for an arbitrary group in Section 17.5.

	E	C_4	C_4^3	C_4^2	N_2	N_1	$\sigma_{y=-x}$	$\sigma_{y=x}$
$\rho^{(1)}$	1	1	1	1	1	1	1	1
$\rho^{(2)}$	1	–1	–1	1	–1	–1	1	1
$\rho^{(3)}$	1	–1	–1	1	1	1	–1	–1
$\rho^{(4)}$	1	1	1	1	–1	–1	–1	–1
$\rho^{(5)}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$	$\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$	$\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$

Table 17.2: Irreps of Sq_8. Different color for each CC. Number of inequivalent irreps = number of CCs=number of colors=5.

	E	C_4	C_4^3	C_4^2	N_2	N_1	$\sigma_{y=-x}$	$\sigma_{y=x}$
$\chi^{(1)}$	1	1	1	1	1	1	1	1
$\chi^{(2)}$	1	–1	–1	1	–1	–1	1	1
$\chi^{(3)}$	1	–1	–1	1	1	1	–1	–1
$\chi^{(4)}$	1	1	1	1	–1	–1	–1	–1
$\chi^{(5)}$	2	0	0	–2	0	0	0	0

Table 17.3: Characters of Sq_8. Different color for each CC. $\chi^\alpha(g) = \mathrm{tr}\rho^\alpha(g)$ for all $g \in \mathcal{G}$. Check that $\sum_{g\in\mathcal{G}} \chi^\alpha(g)\chi^{\beta*}(g) = |\mathcal{G}|\delta_{\alpha\beta}$.

we say S is an **invariant subspace** of L under $\mathcal{G}$, and we say L is **reducible** under $\mathcal{G}$.

Claim 44 *Suppose S is an invariant subspace of L under $\mathcal{G}$. Then for any rep (L, ρ_L) of $\mathcal{G}$, we must have*

$$\rho_L(g) = \begin{array}{c|cc} & S & S^c \\ \hline S & A^{d_S\times d_S} & 0 \\ S^c & C^{d_{S^c}\times d_S} & D^{d_{S^c}\times d_{S^c}} \end{array} \tag{17.2}$$

for all $g \in \mathcal{G}$, where $S^c = L - S$, d_S = dimension of vector space S, d_{S^c} = dimension of vector space S^c. Furthermore, if $\rho_L()$ is a unitary rep, then

$$C^{d_{S^c}\times d_S} = 0 \tag{17.3}$$

proof:

The zero matrix in 17.2 follows because $\mathcal{G}S \subset S$. Note that if

$$\rho_L(g_1) = \begin{pmatrix} A_1 & 0 \\ C_1 & D_1 \end{pmatrix}, \quad \rho_L(g_2) = \begin{pmatrix} A_2 & 0 \\ C_2 & D_2 \end{pmatrix} \tag{17.4}$$

then

$$\rho_L(g_1)\rho_L(g_2) = \begin{pmatrix} A_1A_2 & 0 \\ X & D_1D_2 \end{pmatrix} \tag{17.5}$$

where

$$X = C_1A_2 + D_1C_2 \tag{17.6}$$

If $\rho_L()$ is a unitary rep, then $X = 0$ because the rows of the full matrix must yield d_L orthonormal vectors and the columns must too. This is possible only if $X = 0$.

If $X = 0$, we can define unitary reps ρ_S and ρ_{S^c} so that

$$\rho_S(g_1) = A_1, \quad \rho_S(g_2) = A_2, \quad \rho_S(g_1g_2) = A_1A_2 \tag{17.7}$$

$$\rho_{S^c}(g_1) = D_1, \quad \rho_{S^c}(g_2) = D_2, \quad \rho_{S^c}(g_1g_2) = D_1D_2 \tag{17.8}$$

QED

Claim 45 *For any rep $\rho()$, there is an equivalent unitary rep $\hat{\rho}()$.*

proof:

Define the Hermitian matrix H by

$$H = \sum_{g\in\mathcal{G}} \rho(g)\rho^\dagger(g) \tag{17.9}$$

Find a unitary matrix U that diagonalizes H:

$$H_d = U^\dagger H U \tag{17.10}$$

$$= U^\dagger \left[\sum_{g\in\mathcal{G}} \rho(g)\rho^\dagger(g)\right] U \tag{17.11}$$

where H_d is a diagonal matrix.

Define a new rep $\rho_1()$ by

$$\rho_1(g) = U^\dagger \rho(g) U \tag{17.12}$$

for all $g \in \mathcal{G}$.

Note that

$$H_d = \sum_{g\in\mathcal{G}} \rho_1(g)\rho_1^\dagger(g) \tag{17.13}$$

Note that the diagonal elements of H_d must be positive. Indeed,

$$\begin{aligned}
(H_d)_{kk} &= \sum_{g\in\mathcal{G}}\sum_j \rho_1(g)_{kj}\rho_1^*(g)_{kj} && (17.14)\\
&= \sum_{g\in\mathcal{G}}\sum_j \left|\rho_1(g)_{kj}\right|^2 && (17.15)\\
&\geq 0 && (17.16)
\end{aligned}$$

Actually, the diagonal elements of H_d must be strictly positive because if the kth one were zero, the k row of $\rho_1(g)$ would be zero for all $g \in \mathcal{G}$. So all $\rho_1(g)$ would have a zero determinant. Then all $\rho_1(g)$ and $\rho(g)$ would have a zero determinant and no inverse. Then the rep $\rho()$ that we started with would be an invalid rep, in contradiction with the premise of the claim.

Now define

$$\hat{\rho}(g) = H_d^{-\frac{1}{2}}\rho_1(g)H_d^{\frac{1}{2}} \tag{17.17}$$

for $g \in \mathcal{G}$.

Finally, check that $\hat{\rho}(g)$ is unitary for all $g \in \mathcal{G}$.

$$\begin{aligned}
\hat{\rho}(g)\hat{\rho}^\dagger(g) &= H_d^{-\frac{1}{2}}\rho_1(g)H_d\rho_1^\dagger(g)H_d^{-\frac{1}{2}} && (17.18)\\
&= H_d^{-\frac{1}{2}}\rho_1(g)\left[\sum_{g'\in\mathcal{G}}\rho_1(g')\rho_1^\dagger(g')\right]\rho_1^\dagger(g)H_d^{-\frac{1}{2}} && (17.19)\\
&= H_d^{-\frac{1}{2}}\left[\sum_{g'\in\mathcal{G}}\rho_1(gg')\rho_1^\dagger(gg')\right]H_d^{-\frac{1}{2}} && (17.20)\\
&= H_d^{-\frac{1}{2}}\left[H_d\right]H_d^{-\frac{1}{2}} && (17.21)\\
&= 1 && (17.22)
\end{aligned}$$

QED

For any square matrices A, B, C (not necessarily of the same dimension)

$$A \oplus B \oplus C = \begin{pmatrix} A & 0 & 0 \\ 0 & B & 0 \\ 0 & 0 & C \end{pmatrix} \tag{17.23}$$

If A_i for $i = 1, 2, \ldots, n$ are square matrices, $A_1 \oplus A_2 \oplus \ldots \oplus A_n$ is called a **block diagonal matrix**.

Note that any reducible (unitary) rep can be expressed as a block diagonal matrix[2]: for all $g \in \mathcal{G}$,

$$\rho(g) \equiv \bigoplus_{\alpha} m_\alpha \rho_\alpha(g) \tag{17.24}$$

where $m_\alpha \in \mathbb{Z}_{>0}$.

17.3 Schur's 2 Lemmas

Claim 46 *(Schur's First Lemma)*
If $\rho()$ is an irrep of group $\mathcal{G}$ and matrix P satisfies

$$P\rho(g) = \rho(g)P \tag{17.25}$$

for all $g \in \mathcal{G}$, then

$$P = cI \tag{17.26}$$

where I is the unit matrix and $c \in \mathbb{C}$.

proof:
Note that

$$P\rho(g) = \rho(g)P \quad \forall g \in \mathcal{G} \tag{17.27}$$

implies

$$\underbrace{\rho^\dagger(g)}_{\rho(g^{-1})} P^\dagger = P^\dagger \underbrace{\rho^\dagger(g)}_{\rho(g^{-1})} \quad \forall g \in \mathcal{G} \tag{17.28}$$

which implies

$$\rho(g)P^\dagger = P^\dagger \rho(g) \quad \forall g \in \mathcal{G} \tag{17.29}$$

Define

$$H = PP^\dagger \tag{17.30}$$

H is Hermitian and satisfies

$$H\rho(g) = \rho(g)H \quad \forall g \in \mathcal{G} \tag{17.31}$$

If we can prove that H is a constant matrix, then P must be a constant matrix too. Since H is Hermitian, it must be diagonalizable. Let

[2]Two matrices A and B are equivalent, written $A \equiv B$ if they are equal up to a similarity transformation: $A = SBS^{-1}$

$$H|h_j\rangle = h_j|h_j\rangle \tag{17.32}$$

for $j = 1, 2, \ldots, n$. Then

$$H\rho(g) = \rho(g)H \implies (h_i - h_j)\langle h_i|\rho(g)|h_j\rangle = 0 \tag{17.33}$$

Hence, if $h_i \neq h_j$ for some i, j, then the matrix $\rho(g)$ can be block diagonalized for all g. So as not to contradict the premise that $\rho()$ is an irrep, we are forced to conclude that all h_i must be equal. Hence H is indeed a constant matrix.

QED

Claim 47 *(Schur's Second Lemma)*

If $\rho_1()$ and $\rho_2()$ are two irreps of a group $\mathcal{G}$ and matrix M_{12} (possibly rectangular) satisfies

$$\rho_1(g)M_{12} = M_{12}\rho_2(g) \tag{17.34}$$

for all $g \in \mathcal{G}$, then $M_{12} = 0$ or M_{12} is a square matrix with $\det M_{12} \neq 0$. In the latter case, ρ_1 and ρ_2 are equivalent reps.

proof:

From Eq.(17.34), it follows that

$$M_{12}^\dagger \underbrace{\rho_1^\dagger(g)}_{\rho_1(g^{-1})} = \underbrace{\rho_2^\dagger(g)}_{\rho_2(g^{-1})} M_{12}^\dagger \quad \forall g \in \mathcal{G} \tag{17.35}$$

so

$$M_{12}^\dagger\rho_1(g) = \rho_2(g)M_{12}^\dagger \quad \forall g \in \mathcal{G} \tag{17.36}$$

Therefore

$$\rho_1(g)M_{12}M_{12}^\dagger = M_{12}M_{12}^\dagger\rho_1(g) \tag{17.37}$$

and

$$\rho_2(g)M_{12}^\dagger M_{12} = M_{12}^\dagger M_{12}\rho_2(g) \tag{17.38}$$

Hence, by Schur's Lemma 1,

$$M_{12}M_{12}^\dagger = c, \quad M_{12}^\dagger M_{12} = c' \tag{17.39}$$

for some $c, c' \in \mathbb{C}$.

Let d_i for $i = 1, 2$ be the matrix dimension of ρ_i.

Assume first that $d_1 = d_2 = n$. Then

$$c^n = \det(M_{12}M_{12}^\dagger) = \det(M_{12})\det(M_{12}^\dagger) \tag{17.40}$$

- if $c \neq 0$:

  Then $\det M_{12} \neq 0$ so M_{12} is invertible. Hence

$$M_{12}^{-1}\rho_1(g)M_{12} = \rho_2(g) \tag{17.41}$$

  for all $g \in \mathcal{G}$. Thus, ρ_1 and ρ_2 are equivalent reps.

- if $c = 0$:

  Then

$$\begin{aligned} \sum_j \langle i|M_{12}|j\rangle \left\langle j|M_{12}^\dagger|i\right\rangle &= \sum_j |\langle i|M_{12}|j\rangle|^2 && (17.42) \\ &= 0 && (17.43) \end{aligned}$$

  so the ith row of M_{12} equals zero for all i. Hence we must have $M_{12} = 0$.

When $d_1 \neq d_2$, we must have $M_{12} = 0$. This is why.

For teaching purposes, we will first assume that $(d_1 = 1, d_2 = 2)$ or $(d_1 = 2, d_2 = 1)$. In this case, M equals either a column vector $x = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \in \mathbb{C}^{2\times 1}$ or a row vector $x^\dagger$. Either way we must have

$$xx^\dagger = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \begin{pmatrix} x_1^* & x_2^* \end{pmatrix} = c \tag{17.44}$$

for some constant $c \in \mathbb{C}$. This is only possible if $x_1 = x_2 = c = 0$.

In the general case, when $d_1 < d_2$ or $d_2 < d_1$, x_1 is a square matrix and x_2 is rectangular one. Eq.(17.44) becomes

$$xx^\dagger = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \begin{pmatrix} x_1^\dagger & x_2^\dagger \end{pmatrix} = c \tag{17.45}$$

Assume $c \neq 0$. Then $x_1 x_1^\dagger = c$ so $x_1/\sqrt{c}$ is a unitary matrix and therefore invertible. Furthermore, $x_2 x_1^\dagger = 0$, so $x_2 = 0$. But $x_2 x_2^\dagger = c$ so $c = 0$. Contradiction.

QED

17.4 Orthogonality of Irreps

Claim 48 *If ρ_α and ρ_β are two irreps of group $\mathcal{G}$, then*

$$\boxed{\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\rho_\alpha(g)_{ij}\quad\underbrace{\rho_\beta(g^{-1})_{j'i'}}_{=\rho^\dagger_\beta(g)_{j'i'}=\rho^*_\beta(g)_{i'j'}}\quad=\delta_{\alpha\beta}\delta_{ii'}\frac{\delta_{jj'}}{d_\alpha}}$$

$$\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\quad\begin{array}{c}\alpha\\ \wr\\ i\leftarrow\rho_\alpha(g)\leftarrow j\end{array}\quad\begin{array}{c}\beta\\ \wr\\ j'\leftarrow\rho_\beta(g^{-1})\leftarrow i'\end{array}\quad=\frac{1}{d_\alpha}\quad\begin{array}{c}\alpha\rightsquigarrow\bullet\rightsquigarrow\beta\\ j\leftarrow\bullet\leftarrow j'\\ i\leftarrow\bullet\leftarrow i'\end{array}\tag{17.46}$$

where d_α and d_β are the matrix dimension of ρ_α and ρ_β.

proof:

As a preliminary sanity check, note that if we set $\alpha=\beta$, $j=j'$ and we sum over j, both sides yield $\delta_{ii'}$.

Define

$$M_{\alpha\beta}=\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\rho_\alpha(g)X\rho_\beta(g^{-1})\tag{17.47}$$

where X is some arbitrary square matrix of the right dimension.

First assume $\rho_\alpha\neq\rho_\beta$.

Then

$$\begin{aligned}\rho_\alpha(h)M_{\alpha\beta}&=\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\rho_\alpha(hg)X\rho_\beta((\underbrace{g}_{h^{-1}hg})^{-1})&(17.48)\\&=\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\rho_\alpha(hg)X\rho_\beta((hg)^{-1})\rho_\beta(h)&(17.49)\\&=M_{\alpha\beta}\rho_\beta(h)&(17.50)\end{aligned}$$

for all $h\in\mathcal{G}$. $\rho_\alpha\neq\rho_\beta$ so by Schur's second lemma,

$$M_{\alpha\beta}=0\tag{17.51}$$

The last equation in component form is

$$\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\sum_{k,k'}\rho_\alpha(g)_{ik}X_{kk'}\rho_\beta(g^{-1})_{k'i'}=0\tag{17.52}$$

Now setting

$$X_{kk'}=\delta_{kj}\delta_{k'j'}\tag{17.53}$$

we get

$$\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\rho_\alpha(g)_{ij}\rho_\beta(g^{-1})_{j'i'}=0 \tag{17.54}$$

Next assume $\rho_\alpha=\rho_\beta$.

Then

$$\rho_\alpha(h)M_{\alpha\alpha}=M_{\alpha\alpha}\rho_\alpha(h) \tag{17.55}$$

for all $h\in\mathcal{G}$, so by Schur's first lemma,

$$M_{\alpha\alpha}=cI \tag{17.56}$$

Taking the trace of both sides of the last equation, we get

$$\mathrm{tr}(X)=cd_\alpha \tag{17.57}$$

so

$$M_{\alpha\alpha}=\frac{\mathrm{tr}(X)}{d_\alpha}I \tag{17.58}$$

The last equation in component form is

$$\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\sum_{k,k'}\rho_\alpha(g)_{ik}X_{kk'}\rho_\alpha(g^{-1})_{k'i'}=\frac{\mathrm{tr}(X)}{d_\alpha}\delta_{ii'} \tag{17.59}$$

Now setting

$$X_{kk'}=\delta_{kj}\delta_{k'j'},\quad \mathrm{tr}(X)=\delta_{jj'} \tag{17.60}$$

we get

$$\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\rho_\alpha(g)_{ij}\rho_\alpha(g^{-1})_{j'i'}=\frac{\delta_{jj'}}{d_\alpha}\delta_{ii'} \tag{17.61}$$

QED

17.5 Orthogonality of Characters

For any rep ρ^α of a group $\mathcal{G}$, define the **character** $\chi^\alpha(g)$ of $g\in\mathcal{G}$ by

$$\chi^\alpha(g)=\mathrm{tr}(\rho^\alpha(g))=\sum_k\rho^\alpha(g)_{kk} \tag{17.62}$$

For any two $a,b\in\mathcal{G}$, define $a\sim b$ if $a=gbg^{-1}$ for some $g\in\mathcal{G}$. This is an equivalence relation that partitions $\mathcal{G}$ into disjoint classes. Now define

$CC(g)=\{hgh^{-1}|h\in\mathcal{G}\}=$ **conjugacy class (CC) of** $g\in\mathcal{G}$.

$g(CC_k)$ = one candidate of the conjugacy class CC_k.
$\{CC_k\}_{k=1}^{N_{CC}}$ = set of CCs of group $\mathcal{G}$.
Recall that $\mathrm{tr}(AB) = \mathrm{tr}(BA)$ so for any $g, h \in \mathcal{G}$,

$$\begin{aligned} \chi^\alpha(hgh^{-1}) &= \mathrm{tr}(\rho^\alpha(hgh^{-1})) = \mathrm{tr}(\rho^\alpha(h)\rho^\alpha(g)\rho^\alpha(h^{-1})) = \mathrm{tr}\rho^\alpha(g) && (17.63) \\ &= \chi^\alpha(g) && (17.64) \end{aligned}$$

Hence, $\chi^\alpha : \mathcal{G} \to \mathbb{R}$ is the same for all the elements g of a CC.
Let

$$\chi_k^\alpha = \chi^\alpha(g(CC_k)) \tag{17.65}$$

Claim 49

$$\frac{1}{|\mathcal{G}|} \sum_{g \in \mathcal{G}} \chi^\alpha(g)\chi^{\beta *}(g) = \delta_{\alpha\beta} \tag{17.66}$$

$$\frac{1}{|\mathcal{G}|} \sum_{k=1}^{N_{CC}} |CC_k| \, \chi_k^\alpha \, \chi_k^{\beta *} = \delta_{\alpha\beta} \tag{17.67}$$

proof:
Setting $i = j$ and $i' = j'$ in Eq.17.46, we get

$$\frac{1}{|\mathcal{G}|} \sum_{g \in \mathcal{G}} \rho_\alpha(g)_{ii}\rho_\beta(g^{-1})_{i'i'} = \delta_{\alpha\beta}\delta_{ii'}\frac{\delta_{ii'}}{d_\alpha} \tag{17.68}$$

Now summing both sides over i and i' gives Eq.17.66.

