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Lecture note on Clifford algebra

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ABSTRACT: This lecture note surveys the gamma matrices in general dimensions with arbitrary signatures, the study of which is essential to understand the supersymmetry in the corresponding spacetime. The contents supplement the lecture presented by the author at *Modave Summer School in Mathematical Physics, Belgium*, june, 2005.

KEYWORDS: gamma matrix, supersymmetry, octonion.

Contents

1. Gamma Matrix

We start with the following well known Lemma.

Lemma
Any matrix, M, satisfying $M^2 = \lambda^2 \neq 0$, $\lambda \in \mathbf{C}$ is diagonalizable, and furthermore if there is another invertible matrix, N, which anti-commutes with M, $\{N, M\} = 0$, then M is $2n \times 2n$ matrix of the form

$$M = S \begin{pmatrix} \lambda & 0 \\ 0 & -\lambda \end{pmatrix} S^{-1} \,. \tag{1.1}$$

In particular, $\mathrm{tr}M = 0$. See Sec.A for our proof.

1.1 In Even Dimensions

In even $d = t + s$ dimensions, with metric

$$\eta^{\mu\nu} = \mathrm{diag}(\underbrace{+ + \cdots +}_{t}\underbrace{- - \cdots -}_{s}) , \tag{1.2}$$

gamma matrices, γ^μ, satisfy the Clifford algebra

$$\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2\eta^{\mu\nu} . \tag{1.3}$$

With[1]

$$\gamma^{\mu_1\mu_2\cdots\mu_m} = \gamma^{[\mu_1}\gamma^{\mu_2}\cdots\gamma^{\mu_m]} , \tag{1.4}$$

we define Γ^M, $M = 1, 2, \cdots 2^d$ by assigning numbers to independent $\gamma^{\mu_1\mu_2\cdots\mu_m}$, e.g. imposing $\mu_1 < \mu_2 < \cdots < \mu_m$,

$$\Gamma^M = (1, \gamma^\mu, \gamma^{\mu\nu}, \cdots, \gamma^{\mu_1\mu_2\cdots\mu_m}, \cdots, \gamma^{12\cdots d}) . \tag{1.5}$$

Then $\{\Gamma^M\}/Z_2$ forms a group

$$\Gamma^M\Gamma^N = \Omega^{MN}\Gamma^L , \qquad \Omega^{MN} = \pm 1 , \tag{1.6}$$

where L is a fuction of M, N and $\Omega_{MN} = \pm 1$ does not depend on the specific choice of representation of the gamma matrices.
Lemma (1.1) implies

$$\frac{1}{2n}\mathrm{tr}(\Gamma^M\Gamma^N) = \Omega_{MN}\delta^{MN} , \tag{1.7}$$

which shows the linear independence of $\{\Gamma^M\}$ so that any gamma matrix should not be smaller than $2^{d/2} \times 2^{d/2}$.

In two-dimensions, one can take the Pauli sigma matrices, σ^1, σ^2 as gamma matrices with a possible factor, i, depending on the signature. In general, one can construct $d+2$ dimensional gamma matrices from d dimensional gamma matrices by taking tensor products as

$$(\gamma^\mu \otimes \sigma^1,\ 1 \otimes \sigma^2,\ 1 \otimes \sigma^3) \qquad : \text{up to a factor } i . \tag{1.8}$$

Thus, the smallest size of irreducible representations is $2^{d/2} \times 2^{d/2}$ and $\{\Gamma^M\}$ forms a basis of $2^{d/2} \times 2^{d/2}$ matrices.

By induction on the dimensions, from eq.(1.8), we may require gamma matrices to satisfy the hermiticity condition

$$\gamma^{\mu\dagger} = \gamma_\mu . \tag{1.9}$$

With this choice of gamma matrices we define $\gamma^{(d+1)}$ as

$$\gamma^{(d+1)} = \sqrt{(-1)^{\frac{t-s}{2}}}\gamma^1\gamma^2\cdots\gamma^d , \tag{1.10}$$

[1] "[]" means the standard anti-symmetrization with "strength one".

satisfying

$$\gamma^{(d+1)} = (\gamma^{(d+1)})^{-1} = \gamma^{(d+1)\dagger} \,,$$
$$\{\gamma^{\mu}, \gamma^{(d+1)}\} = 0 \,. \tag{1.11}$$

For two sets of irreducible gamma matrices, γ^{μ}, γ'^{μ} which are $n\times n$, $n'\times n'$ respectively, we consider a matrix

$$S = \sum_{M} \Gamma'^{M} T (\Gamma^{M})^{-1} \,, \tag{1.12}$$

where T, is an arbitrary $2n' \times 2n$ matrix.
This matrix satisfies for any N from eq.(1.6)

$$\Gamma'^{N} S = S \Gamma^{N} \,. \tag{1.13}$$

By Schur's Lemmas, it should be either $S = 0$ or $n = n', \det S \neq 0$. Furthermore, S is unique up to constant, although T is arbitrary. This implies the uniqueness of the irreducible $2^{d/2} \times 2^{d/2}$ gamma matrices in even d dimensions, up to the similarity transformations. These similarity transformations are also unique up to constant. Consequently there exist similarity transformations which relate γ^{μ} to $\gamma^{\mu\dagger}$, $\gamma^{\mu *}$, $\gamma^{\mu T}$ since the latter form also representations of the Clifford algebra. By combining $\gamma^{(d+1)}$ with the similarity transformations, from eq.(1.11), we may acquire the opposite sign, $-\gamma^{\mu\dagger}$, $-\gamma^{\mu *}$, $-\gamma^{\mu T}$ as well. Explicitly we define[2]

$$A = \sqrt{(-1)^{\frac{t(t-1)}{2}}}\, \gamma^{1} \gamma^{2} \cdots \gamma^{t} \,, \tag{1.14}$$

satisfying

$$A = A^{-1} = A^{\dagger} \,, \tag{1.15}$$

$$\gamma^{\mu\dagger} = (-1)^{t+1} A \gamma^{\mu} A^{-1} \,. \tag{1.16}$$

If we write

$$\pm \gamma^{\mu *} = B_{\pm} \gamma^{\mu} B_{\pm}^{-1} \,, \tag{1.17}$$

then from

$$\gamma^{\mu} = (\gamma^{\mu *})^{*} = B_{\pm}^{*} B_{\pm} \gamma^{\mu} (B_{\pm}^{*} B_{\pm})^{-1} \,, \tag{1.18}$$

one can normalize $B_{\pm}$ to satisfy [2, 3]

$$B_{\pm}^{*} B_{\pm} = \varepsilon_{\pm} 1 \,, \qquad \varepsilon_{\pm} = (-1)^{\frac{1}{8}(s-t)(s-t\pm 2)} \,, \tag{1.19}$$

$$B_{\pm}^{\dagger} B_{\pm} = 1 \,, \tag{1.20}$$

$$B_{\pm}^{T} = \varepsilon_{\pm} B_{\pm} \,, \tag{1.21}$$

[2] Alternatively, one can construct $C_{\pm}$ explicitly out of the gamma matrices in a certain representation [1].

