

Cross Products

Most of the material presented here is taken from [1].

Given a finite dimensional vector space \mathcal{V} over a field \mathbb{F} with characteristic zero and with an inner product $g : \mathcal{V} \times \mathcal{V} \rightarrow \mathbb{F}$ define a bilinear map $E : \mathcal{V} \times \mathcal{V} \rightarrow \mathcal{V}$ with the following properties:

- I. Bilinear property: $E(ax + by, z) = aE(x, z) + bE(y, z)$, $E(x, ay + bz) = aE(x, y) + bE(x, z)$ where $x, y, z \in \mathcal{V}$ and $a, b \in \mathbb{F}$.
- II. Antisymmetric property:

$$g(E(\mathbf{x}, \mathbf{y}), E(\mathbf{x}, \mathbf{y})) = \begin{vmatrix} g(\mathbf{x}, \mathbf{x}) & g(\mathbf{x}, \mathbf{y}) \\ g(\mathbf{y}, \mathbf{x}) & g(\mathbf{y}, \mathbf{y}) \end{vmatrix}$$

for all $\mathbf{x}, \mathbf{y} \in \mathcal{V}$. This is an expression of the antisymmetric property since

$$\begin{aligned} g(E(\mathbf{x}, \mathbf{y}), E(\mathbf{y}, \mathbf{x})) &= \begin{vmatrix} g(\mathbf{x}, \mathbf{y}) & g(\mathbf{x}, \mathbf{x}) \\ g(\mathbf{y}, \mathbf{y}) & g(\mathbf{y}, \mathbf{x}) \end{vmatrix} = -\begin{vmatrix} g(\mathbf{x}, \mathbf{x}) & g(\mathbf{x}, \mathbf{y}) \\ g(\mathbf{y}, \mathbf{x}) & g(\mathbf{y}, \mathbf{y}) \end{vmatrix} \\ &= -g(E(\mathbf{x}, \mathbf{y}), E(\mathbf{x}, \mathbf{y})) = g(E(\mathbf{x}, \mathbf{y}), -E(\mathbf{x}, \mathbf{y})) \end{aligned}$$

and so we must have $E(\mathbf{x}, \mathbf{y}) = -E(\mathbf{y}, \mathbf{x})$.

- III. Orthogonal property: $g(E(\mathbf{x}, \mathbf{y}), \mathbf{x}) = g(E(\mathbf{x}, \mathbf{y}), \mathbf{y}) = 0$.

We can use the bilinear map E to induce a linear map $L_x : \mathcal{V} \rightarrow \mathcal{V}$ as follows:

$$L_x(\mathbf{y}) = E(\mathbf{x}, \mathbf{y}), \text{ for all } \mathbf{y} \in \mathcal{V}.$$

This follows from property I. We note that

$$L_x^2(\mathbf{y}) = L_x E(\mathbf{x}, \mathbf{y}) = E(\mathbf{x}, E(\mathbf{x}, \mathbf{y})).$$

From property II we have

$$\begin{aligned} g(E(\mathbf{x}, E(\mathbf{x}, \mathbf{y})), E(\mathbf{x}, E(\mathbf{x}, \mathbf{y}))) &= \begin{vmatrix} g(\mathbf{x}, \mathbf{x}) & g(\mathbf{x}, E(\mathbf{x}, \mathbf{y})) \\ g(E(\mathbf{x}, \mathbf{y}), \mathbf{x}) & g(E(\mathbf{x}, \mathbf{y}), E(\mathbf{x}, \mathbf{y})) \end{vmatrix} \\ &= \begin{vmatrix} g(\mathbf{x}, \mathbf{x}) & 0 \\ 0 & g(E(\mathbf{x}, \mathbf{y}), E(\mathbf{x}, \mathbf{y})) \end{vmatrix} \\ &= g(\mathbf{x}, \mathbf{x})g(E(\mathbf{x}, \mathbf{y}), E(\mathbf{x}, \mathbf{y})) \\ &= g(\mathbf{x}, \mathbf{x})(g(\mathbf{x}, \mathbf{x})g(\mathbf{y}, \mathbf{y}) - g(\mathbf{x}, \mathbf{y})^2) \\ &= g(\mathbf{x}, \mathbf{x})^2g(\mathbf{y}, \mathbf{y}) - g(\mathbf{x}, \mathbf{y})^2g(\mathbf{x}, \mathbf{x}) \\ &= g(\mathbf{x}, \mathbf{x})^2g(\mathbf{y}, \mathbf{y}) + g(\mathbf{x}, \mathbf{y})^2g(\mathbf{x}, \mathbf{x}) \\ &\quad - 2g(\mathbf{x}, \mathbf{y})^2g(\mathbf{x}, \mathbf{x}) \end{aligned}$$

