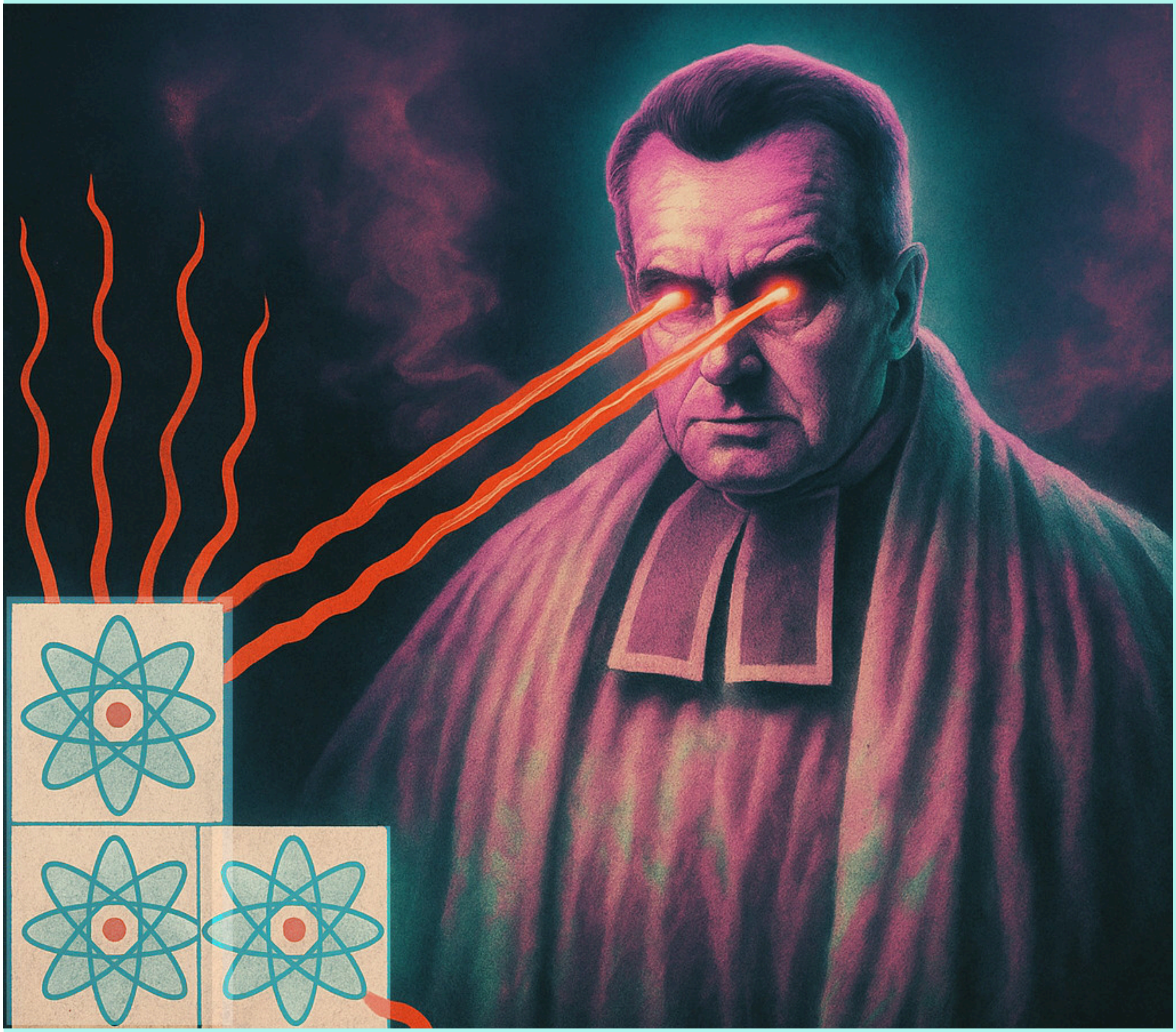
BAYESUVIUS QUANTICO

A VISUAL DICTIONARY OF QUANTUM BAYESIAN NETWORKS



ROBERT R. TUCCI

Bayesuvius Quantico,
a visual dictionary of Quantum Bayesian Networks

Robert R. Tucci
www.ar-tiste.xyz

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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`

Bayes Quantico
by Robert R. Tucci

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Appendix A

Notational Conventions and Preliminaries

A.1 Vector Notation

$(x_1, x_2, \ldots, x_n) = x^{:n}$
$y^b = \sum_b g^{ba} x^{:n}$
$(y^1, y^2, \ldots, y^n) = g x^{:n}$
Reverse of vector $rev(x^{:n}) = (x_n, x_{n-1}, \ldots, x_1)$
Implicit Summation Convention

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

A.2 Tensors

A.3 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.,

$$(ab)c = a(bc) \tag{A.2}$$

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

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

$$ea = ae = a \tag{A.3}$$

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

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

$$aa^{-1} = a^{-1}a = e \tag{A.4}$$

The number of elements in any set S is denoted by $|S|$. $|\mathcal{G}|$ 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.4 Group Representation

A **group representation** of a group $\mathcal{G}$ is a map $\phi : \mathcal{G} \to \mathbb{C}^{n\times n}$[1] such that

$$\phi(a)\phi(b) = \phi(ab) \tag{A.5}$$

Such a map is called a **homomorphism**. When a group is defined using matrices, those matrices are called the **defining representation**. The map ϕ partitions $\mathcal{G}$ into disjoints subsets (equivalence classes), such that all elements of $\mathcal{G}$ in a disjoint set are represented by the same matrix.

For example, the group of **General Linear Transformations** is defined by

$$GL(n, \mathbb{C}) = \{M \in \mathbb{C}^{n\times n} : \det M \neq 0\} \tag{A.6}$$

A.5 Invariance

A.6 Spectral Decomposition and Eigenvalue Projection Operators

$M \in \mathbb{C}^{d\times d}$

$$M|v\rangle = \lambda|v\rangle \tag{A.7}$$

If M is Hermitian ($H^\dagger = H$), its eigenvalues are real. ($\lambda = \langle\lambda|M\lambda\rangle \in \mathbb{R}$)

$$cp(\lambda) \stackrel{\text{def}}{=} \det(M - \lambda) = 0 \tag{A.8}$$

If M is a Hermitain matrix, then there exists a unitary matric ($CC^\dagger = C^\dagger C = 1$) such that

[1]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 $\mathbb{F}$

$$CMC^\dagger = \begin{bmatrix} D_{\lambda_1} & 0 & 0 & 0 \\ 0 & D_{\lambda_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & D_{\lambda_r} \end{bmatrix} \tag{A.9}$$

where

$$D_{\lambda_i} = \text{diag}\,\underbrace{(\lambda_i, \lambda_i, \ldots, \lambda_i)}_{d_i \text{ times}} \tag{A.10}$$

$$d = \sum_{i=1}^{r} d_i \tag{A.11}$$

$$CMC^\dagger = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \tag{A.12}$$

$$CP_1C^\dagger = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} = \frac{CMC^\dagger - \lambda_2}{\lambda_1 - \lambda_2} \tag{A.13}$$

$$CP_2C^\dagger = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} = \frac{CMC^\dagger - \lambda_1}{\lambda_2 - \lambda_1} \tag{A.14}$$

If $I^{d_i \times d_i}$ is the d_i dimensional unit matrix,

$$P_i = C^\dagger diag(0, \ldots, 0, I^{d_i \times d_i}, 0, \ldots, 0)C \tag{A.15}$$

$$= \prod_{j \neq i} \frac{M - \lambda_j}{\lambda_i - \lambda_j} \tag{A.16}$$

Note that P_i are Hermitian ($P_i^\dagger = P_i$) because M is Hermitian and its eigenvalues are real.)