where the unitarity follows from

$$\gamma^{\mu}=\gamma_{\mu}^{\dagger}=(\pm B_{\pm}^{-1}\gamma_{\mu}^{*}B_{\pm})^{\dagger}=\pm B_{\pm}^{\dagger}\gamma^{\mu *}(B_{\pm}^{\dagger})^{-1}=B_{\pm}^{\dagger}B_{\pm}\gamma^{\mu}(B_{\pm}^{\dagger}B_{\pm})^{-1}\,, \tag{1.22}$$

and the positive definiteness of $B_{\pm}^{\dagger}B_{\pm}$. The calculation of $\varepsilon_{\pm}$ is essentially counting the dimensions of symmetric and anti-symmetric matrices [2, 3].

The charge conjugation matrix, $C_{\pm}$, given by

$$C_{\pm}=B_{\pm}^{T}A\,, \tag{1.23}$$

satisfies[3] from the properties of A and $B_{\pm}$

$$C_{\pm}\gamma^{\mu}C_{\pm}^{-1}=\zeta\gamma^{\mu T}\,,\qquad\qquad \zeta=\pm(-1)^{t+1}\,, \tag{1.24}$$

$$C_{\pm}^{\dagger}C_{\pm}=1\,, \tag{1.25}$$

$$C_{\pm}^{T}=(-1)^{\frac{1}{8}d(d-\zeta 2)}\,C_{\pm}=\varepsilon_{\pm}(\pm 1)^{t}(-1)^{\frac{1}{2}t(t-1)}\,C_{\pm}\,, \tag{1.26}$$

$$\zeta^{t}(-1)^{\frac{1}{2}t(t-1)}A^{T}=B_{\pm}AB_{\pm}^{-1}=C_{\pm}AC_{\pm}^{-1}\,. \tag{1.27}$$

$\varepsilon_{\pm}$ is related to ζ as

$$\varepsilon_{\pm}=\zeta^{t}(-1)^{\frac{1}{2}t(t-1)+\frac{1}{8}d(d-\zeta 2)}\,. \tag{1.28}$$

Eqs.(1.24, 1.26) imply

$$\begin{aligned}(C_{\pm}\gamma^{\mu_1\mu_2\cdots\mu_n})^{T}&=\zeta^{n}(-1)^{\frac{1}{8}d(d-\zeta 2)+\frac{1}{2}n(n-1)}\,C_{\pm}\gamma^{\mu_1\mu_2\cdots\mu_n}\\&=\varepsilon_{\pm}(\pm 1)^{t+n}(-1)^{n+\frac{1}{2}(t+n)(t+n-1)}\,C_{\pm}\gamma^{\mu_1\mu_2\cdots\mu_n}\,.\end{aligned} \tag{1.29}$$

$\gamma^{(d+1)}$ satisfies

$$\begin{aligned}\gamma^{(d+1)\dagger}&=(-1)^{t}A_{\pm}\gamma^{(d+1)}A_{\pm}^{-1}=\gamma^{(d+1)}\,,\\ \gamma^{(d+1)*}&=(-1)^{\frac{t-s}{2}}B_{\pm}\gamma^{(d+1)}B_{\pm}^{-1}\,,\\ \gamma^{(d+1)T}&=(-1)^{\frac{t+s}{2}}C_{\pm}\gamma^{(d+1)}C_{\pm}^{-1}\,,\end{aligned} \tag{1.30}$$

where $\{A_{+},A_{-}\}=\{A,\gamma^{(d+1)}A\}$.

In stead of eq.(1.8) one can construct $d+2$ dimensional gamma matrices from d dimensional gamma matrices by taking tensor products as

$$(\gamma^{\mu}\otimes\sigma^{1},\ \gamma^{(d+1)}\otimes\sigma^{1},\ 1\otimes\sigma^{2})\qquad\quad :\text{up to a factor } i\,. \tag{1.31}$$

[3]Essentially all the properties of the charge conjugation matrix, $C_{\pm}$ depends only on d and ζ. However it is useful here to have expression in terms of the signature to dicuss the Majorana supersymmetry later.

Therefore the gamma matrices in even dimensions can be chosen to have the "off-block diagonal" form

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \tilde{\sigma}^\mu & 0 \end{pmatrix}, \qquad \gamma^{(d+1)} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \tag{1.32}$$

where the $2^{\frac{d}{2}-1} \times 2^{\frac{d}{2}-1}$ matrices, $\sigma^\mu, \tilde{\sigma}^\mu$ satisfy

$$\sigma^\mu \tilde{\sigma}^\nu + \sigma^\nu \tilde{\sigma}^\mu = 2\eta^{\mu\nu}, \tag{1.33}$$

$$\sigma^{\mu\dagger} = \tilde{\sigma}_\mu . \tag{1.34}$$

In this choice of gamma matrices, from eq.(1.30), $A_\pm, B_\pm, C_\pm$ are either "block diagonal" or "off-block diagonal" depending on whether t, $\frac{t-s}{2}$, $\frac{t+s}{2}$ are even or odd respectively.
In particular, in the case of odd t, we write from eqs.(1.14, 1.15) A as

$$A = \begin{pmatrix} 0 & \mathrm{a} \\ \tilde{\mathrm{a}} & 0 \end{pmatrix}, \qquad \mathrm{a} = \sqrt{(-1)^{\frac{t(t-1)}{2}}}\,\sigma^1 \tilde{\sigma}^2 \cdots \sigma^t = \tilde{\mathrm{a}}^\dagger = \tilde{\mathrm{a}}^{-1}, \tag{1.35}$$

and in the case of odd $\frac{t+s}{2}$ we write from eq.(1.26) $C_\pm$ as

$$C_\pm = \begin{pmatrix} 0 & \mathrm{c} \\ \pm\tilde{\mathrm{c}} & 0 \end{pmatrix}, \qquad \mathrm{c} = \varepsilon_+ (-1)^{\frac{t(t-1)}{2}} \tilde{\mathrm{c}}^T = (\mathrm{c}^\dagger)^{-1}, \tag{1.36}$$

where a, ã, c, c̃ satisfy from eqs.(1.16, 1.24)

$$\begin{aligned} \sigma^{\mu\dagger} &= \tilde{\mathrm{a}} \sigma^\mu \tilde{\mathrm{a}}, & \tilde{\sigma}^{\mu\dagger} &= \mathrm{a} \tilde{\sigma}^\mu \mathrm{a}, \\ \sigma^{\mu T} &= (-1)^{t+1} \tilde{\mathrm{c}} \sigma^\mu \mathrm{c}^{-1}, & \tilde{\sigma}^{\mu T} &= (-1)^{t+1} \mathrm{c} \tilde{\sigma}^\mu \tilde{\mathrm{c}}^{-1}. \end{aligned} \tag{1.37}$$