$$= g(g(\mathbf{x}, \mathbf{y})\mathbf{x} - g(\mathbf{x}, \mathbf{x})\mathbf{y}, g(\mathbf{x}, \mathbf{y})\mathbf{x} - g(\mathbf{x}, \mathbf{x})\mathbf{y}).$$

Therefore

$$E(\mathbf{x}, E(\mathbf{x}, \mathbf{y})) = g(\mathbf{x}, \mathbf{y})\mathbf{x} - g(\mathbf{x}, \mathbf{x})\mathbf{y}$$

and

$$L_x^2(\mathbf{y}) = g(\mathbf{x}, \mathbf{y})\mathbf{x} - g(\mathbf{x}, \mathbf{x})\mathbf{y}.$$

The tensor product $\mathbf{x} \otimes \mathbf{y}$ induces a linear map $T_{x \otimes y} : \mathcal{V} \rightarrow \mathcal{V}$ defined as

$$T_{x \otimes y}(\mathbf{z}) = g(\mathbf{y}, \mathbf{z})\mathbf{x}, \text{ for all } \mathbf{z} \in \mathcal{V}.$$

From these definitions we can also generate the composite maps

$$T_{x \otimes y} L_z(\mathbf{u}) = T_{x \otimes y}(E(\mathbf{z}, \mathbf{u})) = g(\mathbf{y}, E(\mathbf{z}, \mathbf{u}))\mathbf{x}$$

and

$$L_x T_{y \otimes z}(\mathbf{u}) = L_x(g(\mathbf{z}, \mathbf{u})\mathbf{y}) = g(\mathbf{z}, \mathbf{u})E(\mathbf{x}, \mathbf{y}) = T_{E(x,y) \otimes z}\mathbf{u}. \quad (1) \quad \boxed{\text{eq:xcrossytensorz}}$$

Note that since

$$g(\mathbf{x} + \mathbf{y}, E(\mathbf{x} + \mathbf{y}, \mathbf{z})) = 0$$

(using property $\overset{\text{num; orthogonal}}{(\text{III})}$ we have

$$\begin{aligned} g(\mathbf{x} + \mathbf{y}, E(\mathbf{x} + \mathbf{y}, \mathbf{z})) &= g(\mathbf{x} + \mathbf{y}, E(\mathbf{x}, \mathbf{z}) + E(\mathbf{y}, \mathbf{z})) \\ &= g(\mathbf{x}, E(\mathbf{x}, \mathbf{z})) + g(\mathbf{y}, E(\mathbf{x}, \mathbf{z})) + g(\mathbf{x}, E(\mathbf{y}, \mathbf{z})) + g(\mathbf{y}, E(\mathbf{y}, \mathbf{z})) \\ &= g(\mathbf{y}, E(\mathbf{x}, \mathbf{z})) + g(\mathbf{x}, E(\mathbf{y}, \mathbf{z})) = 0. \end{aligned}$$