Note that P_i and M commute

$$[P_i, M] = P_iM - MP_i = 0 \tag{A.17}$$

orthogonal

$$P_iP_j = \delta(i,j)P_j \tag{A.18}$$

complete

$$\sum_i P_i = 1 \tag{A.19}$$

$$M = \sum_{i=1}^{r} P_iMP_i \tag{A.20}$$

$$d_i = \text{tr}P_i \tag{A.21}$$

$$CMP_1C^\dagger = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \tag{A.22}$$

$$= \lambda_1 \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \tag{A.23}$$

$$MP_i = \lambda_i P_i \text{ (no } i \text{ sum)} \tag{A.24}$$

$$f(M)P_i = f(\lambda_i)P_i \text{ (no } i \text{ sum)} \tag{A.25}$$

$M^{(1)}, M^{(2)}$

$$[M^{(1)}, M^{(2)}] = 0 \tag{A.26}$$

Use $M^{(1)}$ to decompose V into $\bigoplus_i V_i$. 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 the eigenvalue projection operators of $M^{(1)}$. The replace $M^{(2)}$ by $P_i^{(1)} M^{(2)} P_i^{(1)}$

$$[M^{(1)}, P_i^{(1)} M^{(2)} P_i^{(1)}] = 0 \tag{A.27}$$

Appendix B

Birdtracks: COMING SOON

Cvitanovic Birdtracks book [1]
Elliott-Dawber book [2]
My paper “Quantum Bayesian Nets” [3]

B.1 Classical Bayesian Networks and their Instantiations

TPM (Transition Probability Matrix) $P(y|x) \in [0,1]$ where $x \in val(\underline{x})$ and $y \in val(\underline{y})$

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

$$\mathcal{C} = \begin{tikzcd} & \underline{b} \arrow[dl] & \\ \underline{c} & & \underline{a} \arrow[ul] \arrow[ll] \end{tikzcd} \tag{B.2}$$

$$\mathcal{C}(a,b,c) = P(c|b,a)P(b|a)P(a) = \begin{tikzcd} & b \arrow[dl] & \\ c & & a \arrow[ul] \arrow[ll] \end{tikzcd} \quad P(a) \tag{B.3}$$

$a^{:2} = (a_1, a_2)$

$$\mathcal{C}' = \begin{tikzcd} & \underline{b} \arrow[dl] & \\ \underline{c} & & \underline{a}^{:2} \arrow[ul, "\underline{a}_1"'] \arrow[ll, "\underline{a}_2"] \end{tikzcd} \tag{B.4}$$

$$\mathcal{C}'(a^{:2},b,c) = P(c|b,a_2)P(a_2|a^{:2})P(b|a_1)P(a_1|a^{:2})P(a^{:2}) = \begin{tikzcd} & b \arrow[dl] & \\ c & & a^{:2} \arrow[ul, "a_1"'] \arrow[ll, "a_2"] \end{tikzcd} \quad P(a^{:2}) \tag{B.5}$$

Marginalizer nodes $\underline{a}_1$ and $\underline{a}_2$ have the TPMs

$$P(a_i'|\underline{a}^{:2} = (a_1, a_2)) = \delta(a_i', a_i) \tag{B.6}$$

for $i = 1, 2$

B.2 Quantum Bayesian Networks and their Instantiations

TPM (Transition Probability Matrix) $A(y|x) \in \mathbb{C}$ where $x \in val(\underline{x})$ and $y \in val(\underline{y})$

$$\sum_{y \in val(\underline{y})} |A(y|x)|^2 = 1 \tag{B.7}$$

$$\mathcal{Q} = \begin{tikzcd} & \underline{b} \arrow[dl] & \\ \underline{c} & & \underline{a} \arrow[ul] \arrow[ll] \end{tikzcd} \tag{B.8}$$

$$\mathcal{Q}(a, b, c) = A(c|b, a)A(b|a)A(a) = \begin{tikzcd} & b \arrow[dl] & \\ c & & a \arrow[ul] \arrow[ll] \end{tikzcd} \quad A(a) \tag{B.9}$$

$a^{:2} = (a_1, a_2)$

$$\mathcal{Q}' = \begin{tikzcd} & \underline{b} \arrow[dl] & \\ \underline{c} & & \underline{a}^{:2} \arrow[ul, "\underline{a}_1"] \arrow[ll, "\underline{a}_2"] \end{tikzcd} \tag{B.10}$$

$$\mathcal{Q}'(a^{:2}, b, c) = A(c|b, a_2)A(a_2|a^{:2})A(b|a_1)A(a_1|a^{:2})A(a^{:2}) = \begin{tikzcd} & b \arrow[dl] & \\ c & & a^{:2} \arrow[ul, "a_1"] \arrow[ll, "a_2"] \end{tikzcd} \quad A(a^{:2}) \tag{B.11}$$

Marginalizer nodes $\underline{a}_1$ and $\underline{a}_2$ have the TAMs

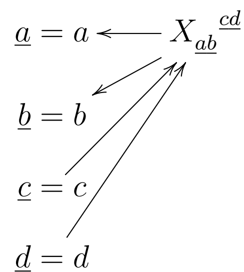
$$A(a_i'|\underline{a}^{:2} = (a_1, a_2)) = \delta(a_i', a_i) \tag{B.12}$$

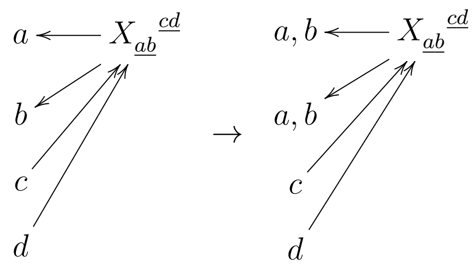
for $i = 1, 2$

B.3 Birdtracks

$$\delta(b,a) = \mathbb{1}(a=b) = \delta_a^b = \; a \leftarrow\!\!\bullet\!\!- \, b \tag{B.13}$$

$$\langle a, b | X_{\underline{ab}}{}^{\underline{cd}} | c, d\rangle = X_{ab}{}^{cd} = \tag{B.14}$$

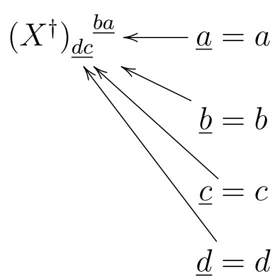




(B.15)