If both of t and $\frac{t+s}{2}$ are odd then from eq.(1.27)

$$\mathrm{a}^T = (-1)^{\frac{t-1}{2}} \tilde{\mathrm{c}}\, \mathrm{a}\, \mathrm{c}^{-1}, \qquad \tilde{\mathrm{a}}^T = (-1)^{\frac{t-1}{2}} \mathrm{c}\, \tilde{\mathrm{a}}\, \tilde{\mathrm{c}}^{-1}. \tag{1.38}$$

1.2 In Odd Dimensions

The gamma matrices in odd $d+1 = t+s$ dimensions are constructed by combining a set of even d dimensional gamma matrices with either $\pm\gamma^{(d+1)}$ or $\pm i\gamma^{(d+1)}$ depending on the signature of even d dimensions. This way of construction is general, since $\gamma^{(d+1)}$ serves the role of γ^{d+1}

$$\begin{aligned} -\gamma^\mu &= \gamma^{d+1} \gamma^\mu (\gamma^{d+1})^{-1}, \qquad \text{for } \mu = 1, 2, \cdots, d, \\ (\gamma^{d+1})^2 &= \pm 1, \end{aligned} \tag{1.39}$$

and such a matrix is unique in irreducible representations up to sign.

However, contrary to the even dimensional Clifford algebra, in odd dimensions two different choices of the signs in γ^{d+1} bring two irreducible representations for the Clifford algebra, which can not be mapped to each other[4] by similarity transformations

$$\gamma^{\mu}=(\gamma^1,\gamma^2,\cdots,\gamma^{d+1})\qquad\text{and}\qquad\gamma^{\prime\mu}=(\gamma^1,\gamma^2,\cdots,\gamma^{d},-\gamma^{d+1})\,. \tag{1.40}$$

If there were a similarity transformation between these two, it should have been identity up to constant because of the uniqueness of the similarity transformation in even dimensions. Clearly this would be a contradiction due to the presence of the two opposite signs in γ^{d+1}.

In general one can put[5]

$$\gamma^{d+1}=\begin{cases}\pm\gamma^{12\cdots d} & \text{for } t-s\equiv 1 \bmod 4\,,\\ \\ \pm i\gamma^{12\cdots d} & \text{for } t-s\equiv 3 \bmod 4\,.\end{cases} \tag{1.41}$$

$2^{d/2}\times 2^{d/2}$ gamma matrices in odd $d+1$ dimensions, $\gamma^{\mu},\mu=1,2,\cdots,d+1$, induce the following basis of $2^{d/2}\times 2^{d/2}$ matrices, $\tilde{\Gamma}^M$

$$\tilde{\Gamma}^M=(1,\gamma^{\mu},\gamma^{\mu\nu},\cdots,\gamma^{\mu_1\mu_2\cdots\mu_{d/2}})\,,\qquad M=1,2,\cdots 2^d\,. \tag{1.42}$$

From eq.(1.41)

$$\tilde{\Gamma}^M\tilde{\Gamma}^N=\tilde{\Omega}_{MN}\tilde{\Gamma}^L\,,$$

$$\tilde{\Omega}_{MN}=\begin{cases}\pm 1 & \text{for } t-s\equiv 1 \bmod 4\,,\\ \\ \pm 1,\pm i & \text{For } t-s\equiv 3 \bmod 4\,.\end{cases} \tag{1.43}$$

Here, contrary to the even dimensional case, $\tilde{\Omega}_{MN}$ depends on each particular choice of the representations due to the arbitrary sign factor in γ^{d+1}. This is why eq.(1.13) does not hold in odd dimensions. Therefore it is not peculiar that not all of $\pm\gamma^{\mu\dagger},\pm\gamma^{\mu *},\pm\gamma^{\mu T}$ are related to γ^{μ} by similarity transformations. In fact, if it were true, say for $\pm\gamma^{\mu *}$, then the similarity transformation should have been $B_{\pm}$ (1.17) by the uniqueness of the similarity transformations in even dimensions, but this would be a contradiction to eq.(1.30), where the sign does not alternate under the change of $B_+\leftrightarrow B_-$. Thus, in odd dimensions, only the half of $\pm\gamma^{\mu\dagger},\pm\gamma^{\mu *},\pm\gamma^{\mu T}$ are related to γ^{μ} by similarity transformations and hence from eq.(1.30) there exist three similarity transformations, A,B,C such that

$$(-1)^{t+1}\gamma^{\mu\dagger}=A\gamma^{\mu}A^{-1}\,, \tag{1.44}$$

[4]Nevertheless, this can be cured by the following transformation. Under $x^{\mu}=(x^1,x^2,\cdots,x^{d+1})\rightarrow x^{\prime\mu}=(x^1,x^2,\cdots,-x^{d+1})$, we transform the Dirac field $\psi(x)$ as $\psi(x)\rightarrow\psi^{\prime}(x^{\prime})=\psi(x)$, to get $\bar{\psi}(x)\gamma\cdot\partial\psi(x)\rightarrow\bar{\psi}^{\prime}(x^{\prime})\gamma^{\prime}\cdot\partial^{\prime}\psi^{\prime}(x^{\prime})=\bar{\psi}(x)\gamma\cdot\partial\psi(x)$. Hence those two representations are equivalent describing the same physical system.

[5]Our results (1.41-1.50) do not depend on the choice of the signature in d dimensions, i.e. they hold for either increasing the time dimensions, $d=(t-1)+s$ or the space dimensions, $d=t+(s-1)$.

$$(-1)^{\frac{t-s-1}{2}}\gamma^{\mu *} = B\gamma^{\mu}B^{-1}\,, \tag{1.45}$$

$$(-1)^{\frac{t+s-1}{2}}\gamma^{\mu T} = C\gamma^{\mu}C^{-1}\,. \tag{1.46}$$

A, B, C are all unitary and satisfy

$$A = A^{-1} = A^{\dagger}\,, \qquad\qquad C = B^{T}A\,, \tag{1.47}$$

$$B^{*}B = \varepsilon\,1 = (-1)^{\frac{1}{8}(t-s+1)(t-s-1)}\,1\,, \tag{1.48}$$

$$B^{T} = \varepsilon B\,, \qquad\qquad C^{T} = \varepsilon(-1)^{\frac{ts}{2}}\,C = (-1)^{\frac{1}{8}(t+s+1)(t+s-1)}C\,, \tag{1.49}$$

$$(-1)^{\frac{ts}{2}}A^{T} = BAB^{-1} = CAC^{-1}\,. \tag{1.50}$$

In particular, A is given by eq.(1.14).