So we obtain

$$g(\mathbf{y}, E(\mathbf{z}, \mathbf{x})) = g(\mathbf{x}, E(\mathbf{y}, \mathbf{z}))$$

using the antisymmetric property of E . In the same way we can prove that this property is cyclic, i.e.

$$g(\mathbf{x}, E(\mathbf{y}, \mathbf{z})) = g(\mathbf{y}, E(\mathbf{z}, \mathbf{x})) = g(\mathbf{z}, E(\mathbf{x}, \mathbf{y})).$$

This means that we can write

$$g(\mathbf{y}, E(\mathbf{z}, \mathbf{u})) = g(\mathbf{z}, E(\mathbf{u}, \mathbf{y})) = g(\mathbf{u}, E(\mathbf{y}, \mathbf{z})) \quad (2) \quad \boxed{\text{eq:cyclic}}$$

and so

$$T_{x \otimes y} L_z(\mathbf{u}) = g(\mathbf{u}, E(\mathbf{y}, \mathbf{z}))\mathbf{x} = T_{x \otimes E(y,z)}(\mathbf{u}). \quad (3) \quad \boxed{\text{eq:xtensorycrossz}}$$

Using these properties we can write

$$L_x^2(\mathbf{y}) = g(\mathbf{x}, \mathbf{y})\mathbf{x} - g(\mathbf{x}, \mathbf{x})\mathbf{y} = T_{x \otimes x}(\mathbf{y}) - g(\mathbf{x}, \mathbf{x})I(\mathbf{y})$$

where $I : \mathcal{V} \rightarrow \mathcal{V}$ is the identity map. So

$$L_x^2 = T_{x \otimes x} - g(\mathbf{x}, \mathbf{x})I.$$

We can obtain the linearization of L_x^2 by writing

$$\begin{aligned} L_{x+h}^2(\mathbf{y}) &= g(\mathbf{x} + \mathbf{h}, \mathbf{y})(\mathbf{x} + \mathbf{h}) - g(\mathbf{x} + \mathbf{h}, \mathbf{x} + \mathbf{h})\mathbf{y} \\ L_{x+h}^2 &= L_{x+h}L_{x+h} = L_x^2 + L_xL_h + L_hL_x + L_h^2 \end{aligned}$$

The r.h.s. of the first equation expands to

$$\begin{aligned} L_{x+h}^2(\mathbf{y}) &= g(\mathbf{x}, \mathbf{y})\mathbf{x} - g(\mathbf{x}, \mathbf{x})\mathbf{y} + g(\mathbf{x}, \mathbf{y})\mathbf{h} - g(\mathbf{x}, \mathbf{h})\mathbf{y} \\ &\quad + g(\mathbf{h}, \mathbf{y})\mathbf{x} - g(\mathbf{h}, \mathbf{x})\mathbf{y} + g(\mathbf{h}, \mathbf{y})\mathbf{h} - g(\mathbf{h}, \mathbf{h})\mathbf{y} \\ &= L_x^2(\mathbf{y}) + g(\mathbf{x}, \mathbf{y})\mathbf{h} - g(\mathbf{x}, \mathbf{h})\mathbf{y} + L_h^2(\mathbf{y}). \end{aligned}$$

We obtain

$$L_xL_h(\mathbf{y}) + L_hL_x(\mathbf{y}) = g(\mathbf{x}, \mathbf{y})\mathbf{h} - g(\mathbf{x}, \mathbf{h})\mathbf{y} + g(\mathbf{h}, \mathbf{y})\mathbf{x} - g(\mathbf{h}, \mathbf{x})\mathbf{y}.$$

If

$$L_xL_h(\mathbf{y}) = g(\mathbf{x}, \mathbf{y})\mathbf{h} - g(\mathbf{x}, \mathbf{h})\mathbf{y} \tag{4} \quad \boxed{\text{eq:linearization}}$$

then

$$L_hL_x(\mathbf{y}) = g(\mathbf{h}, \mathbf{y})\mathbf{x} - g(\mathbf{h}, \mathbf{x})\mathbf{y}.$$