QED
Define the multiplication of 2 CCs by

$$CC_i \cdot CC_j = \{ab \mid a \in CC_i, b \in CC_j\} \tag{17.69}$$

Note from the multiplication table for group Sq_8 that the product of 2 CCs is a union of CCs, with some CCs appearing multiple times in the product. For example, in Table 17.1,

$$\{C_4, C_4^3\} \cdot \{C_4, C_4^3\} = 2\{E\} + 2\{C_4^2\} \tag{17.70}$$

The two integers 2 indicate that classes $\{E\}$ and $\{C_4^2\}$ each appears twice.

Claim 50 *If $g \in CC_i \cdot CC_j$ then $CC(g) \subset CC_i \cdot CC_j$*

proof:

If $g \in CC_i \cdot CC_j$, then $g = ab$ where $a \in CC_i$ and $b \in CC_j$. Any element of $CC(g)$ must be of the form hgh^{-1} for some $h \in \mathcal{G}$. Hence

$$hgh^{-1} = habh^{-1} = (hah^{-1})(hbh^{-1}) \in CC_i \cdot CC_j \tag{17.71}$$

QED

From Claim 50, it follows that

$$CC_i \cdot CC_j = \sum_k a_{ijk} CC_k \tag{17.72}$$

where $a_{ijk} \in \mathbb{Z}_{>0}$.

Claim 51 *For a group $\mathcal{G}$ with conjugacy classes CC_i and an irrep ρ^α with $\chi_i^\alpha = \mathrm{tr}\rho^\alpha(g(CC_i))$, if*

$$CC_i \cdot CC_j = \sum_k a_{ijk} CC_k \tag{17.73}$$

then

$$|CC_i|\,|CC_j|\chi_i^\alpha \chi_j^\alpha = d_\alpha \sum_k a_{ijk} |CC_k| \chi_k^\alpha \tag{17.74}$$

proof:

Define the matrix R_k^α by

$$R_k^\alpha = \sum_{g \in CC_k} \rho^\alpha(g) \tag{17.75}$$

Note that

$$\begin{aligned} \rho^\alpha(g) R_k^\alpha \rho^\alpha(g^{-1}) &= \sum_{g_1 \in CC_k} \rho^\alpha(g)\rho^\alpha(g_1)\rho^\alpha(g^{-1}) && (17.76) \\ &= \sum_{g_1 \in CC_k} \rho^\alpha(g g_1 g^{-1}) && (17.77) \\ &= R_k^\alpha && (17.78) \end{aligned}$$

Hence, by Schur's First Lemma,

$$R_k^\alpha = c_k^\alpha I \tag{17.79}$$

for some $c_k^\alpha \in \mathbb{C}$. If we now trace both sides of the last equation, we get

$$|CC_k|\chi_k^\alpha = c_k^\alpha d_\alpha \tag{17.80}$$

Hence

$$R_k^\alpha = \frac{|CC_k|}{d_\alpha}\chi_k^\alpha I \tag{17.81}$$

Furthermore,

$$\begin{aligned} R_i^\alpha R_j^\alpha &= \sum_{g_1\in CC_i}\sum_{g_2\in CC_j}\rho^\alpha(g_1g_2) && (17.82)\\ &= \sum_{g\in CC_i\cdot CC_j}\rho^\alpha(g) && (17.83)\\ &= \sum_k a_{ijk}\sum_{g\in CC_k}\rho^\alpha(g) && (17.84)\\ &= \sum_k a_{ijk}R_k^\alpha && (17.85)\end{aligned}$$

If we trace both sides of the last equation, we finally get

$$\frac{|CC_i|}{d_\alpha}\chi_i^\alpha\frac{|CC_j|}{d_\alpha}\chi_j^\alpha = \sum_k a_{ijk}\frac{|CC_k|}{d_\alpha}\chi_k^\alpha \tag{17.86}$$

QED

Claim 52 *Suppose*[3]

$$\rho(g) \equiv \bigoplus_\alpha m_\alpha\rho^\alpha(g) \tag{17.87}$$

and

$$\chi(g) = \sum_\alpha m_\alpha\chi^\alpha(g) \tag{17.88}$$

for all $g\in\mathcal{G}$, where $m_\alpha\in\mathbb{Z}_{>0}$ and the ρ^α are distinct irreps. Then

$$\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\chi^{\alpha*}(g)\chi(g) = m_\alpha \tag{17.89}$$

and

$$\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}}\chi^*(g)\chi(g) = \sum_\alpha |m_\alpha|^2 \tag{17.90}$$

[3]Recall that $A\equiv B$ means that A is equivalent to B; i.e., A and B are equal up to a similarity transformation.

proof:

$$\sum_{g\in\mathcal{G}} \chi^{\alpha *}(g)\chi(g) = \sum_{\beta} m_\beta \sum_{g\in\mathcal{G}} \chi^{\alpha *}(g)\chi^{\beta}(g) \tag{17.91}$$

$$= m_\alpha |\mathcal{G}| \tag{17.92}$$

$$\frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}} \chi^{*}(g)\chi(g) = \frac{1}{|\mathcal{G}|}\sum_{\alpha}\sum_{\beta} m_\alpha^* m_\beta \sum_{g\in\mathcal{G}} \chi^{\alpha *}(g)\chi^{\beta}(g) \tag{17.93}$$

$$= \sum_{\alpha} |m_\alpha|^2 \tag{17.94}$$

QED

Claim 53 *The rep ρ of group $\mathcal{G}$ is irreducible iff*

$$\sum_{g\in\mathcal{G}} \chi^{*}(g)\chi(g) = |\mathcal{G}| \tag{17.95}$$

or, equivalently,

$$\sum_{k} |CC_k|\ \chi_k^* \chi_k = |\mathcal{G}| \tag{17.96}$$

where $\chi(g) = \mathrm{tr}(\rho(g))$ and $\chi_k = \chi(g(CC_k))$.

proof:

This claim follows from Eq.(17.90) with $m_\alpha = 1$ for a single irrep α.

QED

17.6 Regular Representation

The **regular representation** of group $\mathcal{G}$ is the map $\rho^{reg} : \mathcal{G} \to \mathbb{C}^{|\mathcal{G}|\times|\mathcal{G}|}$ such that

$$\rho^{reg}(g)_{g_1,g_2} = \mathbb{1}(g = g_1^{-1}g_2) = \delta_{g,g_1^{-1}g_2} \tag{17.97}$$

for $g, g_1, g_2 \in \mathcal{G}$. The regular rep for any $g \in \mathcal{G}$ is a $|\mathcal{G}| \times |\mathcal{G}|$ matrix with each row and column being one-hot[4]. Each row is one-hot because given (g, g_1), there is only one suitable g_2 for which $g = g_1^{-1}g_2$. Likewise, each column is one-hot because given one (g, g_2), there is only one suitable g_1.

Note that when $g_1 = g_2$,

[4] A one-hot vector has all its components equal to zero except one component equal to one.

$$\rho^{reg}(g)_{g_1,g_1} = \delta_{g,e} \quad \text{so} \quad \chi^{reg}(g) = \delta_{g,e}|\mathcal{G}| \tag{17.98}$$

for all $g \in \mathcal{G}$.

Note that

$$\begin{aligned}
\sum_{g_2} \rho^{reg}(a)_{g_1,g_2}\rho^{reg}(b)_{g_2,g_3} &= \sum_{g_2} \delta_{a,g_1^{-1}g_2}\delta_{b,g_2^{-1}g_3} && (17.99)\\
&= \delta_{a,g_1^{-1}(g_3b^{-1})} && (17.100)\\
&= \delta_{ab,g_1^{-1}g_3} && (17.101)\\
&= \rho^{reg}(ab) && (17.102)
\end{aligned}$$

so ρ^{reg} is a valid group rep.

Claim 54 *Let*

$$\rho^{reg} \equiv \bigoplus_\alpha m_\alpha \rho^\alpha \tag{17.103}$$

where ρ^α are irreps and $m_\alpha \in \mathbb{Z}_{>0}$. Then

$$m_\alpha = d_\alpha \tag{17.104}$$

where d_α is the matrix dimension of rep ρ^α. Furthermore,

$$\chi^{reg} = \sum_\alpha d_\alpha \chi^\alpha \tag{17.105}$$

and

$$|\mathcal{G}| = \sum_\alpha d_\alpha^2 \tag{17.106}$$

proof:

$$\begin{aligned}
m_\alpha &= \frac{1}{|\mathcal{G}|}\sum_{g\in\mathcal{G}} \chi^{\alpha *}(g)\underbrace{\chi_{rep}(g)}_{\delta_{g,e}|\mathcal{G}|} && (17.107)\\
&= \underbrace{\chi^{\alpha *}(e)}_{d_\alpha} && (17.108)
\end{aligned}$$

Eq.(17.105) follows by taking the trace of both sides of Eq.(17.103).

Eq.(17.106) follows by evaluating both sides of Eq.(17.105) at the identity e.

QED

17.7 Other Reps

1. (plane-wave 8-dim rep of Sq_8)

   $\vec{r} = (p_1 x_1, p_2 x_2)$

   $\vec{k} = (k_1, k_2)$

   $\mathcal{G} = Sq_8 = \{G_a\}_{a=1}^8 = \{E, C_4, C_4^3, C_4^2, N_2, N_1, \sigma_{y=-x}, \sigma_{y=x}\}$

   $\vec{r}_a = G_a \vec{r}$

   $G_a|\vec{r}\rangle = |G_a \vec{r}\rangle = |\vec{r}_a\rangle$

$$\left\langle \vec{k}|\phi_a(\vec{r})\right\rangle = \left\langle \vec{k}|\vec{r}_a\right\rangle = \exp(i\vec{k}\cdot\vec{r}_a) \tag{17.109}$$

$$\begin{aligned} \langle \vec{r}_{a_1}|\vec{r}_{a_2}\rangle &= \int \frac{d^2k}{(2\pi)^2} \left\langle \vec{r}_{a_1}|\vec{k}\right\rangle \left\langle \vec{k}|\vec{r}_{a_2}\right\rangle & (17.110) \\ &= \delta(\vec{r}_{a_1} - \vec{r}_{a_2}) & (17.111) \end{aligned}$$

   Define a plane-wave 8-dim rep of Sq_8 by $\rho : \mathcal{G} \to \mathbb{C}^{8\times 8}$ and

$$\rho(G_a)_{a_1,a_2} = \langle \vec{r}_{a_1}|G_a|\vec{r}_{a_2}\rangle = \langle \vec{r}_{a_1}|G_a G_{a_2}\vec{r}\rangle \tag{17.112}$$

   Note that

$$\rho \equiv \rho^{reg} \equiv \bigoplus_\beta m_\beta \rho^\beta = \rho^{(1)} \oplus \rho^{(2)} \oplus \rho^{(3)} \oplus \rho^{(4)} \oplus 2\rho^{(5)} \tag{17.113}$$

$$U^\dagger \rho(G_a) U = \bigoplus_\beta m_\beta \rho^\beta(G_a) \tag{17.114}$$

$$\left\langle \vec{k}|\psi_a(\vec{r})\right\rangle = \left\langle \vec{k}|U|\vec{r}_a\right\rangle = \sum_{a_1} \left\langle \vec{k}|\vec{r}_{a_1}\right\rangle \langle \vec{r}_{a_1}|U|\vec{r}_a\rangle \tag{17.115}$$

   $span\{U|\vec{r}_a\rangle\}_{a=1}^8$ is a vector space upon the 8-dim rep ρ is block diagonal

2. (plane wave 4-dim rep of Sq_8)

   $\vec{r} = (p_1 x_1, p_2 x_2)$

   $\vec{k} = (k_1, k_2)$

   $a \in \{1, 2, 3, 4\}$, $A \in \{1, 2, \ldots, 8\}$

   $\mathcal{G} = Sq_8 = \{G_A\}_{A=1}^8 = \{E, C_4, C_4^3, C_4^2, N_2, N_1, \sigma_{y=-x}, \sigma_{y=x}\}$

   $\mathcal{H} = \{G_a\}_{a=1}^4 = \{E, C_4, C_4^3, C_4^2\}$, $\mathcal{H}$ is a subgroup of $\mathcal{G}$

   $\vec{r}_a = G_a \vec{r}$

$G_a|\vec{r}\rangle = |G_a\vec{r}\rangle = |\vec{r}_a\rangle$

$$\left\langle \vec{k}|\phi_a(\vec{r})\right\rangle = \left\langle \vec{k}|\vec{r}_a\right\rangle = \exp(i\vec{k}\cdot\vec{r}_a) \tag{17.116}$$

$$\begin{aligned}\langle \vec{r}_{a_1}|\vec{r}_{a_2}\rangle &= \int \frac{d^2k}{(2\pi)^2}\left\langle \vec{r}_{a_1}|\vec{k}\right\rangle\left\langle \vec{k}|\vec{r}_{a_2}\right\rangle && (17.117)\\ &= \delta(\vec{r}_{a_1}-\vec{r}_{a_2}) && (17.118)\end{aligned}$$

Define a plane-wave 4-dim rep of Sq_8 by $\rho : \mathcal{G} \to \mathbb{C}^{4\times 4}$ and

$$\rho(G_A)_{a_1,a_2} = \langle \vec{r}_{a_1}|G_A|\vec{r}_{a_2}\rangle = \langle \vec{r}_{a_1}|G_A G_{a_2}\vec{r}\rangle \tag{17.119}$$

$$U^\dagger \rho(G_A) U = \bigoplus_\beta m_\beta \rho^\beta(G_A) = \rho^{(1)} \oplus \rho^{(2)} \oplus \rho^{(5)} \tag{17.120}$$

$$\left\langle \vec{k}|\psi_a(\vec{r})\right\rangle = \left\langle \vec{k}|U|\vec{r}_a\right\rangle = \sum_{a_1}\left\langle \vec{k}|\vec{r}_{a_1}\right\rangle\langle \vec{r}_{a_1}|U|\vec{r}_a\rangle \tag{17.121}$$

$span\{U|\vec{r}_a\rangle\}_{a=1}^4$ is a vector space upon the 8-dim rep ρ is block diagonal

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3. **tensor product of reps**

   The Kronecker tensor product of two matrices is defined in A.4. It satisfies

$$(A\otimes B)(A'\otimes B') = (AA')\otimes(BB') \tag{17.122}$$

and

$$\mathrm{tr}(A\otimes B) = \mathrm{tr}(A)\mathrm{tr}(B) \tag{17.123}$$

Define the tensor product rep ρ of two reps $\rho_i : \mathcal{G} \to \mathbb{C}^{n_i\times n_i}$ for $i = 1, 2$, by $\rho : \mathcal{G} \to \mathbb{C}^{n_1n_2\times n_1n_2}$ and

$$\rho(g) = \rho_1(g)\otimes\rho_2(g) \quad \forall g \in \mathcal{G} \tag{17.124}$$

ρ is a valid rep because

$$\begin{aligned}\rho(g)\rho(h) &= [\rho_1(g)\otimes\rho_2(g)][\rho_1(h)\otimes\rho_2(h)] && (17.125)\\ &= [\rho_1(g)\rho_1(h)]\otimes[\rho_2(g)\rho_2(h)] && (17.126)\\ &= \rho_1(gh)\otimes\rho_2(gh) && (17.127)\\ &= \rho(gh) && (17.128)\end{aligned}$$

Tracing both sides of Eq.(17.124), we get

$$\chi(g) = \chi_1(g)\chi_2(g) \quad \forall g \in \mathcal{G} \tag{17.129}$$

Note that

$$\rho^\alpha \otimes \rho^\beta \equiv \bigoplus_\gamma m_{\alpha\beta\gamma}\rho^\gamma \tag{17.130}$$

where $\rho^\alpha, \rho^\beta, \rho^\gamma$ are irreps of $\mathcal{G}$ and $m_{\alpha\beta\gamma} \in \mathbb{Z}_{>0}$. For example, for Sq_8,

$$\rho^{(1)} \otimes \rho^{(1)} \equiv \rho^{(1)} \tag{17.131}$$

$$\rho^{(1)} \otimes \rho^{(2)} \equiv \rho^{(2)} \tag{17.132}$$

$$\rho^{(5)} \otimes \rho^{(5)} \equiv \rho^{(1)} \oplus \rho^{(2)} \oplus \rho^{(3)} \oplus \rho^{(4)} \tag{17.133}$$

Tracing both sides of Eq.(17.130), we get

$$\chi^\alpha(g)\chi^\beta(g) = \sum_\gamma m_{\alpha\beta\gamma}\chi^\gamma(g) \tag{17.134}$$

Note that if ρ_1 and ρ_2 are reps of $\mathcal{G}$ but not necessarily irreps, whereas $\rho^\alpha, \rho^\beta, \rho^\gamma$ are guaranteed to be irreps of $\mathcal{G}$, then

$$\rho_1 \equiv \bigoplus_\alpha m_{1,\alpha}\rho^\alpha, \quad \rho_2 \equiv \bigoplus_\alpha m_{2,\beta}\rho^\beta \tag{17.135}$$

where $m_{1\alpha}, m_{2\beta} \in \mathbb{Z}_{>0}$. Hence

$$\rho_1 \otimes \rho_2 \equiv \bigoplus_\gamma \left[\sum_\alpha \sum_\beta m_{1\alpha} m_{2\beta} m_{\alpha\beta\gamma}\right] \rho^\gamma \tag{17.136}$$

where $m_{\alpha\beta\gamma} \in \mathbb{Z}_{>0}$.