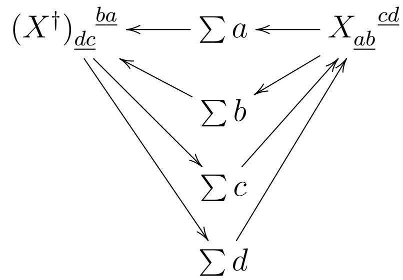
$X_{\underline{ab}}{}^{\underline{cd}} \in V^2 \otimes V_2$. Sometimes, we will omit denote this node simply by X. This if okay as long as we are not using, X to also denote a different version of $X_{\underline{ab}}{}^{\underline{cd}}$ with some of the indices raised or lowered or their order has been changed. [1]

$$(X^\dagger)_{dc}{}^{ba} = \tag{B.16}$$

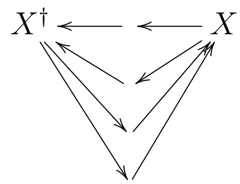


[1] For matrices, $(A^\dagger)_{i,j} = (A_{j,i})^*$ so taking a Hermitian conjugate involves both taking the complex conjugate of the matrix element and reversing the left-to-right (L2R) order of its indices. This generalizes to $(X^\dagger)_{dc}{}^{ba} = (X_{ab}{}^{cd})^*$. Besides raising and lowering indices, we reverse their L2R order.

$$(X^\dagger)_{dc}{}^{ba} X_{ab}{}^{cd} \quad = \tag{B.17}$$



$$= \tag{B.18}$$



Birdtracks originated as a graphical way to represent the tensors in General Relativity (Gravitation). In General Relativity, one deals with tensors such as $T_a{}^b{}_c$ which have some indices raised and some lowered. One can use the metric $g^{a,b}$ to raise all the lowered indices to get T^{abc}. If we represent this graphically as a node with incoming arrows a, b, c, we need to follow one of the following 2 conventions: either

1. label the arrows as $\underline{a}$, $\underline{b}$, $\underline{c}$, and define the node as $T^{\underline{abc}}$, or

2. instead of labelling the arrows explicitly $\underline{a}, \underline{b}, \underline{c}$, indicate in the node where is the first arrow $\underline{a}$, and draw the arrows $\underline{a}, \underline{b}, \underline{c}$ so that they enter the node in **counterclockwise** (CC) order. The **left-to-right** (L2R) order of the indices on T corresponds the CC order of the arrows.

If we don't do either 1 or 2, we won't be able to distinguish between the graphical representations of $T^{1,2,3}$ and $T^{2,1,3}$, for example. Cvitanovic's Birdtracks book Ref.[1] follows Convention 2, but most of the time, in this book, we will follow Convention 1 [2] The reason I chose to do so is for the sake of consistency: Convention 2 is closer to the quantum bnet conventions.

Another issue that arises in using birdtracks is this. When is it permissible to represent a tensor by T^{cd}_{ab}? If we define T^{cd}_{ab} by

$$T^{cd}_{ab} = T_{ab}{}^{cd} \tag{B.19}$$

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

$$T_a{}^{bcd} = g^{bb'} T_{ab'}{}^{cd} = g^{bb'} T^{cd}_{ab'} \tag{B.20}$$

[2]If we follow Convention 1, we don't need to reverse the L2R order of the indices when taking a Hermitian conjugate. Thus, $(X^\dagger)^{\underline{ab}}{}_{\underline{cd}} = X_{\underline{ab}}{}^{\underline{cd}} = X^{\underline{dc}}{}_{\underline{ba}}$. As long as $\underline{a}, \underline{b}$ are lower indices and $\underline{c}, \underline{d}$ are upper indices of X, any L2R order of $\underline{a}, \underline{b}, \underline{c}, \underline{d}$ is equivalent under Convention 1.

Hence, one drawback of using the notation T_{ab}^{cd} is that if one is interested in using versions of T_{ab}^{cd} with some indices raised or lowered, one has to write down explicitly the metric tensors that do the lowering and raising. Instead of writing $T_a{}^{bcd}$, you'll have to write $g^{bb'}T_{ab'}^{cd}$. 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 elegantly concise.

$a^{:m} \in \mathbb{Z}_+^m$

$$R^{a_3^{:m_3},b_2^{:n_2}}_{b_3^{:n_3},a_2^{:m_2}} S^{a_2^{:m_2},b_1^{:n_1}}_{b_2^{:n_2},a_1^{:m_1}} = \begin{tikzcd} b_3^{:n_3} & R \arrow[l] \arrow[dr] & \sum b_2^{:n_2} \arrow[l] & S \arrow[l] \arrow[dr] & b_1^{:n_1} \arrow[l] \\ a_3^{:m_3} \arrow[ur] & & \sum a_2^{:m_2} \arrow[ur] & & a_1^{:m_1} \end{tikzcd} \tag{B.21}$$

$$\mathrm{tr}_{\underline{b}} X_{a\underline{b}}{}^{\underline{b}d} = \sum_b X_{ab}{}^{bd} = \begin{tikzcd} a & X_{\underline{ab}}{}^{\underline{cd}} \arrow[l] \arrow[dl] \\ {} \arrow[ur] & \\ d \arrow[uur] & \end{tikzcd} \tag{B.22}$$

$$\begin{tikzcd} {} \arrow[d] & & & {} & \\ {} & R \arrow[l] \arrow[dr] & & S \arrow[u] \arrow[dr] & {} \arrow[l] \\ {} \arrow[ur] & & {} \arrow[ur] & & {} \end{tikzcd} \tag{B.23}$$

Chapter 1

Casimir Operators: COMING SOON

Chapter 2

Clebsch-Gordan Coefficients: COMING SOON

$$\begin{bmatrix} 0 \\ C_\lambda^{d_\lambda \times d} \\ 0 \end{bmatrix}^{d \times d} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & I^{d_\lambda \times d_\lambda} & 0 \\ 0 & 0 & 0 \end{bmatrix}^{d \times d} C^{d \times d} \tag{2.1}$$

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

$$d_\lambda = \prod_{i=1}^{:nb} db_i \tag{2.2}$$

$$\begin{tikzcd}
& & & b_1 \arrow[dl] \\
(C_\lambda)_a^{b^{:nb}} = & a & C_\lambda \arrow[l] & b_2 \arrow[l] \\
& & & b_{nb} \arrow[ul]
\end{tikzcd} \tag{2.3}$$

$$\begin{bmatrix} 0 & (C^\dagger)_\lambda^{d \times d_\lambda} & 0 \end{bmatrix}^{d \times d} = (C^\dagger)^{d \times d} \begin{bmatrix} 0 & 0 & 0 \\ 0 & I^{d_\lambda \times d_\lambda} & 0 \\ 0 & 0 & 0 \end{bmatrix}^{d \times d} \tag{2.4}$$

$$\begin{tikzcd}
& b_1 & & \\
(C^\dagger_\lambda)^a_{b^{:nb}} = & b_2 & (C^\dagger_\lambda) \arrow[l] \arrow[ul] \arrow[dl] & a \arrow[l] \\
& b_{nb} & &
\end{tikzcd} \tag{2.5}$$