Note that this linearization agrees with the property

$$\begin{aligned} L_xL_h(\mathbf{y}) &= g(\mathbf{x}, \mathbf{y})\mathbf{h} - g(\mathbf{x}, \mathbf{h})\mathbf{y} \\ &= -(g(\mathbf{x}, \mathbf{h})\mathbf{y} - g(\mathbf{x}, \mathbf{y})\mathbf{h}) \\ &= -L_yL_x(\mathbf{h}). \end{aligned}$$

We can use the linearization of L_x^2 to complete the following derivation:

$$\begin{aligned} (L_{E(x,y)} + L_xL_y)(\mathbf{z}) &= E(E(\mathbf{x}, \mathbf{y}), \mathbf{z}) + L_xLy(\mathbf{z}) \\ &= -E(\mathbf{z}, E(\mathbf{x}, \mathbf{y})) + L_xLy(\mathbf{z}) \\ &= -L_zL_x(\mathbf{y}) + L_xLy(\mathbf{z}) \\ &= -(g(\mathbf{z}, \mathbf{y})\mathbf{x} - g(\mathbf{z}, \mathbf{x})\mathbf{y}) + g(\mathbf{x}, \mathbf{z})\mathbf{y} - g(\mathbf{x}, \mathbf{y})\mathbf{z} \\ &= 2g(\mathbf{x}, \mathbf{z})\mathbf{y} - g(\mathbf{z}, \mathbf{y})\mathbf{x} - g(\mathbf{x}, \mathbf{y})\mathbf{z}. \end{aligned}$$

This result can be used to write

$$L_{E(x,y)} + L_xL_y = 2T_{y \otimes x} - T_{x \otimes y} - g(\mathbf{x}, \mathbf{y})I. \tag{5} \quad \boxed{\text{eq:Exy_xy}}$$

From this equation we get

$$L_{E(x,y)}L_x + L_xL_yL_x = 2T_{y \otimes x}L_x - T_{x \otimes y}L_x - g(\mathbf{x}, \mathbf{y})L_x$$

$$\begin{aligned} L_x L_y L_x &= -L_{E(x,y)} L_x + 2T_{y \otimes x} L_x - T_{x \otimes y} L_x - g(\mathbf{x}, \mathbf{y}) L_x \\ L_x L_y L_x &= -L_{E(x,y)} L_x - T_{x \otimes E(y,x)} - g(\mathbf{x}, \mathbf{y}) L_x \end{aligned} \quad (6) \quad \boxed{\text{eq:first}}$$

since

$$\begin{aligned} T_{y \otimes x} L_x(\mathbf{z}) &= T_{y \otimes x}(E(\mathbf{x}, \mathbf{z})) = g(\mathbf{x}, E(\mathbf{x}, \mathbf{z})) \mathbf{y} = 0. \\ \text{From (5)} &\quad \boxed{\text{eq:Exy_xy}} \end{aligned}$$

$$\begin{aligned} L_{E(x,y)} L_x &= -L_{E(E(x,y),x)} + 2T_{x \otimes E(x,y)} - T_{E(x,y) \otimes x} - g(E(\mathbf{x}, \mathbf{y}), \mathbf{y}) I \\ &= -L_{E(E(x,y),x)} + 2T_{x \otimes E(x,y)} - T_{E(x,y) \otimes x}; \end{aligned}$$

this produces a second equation for $L_x L_y L_x$:

$$\begin{aligned} L_x L_y L_x &= -(-L_{E(E(x,y),x)} + 2T_{x \otimes E(x,y)} - T_{E(x,y) \otimes x}) - T_{x \otimes E(y,x)} - g(\mathbf{x}, \mathbf{y}) L_x \\ &= L_{E(E(x,y),x)} - 2T_{x \otimes E(x,y)} + T_{E(x,y) \otimes x} - T_{x \otimes E(y,x)} - g(\mathbf{x}, \mathbf{y}) L_x \\ &= L_{E(E(x,y),x)} - 2T_{x \otimes E(x,y)} + T_{E(x,y) \otimes x} + T_{x \otimes E(x,y)} - g(\mathbf{x}, \mathbf{y}) L_x \\ &= L_{E(E(x,y),x)} - T_{x \otimes E(x,y)} + T_{E(x,y) \otimes x} - g(\mathbf{x}, \mathbf{y}) L_x. \end{aligned} \quad (7) \quad \boxed{\text{eq:second}}$$

Next

$$E(E(\mathbf{x}, \mathbf{y}), \mathbf{x}) = -E(\mathbf{x}, E(\mathbf{x}, \mathbf{y})) = -(g(\mathbf{x}, \mathbf{y}) \mathbf{x} - g(\mathbf{x}, \mathbf{x}) \mathbf{y}) = g(\mathbf{x}, \mathbf{x}) \mathbf{y} - g(\mathbf{x}, \mathbf{y}) \mathbf{x}.$$

Therefore

$$\begin{aligned} L_{E(E(x,y),x)}(\mathbf{z}) &= E(g(\mathbf{x}, \mathbf{x}) \mathbf{y} - g(\mathbf{x}, \mathbf{y}) \mathbf{x}, \mathbf{z}) = g(\mathbf{x}, \mathbf{x}) E(\mathbf{y}, \mathbf{z}) - g(\mathbf{x}, \mathbf{y}) E(\mathbf{x}, \mathbf{z}) \\ &= g(\mathbf{x}, \mathbf{x}) L_y(\mathbf{z}) - g(\mathbf{x}, \mathbf{y}) L_x(\mathbf{z}). \end{aligned}$$

The third equation for $L_x L_y L_x$ is:

$$\begin{aligned} L_x L_y L_x &= g(\mathbf{x}, \mathbf{x}) L_y - g(\mathbf{x}, \mathbf{y}) L_x - T_{x \otimes E(x,y)} + T_{E(x,y) \otimes x} - g(\mathbf{x}, \mathbf{y}) L_x \\ &= g(\mathbf{x}, \mathbf{x}) L_y - 2g(\mathbf{x}, \mathbf{y}) L_x - T_{x \otimes E(x,y)} + T_{E(x,y) \otimes x}. \end{aligned} \quad (8) \quad \boxed{\text{eq:third}}$$

We choose an orthonormal basis $\{\mathbf{e}_i\}_{i=1}^d$ where $\dim \mathcal{V} = d$. Define the following linear map $S : \text{end}(\mathcal{V}) \rightarrow \text{end}(\mathcal{V})$

$$f \mapsto \sum_{i=1}^d L_{e_i} \circ f \circ L_{e_i}.$$

If $f = I$ then

$$S(I) = \sum_{i=1}^d L_{e_i}^2 = \sum_{i=1}^d T_{e_i \otimes e_i} - \sum_{i=1}^d I = \sum_{i=1}^d T_{e_i \otimes e_i} - dI.$$

Since

$$\sum_{i=1}^d T_{e_i \otimes e_i}(\mathbf{x}) = \sum_{i=1}^d g(\mathbf{e}_i, \mathbf{x}) \mathbf{e}_i = \mathbf{x},$$

$$S(I) = (1 - d)I. \quad (9) \quad \boxed{\text{eq:SI}}$$

If $f = T_{x \otimes y}$ then

$$\begin{aligned} S(T_{x \otimes y}) &= \sum_{i=1}^d L_{e_i} \circ T_{x \otimes y} \circ L_{e_i} \\ &= \sum_{i=1}^d L_{e_i} \circ T_{x \otimes E(y, e_i)} && \text{using (3)} \\ &= \sum_{i=1}^d T_{E(e_i, x) \otimes E(y, e_i)} && \text{using (I).} \end{aligned}$$