1.3 Lorentz Transformations

Lorentz transformations, L can be represented by the following action on gamma matrices in a standard way

$$\mathcal{L}^{-1}\gamma^{\mu}\mathcal{L} = L^{\mu}{}_{\nu}\gamma^{\nu}\,, \tag{1.51}$$

where L and $\mathcal{L}$ are given by

$$\begin{aligned} L = e^{w_{\mu\nu}M^{\mu\nu}}\,, &\qquad\qquad \mathcal{L} = e^{\frac{1}{2}w_{\mu\nu}\gamma^{\mu\nu}}\,, \\ (M^{\mu\nu})^{\lambda}{}_{\rho} &= \eta^{\mu\lambda}\delta^{\nu}{}_{\rho} - \eta^{\nu\lambda}\delta^{\mu}{}_{\rho}\,. \end{aligned} \tag{1.52}$$

For a even d, if a $2^{d/2}\times 2^{d/2}$ matrix, $M^{\mu_1\mu_2\cdots\mu_n}$, is totally anti-symmetric over the n spacetime indices

$$M^{\mu_1\mu_2\cdots\mu_n} = M^{[\mu_1\mu_2\cdots\mu_n]}\,, \tag{1.53}$$

and transforms covariantly under Lorentz transformations in d or $d+1$ dimensions as

$$\mathcal{L}^{-1}M^{\mu_1\mu_2\cdots\mu_n}\mathcal{L} = \prod_{i=1}^{n} L^{\mu_i}{}_{\nu_i}\,M^{\nu_1\nu_2\cdots\nu_n}\,, \tag{1.54}$$

then for $0\leq n\leq \max(d/2,2)$, the general forms of $M^{\mu_1\mu_2\cdots\mu_n}$ are

$$M^{\mu_1\mu_2\cdots\mu_n} = \begin{cases} (1+c\gamma^{(d+1)})\gamma^{\mu_1\mu_2\cdots\mu_n} & \text{In even } d \text{ dimensions}\,, \\ \\ \gamma^{\mu_1\mu_2\cdots\mu_n} & \text{In odd } d+1 \text{ dimensions}\,, \end{cases} \tag{1.55}$$

where c is a constant.

To show this, one may first expand $M^{\mu_1\mu_2\cdots\mu_n}$ in terms of $\gamma_{\nu_1\nu_2\cdots\nu_m}$, $\gamma^{(d+1)}\gamma_{\nu_1\nu_2\cdots\nu_m}$ or $\gamma_{\nu_1\nu_2\cdots\nu_m}$ depending on the dimensions, d or $d+1$, with $0 \leq m \leq d/2$. Then eq.(1.54) implies that the coefficients of them, say $T^{\mu_1\mu_2\cdots\mu_{m+n}}$, are Lorentz invariant tensors satisfying

$$\prod_{i=1}^{m+n} L^{\mu_i}{}_{\nu_i}\, T^{\nu_1\nu_2\cdots\nu_{m+n}} = T^{\mu_1\mu_2\cdots\mu_{m+n}} \tag{1.56}$$

Finally one can recall the well known fact [4] that the general forms of Lorentz invariant tensors are multi-products of the metric, $\eta^{\mu\nu}$, and the totally antisymmetric tensor, $\epsilon^{\mu_1\mu_2\cdots}$, which verifies eq.(1.55).

1.4 Crucial Identities for Super Yang-Mills

The following identities are crucial to show the existence of the non-Abelian super Yang-Mills in THREE, FOUR, SIX and TEN dimensions.

(i) The following identity holds only in THREE or FOUR dimensions with arbitrary signature

$$0 = (\gamma^\mu C^{-1})_{\alpha\beta}(\gamma_\mu C^{-1})_{\gamma\delta} + \text{cyclic permutations of } \alpha, \beta, \gamma \tag{1.57}$$

To verify the identity in even dimensions we contract $(\gamma^\mu C^{-1})_{\alpha\beta}(\gamma_\mu)_{\gamma\delta}$ with $(C\gamma^{\nu_1\nu_2\cdots\nu_n})_{\beta\alpha}$ and take cyclic permutations of α, β, γ to get

$$0 = 2^{d/2}\delta^n_1 + (d-2n)(\zeta + \zeta^n(-1)^{\frac{1}{2}n(n-1)})(-1)^{n+\frac{1}{8}d(d-\zeta 2)} \tag{1.58}$$

This equation must be satisfied for all $0 \leq n \leq d$, which is valid only in $d = 4, \zeta = -1$. Similar analysis can be done for the $d+1$ odd dimensions by adding $(\gamma^{(d+1)}C^{-1})_{\alpha\beta}(\gamma^{(d+1)}C^{-1})_{\gamma\delta}$ term into eq.(1.57). We get

$$0 = 2^{d/2}(\delta^n_1 + \delta^n_d) + (d-2n+1)(\zeta + \zeta^n(-1)^{\frac{1}{2}n(n-1)})(-1)^{n+\frac{1}{8}d(d-\zeta 2)}, \qquad \zeta = (-1)^{d/2} \tag{1.59}$$

Only in $d = 2$ and hence three dimensions, this equation is satisfied for all $0 \leq n \leq d$.

(ii) The following identity holds only in TWO, FOUR or SIX dimensions with arbitrary signature

$$0 = (\sigma^\mu)_{\alpha\beta}(\sigma_\mu)_{\gamma\delta} + (\sigma^\mu)_{\gamma\beta}(\sigma_\mu)_{\alpha\delta} \tag{1.60}$$

To verify this identity we take d dimensional sigma matrices from $f = d-2$ dimensional gamma matrices as in eq.(1.31)

$$\sigma^\mu = (\gamma^\mu, \gamma^{(f+1)}, i) \tag{1.61}$$

to get

$$(\sigma^\mu)_{\alpha\beta}(\sigma_\mu)_{\gamma\delta} = (\gamma^\mu)_{\alpha\beta}(\gamma_\mu)_{\gamma\delta} + (\gamma^{(f+1)})_{\alpha\beta}(\gamma^{(f+1)})_{\gamma\delta} - \delta_{\alpha\beta}\delta_{\gamma\delta} \tag{1.62}$$

Again this expression is valid for any signature, (t,s). Now we contract this equation with $(\gamma^{\nu_1\nu_2\cdots\nu_n}C_+^{-1})_{\beta\delta}$. From eqs.(1.24, 1.30) in the case of odd t we get

$$\left((-1)^n(f-2n)+(-1)^{\frac{f}{2}+n}-1\right)(\gamma^{\nu_1\nu_2\cdots\nu_n}C_+^{-1})_{\alpha\gamma} \tag{1.63}$$

To satisfy eq.(1.60) this expression must be anti-symmetric over $\alpha\leftrightarrow\gamma$ for any $0\leq n\leq f$. Thus from eq.(1.29) we must require $0=(-1)^n(f-2n)+(-1)^{\frac{f}{2}+n}-1$ for all n satisfying $(-1)^{\frac{1}{8}f(f-2)+\frac{1}{2}n(n-1)}=1$. This condition is satisfied only in $f=0,2,4$ and hence $d=2,4,6$ ($f=6$ case is excluded by choosing $n=6$ and $f\geq 8$ cases are excluded by choosing either $n=0$ or $n=3$).