More generally, some of the b_i indices may lowered and their arrows changed to outgoing instead of ingoing. Each b_i represents a different rep (or irrep)

$$\boxed{(C^\dagger_\lambda)_a^{b^{:nb}}(C_\lambda)^a_{(b')^{:nb}} = (P_\lambda)^{b^{:nb}}_{(b')^{:nb}}}$$

$$\begin{tikzcd}
b_1 & & & & b'_1 \arrow[dl] \\
b_2 & (C^\dagger_\lambda) \arrow[l] \arrow[ul] \arrow[dl] & \sum a \arrow[l] & C_\lambda \arrow[l] & b'_2 \arrow[l] \\
b_{nb} & & & & b'_{nb} \arrow[ul]
\end{tikzcd}
\quad = \; b^{:nb} \longleftarrow P_\lambda \longleftarrow (b')^{:nb} \tag{2.6}$$

$$\boxed{(C_\lambda)^{a'}_{b^{:nb}}(C^\dagger_\mu)^{b^{:nb}}_a = \delta(\lambda,\mu)\delta^{a'}_a}$$

$$\begin{tikzcd}
 & & \sum b_1 \arrow[dl] & & \\
a & C_\lambda \arrow[l] & \sum b_2 \arrow[l] & (C^\dagger_\mu) \arrow[l] \arrow[ul] \arrow[dl] & a' \arrow[l] \\
 & & \sum b_{nb} \arrow[ul] & &
\end{tikzcd}
\quad = \delta(\mu,\lambda)\; a \longleftarrow\!\bullet\!\!-\!\!- a' \tag{2.7}$$

Chapter 3

Determinants: COMING SOON

Chapter 4

General Relativity Nets: COMING SOON

Chapter 5

Group Integrals: COMING SOON

Chapter 6

Levi-Civita Tensor

$$\epsilon^{123\ldots p} = \epsilon_{123\ldots p} = 1 \tag{6.1}$$

$$\epsilon_{rev(a^{:p})} = (-1)^{\binom{p}{2}}\epsilon_{a^{:p}} \tag{6.2}$$

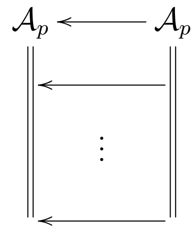
where $rev(a^{:p})$ is the reverse of $a^{:p}$. $rev(a_1, a_2, \ldots, a_p) = (a_p, a_{p-1}, \ldots, a_1)$

$$(C_{\mathcal{A}_p})_1^{a^{:p}} = e^{i\phi}\frac{\epsilon^{a^{:p}}}{\sqrt{p!}} = \begin{array}{l} \mathcal{A}_p \leftarrow a_1 \\ \| \leftarrow a_2 \\ \quad\ \vdots \\ \| \leftarrow a_p \end{array} \tag{6.3}$$

$$(C^{\dagger}_{\mathcal{A}_p})^1_{a^{:p}} = e^{-i\phi}\frac{\epsilon_{a^{:p}}}{\sqrt{p!}} = \begin{array}{r} a_1 \leftarrow \mathcal{A}_p \\ a_2 \leftarrow \| \\ \vdots \quad\ \\ a_p \leftarrow \| \end{array} \tag{6.4}$$

$$\boxed{\frac{1}{p!}\epsilon_{a^{:p}}\epsilon^{b^{:p}} = (\mathcal{A}_p)^{b^{:p}}_{a^{:p}}} \quad \begin{array}{r} a_1 \leftarrow \mathcal{A}_p \\ a_2 \leftarrow \| \\ \vdots \quad\ \\ a_p \leftarrow \| \end{array} \begin{array}{l} \mathcal{A}_p \leftarrow b_1 \\ \| \leftarrow b_2 \\ \quad\ \vdots \\ \| \leftarrow b_p \end{array} = \begin{array}{c} a_1 \leftarrow \mathcal{A}_p \leftarrow b_1 \\ a_2 \leftarrow \| \leftarrow b_2 \\ \vdots \qquad\qquad \vdots \\ a_p \leftarrow \| \leftarrow b_p \end{array} \tag{6.5}$$

$$\boxed{e^{i2\phi}\frac{1}{p!}\epsilon^{a:n}\epsilon_{a:n} = \delta^1_1 = 1}$$



$$= 1 \tag{6.6}$$

For Convention 1, we will use $\phi = 0$.
For Convention 2, we must choose

$$e^{i2\phi} = (-1)^{\binom{p}{2}} = e^{i\pi\frac{p(p-1)}{2}} \tag{6.7}$$

so

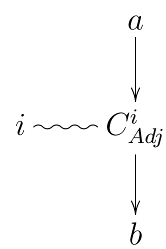
$$\phi = \frac{\pi}{4}p(p-1) \tag{6.8}$$

Chapter 7

Lie Algebra Definition: COMING SOON

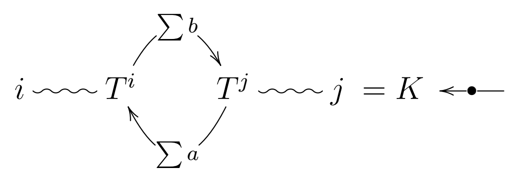
$i \in \mathbb{Z}_{[1,N]}$, $a, b \in \mathbb{Z}_{[1,n]}$

$$(C^i_{Adj})^a_b = \frac{1}{\sqrt{K}}(T^i)^a_b = \tag{7.1}$$

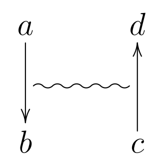


The matrices T^i are called the generators. It's customary to choose them so that they are Hermitian and $K = \frac{1}{2}$

$$\boxed{(T^i)^a_b(T^j)^b_a = \mathrm{tr}(T^iT^j) = K\delta(i,j)} \tag{7.2}$$



$$(P_{Adj})^{a,c}_{b,d} = \sum_i \frac{1}{K}(T^i)^a_b(T^i)^c_d = \frac{1}{K} \tag{7.3}$$



$H \in V^{\underline{a}} \otimes V_{\underline{a}}$

$$(P_{Adj})^{ac}_{bd}H^d_c = \sum_i (T^i)^a_b \underbrace{\left[\frac{1}{K}(T^i)^c_d H^d_c\right]}_{h_i \in \mathbb{R}} \tag{7.4}$$

$G = 1 + iD \in \mathcal{G}$
$\epsilon_i \in \mathbb{R}$, $|\epsilon_i| << 1$

$D = \sum_i \epsilon_i T^i = V^{\underline{a}} \otimes V_{\underline{a}}$

$$\mathcal{T}^i q = 0 \tag{7.5}$$

Chapter 8

Lie Algebra Classification, Dynkin Diagrams: COMING SOON

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Orthogonal Groups: COMING SOON

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Quantum Shannon Information Theory: COMING SOON

Chapter 11

Recoupling Equations: COMING SOON

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Chapter 15

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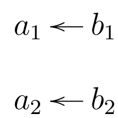
Chapter 16

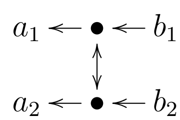
Symmetrization and Antisymmetrization: COMING SOON

$(1,2)$ transposition, swaps 1 and 2, $1 \to 2 \to 1$. $(3,2,1)$ means $3 \to 2 \to 1 \to 3$. A reordering of $(1,2,3,\ldots,p)$ is a permutation on p letters. A permutation can be expressed as a product of transpositions $(3,2,1) = (3,2)(2,1)$ is an even permutation because it 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 permutations.