Using (2) $\boxed{\text{eq:cyclic}}$

$$\begin{aligned} T_{E(e_i, x) \otimes E(y, e_i)}(\mathbf{z}) &= g(E(\mathbf{y}, \mathbf{e}_i), \mathbf{z})E(\mathbf{e}_i, \mathbf{x}) \\ &= g(\mathbf{z}, E(\mathbf{y}, \mathbf{e}_i))E(\mathbf{e}_i, \mathbf{x}) \\ &= g(\mathbf{e}_i, E(\mathbf{z}, \mathbf{y}))E(\mathbf{e}_i, \mathbf{x}) \\ &= g(\mathbf{e}_i, E(\mathbf{y}, \mathbf{z}))E(\mathbf{x}, \mathbf{e}_i) \\ &= E(\mathbf{x}, g(\mathbf{e}_i, E(\mathbf{y}, \mathbf{z})))\mathbf{e}_i \end{aligned}$$

which substituted back in the summation gives

$$\begin{aligned} S(T_{x \otimes y}) &= \sum_{i=1}^d E(\mathbf{x}, g(\mathbf{e}_i, E(\mathbf{y}, \mathbf{z})))\mathbf{e}_i \\ &= E\left(\mathbf{x}, \sum_{i=1}^d g(\mathbf{e}_i, E(\mathbf{y}, \mathbf{z}))\mathbf{e}_i\right) \\ &= E(\mathbf{x}, E(\mathbf{y}, \mathbf{z})) = L_x L_y(\mathbf{z}) \end{aligned}$$

and so

$$S(T_{x \otimes y}) = L_x L_y. \quad (10) \quad \boxed{\text{eq:Sxoy}}$$

If $f = L_y$ then using (8) $\boxed{\text{eq:third}}$

$$S(L_y) = \sum_{i=1}^d L_{e_i} \circ L_y \circ L(e_i) \quad (11)$$

$$= \sum_{i=1}^d \left(g(\mathbf{e}_i, \mathbf{e}_i) L_y - 2g(\mathbf{e}_i, \mathbf{y}) L_{e_i} - T_{e_i \otimes E(e_i, y)} + T_{E(e_i, y) \otimes e_i} \right). \quad (12)$$

Since $g(\mathbf{e}_i, \mathbf{e}_i) = 1$ the first term is simply dL_y ; for the second term write

$$\sum_{i=1}^d g(\mathbf{e}_i, \mathbf{y}) L_{e_i}(\mathbf{z}) = \sum_{i=1}^d g(\mathbf{e}_i, \mathbf{y}) E(\mathbf{e}_i, \mathbf{z}) = \sum_{i=1}^d E(g(\mathbf{e}_i, \mathbf{y}) \mathbf{e}_i, \mathbf{z})$$

$$= E\left(\sum_{i=1}^d g(\mathbf{e}_i, \mathbf{y}) \mathbf{e}_i, \mathbf{z}\right) = E(\mathbf{y}, \mathbf{z}) = L_y(\mathbf{z}).$$

For the third term

$$\begin{aligned} \sum_{i=1}^d T_{e_i \otimes E(e_i, y)}(\mathbf{z}) &= \sum_{i=1}^d g(\mathbf{z}, E(\mathbf{e}_i, \mathbf{y})) \mathbf{e}_i = \sum_{i=1}^d g(\mathbf{e}_i, E(\mathbf{y}, \mathbf{z})) \mathbf{e}_i \\ &= E(\mathbf{y}, \mathbf{z}) = L_y(\mathbf{z}). \end{aligned}$$