(iii) The following identity holds only in TWO or TEN dimensions with arbitrary signature

$$0=(\sigma^\mu \mathrm{c}^{-1})_{\alpha\beta}(\sigma_\mu \mathrm{c}^{-1})_{\gamma\delta}+\text{cyclic permutations of }\alpha,\beta,\gamma \tag{1.64}$$

2. Spinors

2.1 Weyl Spinor

In any even d dimensions, Weyl spinor, ψ, satisfies

$$\gamma^{(d+1)}\psi = \psi \tag{2.1}$$

and so $\bar{\psi} = \psi^{\dagger}A$ satisfies from eq.(1.30)

$$\bar{\psi}\gamma^{(d+1)} = (-1)^t\bar{\psi} \qquad \gamma^{(d+1)}C_{\pm}^{-1}\bar{\psi}^T = (-1)^{\frac{t-s}{2}}C_{\pm}^{-1}\bar{\psi}^T \tag{2.2}$$

2.2 Majorana Spinor

By definition Majorana spinor satisfies

$$\bar{\psi} = \psi^T C_{\pm} \qquad \text{or} \qquad \bar{\psi} = \psi^T C \tag{2.3}$$

depending on the dimensions, even or odd. This is possible only if $\varepsilon_{\pm}, \varepsilon = 1$ and so from eqs.(1.19, 1.48)

$$\begin{aligned} \eta = +1 \;\; &: \qquad t - s = 0, 1, 2 \bmod 8 \\ \eta = -1 \;\; &: \qquad t - s = 0, 6, 7 \bmod 8 \end{aligned} \tag{2.4}$$

where η is the sign factor, ± 1, occuring in eq.(1.17) or eq.(1.45)[6].

2.3 Majorana-Weyl Spinor

Majorana-Weyl spinor satisfies both of the two conditions above

$$\gamma^{(d+1)}\psi = \psi \qquad \bar{\psi} = \psi^T C_{\pm} \tag{2.5}$$

Majorana-Weyl Spinor exists only if

$$\begin{aligned} \eta = +1 \;\; &: \qquad t - s = 0 \bmod 8 \\ \eta = -1 \;\; &: \qquad t - s = 0 \bmod 8 \end{aligned} \tag{2.6}$$

[6] In [2], $\eta = -1$ case is called Majorana and $\eta = +1$ case is called pseudo-Majorana.

3. Majorana Representation and SO(8)

Fact 1:
Consider a finite dimensional vector space, $\mathcal{V}$ with the unitary and symmetric matrix, $\mathcal{B} = \mathcal{B}^T$, $\mathcal{B}\mathcal{B}^\dagger = 1$. For every $|v\rangle \in \mathcal{V}$ if $\mathcal{B}|v\rangle^* \in \mathcal{V}$ then there exists an orthonormal "semi-real " basis, $\mathcal{V} = \{|l\rangle,\, l = 1, 2, \cdots\}$ such that $\mathcal{B}|l\rangle^* = |l\rangle$.

Proof
Start with an arbitrary orthonormal bais, $\{|v_l\rangle,\, l = 1, 2, \cdots\}$ and let $|1\rangle \propto |v_1\rangle + \mathcal{B}|v_1\rangle^*$. After the normalization, $\langle 1|1\rangle = 1$, we can take a new orthonormal basis, $\{|1\rangle, |2'\rangle, |3'\rangle, \cdots\}$. Now we assume that $\{|1\rangle, |2\rangle, \cdots |k-1\rangle, |k'\rangle, |(k+1)'\rangle, \cdots\}$ is an orhonormal basis such that $\mathcal{B}|j\rangle^* = |j\rangle$ for $1 \leq j \leq k-1$. To construct the k th such a vector, $|k\rangle$ we set $|k\rangle \propto |k'\rangle + \mathcal{B}|k'\rangle^*$ with the normalization. We check this is orthogonal to $|j\rangle$, $1 \leq j \leq k-1$

$$\langle j|\big(\,|k'\rangle + \mathcal{B}|k'\rangle^*\,\big) = 0 + \langle k|j\rangle = 0\,. \tag{3.1}$$

In this way one can construct the desired basis.

In the spacetime which admits Majorana spinor from Eq.(2.4)

$$\begin{aligned} \eta = +1 \;\; &: \qquad t - s = 0, 1, 2 \text{ mod } 8 \\ \eta = -1 \;\; &: \qquad t - s = 0, 6, 7 \text{ mod } 8\,, \end{aligned} \tag{3.2}$$

more explicitly in the even dimensions having $\varepsilon_+ = 1$ (or $\varepsilon_- = 1$) where B_+ (or B_-) is symmetric and also in the odd dimensions of $\varepsilon = 1$ where B is symmetric, from the **fact 1** above we can choose an "semi-real " orthonormal basis such that $B_\eta^\dagger|l\rangle^* = |l\rangle$ In the basis, we write the gamma matrices

$$\gamma^\mu = \sum R^\mu_{lm}|l\rangle\langle m|\,. \tag{3.3}$$

From $\eta\,\gamma^{\mu *} = B_\eta\gamma^\mu B_\eta^{-1}$ and the property of the semi-real basis, $B_\eta|l\rangle^* = |l\rangle$ we get

$$(R^\mu_{lm})^* = \eta R^\mu_{lm}\,. \tag{3.4}$$

Since R^μ is also a representation of the gamma matrix

$$R^\mu R^\nu + R^\nu R^\mu = 2\eta^{\mu\nu}\,, \tag{3.5}$$

adopting the true real basis, we conclude that **there exists a Majorana represention where the gamma matrices are real, $\eta = +$ or pure imaginary, $\eta = -$ in any spacetime admitting Majorana spinors.**