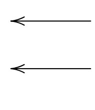
16.1 Symmetrization

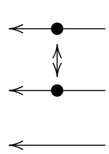
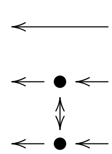
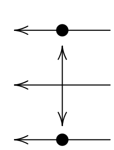
$$\mathbb{1}^{b_2,b_1}_{a_1,a_2} = \delta^{b_1}_{a_1}\delta^{b_2}_{a_2} =$$ 

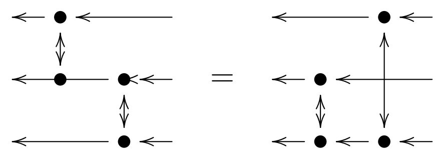
(16.1)

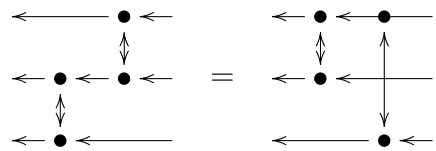
$$(\sigma_{(1,2)})^{b_2,b_1}_{a_1,a_2} = \delta^{b_2}_{a_1}\delta^{b_1}_{a_2} =$$ 

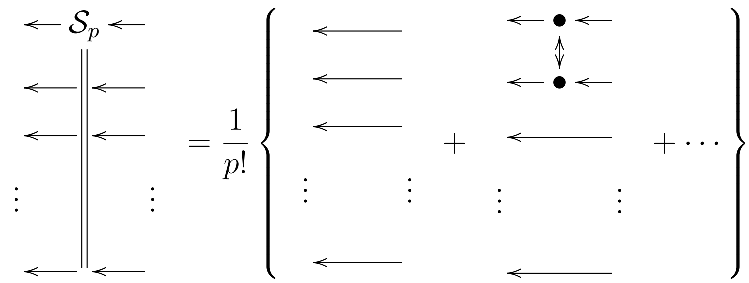
(16.2)

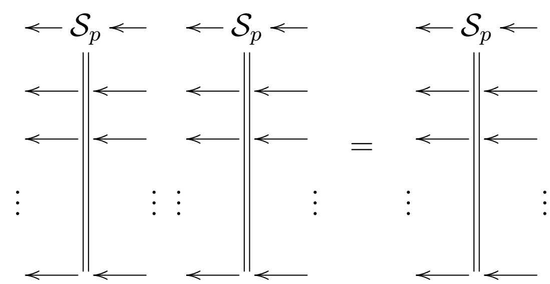
$$\mathbb{1} =$$  (16.3)

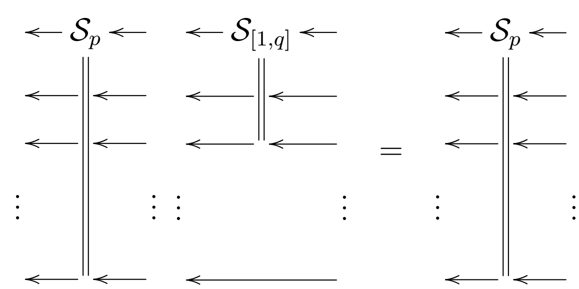
$$\sigma_{(1,2)} =$$  $$\sigma_{(2,3)} =$$  $$\sigma_{(1,3)} =$$  (16.4)

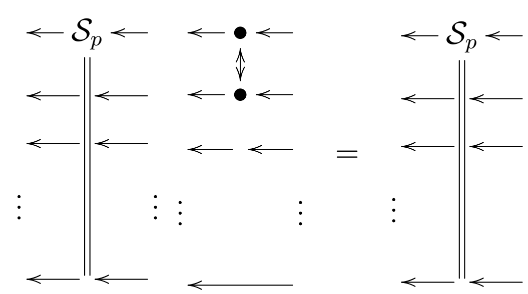
$\sigma_{(1,2,3)} =$  (16.5)

$\sigma_{(1,3,2)} =$  (16.6)

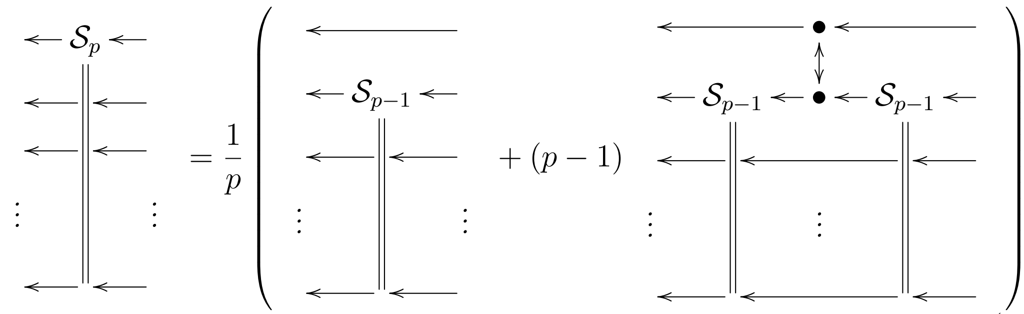
 (16.7)

$\boxed{\mathcal{S}_p^2 = \mathcal{S}_p}$  (16.8)

$\boxed{\mathcal{S}_p \mathcal{S}_{[1,q]} = \mathcal{S}_p}$  (16.9)

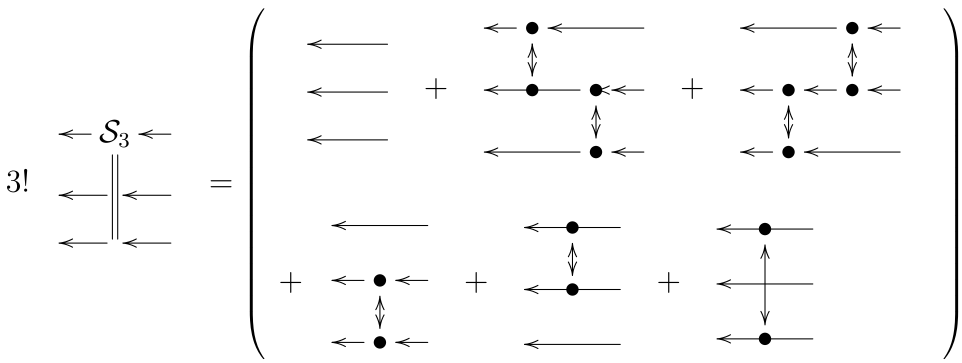
$\boxed{\mathcal{S}_p \sigma_{(1,2)} = \mathcal{S}_p}$  (16.10)

Claim 1

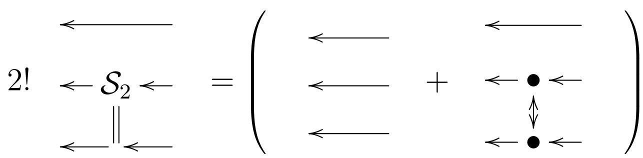


(16.11)