The vector space on which the $\mathcal{G}$ rep $\rho_1 \otimes \rho_2$ acts is spanned by $\{|\psi_{i,j}\rangle\}_{i=1,2,\ldots,n_1, j=1,2,\ldots,n_2}$, where

$$|\psi_{ij}\rangle = |\psi_i\rangle|\psi_j\rangle = |\psi_i\rangle \otimes |\psi_j\rangle \tag{17.137}$$

$$\langle\psi_{ij}|\rho_1(g) \otimes \rho_2(g)|\psi_{i'j'}\rangle = [\langle\psi_i|\rho_1(g)|\psi_{i'}\rangle]\,[\langle\psi_j|\rho_1(g)|\psi_{j'}\rangle] \tag{17.138}$$

4. **rep of Cartesian product of groups**

The Cartesian product two groups $\mathcal{G}$ and $\mathcal{H}$

$$\mathcal{H} \times \mathcal{G} = \{(g, h) \mid g \in \mathcal{G}, h \in \mathcal{H}\} \tag{17.139}$$

becomes a group when endowed with the following group multiplication

$$(g_1, h_1)(g_2, h_2) = (g_1 g_2, h_1 h_2) \tag{17.140}$$

for $g_1, g_2 \in \mathcal{G}$ and $h_1, h_2 \in \mathcal{H}$. If $\rho^{\mathcal{G}} : \mathcal{G} \to \mathbb{C}^{n\times n}$ is a rep of $\mathcal{G}$, and $\rho^{\mathcal{H}} : \mathcal{H} \to \mathbb{C}^{m\times m}$ is a rep of $\mathcal{H}$, then the natural representation $\rho^{\mathcal{G}\times\mathcal{H}}$ of $\mathcal{G} \times \mathcal{H}$ is defined by

$$\rho^{\mathcal{G}\times\mathcal{H}} : \mathcal{G} \times \mathcal{H} \to \mathbb{C}^{mn\times mn} \tag{17.141}$$

$$\rho^{\mathcal{G}\times\mathcal{H}}(g, h) = \underbrace{\rho^{\mathcal{G}}(g)}_{G} \otimes \underbrace{\rho^{\mathcal{H}}(h)}_{H} \tag{17.142}$$

$$(G_1 \otimes H_1)(G_2 \otimes H_2) = (G_1 G_2) \otimes (H_1 H_2) \tag{17.143}$$

Recall that $\mathrm{tr}(A \otimes B) = \mathrm{tr}(A)\mathrm{tr}(B)$ so

$$\rho^{\mathcal{G}}(1) = \rho^{\mathcal{G}}(g^{-1}) \otimes \rho^{\mathcal{G}}(g) \quad \forall g \in \mathcal{G} \implies |\mathcal{G}| = \sum_{g\in\mathcal{G}} \chi^{\mathcal{G}*}(g)\chi^{\mathcal{G}}(g) \tag{17.144}$$

$$\rho^{\mathcal{H}}(1) = \rho^{\mathcal{H}}(h^{-1}) \otimes \rho^{\mathcal{H}}(h) \quad \forall h \in \mathcal{H} \implies |\mathcal{H}| = \sum_{h\in\mathcal{H}} \chi^{\mathcal{H}*}(h)\chi^{\mathcal{H}}(h) \tag{17.145}$$

Taking the trace of both sides of Eq.(17.142) gives

$$\chi^{\mathcal{G}\times\mathcal{H}}(g, h) = \chi^{\mathcal{G}}(g)\chi^{\mathcal{H}}(h) \tag{17.146}$$

If we now combine Eq.(17.144), Eq.(17.145) and Eq.(17.146), we get

$$\begin{aligned} |\mathcal{G} \times \mathcal{H}| &= |\mathcal{G}|\,|\mathcal{H}| && (17.147)\\ &= \left[\sum_{g\in\mathcal{G}} \chi^{\mathcal{G}*}(g)\chi^{\mathcal{G}}(g)\right]\left[\sum_{h\in\mathcal{H}} \chi^{\mathcal{H}*}(h)\chi^{\mathcal{H}}(h)\right] && (17.148)\\ &= \sum_{(g,h)\in\mathcal{G}\times\mathcal{H}} \chi^{\mathcal{G}\times\mathcal{H}*}(g, h)\chi^{\mathcal{G}\times\mathcal{H}}(g, h) && (17.149) \end{aligned}$$

The vector space on which the $\mathcal{G} \times \mathcal{H}$ rep $\rho^{\mathcal{G}} \otimes \rho^{\mathcal{H}}$ acts is spanned by $\{|\psi_{i,j}\rangle\}_{i=1,2,\ldots,n,j=1,2,\ldots,m}$, where

$$|\psi_{ij}\rangle = |\psi_i\rangle|\psi_j\rangle = |\psi_i\rangle \otimes |\psi_j\rangle \tag{17.150}$$

$$\left\langle \psi_{ij}|\rho^{\mathcal{G}}(g) \otimes \rho^{\mathcal{H}}(h)|\psi_{i'j'}\right\rangle = \left[\left\langle \psi_i|\rho^{\mathcal{G}}(g)|\psi_{i'}\right\rangle\right] \left[\left\langle \psi_j|\rho^{\mathcal{H}}(h)|\psi_{j'}\right\rangle\right] \tag{17.151}$$

Chapter 18

Reducibility of Representations, II

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

18.1 Eigenvalue Projectors

Suppose $M \in \mathbb{C}^{d\times d}$ has eigenvalues λ_i with corresponding eigenvectors $|\lambda_i\rangle$

$$M|\lambda_i\rangle = \lambda_i|\lambda_i\rangle \tag{18.1}$$

for $i \in \mathbb{Z}_{[1,r]}$. The characteristic polynomial of M is defined as

$$cp(\lambda) \stackrel{\text{def}}{=} \det(M-\lambda) = \prod_{i=1}^{r}(\lambda-\lambda_i)^{d_i} \tag{18.2}$$

It satisfies

$$cp(\lambda) = 0 \tag{18.3}$$

for $\lambda = \lambda_i$.

Note that if M is Hermitian ($M^\dagger = M$), then all its eigenvalues are real. (because $\lambda_i = \langle\lambda_i|M|\lambda_i\rangle \in \mathbb{R}$)

If M is Hermitian, then there exists a matrix C that is unitary ($CC^\dagger = C^\dagger C = 1$) and diagonalizes M

$$CMC^\dagger = \begin{bmatrix} \Lambda_{\lambda_1} & 0 & 0 & 0 \\ 0 & \Lambda_{\lambda_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \Lambda_{\lambda_r} \end{bmatrix} \tag{18.4}$$

where

$$\Lambda_{\lambda_i} = \lambda_i \mathrm{diag}\underbrace{(1,1,\ldots,1)}_{d_i \text{ times}} = \lambda_i I^{d_i\times d_i} \tag{18.5}$$

and

$$d = \sum_{i=1}^{r} d_i \tag{18.6}$$

As in Chapter 4, let us set

$$\pi_i = \begin{bmatrix} 0 & 0 & 0 \\ 0 & I^{d_i \times d_i} & 0 \\ 0 & 0 & 0 \end{bmatrix}^{d \times d} \tag{18.7}$$

and

$$P_i = C^\dagger \pi_i C \tag{18.8}$$

For example, when $d = 2$,

$$CMC^\dagger = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \tag{18.9}$$

so

$$\pi_1 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} = \frac{CMC^\dagger - \lambda_2}{\lambda_1 - \lambda_2}, \quad P_1 = \frac{M - \lambda_2}{\lambda_1 - \lambda_2} \tag{18.10}$$

$$\pi_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} = \frac{CMC^\dagger - \lambda_1}{\lambda_2 - \lambda_1}, \quad P_2 = \frac{M - \lambda_1}{\lambda_2 - \lambda_1} \tag{18.11}$$

$\{\pi_1, \pi_2\}$ is a complete orthogonal set of projection operators, and so is $\{P_1, P_2\}$.

Similarly, for $d > 2$, we have

$$\pi_i = \prod_{j \neq i} \frac{CMC^\dagger - \lambda_j}{\lambda_i - \lambda_j}, \quad P_i = \prod_{j \neq i} \frac{M - \lambda_j}{\lambda_i - \lambda_j} \tag{18.12}$$

$\{\pi_i\}_{i=1}^r$ is a complete set of orthogonal projection operators and $\{P_i\}_{i=1}^r$ is too.

Note that

$$d_i = \mathrm{tr}(\pi_i) = \mathrm{tr}(P_i) \tag{18.13}$$

18.2 $[P_i, M] = 0$ Consequences

From Eq.(18.12), it is clear that P_i and M commute

$$[P_i, M] = P_i M - M P_i = 0 \tag{18.14}$$

From the P_i's completeness and commutativity with M, we get

$$M = \sum_{i=1}^{r}\sum_{j=1}^{r} P_i M P_j \tag{18.15}$$

$$= \sum_{i=1}^{r} P_i M P_i \tag{18.16}$$

Claim 55 *For all i,*

$$MP_i = \lambda_i P_i \text{ (no } i \text{ sum)} \tag{18.17}$$

proof:

$$MP_i = [C^\dagger \Lambda C][C^\dagger \pi_i C] \tag{18.18}$$

$$= \lambda_i [C^\dagger \pi_i C] \tag{18.19}$$

$$= \lambda_i P_i \tag{18.20}$$

QED

From the last claim, it immediately follows that if $f(x)$ can be expressed as a power series in x, then [1]

$$f(M)P_i = f(\lambda_i)P_i \text{ (no } i \text{ sum)} \tag{18.21}$$

18.3 Multiple Invariant Matrices

Suppose $M^{(1)}, M^{(2)} \in \mathbb{C}^{d\times d}$ are Hermitian matrices that commute

$$[M^{(1)}, M^{(2)}] = 0 \tag{18.22}$$

Use $M^{(1)}$ to decompose $V = \mathbb{C}^{d\times d}$ into a direct sum of vector spaces $\bigoplus_i V_i$. Then we can use $M^{(2)}$ to decompose V_i into $\bigoplus_j V_{i,j}$. If $M^{(1)}$ and $M^{(2)}$ don't commute, let $P_i^{(1)}$ be an eigenvalue projection operator of $M^{(1)}$. Then replace $M^{(2)}$ by $P_i^{(1)} M^{(2)} P_i^{(1)}$. Now

$$[M^{(1)}, P_i^{(1)} M^{(2)} P_i^{(1)}] = \sum_j \lambda_j^{(1)} [P_j^{(1)}, P_i^{(1)} M^{(2)} P_i^{(1)}] \tag{18.23}$$

$$= 0 \tag{18.24}$$

[1] M must also satisfy some convergence conditions that we won't get into.

18.4 $[G, M] = 0$ Consequences

An invariant matrix (see Ch.8) commutes with all the elements G of a group $\mathcal{G}$

$$[G, M] = 0 \tag{18.25}$$

If P_i are the projection operators of M, then $P_i = f_i(M)$ so

$$[G, P_i] = 0 \tag{18.26}$$

for all $G \in \mathcal{G}$ and i. Hence,

$$G = 1G1 = \sum_i \sum_j P_i G P_j = \sum_j \underbrace{P_j G P_j}_{\stackrel{\text{def}}{=} G'_j} \tag{18.27}$$

Since $P_i = C^\dagger \pi_i C$,

$$[CGC^\dagger, \pi_i] = 0 \tag{18.28}$$

Hence

$$CGC^\dagger = 1G1 = \sum_i \sum_j \pi_i CGC^\dagger \pi_j = \sum_j \underbrace{\pi_j CGC^\dagger \pi_j}_{\stackrel{\text{def}}{=} G_j} = diag(G_1, G_2, \ldots, G_r) \tag{18.29}$$

Note that

$$C^\dagger G_j C = G'_j \tag{18.30}$$

A rep-matrix G'_i acts only on a d_i dimensional vector space $V^{d_i} = P_i V^d$. In this way, an invariant matrix $M \in \mathbb{C}^{d \times d}$ with r distinct eigenvalues, induces a decomposition of V^d into a direct sum of vector spaces

$$V^d \xrightarrow[M]{} V_1^{d_1} \oplus V_2^{d_2} \oplus \ldots \oplus V_r^{d_r} \tag{18.31}$$

If a rep-matrix G'_i cannot itself be reduced further, it is said to be an **irreducible representation (irrep)**.

Note that sometimes the term representation is used to refer to the vector space $V_i^{d_i}$ instead of the matrix G_i.

Chapter 19

Spinors

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

The reader should read Chapter 13 before reading this chapter. There he will learn about the group $Spin(n)_{\mathbb{R}}$.

Let

$$\gamma_{\mu\nu} = \frac{1}{2}[\gamma_\mu, \gamma_\nu] \tag{19.1}$$

If $\gamma_\mu^\dagger = \gamma_\mu$ for $\mu = 1, 2, \ldots, n$ (this assumes the Euclidean metric which is $g_{\mu\nu} = diag(1, 1, 1, 1)$ for $n = 4$)

$$Spin(n)_{\mathbb{R}} = \{e^{\omega^{\mu\nu}\gamma_{\mu\nu}} | \omega_{\mu\nu} = -\omega_{\nu\mu} \in \mathbb{R}\}\} \tag{19.2}$$

If $\gamma_0^\dagger = \gamma_0$, and $\gamma_i^\dagger = -\gamma_i$ (this assumes the mostly-minus metric which is $g_{\mu\nu} = diag(1, -1, -1, -1)$ for $n = 4$)

$$Spin(1,3)_{\mathbb{R}} = \{e^{-i\omega^{\mu\nu}\gamma_{\mu\nu}} | \omega_{\mu\nu} = -\omega_{\nu\mu}, \omega_{0,i} \in \mathbb{R}, \omega_{i,j} \in i\mathbb{R}\} \tag{19.3}$$

Spinors are the vectors in the vector space upon which the group $Spin(n)_{\mathbb{R}}$ acts.

n	1	2	3	4	5	6	7	8	9	10
$int(n/2)$	0	1	1	2	2	3	3	4	4	5
$d = 2^{int(n/2)}$	1	2	2	4	4	8	8	16	16	32

Table 19.1: $\gamma_\mu \in \mathbb{C}^{d\times d}$

Let $\mu \in \{1, 2, \ldots, n\}$
$int(x)$ = integer part of $x \in \mathbb{R}$
$a, b \in \{1, 2, \ldots, 2^{int(n/2)}\}$
$\gamma_\mu \in \mathbb{C}^{d\times d}$ where $d = 2^{int(n/2)}$ (See Table 19.1)

Define the following birdtracks

$\gamma^{\mu}_{ab} =$

, $(\gamma_\mu)_{ab} =$

, $\delta^b_a =$

(19.4)

$g_{\mu\nu} =$

, $g^{\mu\nu} =$

(19.5)

Note that

$g_\mu{}^\mu =$ $= 2^{int(n/2)}$

(19.6)

Clifford Algebra anticommutator:

$$g_{\mu,\nu}\mathbb{1} = \frac{1}{2}[\gamma_\mu, \gamma_\nu]_+$$

(19.7)

By virtue of Eq.(19.7), it is possible to replace all g's by swaps, and vice versa, in a linear combination of birdtracks.

Claim 56

(19.8)

proof:

(19.9)

QED

Claim 57

(19.10)

proof:

The claim for $p = 2$ is

(19.11)

where we define

(19.12)

The claim for $p = 3$ is

(19.13)

(19.14)

where we define

(19.15)

Now let us express each of the 6 birdtracks on the right hand side of Eq.(19.15) in terms of g's instead of swaps.

(19.16)

(19.17)

(19.18)

(19.19)

(19.20)

(19.21)

(19.22)

QED

Claim 58

$$\frac{1}{2}\left[\gamma_\nu\gamma_{\mu_1}\dots\gamma_{\mu_a} - (-1)^a\gamma_{\mu_1}\dots\gamma_{\mu_a}\gamma_\nu\right] = \sum_{k=1}^{a}(-1)^{k-1}g_{\nu\mu_k}\gamma_{\mu_1}\dots\widehat{\gamma_{\mu_k}}\dots\gamma_{\mu_a} \tag{19.23}$$

where a hat means omission. For $a = 2$,

(19.24)

proof:

Note that

(19.25)

so this claim has been proven before for $a = 2$ in Eq.(19.22)
QED

Claim 59 *If $n \neq a$ and a is odd*

$$\mathrm{tr}(\gamma_{\mu_1}\gamma_{\mu_2}\ldots\gamma_{\mu_a}) = 0 \tag{19.26}$$

proof:

If we left-multiply both sides of Eq.(19.24) by γ_{μ_1} where μ_1 is the first index, and then we trace over the spinor indices, we get

(19.27)

Assuming a is odd, we get

(19.28)

Hence, if $n \neq a$ and a is odd, the trace of a gammas is zero.

The above proof is now complete and it works for odd or even n. However, let us mention that for even n, a chirality operator Γ_5, exists, and this claim can be proven using Γ_5. Indeed, for n even, let

$$\Gamma_5 = K\gamma_1\gamma_2\ldots\gamma_n \tag{19.29}$$

Γ_5 anti-commutes with all γ_μ:

$$\Gamma_5\gamma_\mu\Gamma_5^{-1} = -\gamma_\mu \tag{19.30}$$

Hence

$$\begin{aligned}
\mathrm{tr}(\gamma_{\mu_1}\gamma_{\mu_2}\ldots\gamma_{\mu_a}) &= \mathrm{tr}(\Gamma_5\gamma_{\mu_1}\gamma_{\mu_2}\ldots\gamma_{\mu_a}\Gamma_5^{-1}) && (19.31)\\
&= (-1)^a\mathrm{tr}(\gamma_{\mu_1}\gamma_{\mu_2}\ldots\gamma_{\mu_a}) && (19.32)
\end{aligned}$$

So for odd a, $\mathrm{tr}(\gamma_{\mu_1}\gamma_{\mu_2}\ldots\gamma_{\mu_a}) = 0$.

QED

Claim 60

(19.33)

(19.34)

proof:
QED

Define the antisymmetrized gamma matrix products $\Gamma^{(k)}$ by:

$$\Gamma^{(0)} = 1 =$$

$$\Gamma^{(1)}_{\mu} = \gamma_\mu =$$

$$\Gamma^{(2)}_{\mu\nu} = \tfrac{1}{2}[\gamma_\mu, \gamma_\nu] =$$

$$\Gamma^{(3)}_{\lambda\mu\nu} = \tfrac{1}{6}[\gamma_\lambda, \gamma_\mu, \gamma_\nu] =$$

(19.35)

Henceforth, let

$$\underline{g}^{(t)} = \prod_{i=1}^{t} g_{\mu_i \nu_i} \tag{19.36}$$

Claim 61

$$\mu^{:a} \longleftarrow \underline{\Gamma}^{(a)} \quad \underline{\Gamma}^{(b)} \longrightarrow \nu^{:b} = \delta^b_a \qquad \mu^{:a} \leftarrow \underline{g}^{(a)} \rightarrow \mathcal{A}_a \rightarrow \nu^{:a} \tag{19.37}$$

proof:
QED

Define χ_c by

$$\chi_c =$$

(19.38)

where

$$
\begin{aligned}
s &= (b+c-a)/2 \\
t &= (b+a-c)/2 \\
u &= (a+c-b)/2
\end{aligned}
\tag{19.39}
$$

Claim 62

(19.40)

proof:
QED

Claim 63

(19.41)

where $t = a - u = b - s$ *and*

$$
K_c = \frac{a!b!c!}{s!t!u!} \tag{19.42}
$$

proof:

Eq.(19.41) follows because the $\Gamma^{(c)}$ span the vector space of $\Gamma^{(c)}$ products.

If we left-multiply both sides of Eq.(19.41) by $\Gamma^{(c')}$ and then we trace over the spinor indices, we get

(19.43)

so K_c satisfies

(19.44)

Hence,

$$K_c = \frac{a!b!c!}{s!t!u!} \tag{19.45}$$

QED

Define the projector $P^{(a)}$ by

(19.46)

and the 3 leg vertex ${}^{b\wedge a}_{\ \ c}$ by

(19.47)

Note that the vertex ${}^{b\wedge a}_{\ \ c}$ is nonzero iff $a+b+c$ is even, and if a, b, and c satisfy the triangle inequalities $|a-b| \leq c \leq |a+b|$

Claim 64

(19.48)

proof:
QED

Note that

$$d^{(a)} = \mathrm{tr}(P^{(a)}) = \frac{1}{} \quad \underline{\Gamma}^{(a)} \quad \overline{\Gamma}^{(a)} \tag{19.49}$$

$$= \mathcal{A}_a \tag{19.50}$$

$$= \begin{cases} \binom{n}{a} & \text{if } a \leq n \text{ (see Eq.(23.43))} \\ 0 & \text{otherwise} \end{cases} \tag{19.51}$$

$$\sum_{a=1}^{n} d^{(a)} = \sum_{a=1}^{n} \binom{n}{a} = (1+1)^2 = 2^a \tag{19.52}$$

Claim 65

$$\underline{\Gamma}^{(b)} \quad \underline{\Gamma}^{(a)} = \sum_{c=1}^{a+b} K'_c \quad C^{b\wedge a} \quad \overline{\Gamma}^{(c)} \tag{19.53}$$

where

$$K'_c = \frac{a!b!c!}{s!t!u!} = K_c \tag{19.54}$$

proof:

Eq.(19.53) follows because the $\Gamma^{(c)}$ span the vector space of $\Gamma^{(c)}$ products.