Furthermore from Eq.(1.30), in the even dimension of $t - s \equiv 0$ mod 8, $\varepsilon_\pm = 1$ and $\gamma^{(d+1)*} = B\gamma^{(d+1)}B^{-1}$ (here we omit the subscript index $\pm$ or η for simplicity.). The action, $|v\rangle \to B^\dagger|v\rangle^*$ preserves the chirality, and from the **fact 1** above we can choose an orthonormal semi-real basis for the chiral and anti-chiral spinor spaces, $\mathcal{V} = \mathcal{V}_+ + \mathcal{V}_-$, $\mathcal{V}_\pm = \{|l_\pm\rangle\}$ such that

$$\langle l_\pm|m_\pm\rangle = \delta_{lm}\,, \qquad \langle l_\pm|m_\mp\rangle = 0\,, \qquad \gamma^{(d+1)}|l_\pm\rangle = \pm|l_\pm\rangle\,, \qquad B^\dagger|l_\pm\rangle^* = |l_\pm\rangle\,. \tag{3.6}$$

With the semi-real basis

$$\gamma^{(d+1)} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\,, \tag{3.7}$$

and the gamma matrices are in the Majorana representation

$$\gamma^\mu = \begin{pmatrix} 0 & r^\mu \\ r^T_\mu & 0 \end{pmatrix}\,, \qquad r^\mu \in \mathrm{O}(2^{d/2-1})\,, \qquad r^\mu r^{\nu T} + r^\nu r^{\mu T} = 2\delta^{\mu\nu}\,. \tag{3.8}$$

From Eq.(3.6) any two sets of semi-real basis, say $\{|l_\pm\rangle\}$ and $\{|\tilde{l}_\pm\rangle\}$ are connected by an $\mathrm{O}((2^{d/2-1}))$ transformation

$$|\tilde{l}_\pm\rangle = \sum_m \Lambda_{\pm ml}|m_\pm\rangle\,, \qquad \sum_m \Lambda_{\pm lm}\Lambda_{\pm nm} = \delta_{ln}\,. \tag{3.9}$$

If we define

$$\Lambda_\pm = \sum_{l,m} \Lambda_{\pm lm}|l_\pm\rangle\langle m_\pm|\,, \tag{3.10}$$

then $|\tilde{l}_\pm\rangle = \Lambda_\pm|l_\pm\rangle$ and from the definition of the semi-real basis

$$\Lambda_\pm = B^\dagger\Lambda^*_\pm B = \Lambda_\pm P_\pm = P_\pm\Lambda_\pm\,, \qquad \Lambda_\pm\Lambda^\dagger_\pm = P_\pm\,. \tag{3.11}$$

We write

$$\Lambda_\pm = e^{M_\pm}\,, \qquad M_\pm \equiv \sum_{n=1}^{\infty}(-1)^{n+1}\frac{1}{n}(\Lambda_\pm - P_\pm)^n = \ln\,\Lambda_\pm\,. \tag{3.12}$$

Thus for $\Lambda_\pm$ such that the infinity sum converges we have

$$M_\pm = -M^\dagger_\pm = B^\dagger M^*_\pm B = M_\pm P_\pm = P_\pm M_\pm\,. \tag{3.13}$$

This gives a strong constraint when we express $M_\pm$ by the gamma matrix products. For the Eucledean eight dimensions only the SO(8) generators for the spinors survive in the expansion!

$$M_\pm = \tfrac{1}{2}w_{ab}\gamma^{ab}P_\pm\,. \tag{3.14}$$

Namely we find an isomorphism between the two SO(8)'s, one for the semi-real vectors and the other for the spinors in the conventional sense. Alternatively this can be seen from

$$\gamma^{ab} = \begin{pmatrix} r^{[a}r^{b]\,T} & 0 \\ 0 & r^{[a\,T}r^{b]} \end{pmatrix}\,, \tag{3.15}$$

where the each block diagonal is a generator of $\mathrm{SO}(D)$ while the dimension of the chiral space is $2^{d/2-1}$. Only in $d = 8$ both coincide leading to the "so(8) triolity" among $\mathrm{so}_v(8)$, $\mathrm{so}_c(8)$ and $\mathrm{so}_{\bar{c}}(8)$.

Fact 2: Relation to octonions.
In Euclidean eight dimensions, the 16×16 gamma matrices can be taken of the off-block diagonal form,

$$\gamma_a = \begin{pmatrix} 0 & r_a \\ r_a^T & 0 \end{pmatrix} , \qquad r_a r_b^T + r_b r_a^T = 2\delta_{ab} , \tag{3.16}$$

where the 8×8 real matrices, r_a, $1 \leq a \leq 8$, give the multiplication of the octonions, o_a,

$$o_a o_b = (r_a)_b{}^c o_c . \tag{3.17}$$

Fact 3:
Consider an arbitrary real self-dual or anti-self-dual four form in $D = 8$

$$T^{\pm}_{abcd} = \pm\tfrac{1}{4}\,\epsilon_{abcdefgh} T^{\pm efgh} . \tag{3.18}$$

Using the SO(8) rotations one can transform the four form into the canonical form where the non-vanishing components are $T^{\pm}_{1234}$, $T^{\pm}_{1256}$, $T^{\pm}_{1278}$, $T^{\pm}_{1357}$, $T^{\pm}_{1368}$, $T^{\pm}_{1458}$, $T^{\pm}_{1467}$ and their dual counter parts only.

Proof
We start with the seven linearly independent traceless Hermitian matrices

$$\begin{array}{l} E_{\pm 1} = \gamma^{2341} P_{\pm} , \quad E_{\pm 2} = \gamma^{2561} P_{\pm} , \quad E_{\pm 3} = \gamma^{2781} P_{\pm} , \quad E_{\pm 4} = \gamma^{1357} P_{\pm} , \\ E_{\pm 5} = \gamma^{3681} P_{\pm} , \quad E_{\pm 6} = \gamma^{4581} P_{\pm} , \quad E_{\pm 7} = \gamma^{4671} P_{\pm} . \end{array} \tag{3.19}$$

As they commute each other, there exists a basis $\mathcal{V}_{\pm} = \{|l_{\pm}\rangle\}$ diagonalizing the seven quantities

$$E_{\pm r} = \sum_l \lambda_{rl} |l_{\pm}\rangle\langle l_{\pm}| , \qquad (\lambda_{rl})^2 = 1 . \tag{3.20}$$

Further, since $C|l_{\pm}\rangle^*$ is also an eigenvector of the same eigenvalues, from the **fact 1** we can impose the semi-reality condition without loss of generality, $C|l_{\pm}\rangle^* = |l_{\pm}\rangle$.