In a similar way the fourth term is

$$\begin{aligned} \sum_{i=1}^d T_{E(e_i, y) \otimes e_i}(\mathbf{z}) &= \sum_{i=1}^d E(\mathbf{e}_i, \mathbf{y}) g(\mathbf{z}, \mathbf{e}_i) \\ &= E\left(\sum_{i=1}^d g(\mathbf{z}, \mathbf{e}_i) \mathbf{e}_i, \mathbf{y}\right) = E(\mathbf{z}, \mathbf{y}) = -E(\mathbf{y}, \mathbf{z}) = -L_y(\mathbf{z}). \end{aligned}$$

Hence we conclude that

$$S(L_y) = (d - 2 - 1 - 1)L_y = (d - 4)L_y. \quad (13) \quad \boxed{\text{eq:Sy}}$$

If $f = L_x L_y$ then

$$\begin{aligned} S(L_x L_y) &= -S(L_{E(x, y)}) + 2S(T_{y \otimes x}) - S(T_{x \otimes y}) - g(\mathbf{x}, \mathbf{y})S(I) && \text{using (5)} \\ &= -(d - 4)L_{E(x, y)} + 2S(T_{y \otimes x}) - S(T_{x \otimes y}) - g(\mathbf{x}, \mathbf{y})S(I) && \text{using (13)} \\ &= -(d - 4)L_{E(x, y)} + 2L_y L_x - L_x L_y - g(\mathbf{x}, \mathbf{y})S(I) && \text{using (10)} \\ &= -(d - 4)L_{E(x, y)} + 2L_y L_x - L_x L_y - (1 - d)g(\mathbf{x}, \mathbf{y})I && \text{using (9). (14)} \quad \boxed{\text{eq:Sxy}} \end{aligned}$$

Using these derivations we can compute the following transformation:

$$g = \sum_{i=1}^d \sum_{j=1}^d L_{e_i} \circ L_x \circ L_{e_j} \circ L_{e_i} \circ L_{e_j}.$$

First using $S(L_{e_i}) = \sum_{j=1}^d L_{e_j} \circ L_{e_i} \circ L_{e_j}$ and (13) we have

$$g = \sum_{i=1}^d L_{e_i} \circ L_x \circ (d - 4)L_{e_i} = (d - 4) \sum_{i=1}^d L_{e_i} \circ L_x \circ L_{e_i} = (d - 4)S(L_x) = (d - 4)^2 L_x.$$

Another way of computing the same transformation is to write

$$\begin{aligned} g &= \sum_{j=1}^d S(L_x L_{e_j}) \circ L_{e_j} \\ &= \sum_{j=1}^d \left(-(d - 4)L_{E(x, e_j)} + 2L_{e_j} L_x - L_x L_{e_j} - (1 - d)g(\mathbf{x}, \mathbf{e}_j)I \right) \circ L_{e_j}. \end{aligned}$$

using (I4). Starting from the last term we have

$$g(\mathbf{x}, \mathbf{e}_j) I \circ L_{\mathbf{e}_j}(\mathbf{z}) = g(\mathbf{x}, \mathbf{e}_j) L_{\mathbf{e}_j}(\mathbf{z}) = g(\mathbf{x}, \mathbf{e}_j) E(\mathbf{e}_j, \mathbf{z})$$

which after applying the summation w.r.t. j becomes

$$\sum_{j=1}^d g(\mathbf{x}, \mathbf{e}_j) I \circ L_{\mathbf{e}_j}(\mathbf{z}) = E\left(\sum_{j=1}^d g(\mathbf{x}, \mathbf{e}_j) \mathbf{e}_j, \mathbf{z}\right) = E(\mathbf{x}, \mathbf{z}) = L_x(\mathbf{z}).$$

For $L_{\mathbf{e}_j} L_x$ using (I3) we have

$$2 \sum_{j=1}^d L_{\mathbf{e}_j} \circ L_x \circ L_{\mathbf{e}_j} = 2S(L_x) = 2(d-4)L_x$$

while for $L_x L_{\mathbf{e}_j}$ we have using (9)

$$L_x \sum_{j=1}^d L_{\mathbf{e}_j} \circ L_{\mathbf{e}_j} = L_x \sum_{j=1}^d L_{\mathbf{e}_j} \circ I \circ L_{\mathbf{e}_j} = L_x S(I) = (1-d)L_x.$$