If we left-multiply both sides of Eq.(19.53) by $\Gamma^{(c')}$ and then we trace over the spinor indices, we get

$$\underline{\Gamma}^{(c')} \quad \underline{\Gamma}^{(b)} \quad \underline{\Gamma}^{(a)} = \sum_{c=1}^{a+b} K'_c \quad C^{b\wedge a} \quad \underline{\Gamma}^{(c')} \quad \overline{\Gamma}^{(c)} \tag{19.55}$$

So K'_c satisfies

$$\frac{a!b!c!}{s!t!u!} \chi_c = K'_c \chi_c \tag{19.56}$$

Hence,

$$K'_c = \frac{a!b!c!}{s!t!u!} = K_c \tag{19.57}$$

QED

Claim 66 *(t-channel to sum of s-channels)*

(19.58)

where

(19.59)

(19.60)

proof:

(19.61)

(19.62)

QED

Chapter 20

Spinors, Their Handedness

This chapter is based on an AI output and Ref.[1].

20.1 In 1+3 dim

Consider $SO(1,3)$ so $n = 1+3 = 4$

γ^{μ}_{ab}

$a, b \in \{1,2,3,4\}$

$\mu = 1, 2, \ldots, n$

Mostly-plus metric (M+M) (a.k.a. East Coast metric) is $g_{\mu\nu} = diag(-1,1,1,1)$

Mostly-minus metric (M-M) (a.k.a. West Coast metric) is $g_{\mu\nu} = diag(1,-1,-1,-1)$

$$[\gamma_\mu, \gamma_\nu]_+ = 2g^{\mu\nu} \quad \text{for } \mu,\nu = 0,1,2,3 \tag{20.1}$$

$$\begin{aligned} \text{M–M}: &\quad \gamma_0^\dagger = \gamma_0, \quad \gamma_i^\dagger = -\gamma_i \quad \text{for } i = 1,2,3 \\ \text{M+M}: &\quad \gamma_0^\dagger = -\gamma_0, \quad \gamma_i^\dagger = \gamma_i \quad \text{for } i = 1,2,3 \end{aligned} \tag{20.2}$$

The last equation is true iff

$$\begin{aligned} \text{M–M}: &\quad \gamma_\mu^\dagger = \gamma_0\gamma_\mu\gamma_0 \\ \text{M+M}: &\quad \gamma_\mu^\dagger = -\gamma_0\gamma_\mu\gamma_0 \end{aligned} \tag{20.3}$$

In 1+3 dimensional relativistic quantum field theory, the **chirality operator** γ_5 is defined in terms of the four Dirac gamma matrices γ_μ, where $\mu = 0,1,2,3$, as follows

$$\begin{aligned} \text{M–M}: &\quad \gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3 = \tfrac{i}{4!}\epsilon^{\mu\nu\rho\sigma}\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma \\ \text{M+M}: &\quad \gamma_5 = -i\gamma_0\gamma_1\gamma_2\gamma_3 \end{aligned} \tag{20.4}$$

In the "Dirac representation",

$$\gamma_5 = \pm \begin{bmatrix} 0 & I_2 \\ I_2 & 0 \end{bmatrix} \tag{20.5}$$

The properties of γ_5 might change by a sign depending on which metric we are using. Henceforth, we will use the M–M

γ_5 properties:

- Anticommutes with γ_μ

$$\gamma_5\gamma_\mu = -\gamma_\mu\gamma_5 \quad \text{for } \mu = 0, 1, 2, 3 \tag{20.6}$$

  This follows because $g_{\mu\nu}$ is diagonal so, by the Clifford algebra definition Eq.(20.1) (anti-cummutator of gammas), the γ_μ anticommutes with 3 of the 4 gamma matrices in γ_5

- Hermitian

$$\gamma_5^\dagger = \gamma_5 \tag{20.7}$$

  This follows because

$$\gamma_5^\dagger = -i(-\gamma_3)(-\gamma_2)(-\gamma_1)(+\gamma_0) = i\gamma_3\gamma_2\gamma_1\gamma_0 = (-1)^6 i(\gamma_0\gamma_1\gamma_2\gamma_3) = \gamma_5 \tag{20.8}$$

- Square is 1

$$\gamma_5^2 = I. \tag{20.9}$$

  Therefore its eigenvalues are $+1$ (positive chirality) and -1 (negative chirality). This follows because

$$(\gamma_5)^2 = -\gamma_0\gamma_1\gamma_2\gamma_3\gamma_0\gamma_1\gamma_2\gamma_3 = -(-1)^6(\gamma_0)^2(\gamma_1)^2(\gamma_2)^2(\gamma_3)^2 = -g_{00}g_{11}g_{22}g_{33} = 1 \tag{20.10}$$

- Traceless

$$\mathrm{tr}(\gamma_5) = 0 \tag{20.11}$$

  This follows immediately from the expression for γ_5 in the Dirac representation. Alternatively, note that if spinor ψ satisfies

$$\gamma_5\psi = +\psi \tag{20.12}$$

  (has positive chirality), then spinor $\gamma_\mu\psi$ has negative chirality because

$$\gamma_5(\gamma_\mu\psi) = -\gamma_\mu\gamma_5\psi = -\gamma_\mu\psi \tag{20.13}$$

  This means that the eigenvalues of γ_5 come in ± 1 pairs. Hence the trace of γ_5 must be zero.

- $$\mathrm{tr}(\gamma_5\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma) = 4i\epsilon^{\mu\nu\rho\sigma}, \tag{20.14}$$
  with $\epsilon^{0123} = +1$
- If
  $$P_L = P_- = \frac{1}{2}(1-\gamma_5), \qquad P_R = P_+ = \frac{1}{2}(1+\gamma_5). \tag{20.15}$$
  where R= right handed, L = left handed then
  $$\psi = \underbrace{\psi_L}_{P_L\psi} + \underbrace{\psi_R}_{P_R\psi} \tag{20.16}$$
- If $\mathbb{P} = \gamma_0$ (Parity Operator) and $\sigma^{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$ (Lorentz generators)
  $$[\gamma_5, \sigma^{\mu\nu}] = 0, \quad \gamma_5\mathbb{P} = -\mathbb{P}\gamma_5 \tag{20.17}$$
  Thus γ_5 is **pseudoscalar** under Lorentz transformations (i.e., invariant under proper Lorentz transformations but flips sign under parity).

20.2 In $p+q$ dim

Consider $SO(p,q)$ so $n = p+q$

γ^μ_{ab}
$int(x)$ = integer part of $x \in \mathbb{R}$
$a, b \in \{1, 2, \ldots, 2^{int(n/2)}\}$
$\mu = 1, 2, \ldots, n$

n	1	2	3	4	5	6	7	8	9	10
$int(n/2)$	0	1	1	2	2	3	3	4	4	5
$d = 2^{int(n/2)}$	1	2	2	4	4	8	8	16	16	32

Table 20.1: $\gamma_\mu \in \mathbb{C}^{d\times d}$

$$[\gamma_\mu, \gamma_\nu]_+ = 2g^{\mu\nu} \quad \text{for } \mu, \nu = 0, 1, 2, \ldots, n \tag{20.18}$$

$\Gamma^{(3)}_{\lambda\mu\nu} =$

(20.19)

Generalize $\gamma_5 \to \Gamma_5$, from $SO(1,3)$ to $SO(p,q)$.

$$\Gamma_5 = \frac{1}{\sqrt{n!}} \quad \mathcal{A}_n^{\frac{1}{2}} \; \underline{\underline{\underline{\

- If n is even and
$$P_\pm = \frac{1}{2}(1 \pm \Gamma_5), \tag{20.28}$$
then
$$P_+^2 = P_-^2 = 1, \quad P_+P_- = 0, \quad P_+ + P_- = 1 \tag{20.29}$$
$$\gamma_\mu P_+ = P_- \gamma_\mu \tag{20.30}$$
$$\gamma_\mu = P_+\gamma_\mu P_- + P_-\gamma_\mu P_+ \tag{20.31}$$

20.3 Weyl and Majorana Spinors

Spinor Type	Condition	# of dofs in 4D	Exists in 4D?
Dirac	none	8	yes
Weyl	$\Gamma_5\psi = \pm\psi$	4	yes
Majorana	$\psi^c = \psi$	4	yes
Majorana-Weyl	both	0	no

Table 20.2: Different types of spinors, their number of dofs (real degrees of freedom) in 4D and whether they exist in 4D.

- Weyl spinors
$$P_L = \frac{1}{2}(1 - \Gamma_5), \quad P_R = \frac{1}{2}(1 + \Gamma_5) \tag{20.32}$$
A **left-handed Weyl spinor** satisfies
$$\psi_L = P_L\psi, \quad \Gamma_5\psi_L = -\psi_L \tag{20.33}$$
A **a right-handed Weyl spinor** satisfies
$$\psi_R = P_R\psi, \quad \Gamma_5\psi_R = +\psi_R. \tag{20.34}$$

- Majorana Spinors

  The **charge conjugation matrix** C is defined by
$$C\gamma^\mu C^{-1} = -(\gamma^\mu)^T, \tag{20.35}$$

and exists in any dimension.

Given a Dirac spinor ψ, its **charge-conjugate** is

$$\psi^c = C\bar{\psi}^T \quad \text{where } \bar{\psi} = \psi^\dagger \gamma^0 \tag{20.36}$$

A **Majorana spinor** is one satisfying

$$\psi = \psi^c \tag{20.37}$$

Whether Majorana spinors exist depends on the spacetime dimension and signature. In 1+3 dimensions, Majorana spinors do exist because one can choose a representation where all gamma matrices are purely real or imaginary so that ψ can be chosen real.

A Dirac spinors has 4 complex components. A Majorana spinor has 4 real components.

The Weyl spinor and Majorana spinor constraints cannot both be imposed simultaneously in 1+3 dim. But in some dimensions, Majorana–Weyl spinors **do** exist. (see Table 20.3)

n	Dirac spinor	Weyl spinor	Majorana spinor	Majorana-Weyl spinor
1	Yes, $\dim_{\mathbb{R}} = 2$	No	No	No
2	Yes, $\dim_{\mathbb{R}} = 4$	Yes, $\dim_{\mathbb{R}} = 2$	Yes, $\dim_{\mathbb{R}} = 2$	Yes, $\dim_{\mathbb{R}} = 1$
3	Yes, $\dim_{\mathbb{R}} = 4$	No	Yes, $\dim_{\mathbb{R}} = 2$	No
4	Yes, $\dim_{\mathbb{R}} = 8$	Yes, $\dim_{\mathbb{R}} = 4$	Yes, $\dim_{\mathbb{R}} = 4$	No
5	Yes, $\dim_{\mathbb{R}} = 8$	No	No	No
6	Yes, $\dim_{\mathbb{R}} = 16$	Yes, $\dim_{\mathbb{R}} = 8$	No	No
7	Yes, $\dim_{\mathbb{R}} = 16$	No	No	No
8	Yes, $\dim_{\mathbb{R}} = 32$	Yes, $\dim_{\mathbb{R}} = 16$	No	No

Table 20.3: Spinor types in Lorentzian signature $(1, n-1)$ (mostly minus). Note that Majorana-Weyl spinors are possible for $n = 2, 10$ (10%8=2). This is why superstring theories are 10 dimensional.

Chapter 21

Squashed Entanglement: COMING SOON

Chapter 22

Symplectic Groups

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

Throughout this chapter, we will assume that n is even. The **symplectic group** $Sp(n)$ is defined as

$$Sp(n) = \{G \in GL(n, \mathbb{C}) : G^\dagger G = 1, G^T f G = f\} \tag{22.1}$$

where f is the anti-symmetric matrix

$$f = \begin{pmatrix} 0 & I_{n/2} \\ -I_{n/2} & 0 \end{pmatrix} \tag{22.2}$$

Note that

$$f^T = -f, \quad f^T f = I_n, \quad f^2 = -I_n \tag{22.3}$$

f^2 is a primitive invariant matrix because f is, so f^2 must be proportional to the identity.

Claim 67 *If $G \in Sp(n)$, then $det(G) = 1$.*

proof:

Note that

$$\underbrace{det(G^T f G)}_{det^2(G)det(f)} = det(f) \tag{22.4}$$

$$det(f) = det(I_{n/2})det(-I_{n/2}) = (-1)^{n/2} \tag{22.5}$$

Hence,

$$det^2(G) = 1 \implies det(G) = \pm 1 \tag{22.6}$$

$Sp(n)$ is connected, $I_n \in Sp(n)$ and $det(I_n) = 1$. Hence $det(G) = 1$.

QED

Define the **pseudo metric tensor** f_{ab} to be a antisymetric matrix that satisfies:

$$f_{ab} = -f_{ba} = [f]_{ab}, \quad f^{ab} = -f^{ba} = [f]_{ab}, \quad f_a{}^b = f_b{}^a = \delta^b_a \tag{22.7}$$

$$f_{ba}x^a = x_b, \quad (f^T)^{cb}x_b = x^c \quad (\text{so } f_{ba}(f^T)^{cb} = \delta^c_a) \tag{22.8}$$

where $a, b, c \in \{1, 2, \ldots, n\}$ and x_a is any tensor.

$Sp(n)$ leaves invariant the following skew symmetric quadratic form:

$$h(x) = f_{ab}x^a x^b \tag{22.9}$$

where $a, b \in \{1, \ldots, n\}$. Thus

$$h(Gx) = h(x) \tag{22.10}$$

$$f_{ab}G^a{}_{a'}G^b{}_{b'}x^{a'}x^{b'} = f_{a'b'}x^{a'}x^{b'} \implies f_{ab}G^a{}_{a'}G^b{}_{b'} = f_{a'b'} \implies G^T f G = f \tag{22.11}$$

In this chapter (and in this book), we will point the arrows in a birdtrack so that the birdtrack is a DAG. Cycles that make the birdtrack not acyclic will have a segment in red. Without that red segment, the birdtrack becomes acyclic. The reason we follow this arrow convention is that it promotes acyclic birdtracks which are more akin to bnets. We will eschew undirected birdtracks for the same reason: bnets are directed.

Let

$$\boxed{f_a{}^b = \delta^b_a}, \qquad \longleftarrow f \longleftarrow \;=\; \longleftarrow \tag{22.12}$$

$$\boxed{f^a{}_b = \delta^a_b}, \qquad \longrightarrow f \longrightarrow \;=\; \longrightarrow \tag{22.13}$$

$$\boxed{f_{ac}(f^T)^{cb} = \delta^b_a} \qquad \longleftarrow \underline{f} \longrightarrow \overline{f}^T \longleftarrow \;=\; \longleftarrow \tag{22.14}$$

Note that we used

$$\underline{f} = [f_{ab}], \quad \overline{f} = [f^{ab}], \quad f^T = -f \tag{22.15}$$

We could write Eq.(22.14) without the overline and underline on f. Those f-decorations are redundant as omitting them would not introduce any ambiguity. However, we will use them because they make spotting errors in the arrow directions easier.

The generators of symplectic groups will be represented by:

$$(T_i)_a{}^b =$$

(22.16)

We will also use

$$(T_i)^a{}_b =$$

$$(T_i)_{ab} =$$

$$(T_i)^{ab} =$$

(22.17)

For $G \in Sp(n)$, $f^T G^T f G = 1$ with $G = e^{iT_i\epsilon_i}$ where $\epsilon_i \in \mathbb{R}$. Hence, the generators T_i must satisfy

$$\underbrace{f^T T_i^T f}_{(f^T T_i f)^T} = -T_i \implies T_i^T = f T_i f \implies (T_i f)^T = T_i f \tag{22.18}$$

$$\boxed{(T_i f)_{ab} = (T_i f)_{ba}}$$

$=$

(22.19)

$f^b_a = \delta^b_a$ is obviously an invariant matrix. f_{ab} must be invariant too, so

$$\boxed{\underbrace{(T_i)_a{}^c f_{cb} + (T_i)_b{}^c f_{ac} = 0}_{(T_i f)_{ab} = (T_i f)_{ba}}}$$

(22.20)

Hence, the invariance condition Eq.(22.20) reduces to to the statement that $(T_i f)_{ab}$ is symmetric.

The anti-symmetrizer $\mathcal{A}_2$ is an invariant tensor (see Section 23.3). Other projectors of the $V \otimes V$ are not invariant tensors. Therefore, we must have

(22.21)

For $SO(n)$ and $O(n)$, the dimension N of the adjoint rep (= number of generators) is

$$N = \frac{n(n-1)}{2} =$$ (22.22)

If you take an $n \times n$ matrix and remove its diagonal, this N is the number of entries in the upper (or lower) triangular sector of the matrix. Recall that for $U(n)$, $N = n^2$, and for $SU(n)$, $N = n^2 - 1$. So for $U(n)$ (or $SU(n)$), there is a generator for each entry (or each entry minus one) of an $n \times n$ matrix.

Claim 68

$$\boxed{\Gamma_{fun}\delta^b_a = \sum_i (T_iT_i)_a{}^b = \frac{n-1}{2}\delta^b_a}$$

$\sum_i$

(22.23)

proof:

$(T_iT_i)_a{}^b =$

(22.24)

$=$

(22.25)

$=$

(22.26)

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

(22.27)

QED

22.1 $V_{def} \otimes V_{def}$ Decomposition

Define

$M_{ab}{}^{cd} =$

(22.28)

Note that M is antisymmetric:

$\mathcal{A}_2 M =$ (22.29)

$= \frac{1}{2}\Big[$ $-$ $\Big]$ (22.30)

$= M$ (22.31)

Since M is ant-symmetric, only the anti-symmetric space decomposes.

Note also that

$$M^2 = nM \tag{22.32}$$

Hence, $(M-n)M = 0$ so M has two eigenvalues $\lambda = 0, n$.

Next we will use the following equation from Chapter 18 [1] to obtain a projection (PO) operator for each eigenvalue

$$P_i = \sum_{j \neq i} \frac{M - \lambda_j}{\lambda_i - \lambda_j} \tag{22.33}$$

Below, we use the following traces to evaluate the traces of our projection operators

$\mathrm{tr}(M) =$ $= \mathrm{tr}(\underline{f}\overline{f}^T) = n$ (22.34)

$\mathrm{tr}(\mathcal{A}_2) = \frac{1}{2}\Big[$ $-$ $\Big]$ (22.35)

$= \frac{1}{2}(n^2 - n) = \frac{1}{2}n(n-1)$ (22.36)

$\mathrm{tr}(\mathcal{S}_2) = \frac{1}{2}\Big[$ $+$ $\Big]$ (22.37)

$= \frac{1}{2}(n^2 + n) = \frac{1}{2}n(n+1)$ (22.38)

[1] Note that this equation projects to zero all eigenvalues except one.