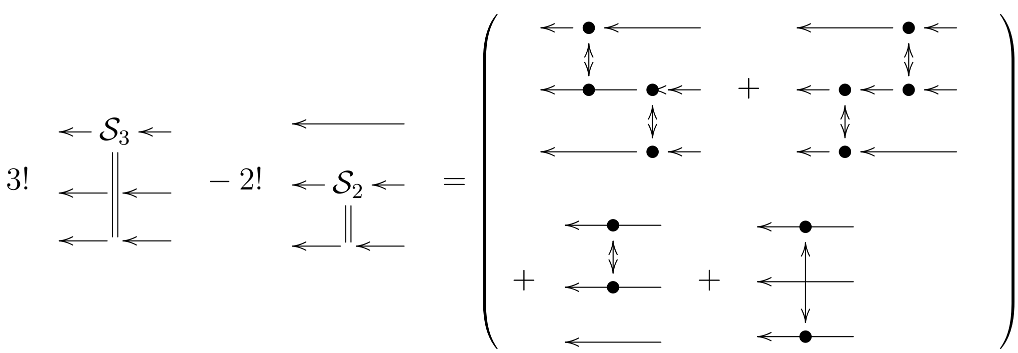
proof: We only prove it for $p = 3$.



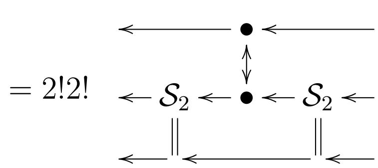
(16.12)



(16.13)

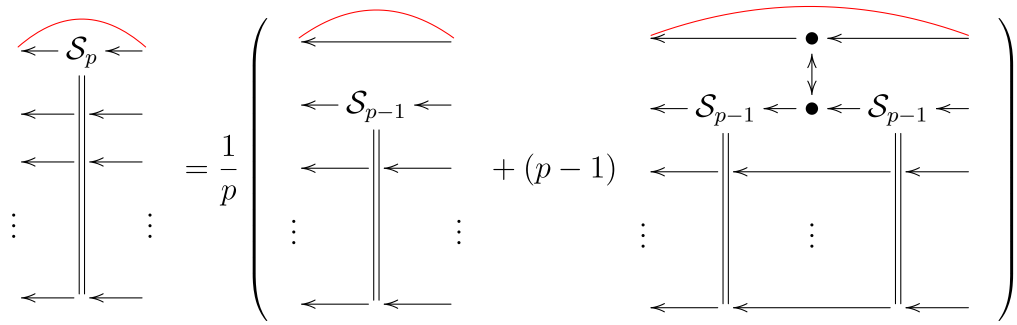


(16.14)

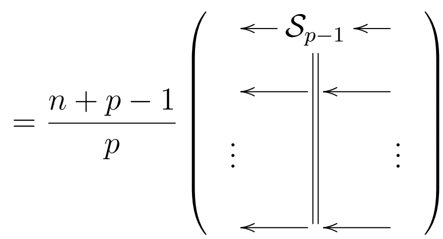


(16.15)

QED



(16.16)



(16.17)

$$\mathrm{tr}_{\underline{a}_1}\mathcal{S}_p = \frac{n+p-1}{p}\mathcal{S}_{p-1} \tag{16.18}$$

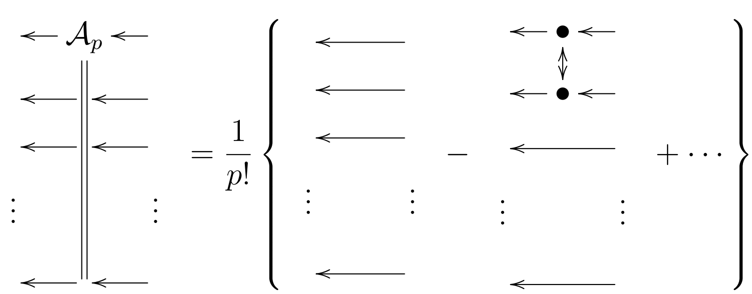
$$\mathrm{tr}_{\underline{a}_1,\underline{a}_2,\ldots,\underline{a}_k}\mathcal{S}_p = \frac{(n+p-1)(n+p-2)\ldots(n=p-k)}{p(p-1)\ldots(p-k+1)}\mathcal{S}_{p-k} \tag{16.19}$$

$$d_{\mathcal{S}_p} = \mathrm{tr}_{\underline{a}^p}\mathcal{S}_p = \frac{(n+p-1)!}{p!(n-1)!} = \binom{n+p-1}{p} \tag{16.20}$$

For $p = 2$,

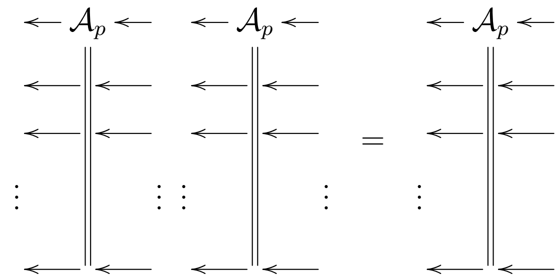
$$d_{\mathcal{S}_2} = \frac{(n+1)n}{2} \tag{16.21}$$

16.2 Antisymmetrization



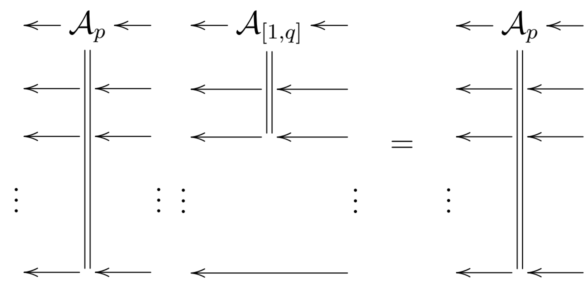
(16.22)

$$\boxed{\mathcal{A}_p^2 = \mathcal{A}_p}$$



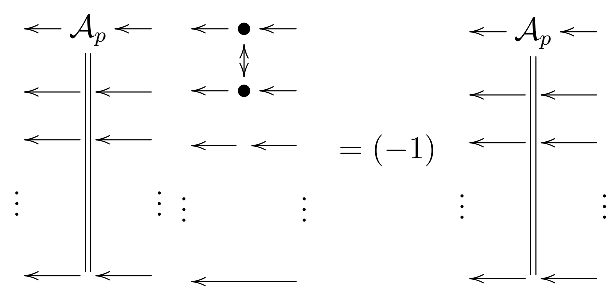
(16.23)

$$\boxed{\mathcal{A}_p \mathcal{A}_{[1,q]} = \mathcal{A}_p}$$



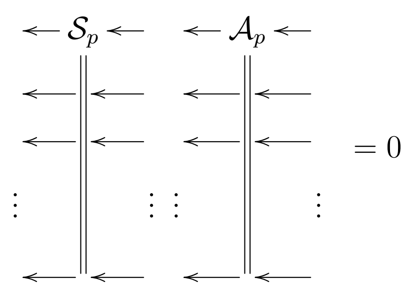
(16.24)