Now for the self-dual four form we let

$$T^{\pm} = \tfrac{1}{4} T^{\pm}_{abcd} \gamma^{abcd} . \tag{3.21}$$

Since $T^{\pm}$ is Hermitian and $C(T^{\pm})^* C^{\dagger} = T^{\pm}$, one can diagonalize $T^{\pm}$ with a semi-real basis

$$T^{\pm} = \sum_l \lambda_l |\tilde{l}_{\pm}\rangle\langle \tilde{l}_{\pm}| , \qquad C|\tilde{l}_{\pm}\rangle^* = |\tilde{l}_{\pm}\rangle . \tag{3.22}$$

For the two semi-real basis above we define a transformation matrix

$$O_{\pm} = |l_{\pm}\rangle\langle \tilde{l}_{\pm}| . \tag{3.23}$$

Then, since $T^{\pm}$ is traceless, $O_{\pm}T^{\pm}O_{\pm}^{\dagger}$ can be written in terms of $E_{\pm i}$'s. Finally the fact $O_{\pm}$ gives a spinorial SO(8) rotation completes our proof.

Some useful formulae are

$$\begin{aligned}\pm P_{\pm} &= E_{\pm 1}E_{\pm 2}E_{\pm 3} = E_{\pm 1}E_{\pm 4}E_{\pm 5} = E_{\pm 1}E_{\pm 6}E_{\pm 7} = E_{\pm 2}E_{\pm 4}E_{\pm 6} \\ &= E_{\pm 2}E_{\pm 5}E_{\pm 7} = E_{\pm 3}E_{\pm 4}E_{\pm 7} = E_{\pm 3}E_{\pm 5}E_{\pm 6}\,.\end{aligned} \tag{3.24}$$

For an arbitrary self-dual or anti-self-dual four form tensor in $D = 8$, from

$$\begin{aligned}T^{\pm}_{acde}T^{\pm bcde} &= (\tfrac{1}{4!})^2\epsilon_{acdefghi}\epsilon^{bcdejklm}T^{\pm fghi}T^{\pm}_{jklm} \\ &= \tfrac{1}{4}\,\delta_a{}^b T^{\pm}_{cdef}T^{\pm cdef} - T^{\pm}_{acde}T^{\pm bcde}\,,\end{aligned} \tag{3.25}$$

we obtain an identity

$$T^{\pm}_{acde}T^{\pm bcde} = \tfrac{1}{8}\,\delta_a{}^b\,T^{\pm}_{cdef}T^{\pm cdef}\,. \tag{3.26}$$

4. Superalgebra

4.1 Graded Lie Algebra

Supersymmetry algebra is a $\hat{Z}_2$ graded Lie algebra, $\mathbf{g} = \{T_a\}$, which is an algebra with commutation and anti-commutation relations [5, 6]

$$[T_a, T_b\} = C^c_{ab} T_c \tag{4.1}$$

where C^c_{ab} is the structure constant and

$$[T_a, T_b\} = T_a T_b - (-1)^{\#a\#b} T_b T_a \tag{4.2}$$

with $\#a$, the $\hat{Z}_2$ grading of T_a,

$$\#a = \begin{cases} 0 \text{ for bosonic } a \\ 1 \text{ for fermionic } a \end{cases} \tag{4.3}$$

The generalized Jacobi identity is

$$[T_a, [T_b, T_c\}\} - (-1)^{\#a\#b}[T_b, [T_a, T_c\}\} = [[T_a, T_b\}, T_c\} \tag{4.4}$$

which implies

$$(-1)^{\#a\#c} C^d_{ab} C^e_{dc} + (-1)^{\#b\#a} C^d_{bc} C^e_{da} + (-1)^{\#c\#b} C^d_{ca} C^e_{db} = 0 \tag{4.5}$$

For a graded Lie algebra we consider

$$g(z) = \exp(z^a T_a) \tag{4.6}$$

where z^a is a superspace coordinate component which has the same bosonic or fermionic property as T_a and hence $z^a T_a$ is bosonic.

In the general case of non-commuting objects, say A and B, the Baker-Campbell-Haussdorff formula gives

$$e^A e^B = \exp\left(\sum_{n=0}^{\infty} C_n(A, B)\right) \tag{4.7}$$

where $C_n(A, B)$ involves n commutators. The first three of these are

$$\begin{aligned} C_0(A, B) &= A + B \\ C_1(A, B) &= \tfrac{1}{2}[A, B] \\ C_2(A, B) &= \tfrac{1}{12}[[A, B], B] + \tfrac{1}{12}[A, [A, B]] \end{aligned} \tag{4.8}$$

Since for the graded algebra

$$[z^a T_a, z^b T_b] = z^b z^a [T_a, T_b\} = z^b z^a C^c_{ab} T_c \tag{4.9}$$

the Baker-Campbell-Haussdorff formula (4.7) implies that $g(z)$ forms a group, the graded Lie group. Hence we may define a function on superspace, $f^a(w,z)$, by

$$g(w)g(z) = g(f(w,z)) \tag{4.10}$$

Since $g(0) = e$, the identity, we have $f(0,z) = z$, $f(w,0) = w$ and further we assume that $f(w,z)$ has a Taylor expansion in the neighbourhood of $w = z = 0$.
Associativity of the group multiplication requires $f(w,z)$ to satisfy

$$f(f(u,w),z) = f(u,f(w,z)) \tag{4.11}$$

4.2 Left & Right Invariant Derivatives

For a graded Lie group, left and right invariant derivatives, L_a, R_a are defined by

$$L_a g(z) = g(z)T_a \tag{4.12}$$

$$R_a g(z) = -T_a g(z) \tag{4.13}$$

Explicitly we have

$$L_a = L_a{}^b(z)\partial_b \qquad L_a{}^b(z) = \left.\frac{\partial f^b(z,u)}{\partial u^a}\right|_{u=0} \tag{4.14}$$

$$R_a = R_a{}^b(z)\partial_b \qquad R_a{}^b(z) = -\left.\frac{\partial f^b(u,z)}{\partial u^a}\right|_{u=0} \tag{4.15}$$

where $\partial_b = \frac{\partial}{\partial z^b}$.
It is easy to see that L_a is invariant under left action, $g(z) \to hg(z)$, and R_a is invariant under right action, $g(z) \to g(z)h$.
From eqs.(4.12, 4.13) we get

$$[L_a, L_b\} = C^c_{ab} L_c \tag{4.16}$$

$$[R_a, R_b\} = C^c_{ab} R_c \tag{4.17}$$

and from eqs.(4.12, 4.13) we can also easily show

$$[L_a, R_b\} = 0 \tag{4.18}$$

Thus, $L_a(z)$, $R_a(z)$ form representations of the graded Lie algebra separately. For the supersymmetry algebra, the left invariant derivatives become covariant derivatives, while the right invariant derivatives become the generators of the supersymmetry algebra acting on superfields.