1. Singlet (Anti-symmetric $\mathcal{A}_2 P_S = 0$) PO

$$P_S = \frac{1}{n}\underline{f}_{ab}(\overline{f}^T)^{cd} = \frac{1}{n}$$

(22.39)

$$\mathrm{tr}(P_S) = \frac{1}{n}\mathrm{tr}(M) = 1 \tag{22.40}$$

2. Traceless Anti-symmetric PO[2]

$$P_{TA} = \frac{1}{2}(\delta_a{}^d\delta_b{}^c - \delta_b{}^d\delta_a{}^c) - \frac{1}{n}\underline{f}_{ab}(\overline{f}^T)^{cd} \tag{22.41}$$

$$=$$

$$-\frac{1}{n}$$

(22.42)

$$\mathrm{tr}(P_{TA}) = \frac{1}{2}(n^2 - n - 2) = \frac{1}{2}(n+1)(n-2) \tag{22.43}$$

3. Symmetric PO

$$P_{SYM} = \frac{1}{2}(\delta_a{}^d\delta_b{}^c + \delta_b{}^d\delta_a{}^c) \tag{22.44}$$

$$=$$

(22.45)

$$\mathrm{tr}(P_{SYM}) = \frac{1}{2}(n^2 + n) = \frac{1}{2}n(n+1) \tag{22.46}$$

Clearly,

$$P_{SYM}^2 = P_{SYM}, \quad P_S^2 = P_S \tag{22.47}$$

[2]Traceless here refers to $P_a{}^a{}_c{}^d V_d{}^c = (PV)_a{}^a = 0$ for any vector $V_d{}^c$. It does not refer to $P_a{}^b{}_b{}^a = 0$

Note that

$$P_{TA}P_S = (\mathcal{A}_2 - P_S)P_S = P_S - P_S = 0 \tag{22.48}$$

Hence

$$P_{TA}^2 = (\mathcal{A}_2 - P_S)^2 = P_{TA} \tag{22.49}$$

P_{SYM} is the only of the 3 POs (P_{SYM}, P_S, P_{TA}) that is an invariant tensor so

(22.50)

Claim 69 *The Clebsch-Gordan series for $V \otimes V$ (i.e., decomposition of $V \otimes V$) is*

(22.51)

The projection operator tree is

proof:
QED

Chapter 23

Symmetrization and Antisymmetrization

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

As preparation for this chapter, read Sec.A.14.

23.1 Symmetrizer

The set of permutations of 2 elements can be represented by the following $2! = 2$ birdtracks.

$$\mathbb{1}_{a_1,a_2}{}^{b_2,b_1} = \delta^{b_1}_{a_1}\delta^{b_2}_{a_2} = \begin{array}{ccccc} a_1 & \leftarrow & \bullet & \leftarrow & b_1 \\ & & & & \\ a_2 & \leftarrow & \bullet & \leftarrow & b_2 \end{array} \tag{23.1}$$

$$\left(\sigma_{(1,2)}\right)_{a_1,a_2}{}^{b_2,b_1} = \delta^{b_2}_{a_1}\delta^{b_1}_{a_2} = \begin{array}{ccccc} a_1 & \leftarrow & \bullet & \leftarrow & b_1 \\ & & \updownarrow & & \\ a_2 & \leftarrow & \bullet & \leftarrow & b_2 \end{array} \tag{23.2}$$

The vertical double headed arrow is called a **swap**. It moves an upstairs particle downstairs and a downstairs particle upstairs.

The set of values that a_i and b_i can assume can be anything, as long as, for some set V, $val(\underline{a}_i) = val(\underline{b}_i) = V$ for all i and $|V| = n$.

The set of permutations of 3 elements can be represented by the following $3! = 6$ birdtracks:

$$\mathbb{1} = \begin{array}{ccccc} a_1 & \longleftarrow & \bullet & \longleftarrow & b_1 \\ & & & & \\ a_2 & \longleftarrow & \bullet & \longleftarrow & b_2 \\ & & & & \\ a_3 & \longleftarrow & \bullet & \longleftarrow & b_3 \end{array} \tag{23.3}$$

$$\sigma_{(1,2)} = \quad \sigma_{(2,3)} = \quad \sigma_{(1,3)} = \tag{23.4}$$

$$\sigma_{(1,2,3)} = \quad = \tag{23.5}$$

$$\sigma_{(1,3,2)} = \quad = \tag{23.6}$$

Note that

$$\boxed{(c,a) = (b,c)(b,a)(b,c)} \tag{23.7}$$

The p**-element symmetrizer** $\mathcal{S}_p$ is defined as the birdtrack

(23.8)

Note that $\mathcal{S}_p$ satisfies the following identities:

$$\boxed{\mathcal{S}_p^2 = \mathcal{S}_p} \tag{23.9}$$

$\mathcal{S}_p\mathcal{S}_{[1,q]} = \mathcal{S}_p$

(23.10)

$\mathcal{S}_p\sigma_{(1,2)} = \mathcal{S}_p$

(23.11)

Claim 70

(23.12)

proof:

We only prove it for $p = 3$.

(23.13)

(23.14)

(23.15)

(23.16)

QED

Tracing over the identity of Claim 70, we get

(23.17)

(23.18)

Hence

$$\mathrm{tr}_{\underline{a}_1}\mathcal{S}_p = \frac{n+p-1}{p}\mathcal{S}_{p-1} \tag{23.19}$$

$$\mathrm{tr}_{\underline{a}_1,\underline{a}_2,\ldots,\underline{a}_k}\mathcal{S}_p = \frac{(n+p-1)(n+p-2)\ldots(n+p-k)}{p(p-1)\ldots(p-k+1)}\mathcal{S}_{p-k} \tag{23.20}$$

$$d_{\mathcal{S}_p} = \mathrm{tr}_{\underline{a}^p}\mathcal{S}_p = \frac{(n+p-1)!}{p!(n-1)!} = \binom{n+p-1}{p} \tag{23.21}$$

For $p = 2$,

$$d_{\mathcal{S}_2} = \frac{(n+1)n}{2} \tag{23.22}$$

23.2 Antisymmetrizer

The p**-element antisymmetrizer** $\mathcal{A}_p$ is defined as the birdtrack

(23.23)

Note that

$$\mathcal{A}_p = 0 \text{ if } n < p \tag{23.24}$$

because when $n < p$, there must be two lines with the same value emerging from $\mathcal{A}_p x$, so $-\mathcal{A}_p x = \mathcal{A}_p x = 0$. For example, for $n = 2$ and $p = 3$

(23.25)

$$\mathcal{A}_3|a,a,b\rangle = \frac{1}{6}\left(\begin{array}{l} |a,a,b\rangle + |a,b,a\rangle + |b,a,a\rangle \\ -|a,b,a\rangle - |a,a,b\rangle - |b,a,a\rangle \end{array}\right) \tag{23.26}$$

$$= 0 \tag{23.27}$$

Note that $\mathcal{A}_p$ satisfies the following identities:

$\mathcal{A}_p^2 = \mathcal{A}_p$

(23.28)

$\mathcal{A}_p\mathcal{A}_{[1,q]} = \mathcal{A}_p$

(23.29)

$\mathcal{A}_p\sigma_{(1,2)} = -\mathcal{A}_p$

(23.30)

$\mathcal{S}_p\mathcal{A}_q = \mathcal{A}_p\mathcal{S}_q = 0$

(23.31)

$\mathcal{S}_p\mathcal{A}_{[1,q]} = \mathcal{A}_p\mathcal{S}_{[1,q]} = 0$

(23.32)

Claim 71

(23.33)

proof:

We only prove it for $p = 3$.

(23.34)

(23.35)

(23.36)

(23.37)

QED

Tracing over the identity of Claim 71, we get

(23.38)

(23.39)

Hence,

$$\mathrm{tr}_{\underline{a}_1} \mathcal{A}_p = \frac{n-p+1}{p} \mathcal{A}_{p-1} \tag{23.40}$$

$$\mathrm{tr}_{\underline{a}_1, \underline{a}_2, \ldots, \underline{a}_k} \mathcal{A}_p = \frac{(n-p+1)(n-p+2)\ldots(n-p+k)}{p(p-1)\ldots(p-k+1)} \mathcal{A}_{p-k} \tag{23.41}$$

$$d_{\mathcal{A}_p} = \mathrm{tr}_{\underline{a}^p} \mathcal{A}_p = \frac{\prod_{i=n}^{n-p+1} i}{p!} \tag{23.42}$$

$$= \begin{cases} \frac{n!}{p!(n-p)!} = \binom{n}{p} & \text{if } p \leq n \\ 0 & \text{otherwise} \end{cases} \tag{23.43}$$

For $p = 2 \leq n$,

$$d_{\mathcal{A}_2} = \binom{n}{2} \tag{23.44}$$

23.3 Invariance of $\mathcal{S}_p$ and $\mathcal{A}_p$

The Kronecker delta is obviously always an invariant matrix because

$$= 0 \tag{23.45}$$

An immediate consequence of the the invariance of the Kronecker delta is that the symmetrizer $\mathcal{S}_p$ and anti-symmetrizer $\mathcal{A}_p$ are tensor invariants too. Indeed,

$$= 0 \tag{23.46}$$

$$= 0 \tag{23.47}$$

23.4 Levi-Civita Tensor

The **Levi-Civita tensor** $\epsilon_{a^{:p}}$ where $a_i \in \{1, 2, \ldots, p\}$ equals $+1$ (resp., -1) if $a^{:p}$ is an even (resp., odd) permutation of $(1, 2, \ldots, p)$. Thus

$$\epsilon_{123} = \epsilon^{123} = 1 \tag{23.48}$$

$$\epsilon_{213} = \epsilon^{213} = -1 \tag{23.49}$$

More generally,

$$\epsilon^{123\ldots p} = \epsilon_{123\ldots p} = 1 \tag{23.50}$$

and

$$\epsilon_{rev(a^{:p})} = (-1)^{\binom{p}{2}} \epsilon_{a^{:p}} \tag{23.51}$$

Define

$$(C_{\mathcal{A}_p})^1_{a^{:p}} = \frac{\epsilon_{a^{:p}}}{\sqrt{p!}} = \tag{23.52}$$

and

$$(C^\dagger_{\mathcal{A}_p})^{rev(a^{:p})}_1 = \frac{\epsilon^{rev(a^{:p})}}{\sqrt{p!}} = \tag{23.53}$$

Then

$$\frac{1}{p!}\epsilon_{a^{:p}}\epsilon^{rev(b^{:p})} = (\mathcal{A}_p)_{a^{:p}}{}^{rev(b^{:p})}$$

(23.54)

and

$$\boxed{e^{i2\phi}\frac{1}{p!}\epsilon^{rev(a^{\cdot n})}\epsilon_{a^{\cdot n}} = 1}$$

$e^{i2\phi}$

$= 1$ (23.55)

For the FL Convention, we will use $\phi = 0$.
For the CC Convention, we must choose

$$e^{i2\phi} = (-1)^{\binom{p}{2}} = e^{i\pi\frac{p(p-1)}{2}} \tag{23.56}$$

so

$$\phi = \frac{\pi}{4}p(p-1) \tag{23.57}$$

23.5 Fully-symmetric and Fully-antisymmetric Tensors

A **fully symmetric (FS) tensor** d

$d_{a_1a_2\ldots a_p} =$

(23.58)

is a tensor that satisfies

$$\boxed{\mathcal{S}_p d = d}$$

(23.59)

If d is a tensor invariant (see Chapter 8), it must satisfy

$0 =$

(23.60)

$0 =$

(23.61)

A **fully antisymmetric(FA) tensor** f

$f_{a_1 a_2 \ldots a_p} =$

(23.62)

is a tensor that satisfies

$\mathcal{A}_p f = f$

(23.63)

If f is a tensor invariant (see Chapter 8), it must satisfy

$0 =$

(23.64)

$0 =$

(23.65)

23.6 Identically Vanishing Birdtracks

Identically vanishing (IV) birdtracks are birdtracks that vanish by virtue of their symmetrized or antisymmetrized components.

- Example of birdtrack that vanishes for any FA tensor f

$$= 0 \qquad \text{(Kuratowsky graph)} \tag{23.66}$$

- Example of birdtrack that vanishes for any f that is a structure constant of a Lie algebra

$$= 0,$$

$$= 0 \tag{23.67}$$

- Birdtrack that is zero for an irrep

$$= 0,$$

$$= 0 \tag{23.68}$$

Chapter 24

Unitary Groups

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

Let

n-dim General Linear group $GL(n;\mathbb{C}) = \{G \in \mathbb{C}^{n\times n} : det(G) \neq 0\}$

n-dim Special Linear group $SL(n;\mathbb{C}) = \{G \in GL(n;\mathbb{C}) : det(G) = 1\}$

n-dim Unitary group, $U(n) = \{G \in GL(n;\mathbb{C}) : GG^\dagger = G^\dagger G = 1\}$

n-dim Special Unitary group $SU(n) = \{G \in U(n) : det(G) = 1\}$

Chapter 27 on Young Tableaux is closely connected to this chapter.

24.1 $SU(n)$

In $SU(n) \subset \mathbb{C}^{n\times n}$ in the defining rep, we have the quadratic form

$$m(p,q) = (p_b)^* \delta^a_b q_a \tag{24.1}$$

Let

$$\mathbb{1}_d{}^a{}_b{}^c = \delta^a_b \delta^c_d = \tag{24.2}$$

and

$$M^d{}_a{}^b{}_c = \delta^a_d \delta^c_b = \tag{24.3}$$

Note that

$$\boxed{M^2 = nM} \tag{24.4}$$

Hence, $(M-n)M = 0$ so M has two eigenvalues $\lambda = 0, n$.

Next we will use the following equation from Chapter 18 [1] to obtain a projection operator (PO) for each eigenvalue

$$P_i = \sum_{j \neq i} \frac{M - \lambda_j}{\lambda_i - \lambda_j} \tag{24.5}$$

1. Singlet PO ($\lambda_S = 0$)

$$\boxed{P_S = \frac{M-0}{n-0} = \frac{1}{n}M}$$

(24.6)

The singlet projection operator P_S projects the singlet part of a tensor x:

$$P_S x = \frac{1}{n} x^b{}_b \delta^c_a \tag{24.7}$$

P_S has dimension 1:

$$dim(P_S) = \mathrm{tr} P_S = \frac{1}{n}$$

(24.8)

$$= 1 \tag{24.9}$$

2. Adjoint PO

$$\boxed{P_{adj} = \frac{M-n}{0-n} = 1 - \frac{1}{n}M}$$

(24.10)

The adjoint projection operator P_{adj} projects the traceless part of a tensor x

$$P_{adj} x = x^a{}_c - \left(\frac{1}{n} x^b{}_b \delta^c_a \right) \tag{24.11}$$

[1] Note that this equation projects to zero all eigenvalues except one.

The P_{adj} has dimension $n^2 - 1$

$$dim(P_{adj}) = \mathrm{tr} P_{adj} \quad = \quad - \frac{1}{n} \tag{24.12}$$

$$= \quad n^2 - 1 \tag{24.13}$$

We will denote the generators T_i of $SU(n)$ by

$$(T_i)_a{}^b = \tag{24.14}$$

For $G \in U(n)$, $G^\dagger G = 1$ with $G = e^{iT_i \epsilon_i}$ where $\epsilon_i \in \mathbb{R}$. Hence, the generators T_i must be Hermitian

$$T_i^\dagger = T_i \tag{24.15}$$

We will assume that they also satisfy

$$\boxed{\mathrm{tr}(T_i T_j) = \kappa \delta_i^j} \tag{24.16}$$

Usually, we set $\kappa = 1$ and, if necessary, restore the κ's at the end by dimensional analysis. (Replace each T_i in a κ-less equation by $T_i/\sqrt{\kappa}$.)

The adjoint projection operator for $SU(n)$ is

(24.17)

The Lie Algebra commutators for $SU(n)$ are

$$\boxed{T_i T_j - T_j T_i = i f_{ijk} T_k}$$

(24.18)

The structure constants f_{ijk} for $SU(n)$ is a totally antisymmetric tensor. In the CC convention, the first index of f_{ijk} corresponds to the green leg in the birdtracks.[2]

Multiplying Lie Algebra commutator by by T_k and taking the trace, we get

$$\boxed{if_{ijk} = \mathrm{tr}([T_i, T_j]T_k)}$$

(24.19)

One can define a totally symmetric tensor d_{ijk} analogously by

$$\boxed{d_{ijk} = \mathrm{tr}([T_i, T_j]_+T_k)}$$

(24.20)

Claim 72 .

- $\mathrm{tr}([T_i, T_j]T_k)$ *is totally anti-symmetric*

[2]Actually, it doesn't matter which index is taken first. This is explained in Chapter B

- $\mathrm{tr}([T_i, T_j]_+ T_k)$ *is totally symmetric*

in the indices i, j, k

proof:

$$\mathrm{tr}([T_i, T_j]T_k) = -\mathrm{tr}([T_k, T_j]T_i) \tag{24.21}$$

$$\mathrm{tr}([T_i, T_j]T_k) = +\mathrm{tr}([T_k, T_j]_+ T_i) \tag{24.22}$$

QED

Claim 73

$$\boxed{\mathrm{tr}(T_i) = 0} \qquad \text{ } \; = 0 \tag{24.23}$$

proof:

$$0 = P_{adj} P_S = \text{ } \tag{24.24}$$

QED

Claim 74

$$\boxed{\Gamma_{fun}\delta^b_a = \sum_i (T_i T_i)_a{}^b = \frac{n^2-1}{n}\delta^b_a}$$

$$\sum_i \text{ } \tag{24.25}$$

proof:

$$(T_i T_i)_a{}^b = \text{ } \tag{24.26}$$

$$= \text{ } \tag{24.27}$$

$$= \text{ } \tag{24.28}$$

$$= \left(n - \frac{1}{n}\right) \text{ } \tag{24.29}$$

QED

Claim 75

(24.30)

proof:

(24.31)

QED

Claim 76

$$\delta(i,j)\Gamma_{adj} = -f_{imn}f_{jnm} = 2n\delta(i,j)$$

(24.32)

proof:

(24.33)

(24.34)

$$A_1 = \frac{n^2-1}{n}\delta(i,j) \tag{24.35}$$

$$A_2 = -\frac{1}{n}\delta(i,j) \tag{24.36}$$

$$A = 2(A_1 - A_2) = 2n\delta(i,j) \tag{24.37}$$

QED

24.2 Differences Between $U(n)$ and $SU(n)$

1. $SU(n)$

   primitive invariants: Kronecker delta, Levi-Civita tensor

(24.38)

(24.39)

$$= n^2 - 1 \tag{24.40}$$

Since the Levi-Civita tensor is an invariant matrix for $SU(n)$, we must have

(24.41)

2. $U(n)$

   primitive invariants: Kronecker delta

(24.42)

$$dim(P_{adj}) = \mathrm{tr} P_{adj} =$$

(24.43)

$$= n^2$$

(24.44)

24.3 $V_{def} \otimes V_{def}$ Decomposition

Let

$V_{def} = V =$ vector space in defining representation $\{|a\rangle\}_{a=1}^{n}$.

(24.45)

(24.46)

(24.47)

$$dim(\mathcal{S}_2) =$$

(24.48)

$$= \frac{n(n+1)}{2}$$

(24.49)

$$dim(\mathcal{A}_2) =$$

(24.50)

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

(24.51)

The projection operator tree is

24.4 $V_{adj} \otimes V_{def}$ Decomposition

Let

$V_{def} = V =$ vector space in defining representation $\{|a\rangle\}_{a=1}^{n}$.
$V_{adj} =$ vector space in adjoint representation $\{|i\rangle\}_{i=1}^{N}$.
$V_{adj} \otimes V \cong (V \otimes V^{\dagger}) \otimes V$

$e =$

(24.52)

$R =$

(24.53)

$Q =$

(24.54)

Recall that for $SU(n)$, the dimension N of the adjoint rep is

$N = n^2 - 1 =$
(24.55)

For example, for $SU(2)$, $N = 3$ and for $SU(3)$, $N = 8$.

