

# *Geometric Algebra Module for Sympy*

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## Introduction

This document describes the implementation, installation and use of a geometric algebra module written in python that utilizes the *sympy* symbolic algebra library. The python module `ga` has been developed for coordinate free calculations using the operations (geometric, outer, and inner products etc.) of geometric algebra. The operations can be defined using a completely arbitrary metric defined by the inner products of a set of arbitrary vectors or the metric can be restricted to enforce orthogonality and signature constraints on the set of vectors. Additionally, a metric that is a function of a coordinate set can be defined so that a geometric algebra over a manifold can be implemented. Geometric algebras over submanifolds of the base manifold are also supported as well as linear multivector differential operators ( $\nabla$ ,  $\nabla^2$ , etc.), linear transformations, and multi-linear transformations (tensors). The module requires the *sympy* module and the `numpy` module for numerical linear algebra calculations. For latex output a latex distribution must be installed.

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# Chapter 1

## What is Geometric Algebra?

Geometric algebra is the Clifford algebra of a real finite dimensional vector space or the algebra that results when the vector space is extended with a product of vectors (geometric product) that is associative, left and right distributive, and yields a real number for the square (geometric product) of any vector [2], [1]. The elements of the geometric algebra are called multivectors and consist of the linear combination of scalars, vectors, and the geometric product of two or more vectors. The additional axioms for the geometric algebra are that for any vectors  $a$ ,  $b$ , and  $c$  in the base vector space ([1],p85):

$$\begin{aligned}a(bc) &= (ab)c \\a(b+c) &= ab+ac \\(a+b)c &= ac+bc \\aa &= a^2 \in \Re\end{aligned}\tag{1.1}$$

The dot product of two vectors is defined by ([1],p86)

$$a \cdot b \equiv (ab + ba)/2\tag{1.2}$$

Then consider

$$c = a + b\tag{1.3}$$

$$c^2 = (a + b)^2\tag{1.4}$$

$$c^2 = a^2 + ab + ba + b^2\tag{1.5}$$

$$a \cdot b = (c^2 - a^2 - b^2)/2 \in \Re\tag{1.6}$$

Thus  $a \cdot b$  is real. The objects generated from linear combinations of scalars and the geometric products of vectors are called multivectors. If a basis for the underlying vector space is the set of vectors formed from  $\mathbf{e}_1, \dots, \mathbf{e}_n$  (we use boldface  $\mathbf{e}$ 's to denote basis vectors) a complete basis for

the geometric algebra is given by the scalar 1, the vectors  $\mathbf{e}_1, \dots, \mathbf{e}_n$  and all geometric products of vectors

$$\mathbf{e}_{i_1} \mathbf{e}_{i_2} \dots \mathbf{e}_{i_r} \text{ where } 0 \leq r \leq n, 0 \leq i_j \leq n \text{ and } i_1 < i_2 < \dots < i_r \quad (1.7)$$

Each base of the complete basis is represented by a noncommutative symbol (except for the scalar 1) with name  $\mathbf{e}_{i_1} \dots \mathbf{e}_{i_r}$  so that the general multivector  $\mathbf{A}$  is represented by ( $A$  is the scalar part of the multivector and the  $A^{i_1, \dots, i_r}$  are scalars)

$$\mathbf{A} = A + \sum_{r=1}^n \sum_{\substack{i_1, \dots, i_r \\ 0 \leq i_j < i_{j+1} \leq n}} A^{i_1, \dots, i_r} \mathbf{e}_{i_1} \mathbf{e}_{i_2} \dots \mathbf{e}_{i_r} \quad (1.8)$$

The critical operation in setting up the geometric algebra is reducing the geometric product of any two bases to a linear combination of bases so that we can calculate a multiplication table for the bases. Since the geometric product is associative we can use the operation (by definition for two vectors  $a \cdot b \equiv (ab + ba)/2$  which is a scalar)

$$\mathbf{e}_{i_{j+1}} \mathbf{e}_{i_j} = 2\mathbf{e}_{i_{j+1}} \cdot \mathbf{e}_{i_j} - \mathbf{e}_{i_j} \mathbf{e}_{i_{j+1}} \quad (1.9)$$