4.3 Superspace & Supermatrices

In general a superspace may be denoted by $\mathbf{R}^{p|q}$, where p, q are the number of real commuting (bosonic) and anti-commuting (fermionic) variables respectively. A supermatrix which takes $\mathbf{R}^{p|q} \to \mathbf{R}^{p|q}$ may be represented by a $(p+q) \times (p+q)$ matrix, M, of the form

$$M = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \tag{4.19}$$

where a, d are $p \times p$, $q \times q$ matrices of Grassmanian even or bosonic variables and b, c are $p \times q$, $q \times p$ matrices of Grassmanian odd or fermionic variables respectively.
The inverse of M can be expressed as

$$M^{-1} = \begin{pmatrix} (a - bd^{-1}c)^{-1} & -a^{-1}b(d - ca^{-1}b)^{-1} \\ -d^{-1}c(a - bd^{-1}c)^{-1} & (d - ca^{-1}b)^{-1} \end{pmatrix} \tag{4.20}$$

where we may write

$$(a - bd^{-1}c)^{-1} = a^{-1} + \sum_{n=1}^{\infty} (a^{-1}bd^{-1}c)^n a^{-1} \tag{4.21}$$

Note that due to the fermionic property of b, c, the power series terminates at $n \leq pq + 1$.
The supertrace and the superdeterminant of M are defined as

$$\operatorname{str} M = \operatorname{tr} a - \operatorname{tr} d \tag{4.22}$$

$$\operatorname{sdet} M = \det(a - bd^{-1}c) / \det d = \det a / \det(d - ca^{-1}b) \tag{4.23}$$

The last equality comes from

$$\det(1 - a^{-1}bd^{-1}c) = \det{}^{-1}(1 - d^{-1}ca^{-1}b) \tag{4.24}$$

which may be shown using

$$\det(1 - a) = \exp\left(- \sum_{n=1}^{\infty} \frac{1}{n} \operatorname{tr} a^n \right) \tag{4.25}$$

and observing

$$\operatorname{tr}\,(a^{-1}bd^{-1}c)^n = -\operatorname{tr}\,(d^{-1}ca^{-1}b)^n \tag{4.26}$$

From eq.(4.23) we note that $\operatorname{sdet} M \neq 0$ implies the existence of M^{-1}. Thus the set of supermatrices for $\operatorname{sdet} M \neq 0$ forms the supergroup, $\mathrm{Gl}(p|q)$. If $\operatorname{sdet} M = 1$ then $M \in \mathrm{Sl}(p|q)$.
The supertrace and the superdeterminant have the properties

$$\operatorname{str}\,(M_1 M_2) = \operatorname{str}\,(M_2 M_1) \tag{4.27}$$

$$\operatorname{sdet}\,(M_1 M_2) = \operatorname{sdet} M_1 \operatorname{sdet} M_2 \tag{4.28}$$

We may define the transpose of the supermatrix, M, either as

$$M^t = \begin{pmatrix} a^t & c^t \\ -b^t & d^t \end{pmatrix} \tag{4.29}$$

or as

$$M^{t'} = \begin{pmatrix} a^t & -c^t \\ b^t & d^t \end{pmatrix} \tag{4.30}$$

where a^t, b^t, c^t, d^t are the ordinary transposes of a, b, c, d respectively.
We note that

$$(M_1 M_2)^t = M_2^t M_1^t \qquad (M_1 M_2)^{t'} = M_2^{t'} M_1^{t'} \tag{4.31}$$

$$(M^t)^{t'} = (M^{t'})^t = M \tag{4.32}$$

A. Proof of the Lemma

Lemma 1
Any $N \times N$ matrix, M, satisfying $M^2 = \lambda^2 1_{N\times N}$, $\lambda \neq 0$, is diagonalizable.

Proof
Suppose for some K, $1 \leq K \leq N$, we have found a basis,

$$\{e_a,\ v_r\ :\ 1 \leq a \leq K,\ 1 \leq r \leq N-K\} \tag{A.1}$$

such that

$$\begin{aligned} Me_a &= \lambda_a e_a\,, && \text{for } 1 \leq a \leq K\,, \\ Mv_r &= P^s{}_r v_s + h^a{}_r e_a\,, && \text{for } K+1 \leq r, s \leq N\,. \end{aligned} \tag{A.2}$$

From $M^2 = \lambda^2 1_{N\times N}$,

$$\begin{aligned} &\lambda_a^2 = \lambda^2\,, \\ &\lambda^2 v_r = (P^2)^s{}_r v_s + [(hP)^a{}_r + \lambda_a h^a{}_r]\, e_a\,, \end{aligned} \tag{A.3}$$

and hence,

$$\begin{aligned} &P^2 = \lambda^2 1_{(N-K)\times(N-K)}\,, \\ &(hP)^a{}_r + \lambda_a h^a{}_r = 0\,. \end{aligned} \tag{A.4}$$

The assumption holds for $K = 1$ surely. In order to construct e_{K+1} we first consider an eigenvector of the $(N-K)\times(N-K)$ matrix, P,

$$P^r{}_s c^s = \lambda_{K+1} c^r\,, \qquad \lambda_{K+1}^2 = \lambda^2\,, \tag{A.5}$$

and set

$$\begin{aligned} &v = c^r v_r\,, \qquad h^a = h^a{}_r c^r\,, \\ &Mv = \lambda_{K+1} v + h^a e_a\,. \end{aligned} \tag{A.6}$$

Consequently

$$(\lambda_{K+1} + \lambda_a) h^a = 0 \qquad : \quad \text{not}\ \ a\ \ \text{sum}\,, \tag{A.7}$$

so that

$$h^a = 0 \qquad \text{if} \qquad \lambda_{K+1} + \lambda_a \neq 0\,. \tag{A.8}$$

We construct e_{K+1}, with K unknown coefficients, d^a, as

$$e_{K+1} = v + d^a e_a\,. \tag{A.9}$$

From

$$Me_{K+1} = \lambda_{K+1} e_{K+1} + [h^a + (\lambda_a - \lambda_{K+1}) d^a]\, e_a\,, \tag{A.10}$$

we determine

$$d^a = \begin{cases} \dfrac{h^a}{\lambda_{K+1} - \lambda_a} & \text{if} \quad \lambda_{K+1} \neq \lambda_a \,, \\ \\ \text{any number} & \text{if} \quad \lambda_{K+1} = \lambda_a \,. \end{cases} \tag{A.11}$$

From (A.8) and $\lambda_{K+1}^2 = \lambda_a^2 = \lambda^2 \neq 0$, we have

$$M e_{K+1} = \lambda_{K+1} e_{K+1} \,. \tag{A.12}$$

This completes our proof.

If we set a $N \times N$ invertible matrix, S, by

$$(S)^b{}_a = (e_a)^b \,, \qquad M e_a = \lambda_a e_a \,, \qquad 1 \leq a, b \leq N \,, \tag{A.13}$$

then

$$S^{-1} M S = \mathrm{diag}(\lambda_1, \lambda_2, \cdots, \lambda_N) \,. \tag{A.14}$$

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