$$\boxed{\mathcal{A}_p \sigma_{(1,2)} = -\mathcal{A}_p}$$



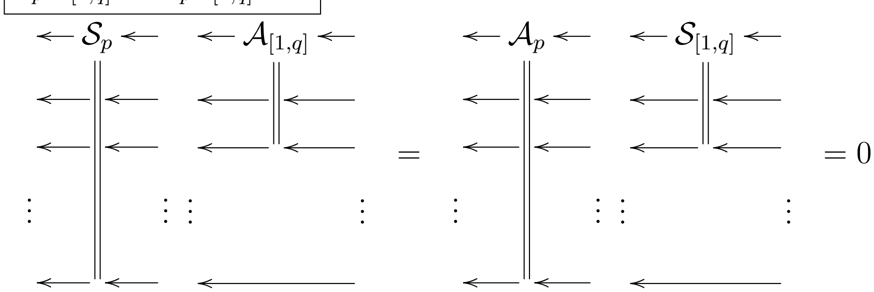
(16.25)

$$\boxed{\mathcal{S}_p \mathcal{A}_q = \mathcal{A}_p \mathcal{S}_q = 0}$$



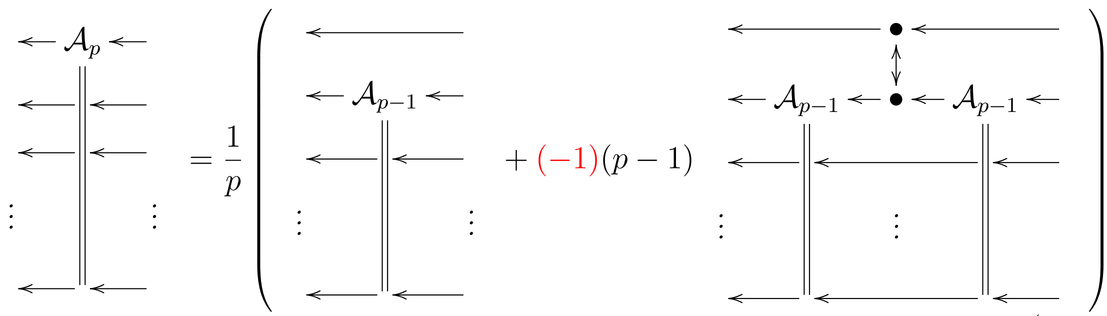
(16.26)

$$\boxed{\mathcal{S}_p \mathcal{A}_{[1,q]} = \mathcal{A}_p \mathcal{S}_{[1,q]} = 0}$$



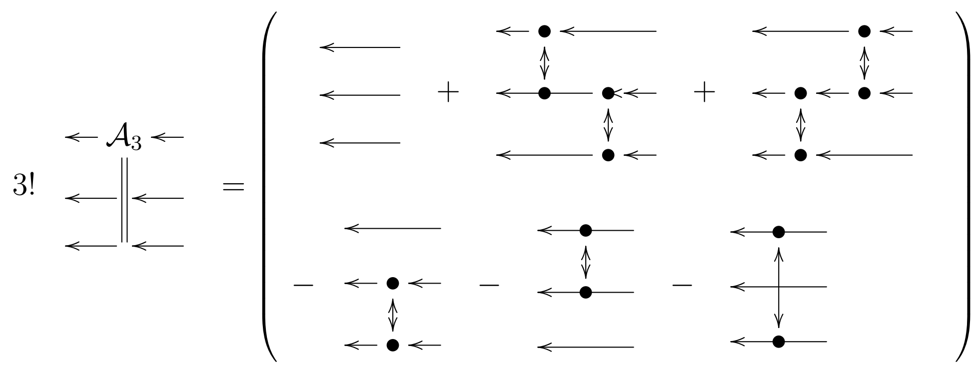
(16.27)

Claim 2

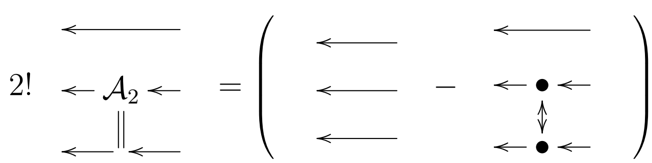


(16.28)

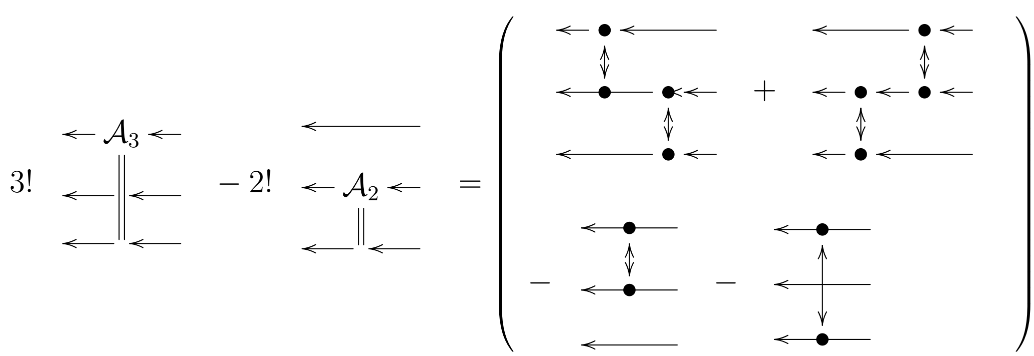
proof: We only prove it for $p = 3$.



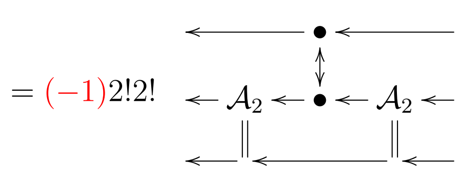
(16.29)



(16.30)

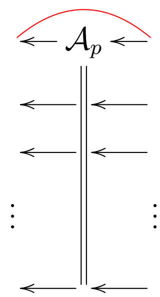


(16.31)

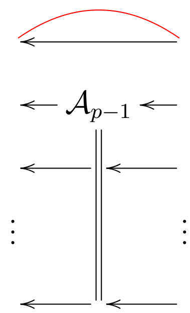


(16.32)

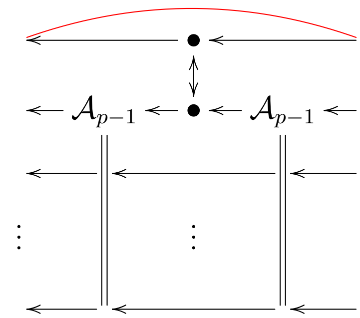
QED



$$= \frac{1}{p}\left(\right.$$

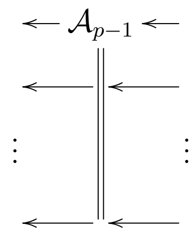


$$+ (-1)(p-1)$$



$$\left.\right) \tag{16.33}$$

$$= \frac{n + (-1)(p-1)}{p}\left(\right.$$



$$\left.\right) \tag{16.34}$$

$$\mathrm{tr}_{\underline{a}_1} \mathcal{A}_p = \frac{n-p+1}{p} \mathcal{A}_{p-1} \tag{16.35}$$

$$\mathrm{tr}_{\underline{a}_1, \underline{a}_2, \ldots, \underline{a}_k} \mathcal{A}_p = \frac{(n-p+1)(n-p+2)\ldots(n-p+k)}{p(p-1)\ldots(p-k+1)} \mathcal{A}_{p-k} \tag{16.36}$$