Note that

$\mathrm{tr}(e) =$ $= Nn$
(24.56)

$\mathrm{tr}(R) =$

$= N$
(24.57)

$\mathrm{tr}(Q) =$

$= N$
(24.58)

Claim 77

$$R^2 = \frac{n^2 - 1}{n} R \tag{24.59}$$

$$QR = RQ = -\frac{1}{n} R \tag{24.60}$$

$$Q^2 - e = -\frac{1}{n}R \tag{24.61}$$

proof:

$R^2 \;=$

(24.62)

$$= \frac{n^2-1}{n}R \quad \text{(by Eq.(24.25))} \tag{24.63}$$

$QR \;=$

(24.64)

Define

$X =$

(24.65)

$X \;=$

(24.66)

$=$

(24.67)

$= -\frac{1}{n}$

(24.68)

so

$$QR = RQ = -\frac{1}{n}R \tag{24.69}$$

$Q^2 =$

(24.70)

$=$

(24.71)

$=$

(24.72)

$=$

(24.73)

$$= e - \frac{1}{n}R \tag{24.74}$$

QED

Claim 78

$$P_1 = \frac{n}{n^2-1}R \tag{24.75}$$

$$P_2 = \frac{1}{2}P_4(1+Q) = \frac{1}{2}\left[e + Q - \frac{1}{n+1}R\right] \tag{24.76}$$

$$P_3 = \frac{1}{2}P_4(1-Q) = \frac{1}{2}\left[e - Q - \frac{1}{n-1}R\right] \tag{24.77}$$

$$P_4 = 1 - P_1 \tag{24.78}$$

are projectors for $SU(n)$. The $V_{adj} \otimes V = \sum_\lambda V_\lambda$ Clebsch-Gordan series is given by

(24.79)

$$
\begin{array}{ccccccc}
(n^2-1)n & = & n & + & \frac{n(n-1)(n+2)}{2} & + & \frac{n(n+1)(n-2)}{2} \\
SU(3):8(3) & = & 3 & + & 15 & + & 6
\end{array}
$$

The projection operator tree is

proof:

$$\mathrm{tr}(P_1) = \frac{n}{n^2-1}N = n \tag{24.80}$$

$$\begin{aligned}
\mathrm{tr}(P_2) &= \frac{N}{2}\left(n+1-\frac{1}{n+1}\right) && (24.81)\\
&= \frac{N}{2}\frac{n^2+2n}{n+1} && (24.82)\\
&= \frac{N}{2}\frac{n(n+2)}{n+1} && (24.83)\\
&= \frac{(n-1)n(n+2)}{2} && (24.84)
\end{aligned}$$

$$\begin{aligned}
\mathrm{tr}(P_3) &= \frac{N}{2}\left(n-1-\frac{1}{n-1}\right) && (24.85)\\
&= \frac{N}{2}\frac{n^2-2n}{n-1} && (24.86)\\
&= \frac{N}{2}\frac{n(n-2)}{n-1} && (24.87)\\
&= \frac{(n+1)n(n-2)}{2} && (24.88)
\end{aligned}$$

From $R^2 = \frac{n^2-1}{n}R$,

$$P_1 = \frac{n}{n^2-1}R \tag{24.89}$$

Define

$$P_4 = e - P_1 \tag{24.90}$$

From $Q^2 - e = -\frac{1}{n}R$, we get

$$P_4(Q^2-1) = 0 \tag{24.91}$$

Let

$$P_2 = \frac{1}{2}P_4(1+Q), \quad P_3 = \frac{1}{2}P_4(1-Q) \tag{24.92}$$

and

$$a = \frac{n}{n^2-1} \tag{24.93}$$

Then

$$\begin{aligned}
P_2 &= \frac{1}{2}P_4(1+Q) && (24.94)\\
&= \frac{1}{2}(e-aR)(1+Q) && (24.95)\\
&= \frac{1}{2}(e-aR+Q-aRQ) && (24.96)\\
&= \frac{1}{2}\left(e+\left(\frac{1}{n}-1\right)aR+Q\right) \quad (\text{use } QR = -\frac{1}{n}R) && (24.97)
\end{aligned}$$

where

$$\begin{aligned}
\left(\frac{1}{n}-1\right)a &= \frac{1-n}{n}\frac{n}{n^2-1} && (24.98)\\
&= -\frac{1}{n+1} && (24.99)
\end{aligned}$$

Furthermore

$$\begin{aligned}
P_3 &= \frac{1}{2}P_4(1-Q) && (24.100)\\
&= \frac{1}{2}(e-aR)(1-Q) && (24.101)\\
&= \frac{1}{2}(e-aR-Q+aRQ) && (24.102)\\
&= \frac{1}{2}\left(e-\left(\frac{1}{n}+1\right)aR-Q\right) \quad (\text{use } QR = -\frac{1}{n}R) && (24.103)
\end{aligned}$$

where

$$\left(\frac{1}{n}+1\right)a=\frac{1}{n-1} \tag{24.104}$$

QED

Let $Q_1, Q_2, Q_3 = e, R, Q$

$$Q_\lambda|Q_j\rangle = |Q_\lambda Q_j\rangle = \sum_i A^\lambda_{ij}|Q_i\rangle \tag{24.105}$$

$$\langle Q_i|Q_\lambda|Q_j\rangle = A^\lambda_{ij} \tag{24.106}$$

If A^λ are diagonalized and divided by their eigenvalues, and they have a single non-zero eigenvalue, then they become a complete set of projectors with 1 or 0 along their diagonals.

Chapter 25

Weight Diagrams

This chapter is based on Refs. [2] and [4].

In this chapter, we will study irreps of semi-simple Lie algebras, paying special attention to $\mathfrak{su}(2)$ and $\mathfrak{su}(3)$. Suppose $\mathfrak{g}$ is the Lie algebra of a group G. Note that an irrep of G always gives an irrep of $\mathfrak{g}$, but an irrep of $\mathfrak{g}$ might not give an irrep of G. Suppose groups G_1 and G_2 with different global topology both have Lie algebra $\mathfrak{g}$. Some irreps of $\mathfrak{g}$ might lead to irreps of G_1 but not of G_2. For example, $SO(3)$ and $SU(2)$ have the same Lie algebra $\mathfrak{su}(2)$. $\mathfrak{su}(2)$ has irreps with integral and half integral spin. But only the ones with integral spin are irreps of $SO(3)$. Luckily, for $SU(n)$, which is the group that most cooncerns us in this chapter, all irreps of $\mathfrak{su}(n)$ are irreps of $SU(n)$ too.

In Chapter 5, we classified semi-simple Lie algebras in terms of their Dynkin diagrams. The Dynkin diagram of a Lie algebra $\mathfrak{g}$ describes its set of root vectors. An irrep of $\mathfrak{g}$ is described by a set of weight vectors. Both **root vectors** and **weight vectors** satisfy an eigenvalue equation, namely

$$\begin{aligned} \text{root } \vec{\alpha}: &\quad \overbrace{[\vec{H}, E_{\vec{\alpha}}]}^{[\vec{H},\,\cdot\,]E_{\vec{\alpha}}} = \vec{\alpha} E_{\vec{\alpha}} \\ \text{weight } \vec{m}: &\quad \vec{H}|j, \vec{m}\rangle = \vec{m}|j, \vec{m}\rangle \end{aligned} \tag{25.1}$$

$\vec{\alpha}, \vec{m} \in \mathbb{R}^r$ where r is the rank of the Lie algebra.

$|1\rangle, |2\rangle, \ldots, |n\rangle \in \mathbb{R}^n$ and $H_i, E_{\vec{\alpha}} \in \mathbb{R}^{n\times n}$ where n is the dimension of the fundamental rep of the Lie algebra $\mathfrak{su}(n)$

$|j, \vec{m}\rangle \in \mathbb{C}^d$ where d is the dimension of the irrep.

The set of weight vectors of an irrep of a Lie algebra will be called the **Weight Diagram (WD)** of the irrep.

Claim 79 *If*

$$\vec{H}|\vec{m}\rangle = \vec{m}|\vec{m}\rangle \tag{25.2}$$

then

$$\vec{H} E_{\vec{\alpha}}|\vec{m}\rangle = (\vec{m} + \vec{\alpha}) E_{\vec{\alpha}}|\vec{m}\rangle \tag{25.3}$$

Figure 25.1: Relationship between 2 weights $\vec{m}$ and $\vec{m}'$.

proof:

$$[\vec{H}, E_{\vec{\alpha}}] = \vec{\alpha} E_{\vec{\alpha}} \tag{25.4}$$

so

$$\begin{aligned} \vec{H} E_{\vec{\alpha}} |\vec{m}\rangle &= E_{\vec{\alpha}} \vec{H} |\vec{m}\rangle + \vec{\alpha} E_{\vec{\alpha}} |\vec{m}\rangle & (25.5) \\ &= (\vec{m} + \vec{\alpha}) E_{\vec{\alpha}} |\vec{m}\rangle & (25.6) \end{aligned}$$

QED

Claim 80 *See Fig.25.1. For any weight $\vec{m}$ and root $\vec{\alpha}$, if k is an integer and*

$$k = -\frac{2\vec{m}\cdot\vec{\alpha}}{\vec{\alpha}\cdot\vec{\alpha}} \tag{25.7}$$

then

$$\vec{m}' = \vec{m} + k\vec{\alpha} \tag{25.8}$$

is a weight with the same eigenvalue multiplicity as $\vec{m}$.

proof:
QED

25.1 $SU(2)$ Weight Diagrams

In this section, we describe the WDs for $SU(2)$. These follow from the theory of angular momentum in Quantum Mechanics.

Define

$$|1\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad |2\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{25.9}$$

$$\sqrt{2} E_{12} = J_+ = |1\rangle\langle 2|, \quad \sqrt{2} E_{-12} = E_{21} = J_- = |2\rangle\langle 1| \tag{25.10}$$

$$J_z = \frac{1}{2}\left(|1\rangle\langle 1| - |2\rangle\langle 2|\right) \tag{25.11}$$

Then

$$\begin{tikzcd} & J_z \arrow[dl, "-J_-"'] \arrow[dr, "J_+"] & \\ J_- & & J_+ \arrow[ll, "2J_z"] \end{tikzcd} \qquad \begin{cases} [J_+, J_-] = 2J_z \\ [J_z, J_+] = J_+ \\ [J_z, J_-] = -J_- \end{cases} \tag{25.12}$$

The WD for irrep j, where[1]

$$J = j \in \left\{0, \frac{1}{2}, 1, \frac{3}{2}, \ldots\right\} \tag{25.13}$$

has weights m, where

$$J_z = j_z = m = \{-j, -j+1, \ldots, j-1, j\} \tag{25.14}$$

$|j, m\rangle$ is the basis vector of irrep j with weight m.

25.2 $SU(3)$ Weight Diagrams

In this section, we describe the WDs for $SU(3)$. These occur in particle physics, when describing particles by their quark constituents.

Define

$$|1\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad |2\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad |3\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \tag{25.15}$$

$$\sqrt{3}E_{12} = T_+ = |1\rangle\langle 2|, \quad \sqrt{3}E_{-12} = E_{21} = T_- = |2\rangle\langle 1| \tag{25.16}$$

$$\sqrt{3}E_{23} = U_+ = |2\rangle\langle 3|, \quad \sqrt{3}E_{-23} = E_{32} = U_- = |3\rangle\langle 2| \tag{25.17}$$

$$\sqrt{3}E_{31} = V_+ = |3\rangle\langle 1|, \quad \sqrt{3}E_{-31} = E_{13} = V_- = |1\rangle\langle 3| \tag{25.18}$$

$$T_z = \frac{1}{2}\left(|1\rangle\langle 1| - |2\rangle\langle 2|\right), \quad U_z = \frac{1}{2}\left(|2\rangle\langle 2| - |3\rangle\langle 3|\right), \quad V_z = \frac{1}{2}\left(|3\rangle\langle 3| - |1\rangle\langle 1|\right) \tag{25.19}$$

$$\sqrt{\frac{3}{2}}H_1 = T_z, \quad \sqrt{2}H_2 = Y = \frac{2}{3}\left(U_z - V_z\right) \tag{25.20}$$

[1]Whenever possible, we will follow the convention of denoting operators by upper case letters and their eigenvalues by the same letter in lower case. For example, the eigenvalues of J, J_z will be denoted by j, j_z.

isospin $T_z \in \mathbb{Z}/2 = 0, \pm\frac{1}{2}, \pm 1, \pm\frac{3}{2}, \pm 2, \ldots$
hypercharge $Y \in \mathbb{Z}/3$
$H_1 \in \frac{1}{\sqrt{6}}\mathbb{Z}$
$H_2 \in \frac{1}{3\sqrt{2}}\mathbb{Z}$

Figure 25.2: $|1\rangle, |2\rangle, |3\rangle$ vectors, and operators that act on them. $E_{-ij} = E_{ji}$ is in opposite direction as E_{ij} for $i \neq j$ and $i, j = 1, 2, 3$.

Fig.25.2 illustrates the states $|1\rangle, |2\rangle, |3\rangle$, and operators E_{ij} that act on them. We can derive the weights of the fundamental rep of $\mathfrak{su}(3)$ as follows.

$$\begin{pmatrix} \sqrt{\frac{3}{2}}H_1 \\ \sqrt{2}H_2 \end{pmatrix} |1\rangle = \begin{pmatrix} T_z \\ Y \end{pmatrix} |1\rangle = \begin{pmatrix} \frac{1}{2} \\ \frac{1}{3} \end{pmatrix} |1\rangle = \vec{m}(1)|1\rangle \tag{25.21}$$

$$\begin{pmatrix} \sqrt{\frac{3}{2}}H_1 \\ \sqrt{2}H_2 \end{pmatrix} |2\rangle = \begin{pmatrix} T_z \\ Y \end{pmatrix} |2\rangle = \begin{pmatrix} -\frac{1}{2} \\ \frac{1}{3} \end{pmatrix} |2\rangle = \vec{m}(2)|2\rangle \tag{25.22}$$

$$\begin{pmatrix} \sqrt{\frac{3}{2}}H_1 \\ \sqrt{2}H_2 \end{pmatrix} |3\rangle = \begin{pmatrix} T_z \\ Y \end{pmatrix} |3\rangle = \begin{pmatrix} 0 \\ -\frac{2}{3} \end{pmatrix} |3\rangle = \vec{m}(3)|3\rangle \tag{25.23}$$

Fig.25.3 shows the root vectors for $\mathfrak{su}(3)$ (derived in Chapter 5) and the weight vectors of the fundamental rep of $\mathfrak{su}(3)$ (just derived). As expected, the difference between any two weight vectors, is k times a root vector.

As shown in Fig.25.4, each of the six root vectors of $\mathfrak{su}(3)$ is associated with a raising operator T_+, U_+, V_+ or a lowering operator T_-, U_-, V_-. In $\mathfrak{su}(2)$ J_+ raises the $J_z = j_z = m$ of a quantum state by 1/2 and J_- lowers it by a 1/2. $T_\pm, U_\pm, V_\pm$ change T_z, U_z, V_z analogously.

25.2.1 Examples

In this section, we give examples of $SU(3)$ WDs.

Figure 25.3: The roots vectors of $\mathfrak{su}(3)$ in green and the weight vectors of the fundamental rep in red.

Figure 25.4: Each of the six root vectors of $\mathfrak{su}(3)$ is associated with a raising operator T_+, U_+, V_+ or a lowering operator T_-, U_-, V_-.

There is a one-to-one map between the the irreps of $\mathfrak{su}(3)$ and the WDs of $\mathfrak{su}(3)$.

The weights on the **boundary of WD** are called **dominant weights**

In a WD, nondegenerate weights are represented by a single dot. k-fold degenerate weights (i.e., eigenvalues with **multiplicity** k) are represented by a dot with $k-1$ rings.

WD are labelled either by

- the dimension d_{rep} of the irrep, with extra labels in case there are multiple irreps with the same dimension,
- the (λ, μ) WD-boundary dimensions. See Fig.25.8

One can show that

$$d_{rep} = \frac{1}{2}(\lambda+1)(\mu+1)(\lambda+\mu+2) \tag{25.24}$$

For example, see Fig.25.5. $\mathfrak{su}(3)$ has 2 fundamental irreps, $\underline{3}$ and $\underline{3}^*$. Both are 3 dimensional. $(\lambda, \mu) = (1, 0)$ for $\underline{3}$, and $(\lambda, \mu) = (0, 1)$ for $\underline{3}^*$. The formula Eq.(25.24) for d_{rep} gives 3 for both.

See the following figures for examples of WDs of $\mathfrak{su}(3)$.

- Fig.25.5 shows $\underline{3}$ and $\underline{3}^*$
- Fig.25.6 shows $\underline{10}$ (decuplet)
- Fig.25.7 shows $\underline{8}$ (octet)
- Fig.25.8 shows $\underline{15}$

An aside about hypercharge

Several different quantum numbers are called hypercharge in particle physics. For example, in the Gell-mann-Nishijima relation

$$Q = T_z + \frac{1}{2}Y' \tag{25.25}$$

hyperchage= $Y' \in \mathbb{Z}$, isospin= $T_z \in \mathbb{Z}/2$, so charge= $Q \in \mathbb{Z}/2$. For example, for nucleons,

$$\text{proton (p)}: \quad T_z = \frac{1}{2}, \quad Y' = 1 \implies Q = 1 \tag{25.26}$$

$$\text{neutron (n)}: \quad T_z = -\frac{1}{2}, \quad Y' = 1 \implies Q = 0 \tag{25.27}$$

As a mnemonic, remember that a nucleon has 3 quarks with $Y = 1/3$, and Y' for the nucleon is the sum of Y for each quark. $Y = 1/3$ for up or down quarks, and $Y = -2/3$ for the strange quark. u, d constitute an $SU(2)$ doublet and s an $SU(2)$ singlet.

Figure 25.5: WDs for the two fundamental irreps of $\mathfrak{su}(3)$, $\underline{3}$ and $\underline{3}^*$. $(\lambda, \mu) = (1, 0)$ for $\underline{3}$, and $(\lambda, \mu) = (0, 1)$ for $\underline{3}^*$.

Figure 25.6: WD for the $\mathfrak{su}(3)$ irrep $\underline{10}$. $(\lambda, \mu) = (3, 0)$.

25.3 Relation between WD and Semi-Standard Young Tableaux

Young Diagrams (YD) and Young Tableaux (YT) are discussed in Chapter 27

Figure 25.7: WD for the $\mathfrak{su}(3)$ irrep $\underline{8}$. $(\lambda, \mu) = (1, 1)$.

Figure 25.8: WD for the $\mathfrak{su}(3)$ irrep $\underline{15}$. $(\lambda, \mu) = (2, 1)$.

Given a YD, its SYT/SSYT (Standard or Semi-Standard YT) satisfies

- Rows strictly/weakly increasing

- Columns strictly increasing
- Entries in $\{1, 2, \ldots, n\}$. $n = 3$ for $SU(3)$

Thus, SYT/SSYT disallow/allow repetitions along a row.

SYT are used, for example, to label the irreps of S_n. Hence, there is a 1-1 relation between Young Symmetrizer operators and SYT.