These processes are repeated untill every basis list in  $\mathbf{A}$  is in normal (ascending) order with no repeated elements. As an example consider the following

$$\mathbf{e}_3 \mathbf{e}_2 \mathbf{e}_1 = (2(\mathbf{e}_2 \cdot \mathbf{e}_3) - \mathbf{e}_2 \mathbf{e}_3) \mathbf{e}_1 \quad (1.10)$$

$$= 2(\mathbf{e}_2 \cdot \mathbf{e}_3) \mathbf{e}_1 - \mathbf{e}_2 \mathbf{e}_3 \mathbf{e}_1 \quad (1.11)$$

$$= 2(\mathbf{e}_2 \cdot \mathbf{e}_3) \mathbf{e}_1 - \mathbf{e}_2 (2(\mathbf{e}_1 \cdot \mathbf{e}_3) - \mathbf{e}_1 \mathbf{e}_3) \quad (1.12)$$

$$= 2((\mathbf{e}_2 \cdot \mathbf{e}_3) \mathbf{e}_1 - (\mathbf{e}_1 \cdot \mathbf{e}_3) \mathbf{e}_2) + \mathbf{e}_2 \mathbf{e}_1 \mathbf{e}_3 \quad (1.13)$$

$$= 2((\mathbf{e}_2 \cdot \mathbf{e}_3) \mathbf{e}_1 - (\mathbf{e}_1 \cdot \mathbf{e}_3) \mathbf{e}_2 + (\mathbf{e}_1 \cdot \mathbf{e}_2) \mathbf{e}_3) - \mathbf{e}_1 \mathbf{e}_2 \mathbf{e}_3 \quad (1.14)$$

which results from repeated application of eq. (1.9). If the product of basis vectors contains repeated factors eq. (1.9) can be used to bring the repeated factors next to one another so that if  $\mathbf{e}_{i_j} = \mathbf{e}_{i_{j+1}}$  then  $\mathbf{e}_{i_j} \mathbf{e}_{i_{j+1}} = \mathbf{e}_{i_j} \cdot \mathbf{e}_{i_{j+1}} = \mathbf{e}_{i_j}^2$  which is a scalar that commutes with all the terms in the product and can be brought to the front of the product. Since every repeated pair of vectors in a geometric product of  $r$  factors reduces the number of noncommutative factors in the product by  $r - 2$ . The number of bases in the multivector algebra is  $2^n$  and the number containing  $r$  factors is  $\binom{n}{r}$  which is the number of combinations or  $n$  things taken  $r$  at a time (binominal coefficient).

The other construction required for formulating the geometric algebra is the outer or wedge product (symbol  $\wedge$ ) of  $r$  vectors denoted by  $a_1 \wedge \dots \wedge a_r$ . The wedge product of  $r$  vectors is called an  $r$ -blade and is defined by ([1],p86)

$$a_1 \wedge \dots \wedge a_r \equiv \sum_{i_{j_1} \dots i_{j_r}} \epsilon^{i_{j_1} \dots i_{j_r}} a_{i_{j_1}} \dots a_{i_{j_r}} \quad (1.15)$$

where  $\epsilon^{i_{j_1} \dots i_{j_r}}$  is the contravariant permutation symbol which is  $+1$  for an even permutation of the superscripts,  $0$  if any superscripts are repeated, and  $-1$  for an odd permutation of the superscripts. From the definition  $a_1 \wedge \dots \wedge a_r$  is antisymmetric in all its arguments and the following relation for the wedge product of a vector  $a$  and an  $r$ -blade  $B_r$  can be derived

$$a \wedge B_r = (aB_r + (-1)^r B_r a)/2 \quad (1.16)$$

Using eq. (1.16) one can represent the wedge product of all the basis vectors in terms of the geometric product of all the basis vectors so that one can solve (the system of equations is lower diagonal) for the geometric product of all the basis vectors in terms of the wedge product of all the basis vectors. Thus a general multivector  $\mathbf{B}$  can be represented as a linear combination of a scalar and the basis blades.