For $L_{E(x, \mathbf{e}_j)}$ write using (6)

$$L_{E(x, \mathbf{e}_j)} L_{\mathbf{e}_j} = -L_{E(\mathbf{e}_j, x)} L_{\mathbf{e}_j} = -(-L_{\mathbf{e}_j} L_x L_{\mathbf{e}_j} - L_{\mathbf{e}_j \otimes E(x, \mathbf{e}_j)} - g(\mathbf{e}_j, \mathbf{x}) L_{\mathbf{e}_j})$$

For the second term

$$L_{\mathbf{e}_j \otimes E(x, \mathbf{e}_j)}(\mathbf{z}) = g(\mathbf{z}, E(\mathbf{x}, \mathbf{e}_j)) \mathbf{e}_j = g(\mathbf{e}_j, E(\mathbf{z}, \mathbf{x})) \mathbf{e}_j$$

which after summation w.r.t. j is equal to $E(\mathbf{z}, \mathbf{x})$. For the third term

$$g(\mathbf{e}_j, \mathbf{x}) L_{\mathbf{e}_j}(\mathbf{z}) = g(\mathbf{e}_j, \mathbf{x}) E(\mathbf{e}_j, \mathbf{z}) = E(g(\mathbf{e}_j, \mathbf{x}) \mathbf{e}_j, \mathbf{z})$$

which after summation w.r.t. j is equal to $E(\mathbf{x}, \mathbf{z})$. Therefore

$$\sum_{j=1}^d L_{E(x, \mathbf{e}_j)} L_{\mathbf{e}_j} = \sum_{j=1}^d L_{\mathbf{e}_j} L_x L_{\mathbf{e}_j} + E(\mathbf{z}, \mathbf{x}) + E(\mathbf{x}, \mathbf{z}) = S(L_x) = (d-4)L_x$$

and so computing the transformation using this method we have

$$\begin{aligned} g &= \sum_{j=1}^d \left(-(d-4)L_{E(x, \mathbf{e}_j)} + 2L_{\mathbf{e}_j} L_x - L_x L_{\mathbf{e}_j} - (1-d)g(\mathbf{x}, \mathbf{e}_j) I \right) \circ L_{\mathbf{e}_j} \\ &= -(d-4) \underbrace{\sum_{j=1}^d L_{E(x, \mathbf{e}_j)} L_{\mathbf{e}_j}}_{(d-4)L_x} + 2 \underbrace{\sum_{j=1}^d L_{\mathbf{e}_j} L_x L_{\mathbf{e}_j}}_{(d-4)L_x} - \underbrace{L_x \sum_{j=1}^d L_{\mathbf{e}_j} L_{\mathbf{e}_j}}_{(1-d)L_x} - (1-d) \underbrace{\sum_{j=1}^d g(\mathbf{x}, \mathbf{e}_j) I L_{\mathbf{e}_j}}_{L_x} \\ &= \left(-(d-4)^2 + 2(d-4) - (1-d) - (1-d) \right) L_x \\ &= \left(-(d-4)^2 + 2(d-4) - 2(1-d) \right) L_x \end{aligned}$$

Since both methods compute the same transformation we must have

$$-(d-4)^2 + 2(d-4) - 2(1-d) = (d-4)^2$$

or

$$(d-4)^2 - (d-4) - (d-1) = d^2 - 10d + 21 = (d-3)(d-7) = 0.$$

References

- [1] Alberto Elduque. Vector cross products. *Electronic copy found at: <http://www.unizar.es/matematicas/algebra/elduque/Talks/crossproducts.pdf>*, 2004.