SSYT are used below to label the basis weight vectors of an irrep of $\mathfrak{su}(n)$. There is a 1-1 relationship between YD and WD, and a 1-1 relationship between the SSYT of a YD and the weights of the corresponding WD. Degenerate weights have different SSYT.

To summarize,

SYTs $\xrightarrow[\text{1 to 1}]{}$ Young operators, SSYTs $\xrightarrow[\text{1 to 1}]{}$ weights of WD

To calculate the isospin, hypercharge (t_z, y) of a SSYT, use the follwing equation

$$(t_z, y) = \sum_{\text{boxes}} \begin{cases} (\frac{1}{2}, \frac{1}{3}), & \text{for each 1 box} \\ (-\frac{1}{2}, \frac{1}{3}), & \text{for each 2 box} \\ (0, -\frac{2}{3}), & \text{for each 3 box} \end{cases} \tag{25.28}$$

Equivalently, if n_i is the number of $i = 1, 2, 3$ boxes in the SSYT, then

$$t_z = \frac{1}{2}(n_1 - n_2) \tag{25.29}$$

$$y = \frac{1}{3}(n_1 + n_2 - 2n_3) \tag{25.30}$$

SU(3) octet example.

An octet ($\underline{8}$, (1,1), Fig.25.7) has the YD

Let

$$\mathcal{Y} = S_{12}A_{13} = [1 + (12)][1 - (13)] \tag{25.31}$$

Then

$$\begin{aligned} |\psi\rangle = \mathcal{Y}|a\rangle|b\rangle|c\rangle &= S_{12}\left(|a\rangle|b\rangle|c\rangle - |c\rangle|b\rangle|a\rangle\right) && (25.32) \\ &= [|a\rangle|b\rangle|c\rangle + |b\rangle|a\rangle|c\rangle] - [|c\rangle|b\rangle|a\rangle + |b\rangle|c\rangle|a\rangle] && (25.33) \end{aligned}$$

The following table gives the SSYT, its (t_z, y) content, and its wavefunction, for each weight of an $SU(3)$ octet. This table's information is conveyed pictorially in Fig.25.9.

1.

$$\begin{array}{|c|c|}\hline 1 & 1 \\ \hline 2 \\ \cline{1-1}\end{array} \;\Big|\; (t_z, y) = \left(+\tfrac{1}{2}, 1\right) \;\Big|\; |\psi\rangle \text{ with } abc \to u_1 u_1 u_2 \tag{25.34}$$

2.

$$\begin{array}{|c|c|}\hline 1 & 2 \\ \hline 2 \\ \cline{1-1}\end{array} \;\Big|\; (t_z, y) = \left(-\tfrac{1}{2}, 1\right) \;\Big|\; |\psi\rangle \text{ with } abc \to u_1 u_2 u_2 \tag{25.35}$$

3.

$$\begin{array}{|c|c|}\hline 1 & 1 \\ \hline 3 \\ \cline{1-1}\end{array} \;\Big|\; (t_z, y) = (+1, 0) \;\Big|\; |\psi\rangle \text{ with } abc \to u_1 u_1 u_3 \tag{25.36}$$

4.

$$\begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 \\ \cline{1-1}\end{array} \;\Big|\; (t_z, y) = (0, 0) \;\Big|\; |\psi\rangle \text{ with } abc \to u_1 u_2 u_3 \tag{25.37}$$

5.

$$\begin{array}{|c|c|}\hline 2 & 2 \\ \hline 3 \\ \cline{1-1}\end{array} \;\Big|\; (t_z, y) = (-1, 0) \;\Big|\; |\psi\rangle \text{ with } abc \to u_2 u_2 u_3 \tag{25.38}$$

6.

$$\begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 \\ \cline{1-1}\end{array} \;\Big|\; (t_z, y) = (0, 0) \;\Big|\; |\psi\rangle \text{ with } abc \to u_1 u_3 u_2 \tag{25.39}$$

7.

$$\begin{array}{|c|c|}\hline 1 & 3 \\ \hline 3 \\ \cline{1-1}\end{array} \;\Big|\; (t_z, y) = \left(+\tfrac{1}{2}, -1\right) \;\Big|\; |\psi\rangle \text{ with } abc \to u_1 u_3 u_3 \tag{25.40}$$

8.

$$\begin{array}{|c|c|}\hline 2 & 3 \\ \hline 3 \\ \cline{1-1}\end{array} \;\Big|\; (t_z, y) = \left(-\tfrac{1}{2}, -1\right) \;\Big|\; |\psi\rangle \text{ with } abc \to u_2 u_3 u_3 \tag{25.41}$$

Figure 25.9: WD for the $SU(3)$ octet with the SSYT for each weight.

Chapter 26

Wigner-Ekart Theorem

This chapter on the Wigner-Ekart (WE) Theorem is based on Cvitanovic's Birdtracks book Ref. [1].

26.1 WE in General

The birdtracks with no incomming or outgoing arrows are know as **reduced matrix elements, isolated DAGs and vacuum bubbles**

The following 3 claims are related. They reduce a tensor with 1, 2 and 3 indices

Claim 81 *(one index)*

If M is an invariant vector (i.e., $G_\lambda(g)M = M$ for all $g \in \mathcal{G}$), then

$$M_a = \sum_\lambda a \leftarrow\!\lambda\!- P_\lambda \leftarrow\!\lambda\!- M \tag{26.1}$$

$$= \sum_{\lambda \in SR} a \leftarrow\!\lambda\!- P_\lambda \leftarrow\!\lambda\!- M \tag{26.2}$$

where $P_\lambda = |\lambda\rangle\langle\lambda| = \mathfrak{C}_\lambda^\dagger \mathfrak{C}_\lambda$ and $SR =$ set of singlet representations.

proof:
QED

Claim 82 *(Schur's Lemma) (2 indices)*

If μ and λ are irreps, and M is an invariant matrix, then

$$M_{\lambda a}{}^{\mu b} = a \leftarrow\!\lambda\!- M \leftarrow\!\mu\!- b \tag{26.3}$$

$$= \frac{1}{d_\mu} \tag{26.4}$$

$$\delta(\mu, \lambda) \leftarrow\!\lambda\!-$$

proof:
QED

Claim 83 *(Wigner-Ekart (WE) Theorem) (3 indices)*
If M is an invariant 3 index tensor,

$$(M^{\lambda i})_{\lambda_2 a}{}^{\lambda_1 b} = \tag{26.5}$$

$$= \sum_{\lambda_2} \frac{d_{\lambda_2}}{\mathfrak{C}^\dagger_{\lambda_2} \xleftarrow{\lambda_2} \mathfrak{C}_{\lambda_2}}$$

(26.6)

$$= \frac{}{\mathfrak{C}^\dagger_{\lambda_2} \xleftarrow{\lambda_2} \mathfrak{C}_{\lambda_2}}$$

λ
λ
λ
λ
λ
λ

$$= \sum_{\alpha,\beta} \frac{1}{\kappa_\alpha \kappa_\beta} \tag{26.9}$$

$$= \sum_{\alpha} \frac{1}{\kappa_\alpha^2 d_\alpha} \tag{26.10}$$

Above, we used

$$= \frac{\delta(\alpha,\beta)}{d_\alpha} \tag{26.11}$$

26.2 WE for Angular Momentum

Let

$\lambda = J$, $\lambda_i = J_i$ for $i = 1, 2$. We will use Greek letters instead of J so as to keep convention of using Greek letters for rep labels.

$m, m' = -\lambda,\ -\lambda+1, \ldots, \lambda-1, \lambda$. Note that $d_\lambda = 2\lambda + 1$

for $i = 1, 2$, $m_i = -\lambda_i, -\lambda_i + 1, \ldots, \lambda_i - 1, \lambda_i$. Note that $d_{\lambda_i} = 2\lambda_i + 1$

Define

$$\langle(\lambda_1\lambda_2)\lambda m|\lambda_1 m_1\lambda_2 m_2\rangle \quad = \quad$$

(26.12)

$$D^\lambda_{mm'}(g) \quad = \quad$$

(26.13)

Then the Clebsch-Gordan decomposition of $D^{\lambda_1} \otimes D^{\lambda_2}$ is

$$D^{\lambda_1}_{m_1 m_1'}(g) D^{\lambda_2}_{m_2 m_2'}(g) = \sum_{\lambda,m,m'} \langle\lambda_1 m_1 \lambda_2 m_2|\lambda_1\lambda_2\lambda m\rangle\, D^\lambda_{mm'}(g)\, \langle\lambda_1\lambda_2\lambda m'|\lambda_1 m_1' \lambda_2 m_2'\rangle$$

(26.14)

We will denote a **tensor operator** M^λ_m by the birdtrack

$$\left\langle\lambda_2 m_2|M^\lambda_m|\lambda_1 m_1\right\rangle =$$

(26.15)

Claim 84 *(Wigner-Ekart for angular momentum)*

$$\left\langle\lambda_2 m_2|M^\lambda_m|\lambda_1 m_1\right\rangle = \langle(\lambda\lambda_1)\lambda_2 m_2|\lambda m\lambda_1 m_1\rangle\, QR$$

(26.16)

where

$$Q(\lambda,\lambda_1,\lambda_2) \quad = \quad \frac{1}{d_{\lambda_2}} \sum_{m_1,m_2,m} \langle\lambda m\lambda_1 m_1|(\lambda\lambda_1)\lambda_2 m_2\rangle \left\langle\lambda_2 m_2|M^\lambda_m|\lambda_1 m_1\right\rangle \quad (26.17)$$

$$= \quad \frac{1}{d_{\lambda_2}}$$

(26.18)

and

$$R(\lambda, \lambda_1, \lambda_2) = \frac{d_{\lambda_2}}{\mathfrak{C}^{\dagger}_{\lambda_2} \overset{\lambda}{\underset{\lambda_1}{\leftrightarrows}} \mathfrak{C}_{\lambda_2}} \tag{26.19}$$

proof:
QED

Chapter 27

Young Tableau

This chapter is based on Cvitanovic's Birdtracks book Ref. [1].

We recommend that the read Chapter 23 on symmetrizers and antisymetrizers before reading this one.

A **Young Diagram** (YD) $\mathcal{Y} = [\lambda_1, \lambda_2, \ldots, \lambda_D]$ consists of λ_1 left-aligned empty boxes (LAEB) over λ_2 LAEB, over λ_3 LAEB, up to λ_{NR} LAEB, where $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_{NR} \geq 1$. $NR =$ number of rows. For example,

$$= [4, 2, 1, 1] \tag{27.1}$$

We will call $[4, 2, 1, 1]$ the **row lengths** (RL) method of labeling YD.

A alternative method of labelling YD is called the **Dynkin (D) labels** or **row changes (RC)**. These labels list the change in number of columns as we go down the YD. For example,

$$= [2, 1, 0, 1, 0 \ldots]_D \tag{27.2}$$

A **Young Tableau** (YT) $\mathcal{Y}_\alpha$ is a YD in which integers from 1 to n where $n \leq n_b$ and n_b is the number boxes, are inserted according to some rules. The rules for insertion are that integers must increase when reading a row left to right and when reading a column from top to bottom. Obviously, for $n < n_b$, some integers are repeated.

A **Standard Young Tableau** (SYT) $\mathcal{Y}_\alpha$ is a YT such that $n = n_b$ and no integer is repeated. Fig.27.1 shows all SYT for $n_b = 1, 2, 3, 4$

- $n_b = 1$

$$\begin{array}{|c|}\hline 1 \\ \hline\end{array}$$

- $n_b = 2$

$$\begin{array}{|c|c|}\hline 1 & 2 \\ \hline\end{array} \qquad \begin{array}{|c|}\hline 1 \\ \hline 2 \\ \hline\end{array}$$

- $n_b = 3$

$$\begin{array}{|c|c|c|}\hline 1 & 2 & 3 \\ \hline\end{array} \qquad \begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 \\ \cline{1-1}\end{array} \qquad \begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 \\ \cline{1-1}\end{array} \qquad \begin{array}{|c|}\hline 1 \\ \hline 2 \\ \hline 3 \\ \hline\end{array}$$

- $n_b = 4$

$$\begin{array}{|c|c|c|c|}\hline 1 & 2 & 3 & 4 \\ \hline\end{array} \qquad \begin{array}{|c|c|c|}\hline 1 & 2 & 3 \\ \hline 4 \\ \cline{1-1}\end{array} \qquad \begin{array}{|c|c|c|}\hline 1 & 2 & 4 \\ \hline 3 \\ \cline{1-1}\end{array} \qquad \begin{array}{|c|c|c|}\hline 1 & 3 & 4 \\ \hline 2 \\ \cline{1-1}\end{array} \qquad \begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 & 4 \\ \hline\end{array}$$

$$\begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 & 4 \\ \hline\end{array} \qquad \begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 \\ \cline{1-1} 4 \\ \cline{1-1}\end{array} \qquad \begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 \\ \cline{1-1} 4 \\ \cline{1-1}\end{array} \qquad \begin{array}{|c|c|}\hline 1 & 4 \\ \hline 2 \\ \cline{1-1} 3 \\ \cline{1-1}\end{array} \qquad \begin{array}{|c|}\hline 1 \\ \hline 2 \\ \hline 3 \\ \hline 4 \\ \hline\end{array}$$

Figure 27.1: All SYT for $n_b = 1, 2, 3, 4$.

We will use $|\mathcal{Y}|$, or $|\mathcal{Y}_\alpha|$ or $|\alpha|$ to denote the number of boxes in a YD or YT.[1]

27.1 Symmetric Group S_{n_b}

Let

S_{n_b} = the symmetric group in n_b letters (or n_b boxes)
$irreps(S_{n_b})$ = the set of all irreps of S_{n_b}.
The **transpose of a YT** is defined as if it were a matrix. For example

$$transpose\left(\begin{array}{|c|c|c|}\hline 1 & 3 & 5 \\ \hline 2 & 6 \\ \cline{1-2} 4 \\ \cline{1-1}\end{array}\right) = \begin{array}{|c|c|c|}\hline 1 & 2 & 4 \\ \hline 3 & 6 \\ \cline{1-2} 5 \\ \cline{1-1}\end{array} \tag{27.3}$$

[1]For many authors and for us too, $|S|$ stands for the number of elements in a finite set S. This should not lead to confusion as a YD or YT are not sets.

n-dim General Linear group $GL(n;\mathbb{C}) = \{G \in \mathbb{C}^{n\times n} : det(G) \neq 0\}$
n-dim Special Linear group $SL(n;\mathbb{C}) = \{G \in GL(n;\mathbb{C}) : det(G) = 1\}$
n-dim Unitary group, $U(n) = \{G \in GL(n;\mathbb{C}) : GG^\dagger = G^\dagger G = 1\}$
n-dim Special Unitary group $SU(n) = \{G \in U(n) : det(G) = 1\}$
$YD(n_b)$ = set of YD with n_b boxes. $YD = \cup_{n_n=1}^{\infty} YD(n_b)$.
$SYD(n_b)$ = set of SYD with n_b boxes. $YT = \cup_{n_b=1}^{\infty} YT(n_b)$.
$SYT(n_b, NR)$ = set of STY with n_b boxes and NR rows.
$YT(\mathcal{Y})$ = set of YT with a YD $\mathcal{Y}$.
$SYT(\mathcal{Y})$ = set of SYT with a YD $\mathcal{Y}$.
$dim(\mathcal{Y}|S_{n_b})$ = dimension of irrep $\mathcal{Y}$ of S_{n_b}
$dim(\mathcal{Y}_\alpha|U(n))$ = dimension of irrep $\mathcal{Y}_\alpha$ of $U(n)$ or $SU(n)$.

Claim 85

1. *The YD with n_b boxes label all irreps of the symmetric group S_{n_b}.*

$$irreps(S_{n_b}) = YD(n_b) \tag{27.4}$$

2. *The SYT with n_b boxes and no more than n rows ($NR \leq n$), label the irreps of $GL(n)$ and of $U(n)$*

$$irreps(U(n)) = \bigcup_{n_b\leq n,\ NR\leq n} STY(n_b, NR) \tag{27.5}$$

3. *The SYT with n_b boxes and no more than $n-1$ rows ($NR \leq n-1$), label the irreps of $SL(n)$ and $SU(n)$.*

$$irreps(SU(n)) = \bigcup_{n_b\leq n,\ NR\leq n-1} STY(n_b, NR) \tag{27.6}$$

proof:
QED

27.1.1 $dim(\mathcal{Y}|S_{n_b})$

Claim 86

$$dim(\mathcal{Y}|S_{n_b}) = |SYT(\mathcal{Y})| \tag{27.7}$$

proof:
QED

For example, there are 3 irreps of S_4 associated withe the YD

$$\mathcal{Y} = \begin{array}{|c|c|}\hline & \\ \hline \\ \cline{1-1} \\ \cline{1-1}\end{array} \tag{27.8}$$

And each of those 3 irreps has dimension 3. Why? Because there are 3 possible SYT for this YD:

$$\begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 \\ \cline{1-1} 4 \\ \cline{1-1}\end{array}, \quad \begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 \\ \cline{1-1} 4 \\ \cline{1-1}\end{array}, \quad \begin{array}{|c|c|}\hline 1 & 4 \\ \hline 2 \\ \cline{1-1} 3 \\ \cline{1-1}\end{array} \implies dim(\mathcal{Y}|S_4) = 3 \tag{27.9}$$

Thus, we can denote the basis vectors of one of these 3 degenerate irreps by

$$|\begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 \\ \cline{1-1} 4 \\ \cline{1-1}\end{array}\rangle, \quad |\begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 \\ \cline{1-1} 4 \\ \cline{1-1}\end{array}\rangle, \quad |\begin{array}{|c|c|}\hline 1 & 4 \\ \hline 2 \\ \cline{1-1} 3 \\ \cline{1-1}\end{array}\rangle \tag{27.10}$$

To compute $hook(\mathcal{Y})$:

1. Fill each box of the YD with the number of boxes below and to the right of the box, including the box itself.
2. Multiply the numbers in all the boxes.