$$\mathbf{B} = B + \sum_{r=1}^n \sum_{i_1, \dots, i_r, \forall 0 \leq i_j \leq n} B^{i_1, \dots, i_r} \mathbf{e}_{i_1} \wedge \mathbf{e}_{i_2} \wedge \dots \wedge \mathbf{e}_{i_r} \quad (1.17)$$

Using the blades  $\mathbf{e}_{i_1} \wedge \mathbf{e}_{i_2} \wedge \dots \wedge \mathbf{e}_{i_r}$  creates a graded algebra where  $r$  is the grade of the basis blades. The grade- $r$  part of  $\mathbf{B}$  is the linear combination of all terms with grade  $r$  basis blades. The scalar part of  $\mathbf{B}$  is defined to be grade-0. Now that the blade expansion of  $\mathbf{B}$  is defined we can also define the grade projection operator  $\langle \mathbf{B} \rangle_r$  by

$$\langle \mathbf{B} \rangle_r = \sum_{i_1, \dots, i_r, \forall 0 \leq i_j \leq n} B^{i_1, \dots, i_r} \mathbf{e}_{i_1} \wedge \mathbf{e}_{i_2} \wedge \dots \wedge \mathbf{e}_{i_r} \quad (1.18)$$

and

$$\langle \mathbf{B} \rangle \equiv \langle \mathbf{B} \rangle_0 = B \quad (1.19)$$

Then if  $\mathbf{A}_r$  is an  $r$ -grade multivector and  $\mathbf{B}_s$  is an  $s$ -grade multivector we have

$$\mathbf{A}_r \mathbf{B}_s = \langle \mathbf{A}_r \mathbf{B}_s \rangle_{|r-s|} + \langle \mathbf{A}_r \mathbf{B}_s \rangle_{|r-s|+2} + \dots + \langle \mathbf{A}_r \mathbf{B}_s \rangle_{r+s} \quad (1.20)$$

and define ([2],p6)

$$\mathbf{A}_r \wedge \mathbf{B}_s \equiv \langle \mathbf{A}_r \mathbf{B}_s \rangle_{r+s} \quad (1.21)$$

$$\mathbf{A}_r \cdot \mathbf{B}_s \equiv \begin{cases} r \text{ and } s \neq 0 : & \langle \mathbf{A}_r \mathbf{B}_s \rangle_{|r-s|} \\ r \text{ or } s = 0 : & 0 \end{cases} \quad (1.22)$$

where  $\mathbf{A}_r \cdot \mathbf{B}_s$  is called the dot or inner product of two pure grade multivectors. For the case of two non-pure grade multivectors

$$\mathbf{A} \wedge \mathbf{B} = \sum_{r,s} \langle \mathbf{A} \rangle_r \wedge \langle \mathbf{B} \rangle_s \quad (1.23)$$

$$\mathbf{A} \cdot \mathbf{B} = \sum_{r,s \neq 0} \langle \mathbf{A} \rangle_r \cdot \langle \mathbf{B} \rangle_s \quad (1.24)$$

Two other products, the right ( $\rfloor$ ) and left ( $\lceil$ ) contractions, are defined by

$$\mathbf{A} \lceil \mathbf{B} \equiv \sum_{r,s} \left\{ \begin{array}{ll} \langle \mathbf{A}_r \mathbf{B}_s \rangle_{r-s} & r \geq s \\ 0 & r < s \end{array} \right\} \quad (1.25)$$

$$\mathbf{A} \rfloor \mathbf{B} \equiv \sum_{r,s} \left\{ \begin{array}{ll} \langle \mathbf{A}_r \mathbf{B}_s \rangle_{s-r} & s \geq r \\ 0 & s < r \end{array} \right\} \quad (1.26)$$