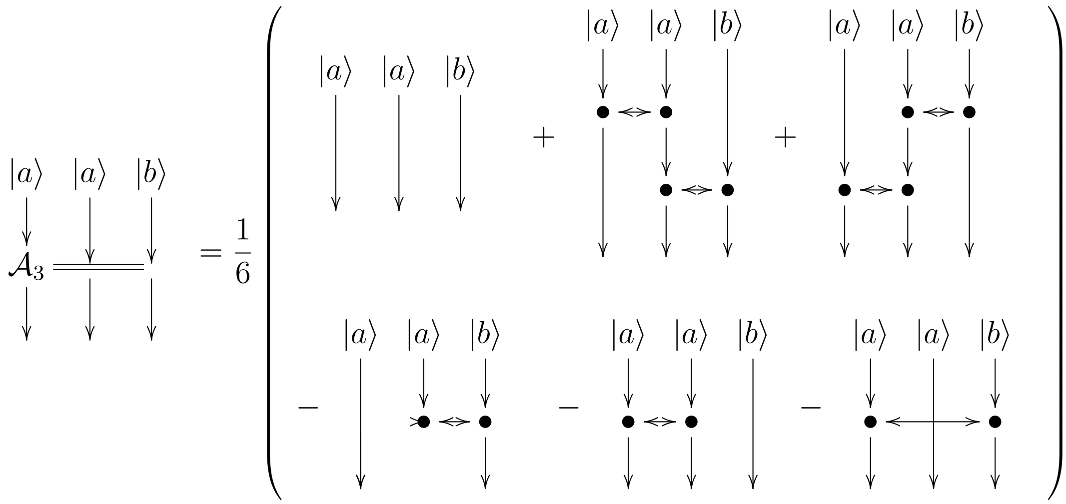
$$\begin{aligned} d_{\mathcal{A}_p} = \mathrm{tr}_{\underline{a}^p} \mathcal{A}_p &= \frac{\prod_{i=n-p+1}^{n} i}{p!} && (16.37) \\ &= \frac{\prod_{i=n}^{n-p+1} i}{p!} && (16.38) \\ &= \begin{cases} \frac{n!}{p!(n-p)!} = \binom{n}{p} & \text{if } p \leq n \\ 0 & \text{otherwise} \end{cases} && (16.39) \end{aligned}$$

For $p = 2 \leq n$,

$$d_{\mathcal{A}_2} = \binom{n}{2} \tag{16.40}$$

$$\mathcal{A}_p = 0 \text{ if } n < p \tag{16.41}$$

For example, for $n = 2$ and $p = 3$



(16.42)

$$\begin{aligned}
\mathcal{A}_3|a,a,b\rangle &= \frac{1}{6}\begin{pmatrix} |a,a,b\rangle + |a,b,a\rangle + |b,a,a\rangle \\ -|a,b,a\rangle - |a,a,b\rangle - |b,a,a\rangle \end{pmatrix} && (16.43)\\
&= 0 && (16.44)
\end{aligned}$$

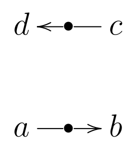
Chapter 17

Unitary Groups: COMING SOON

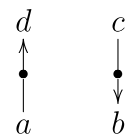
17.1 SU(n)

$$m(p,q) = \delta^a_b \sum_{a=1}^{n} (p_a)^* q_a \tag{17.1}$$

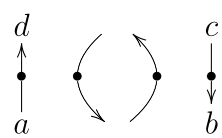
$$\mathbb{1}^{a,c}_{d,b} = \delta^a_b \delta^c_d = \tag{17.2}$$



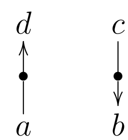
$$\uparrow\downarrow^{a,c}_{d,b} = \delta^a_d \delta^c_b = \tag{17.3}$$



$$\boxed{\uparrow\downarrow^2 = n \uparrow\downarrow} \tag{17.4}$$



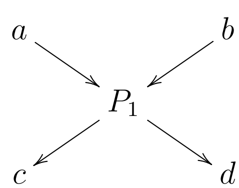
$= n$



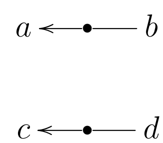
$$P_i = \sum_{j \neq i} \frac{M - \lambda_j}{\lambda_i - \lambda_j} \tag{17.5}$$

$\lambda_1 = n$

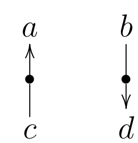
$$\boxed{P_1 = \frac{\uparrow\downarrow - n}{0 - n} = 1 - \frac{1}{n} \uparrow\downarrow} \tag{17.6}$$



$=$

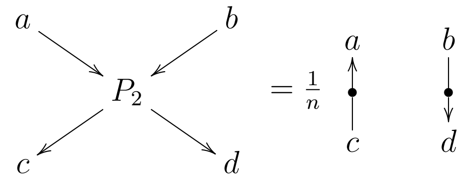


$- \frac{1}{n}$



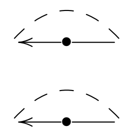
$\lambda_2 = 0$

$$\boxed{P_2 = \frac{\uparrow\downarrow - 0}{n-0} = \frac{1}{n}\uparrow\downarrow}$$

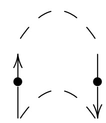


$$\tag{17.7}$$

$$\mathrm{tr}P_1 \quad = $$



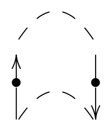
$$- \frac{1}{n}$$



$$\tag{17.8}$$

$$= \quad n^2 - 1 \tag{17.9}$$

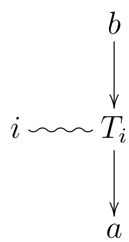
$$\mathrm{tr}P_2 \quad = \quad \frac{1}{n}$$



$$\tag{17.10}$$

$$= \quad 1 \tag{17.11}$$

$$(T_i)_a^b =$$



$$\tag{17.12}$$

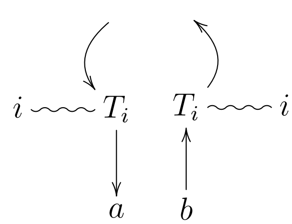
$$T_i^\dagger = T_i \tag{17.13}$$

Claim 3

$$C_F \delta_a^b = (T_i T_i)_a^b = \frac{n^2-1}{n}\delta_a^b \tag{17.14}$$

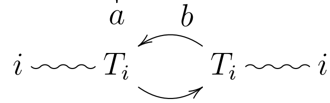
proof:

$$(T_i T_i)_a^b \quad = \quad \sum_i$$



$$\tag{17.15}$$

$$= \quad \sum_i$$



$$\tag{17.16}$$

QED

Chapter 18

Wigner Coefficients: COMING SOON

Chapter 19

Wigner-Ekart Theorem: COMING SOON

Chapter 20

Young Tableau: COMING SOON

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