For example,

$$\mathcal{Y} = \begin{array}{|c|c|c|c|}\hline & & & \\ \hline & & \\ \cline{1-3} & \\ \cline{1-2}\end{array} \implies hook(\mathcal{Y}) = \begin{array}{|c|c|c|c|}\hline 6 & 5 & 3 & 1 \\ \hline 4 & 3 & 1 \\ \cline{1-3} 2 & 1 \\ \cline{1-2}\end{array} = 6!3 \tag{27.11}$$

Claim 87 *(***hook rule** *for computing $dim(\mathcal{Y}|S_{n_b})$)*

$$dim(\mathcal{Y}|S_{n_b}) = \frac{n_b!}{hook(\mathcal{Y})} \tag{27.12}$$

proof:
QED

For example

$$\mathcal{Y} = \begin{array}{|c|c|}\hline & \\ \hline \\ \cline{1-1} \\ \cline{1-1}\end{array} \implies hook(\mathcal{Y}) = \begin{array}{|c|c|}\hline 4 & 1 \\ \hline 2 \\ \cline{1-1} 1 \\ \cline{1-1}\end{array} = 8 \tag{27.13}$$

so

$$dim(\mathcal{Y}|S_4) = \frac{4!}{4(2)} = 3 \tag{27.14}$$

27.1.2 Regular Representation

The **regular representation** of the symmetric group S_{n_b} is defined as follows. For each permutation $\sigma \in S_{n_b}$, define an independent vector $|\sigma\rangle$ in a vector space $\mathcal{V} = \{|\sigma\rangle : \sigma \in S_{n_b}\} = \{|\sigma_i\rangle : i = 1, 2, \ldots, n_b!\}$. Let

$$|x\rangle = \sum_i x_i |\sigma_i\rangle \tag{27.15}$$

For any $\tau \in S_{n_b}$, suppose

$$\langle \sigma_j | \tau | \sigma_i \rangle = \langle \sigma_j \tau | \sigma_i \rangle \tag{27.16}$$

$$\langle \sigma_j | \tau | x \rangle = \langle \sigma_j \tau | x \rangle = \sum_i x_i \langle \sigma_j \tau | \sigma_i \rangle \tag{27.17}$$

Claim 88 *The regular rep is $n_b!$ dimensional and reducible. In the decomposition of the regular rep of S_{n_b}, each $\lambda \in irreps(S_{n_b})$ appears $dim(\lambda|S_{n_b})$ times.*

proof:
QED

From the last claim, it follows that

$$n_b! = |S_{n_b}| = \sum_{\lambda \in irreps(S_{n_b})} [dim(\lambda|S_{n_b})]^2 \tag{27.18}$$

$$= [n_b!]^2 \sum_{\mathcal{Y} \in YD(n_b)} \frac{1}{[hook(\mathcal{Y})]^2} \quad \text{(Because } |irreps(S_{n_b})| = |YD(n_b)|\text{)} \tag{27.19}$$

Hence,

$$1 = n_b! \sum_{\mathcal{Y} \in YD(n_b)} \frac{1}{[hook(\mathcal{Y})]^2} \tag{27.20}$$

The Clebsch-Gordan series for the regular rep of S_{n_b} is

$$1 = \sum_{\mathcal{Y} \in YD(n_b)} P_{\mathcal{Y}} \tag{27.21}$$

where each $P_{\mathcal{Y}}$ can be further decomposed into

$$P_{\mathcal{Y}} = \sum_{\mathcal{Y}_\alpha \in SYT(\mathcal{Y})} \underbrace{|\mathcal{Y}_\alpha\rangle\langle\mathcal{Y}_\alpha|}_{P_{\mathcal{Y}_\alpha}} \tag{27.22}$$

The projection operators

$$\{P_{\mathcal{Y}_\alpha} : \mathcal{Y}_\alpha \in STY(\mathcal{Y}), \mathcal{Y} \in YD(n_b)\} = \{P_{\mathcal{Y}_\alpha} : \mathcal{Y}_\alpha \in SYT(n_b)\} \tag{27.23}$$

are complete and orthogonal.

27.1.3 Tensor Product Decompositions

(27.24)

(27.25)

27.2 Unitary group $U(n)$

Let

$STY(n_b, NR < n')$ = set of STY with n_b boxes and number of rows $NR < n'$

Recall that[2]

$$irreps(U(n)) = \bigcup_{n_b \le n,\ NR \le n} STY(n_b, NR) = \bigcup_{n_b=1}^{n} STY(n_b, NR < n) \tag{27.26a}$$

$$irreps(SU(n)) = \bigcup_{n_b \le n,\ NR \le n-1} STY(n_b, NR) = \bigcup_{n_b=1}^{n} STY(n_b, NR < n-1) \tag{27.26b}$$

A SYT with n_b boxes represents a tensor with n_b indices (n_b-particles state). Each index ranges from 1 to n.

$n_b = 1$: A 1-index, 1-box tensor is a 1-particle with n states. This corresponds to the fundamental representation.

$n_b = 2$: A 2-index, 2-box tensor is a 2-particle with n^2 states. These n^2 states break into two sets, symmetric and anti-symmetric.

$$\boxed{1} \otimes \boxed{1} = \begin{array}{c}\boxed{1}\\ \boxed{2}\end{array} \oplus \boxed{1}\boxed{2} \tag{27.27}$$

(27.28)

[2]Note that $STY(n_b)$ only contains STY with $n_b \le n$ boxes, so the $n_b \le n$ constraint might seem redundant in Eqs.(27.26). It isn't redundant because by $\cup_{n_b \le n}$ we mean $\cup_{n_b=1}^{n}$.

The SYT of an irrep describes the symmetry of the indices of a tensor in that irrep. A single column SYT indicates a totally anti-symmetric tensor, a single row SYT indicates a totally symmetric tensor, and a SYT with more than one row or column indicates a mixed symmetry tensor. This is why we can't have more than n rows, because there are only n integers to fill all boxes so more than n rows would require a repetition of an integer in a column, and such a column, after antisymetrizing, would lead to zero.

27.2.1 Young Projection Operators

For each SYT $\mathcal{Y}_\alpha \in irreps(U(n))$, define the **Young projection operator**

$$P_{\mathcal{Y}\alpha} = \mathcal{N}\left(\prod_i S_i\right)\left(\prod_j A_j\right) \tag{27.29}$$

for some normalization constant $\mathcal{N}$ yet to be determined. These projection operators are not unique.

Claim 89

$$\mathcal{N} = \frac{\left(\prod_i |S_i|!\right)\left(\prod_j |A_j|!\right)}{hook(\mathcal{Y})} \tag{27.30}$$

where $|S_i|$ and $|A_j|$ are the number of arrows entering the symmetrizer or anti-symmetrizer. Note that the normalization constant $\mathcal{N}$ depends only on the YD $\mathcal{Y}$. Furthermore, the operators $P_{\mathcal{Y}_\alpha}$ are idempotent (i.e., their square equals themselves) mutually orthogonal and complete:

$$P_{\mathcal{Y}_\alpha} P_{\mathcal{Y}_\beta} = P_{\mathcal{Y}_\alpha}\delta(\alpha,\beta) \tag{27.31}$$

$$1 = \sum_{\mathcal{Y}_\alpha \in SYT(n_b,\, NR<n')} P_{\mathcal{Y}_\alpha} \tag{27.32}$$

where

$$n' = \begin{cases} n & \text{for } U(n) \\ n-1 & \text{for } SU(n) \end{cases} \tag{27.33}$$

proof:

$$P_{\mathcal{Y}_\alpha} = \mathcal{N}\frac{1}{\prod_i |S_i|! \prod_j |A_j|!}\left(\underbrace{\begin{array}{c} \longleftarrow \\ \longleftarrow \\ \vdots \\ \longleftarrow \end{array}}_{\mathbb{1}} + \cdots\right) \tag{27.34}$$

From Eq.(27.32)

$$
\begin{aligned}
\mathbb{1} &= \sum_{\mathcal{Y}_\alpha \in SYT(n_b, NR<n')} \mathcal{N} \frac{1}{\prod_i |S_i|! \prod_j |A_j|!} \quad \mathbb{1} && (27.35)\\
&= \sum_{\mathcal{Y} \in YD(n_b)} \frac{n_b!}{hook(\mathcal{Y})} \mathcal{N} \frac{1}{\prod_i |S_i|! \prod_j |A_j|!} \quad \mathbb{1} && (27.36)\\
&= \sum_{\mathcal{Y} \in YD(n_b)} \frac{n_b!}{[hook(\mathcal{Y})]^2} \frac{1}{\prod_i |S_i|! \prod_j |A_j|!} \quad \mathbb{1} \quad \text{(if assume Eq.(27.30))} && (27.37)\\
&= \mathbb{1} \quad \text{(by Eq.(27.20))} && (27.38)
\end{aligned}
$$

QED

27.2.2 $dim(\mathcal{Y}_\alpha | U(n))$

Let $dim(\mathcal{Y}_\alpha | U(n))$ be the dimension of an irrep of $U(n)$ with STY given by $\mathcal{Y}_\alpha \in STY(n_b, NR < n)$.

Claim 90

$$dim(\mathcal{Y}_\alpha | U(n)) = |YT(\mathcal{Y})| \tag{27.39}$$

Note that the right hand side is independent of α, so this dimension is the same for all irreps α with the same YD $\mathcal{Y}$.

proof:
QED

Hence, $\{|\alpha\rangle : \alpha \in YT(\mathcal{Y})\}$ are a basis for the irrep $\mathcal{Y}_\alpha$ of $U(n)$. Note that the irreps of $U(n)$ are given by SYT $\mathcal{Y}_\alpha$, whereas the basis vectors of an irrep are given by YT (not just STY). For example, for

$$\mathcal{Y}_\alpha = \begin{array}{|c|c|}\hline 1 & 2 \\ \hline \end{array} \tag{27.40}$$

the basis vectors are

$$|\begin{array}{|c|c|}\hline 1 & 1 \\ \hline \end{array}\rangle, \quad |\begin{array}{|c|c|}\hline 1 & 2 \\ \hline \end{array}\rangle, \quad |\begin{array}{|c|c|}\hline 2 & 2 \\ \hline \end{array}\rangle \tag{27.41}$$

so

$$dim(\mathcal{Y}_\alpha | U(2)) = 3 \tag{27.42}$$

In Eq.(27.39) we gave a way of finding $dim(\mathcal{Y}_\alpha | U(n))$ A second way is by taking the trace of the corresponding projection operator

$$dim(\mathcal{Y}_\alpha | U(n)) = \mathrm{tr}(P_{\mathcal{Y}_\alpha}) \tag{27.43}$$

For example, if

$$\mathcal{Y}_\alpha = \begin{array}{|c|c|}\hline 1 & 2 \\ \hline \end{array} \tag{27.44}$$

then

$$dim(\mathcal{Y}_\alpha|U(n)) = \tag{27.45}$$

$$= \frac{1}{2}\Bigg(\tag{27.46}$$

$$= \frac{1}{2}(n^2+n) \tag{27.47}$$

$$= 3 \text{ for } n = 2 \tag{27.48}$$

A third way of computing $dim(\mathcal{Y}_\alpha|U(n))$ is by computing the hook and coat functions and using the formula

$$dim(\mathcal{Y}_\alpha|U(n)) = \frac{coat(\mathcal{Y})}{hook(\mathcal{Y})} \tag{27.49}$$

Note that right hand side is independent of α; it depends only on the YD. We've already discussed how to compute $hook(\mathcal{Y})$. $coat(\mathcal{Y})$ is calculated as follows.[3]

1. Fill $\mathcal{Y}$ with
   - n at the diagonal blocks
   - n increasing by 1 per block when reading from left to right
   - n decreasing by 1 per blockk when reading from top to bottom
2. multiply all the boxes

   Examples

$$dim(\begin{array}{|c|c|}\hline 1 & 2 \\ \hline \end{array}, U(2)) = \frac{\begin{array}{|c|c|}\hline \text{n} & \text{n+1} \\ \hline \end{array}}{\begin{array}{|c|c|}\hline 2 & 1 \\ \hline \end{array}} = \frac{n(n+1)}{2} \tag{27.50}$$

$$dim(\begin{array}{|c|}\hline 1 \\ \hline 2 \\ \hline \end{array}, U(2)) = \frac{\begin{array}{|c|}\hline \text{n} \\ \hline \text{n-1} \\ \hline \end{array}}{\begin{array}{|c|}\hline 2 \\ \hline 1 \\ \hline \end{array}} = \frac{n(n-1)}{2} \tag{27.51}$$

[3] I invented the name $coat(\mathcal{Y})$. I don't know if it has a name.

$$dim(\begin{array}{|c|c|c|c|}\hline 1 & 2 & 3 & 4 \\ \hline \multicolumn{1}{|c|}{5} & \multicolumn{1}{c|}{6} \\ \cline{1-2} \multicolumn{1}{|c|}{7} \\ \cline{1-1}\end{array}, U(7)) = \frac{\begin{array}{|c|c|c|c|}\hline n & n+1 & n+2 & n+3 \\ \hline \multicolumn{1}{|c|}{n-1} & \multicolumn{1}{c|}{n} \\ \cline{1-2} \multicolumn{1}{|c|}{n-2} \\ \cline{1-1}\end{array}}{\begin{array}{|c|c|c|c|}\hline 6 & 4 & 2 & 1 \\ \hline \multicolumn{1}{|c|}{3} & \multicolumn{1}{c|}{1} \\ \cline{1-2} \multicolumn{1}{|c|}{1} \\ \cline{1-1}\end{array}} = \frac{n^2(n^2-1)(n^2-4)(n+3)}{144} \tag{27.52}$$

27.2.3 Young Projection Operators for $n_b = 1, 2, 3, 4$

Symmetrizers $\mathcal{S}_p$ and antisymmetriers $\mathcal{A}_p$ are discussed in Chapter 23.

In this section, we will use symmetrizers and antisymmetrizers with "holes" A hole, denoted by an empty square, will signify a particle that the symmetrizer or antisymmetrizer does not touch. For example

(27.53)

denotes a symmetrizer of the particles 1 and 3 but not 2.

Note that

$$(c, a) = (b, c)(b, a)(b, c)$$

(27.54)

Similarly

(27.55)

Hence, one can avoid using symmetrizers and antisymmetrizers with holes, if one is willing to use swaps instead of holes.

Below, we use holes, but keep in mind that those holes can we replaced by swaps.

Below, we give the Clebsch-Gordan decomposition of

(27.56)

for $n_b = 1, 2, 3, 4$.

- $n_b = 1$

- $n_b = 2$

- $n_b = 3$

- $n_b = 4$

1 2 3
4
$\mathcal{S}_3$ $\mathcal{A}_2$
3/2
1 2 4
3
$\mathcal{S}_3$ $\mathcal{A}_2$
3/2
1 3 4
2
$\mathcal{S}_3$ $\mathcal{A}_2$
3/2
1 2
3 4
$\mathcal{S}_2$ $\mathcal{A}_2$
4/3
$\mathcal{A}_2$
$\mathcal{S}_2$
1 3
2 4
$\mathcal{S}_2$ $\mathcal{A}_2$
4/3
$\mathcal{S}_2$
$\mathcal{A}_2$
1 2
3
4
$\mathcal{S}_2$ $\mathcal{A}_3$
3/2
1 3
2
4
$\mathcal{S}_2$ $\mathcal{A}_3$
3/2
1 4
2
3
$\mathcal{S}_2$ $\mathcal{A}_3$
3/2
1
2
3
4
$\mathcal{A}_4$

27.2.4 Young Projection Operator with Swaps

Eq.(27.57) gives a particular STY $\mathcal{Y}_\alpha$, and its projector $P_{\mathcal{Y}_\alpha}$. the projector is expressed using swaps instead of holes.

$\mathcal{Y}_\alpha =$

	A_a	A_b	A_c	A_d	A_e
S_x	1	2	3	4	5
S_y	6	7	8	9	
S_z	10	11			

$a1 \longleftrightarrow 1$	
$a2 \longleftrightarrow 6$	
$a3 \longleftrightarrow 10$	
$b1 \longleftrightarrow 2$	
$b2 \longleftrightarrow 7$	
$b3 \longleftrightarrow 11$	
$c1 \longleftrightarrow 3$	
$c2 \longleftrightarrow 8$	
$d1 \longleftrightarrow 4$	
$d2 \longleftrightarrow 9$	
$e1 \longleftrightarrow 5$	

$P_{\mathcal{Y}_\alpha} =$

(27.57)

27.2.5 Tensor Product Decompositions

$$\boxed{1} \otimes \boxed{2} \otimes \boxed{3} = \left(\begin{array}{|c|c|} \hline 1 & 2 \\ \hline \end{array} \oplus \begin{array}{|c|} \hline 1 \\ \hline 2 \\ \hline \end{array} \right) \otimes \boxed{3} \tag{27.58}$$

$$= \begin{array}{|c|c|c|} \hline 1 & 2 & 3 \\ \hline \end{array} \oplus \begin{array}{|c|c|} \hline 1 & 2 \\ \hline 3 & \multicolumn{1}{c}{} \\ \cline{1-1} \end{array} \oplus \begin{array}{|c|c|} \hline 1 & 3 \\ \hline 2 & \multicolumn{1}{c}{} \\ \cline{1-1} \end{array} \oplus \begin{array}{|c|} \hline 1 \\ \hline 2 \\ \hline 3 \\ \hline \end{array} \tag{27.59}$$

(27.60)

$$n^3 = \frac{n(n+1)(n+2)}{6} + \frac{n(n^2-1)}{3} + \frac{n(n^2-1)}{3} = \frac{(n-2)(n-1)n}{6} \tag{27.61}$$

(27.62)

For $SU(n)$, the yellow YDs are zero for $n = 2$, and non-zero for $n \geq 2$.

27.2.6 $SU(n)$

For $U(n)$ (as opposed to $SU(n)$), there are no antiparticles (i.e., one can use only lowered indices). A consequence of this is that for proper operators in $U(n)$, the total particle number is conserved.

The elements G of $SU(n)$ satisfy

$$\underbrace{\epsilon_{12\ldots n}}_{1} = \underbrace{G_1{}^{a'_1} G_2{}^{a'_2} \cdots G_n{}^{a'_n}\ \epsilon_{a'_1 a'_2 \ldots a'_n}}_{\det G} \tag{27.63}$$

$$\epsilon_{a_1 a_2 \ldots a_n} = G_{a_1}{}^{a'_1} G_{a_2}{}^{a'_2} \cdots G_{a_n}{}^{a'_n}\ \epsilon_{a'_1 a'_2 \ldots a'_n} \tag{27.64}$$

so the Levi-Civita tensor is a primitive invariant of $SU(n)$ (but not of $U(n)$)

This leads to 2 consequences.

1. YD for $SU(n)$ has a maximum of $n-1$ rows.

   For an example of this, see Fig.27.2. The yellow columns in that figure are singlets obtained by fully contracting Levi-Civita tensors. Hence, those yellow columns can removed.

2. Conjugate YD

   Given a YD $\mathcal{Y}$, its **conjugate YD** $conj(\mathcal{Y})$ is obtained as follows:

   - add yellow colored boxes to the original YD so that the resulting YD is rectangular and has n rows for each column.
   - keep only the yellow boxes, and rotate those clockwise by 180 degrees.

   See Fig.27.3 for an example of constructing a conjugate YD.

   This is possible because in the intermediate rectangular YD, the columns with n white and yellow boxes represent a fully contracted Levi-Civita tensor.

   Claim 91 *The reps corresponding to YDs $\mathcal{Y}$ and $conj(\mathcal{Y})$ have the same dimension.*

   proof:
   QED

Figure 27.2: Iluustration of removal of columns 4 boxes long when dealing with $SU(4)$. In this case, the YD in Dynkin notation goes from $[2,1,2,2,0,\ldots]_D$ to $[2,1,2,0,\ldots]_D$

Figure 27.3: Construction of a conjugate YD for $SU(6)$

Besides the RL (row lengths) and RC/D (row change/Dynkin) methods discussed previously, a third method commonly used to label YDs for $SU(n)$ is as follows. Label them by their dimension, and then add a subscript or overline if there are more than one reps with a different YD but the same dimension. This method is

used mostly by physicists for $SU(3)$ (The Eightfold Way). Note that all SYT with the same YD have the same dimension, so this really labels YD instead of YT. For example, for $SU(3)$ we have

(27.65)

Using this notation, we have for $SU(n)$,

(27.66)

$$n \otimes \overline{n} = 1 \oplus (n^2 - 1) \tag{27.67}$$

$$\text{fun rep} \otimes \text{conjugate rep} = \text{singlet rep} \oplus \text{ adjoint rep} \tag{27.68}$$

Adjoint representation

$$P_{adj} = \frac{2(n-1)}{n}$$

(27.69)

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