A final operation for multivectors is the reverse. If a multivector  $\mathbf{A}$  is the geometric product of  $r$  vectors (versor) so that  $\mathbf{A} = a_1 \dots a_r$  the reverse is defined by

$$\mathbf{A}^\dagger \equiv a_r \dots a_1 \quad (1.27)$$

where for a general multivector we have (the the sum of the reverse of versors)

$$\mathbf{A}^\dagger = A + \sum_{r=1}^n (-1)^{r(r-1)/2} \sum_{i_1, \dots, i_r, \forall 0 \leq i_j \leq n} A^{i_1, \dots, i_r} \mathbf{e}_{i_1} \wedge \mathbf{e}_{i_2} \wedge \dots \wedge \mathbf{e}_{i_r} \quad (1.28)$$

note that if  $\mathbf{A}$  is a versor then  $\mathbf{A}\mathbf{A}^\dagger \in \mathfrak{R}$  and  $(\mathbf{A}\mathbf{A}^\dagger \neq 0)$

$$\mathbf{A}^{-1} = \frac{\mathbf{A}^\dagger}{\mathbf{A}\mathbf{A}^\dagger} \quad (1.29)$$

## 1.1 Representation of Multivectors in *sympy*

The *sympy* python module offers a simple way of representing multivectors using linear combinations of commutative expressions (expressions consisting only of commuting *sympy* objects) and noncommutative symbols. We start by defining  $n$  noncommutative *sympy* symbols as a basis for the vector space

```
(e_1, ..., e_n) = symbols('e_1, ..., e_n', commutative=False)
```

Several software packages for numerical geometric algebra calculations are available from Doran-Lasenby group and the Dorst group. Symbolic packages for Clifford algebra using orthongonal bases such as  $\mathbf{e}_i \mathbf{e}_j + \mathbf{e}_j \mathbf{e}_i = 2\eta_{ij}$ , where  $\eta_{ij}$  is a numeric array are available in Maple and Mathematica. The symbolic algebra module, *ga*, developed for python does not depend on an orthogonal basis representation, but rather is generated from a set of  $n$  arbitrary symbolic vectors



$A + B$	sum of multivectors
$A - B$	difference of multivectors
$A * B$	geometric product of multivectors
$A \wedge B$	outer product of multivectors
$A B$	inner product of multivectors
$A < B$	left contraction of multivectors
$A > B$	right contraction of multivectors

Table 1.2: Multivector operations for GA

$\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_n$  and a symbolic metric tensor  $g_{ij} = \mathbf{e}_i \cdot \mathbf{e}_j$  (the symbolic metric can be symbolic constants or symbolic function in the case of a manifold).

In order not to reinvent the wheel all scalar symbolic algebra is handled by the python module *sympy* and the abstract basis vectors are encoded as noncommuting *sympy* symbols.

The basic geometric algebra operations will be implemented in python by defining a geometric algebra class, *Ga*, which defines the geometric algebra and a multivector class, *Mv*, that instantiates multivectors as *sympy* expressions of the form (Einstein summation convention)

$$F + \sum_{r=1}^n F^{i_1 \dots i_r} \mathbf{e}_{i_1} \dots \mathbf{e}_{i_r} \quad (1.30)$$

where the  $F$ 's are *sympy* symbolic constants or functions of the coordinates. The class *Mv* then overloads the python operators to provide all the needed multivector operations as shown in Table 1.2 where  $A$  and  $B$  are any two multivectors (In the case of  $+$ ,  $-$ ,  $*$ ,  $\wedge$ ,  $|$ ,  $<$ , and  $>$  the operation is also defined if  $A$  or  $B$  is a *sympy* symbol or a *sympy* real number).

Since  $<$  and  $>$  have no r-forms (in python for the  $<$  and  $>$  operators there are no `__rlt__()` and `__rgt__()` member functions to overload) we can only have mixed modes (scalars and multivectors) if the first operand is a multivector.

Except for  $<$  and  $>$  all the multivector operators have r-forms so that as long as one of the operands, left or right, is a multivector the other can be a multivector or a scalar (*sympy* symbol or integer).

Note that the operator order precedence is determined by python and is not necessarily that used by geometric algebra. It is *absolutely essential* to use parenthesis in multivector expressions

containing  $\wedge$ ,  $|$ ,  $<$ , and/or  $>$ . As an example let  $A$  and  $B$  be any two multivectors. Then  $A + A*B = A + (A*B)$ , but  $A+A^{\wedge}B = (2*A)^{\wedge}B$  since in python the  $\wedge$  operator has a lower precedence than the  $+$  operator. In geometric algebra the outer and inner products and the left and right contractions have a higher precedence than the geometric product and the geometric product has a higher precedence than addition and subtraction. In python the  $\wedge$ ,  $|$ ,  $>$ , and  $<$  all have a lower precedence than  $+$  and  $-$  while  $*$  has a higher precedence than  $+$  and  $-$ .

For those users who wish to define a default operator precedence the functions `def_prec()` and `GAeval()` are available in the module `printer`.

```
def_prec(gd,op_ord='<>|,^,*')
```

Define the precedence of the multivector operations. The function `def_prec()` must be called from the main program and the first argument `gd` must be set to `globals()`. The second argument `op_ord` determines the operator precedence for expressions input to the function `GAeval()`. The default value of `op_ord` is `'<>|,^,*'`. For the default value the  $<$ ,  $>$ , and  $|$  operations have equal precedence followed by  $\wedge$ , and  $\wedge$  is followed by  $*$ .

```
GAeval(s,pstr=False)
```

The function `GAeval()` returns a multivector expression defined by the string `s` where the operations in the string are parsed according to the precedences defined by `define_precedence()`. `pstr` is a flag to print the input and output of `GAeval()` for debugging purposes. `GAeval()` works by adding parenthesis to the input string `s` with the precedence defined by `op_ord='<>|,^,*'`. Then the parsed string is converted to a *sympy* expression using the python `eval()` function. For example consider where  $X$ ,  $Y$ ,  $Z$ , and  $W$  are multivectors

```
def_prec(globals())
V = GAeval('X|Y^Z*W')
```

The *sympy* variable `V` would evaluate to  $((X|Y)^{\wedge}Z)*W$ .

## 1.2 Vector Basis and Metric

The two structures that define the `metric` class (inherited by the geometric algebra class) are the symbolic basis vectors and the symbolic metric and the coordinates if the metric is position dependent or if differential operators are required. The symbolic basis vectors are input as

a string with the symbol name separated by spaces. For example if we are calculating the geometric algebra of a system with three vectors that we wish to denote as **a0**, **a1**, and **a2** we would define the string variable:

```
basis = 'a0 a1 a2'
```

that would be input into the multivector setup function which instantiates the geometric algebra. The next step would be to define the symbolic metric for the geometric algebra of the basis we have defined. The default metric is the most general and is the matrix of the following symbols

$$g = \begin{bmatrix} (a0.a0) & (a0.a1) & (a0.a2) \\ (a0.a1) & (a1.a1) & (a1.a2) \\ (a0.a2) & (a1.a2) & (a2.a2) \end{bmatrix} \quad (1.31)$$

where each of the  $g_{ij}$  is a symbol representing all of the dot products of the basis vectors. Note that the symbols are named so that  $g_{ij} = g_{ji}$  since for the symbol function  $(a0.a1) \neq (a1.a0)$ .

Note that the strings shown in eq. (1.31) are only used when the values of  $g_{ij}$  are output (printed). In the `ga` module (library) the  $g_{ij}$  symbols are stored in a member of the geometric algebra instance so that if `o3d` is a geometric algebra then the `o3d.g` *sympy* matrix is the metric tensor ( $g_{ij} = \text{o3d.g}[i,j]$ ) for that algebra.

The default definition of  $g$  can be overwritten by specifying a string that will define  $g$ . As an example consider a symbolic representation for conformal geometry. Define for a basis

```
basis = 'a0 a1 a2 n nbar'
```

and for a metric

```
g = '# # # 0 0, # # # 0 0, # # # 0 0, 0 0 0 0 2, 0 0 0 2 0'
```

then calling `cf3d = Ga(basis,g=g)` would initialize the metric tensor

$$g = \begin{bmatrix} (a0.a0) & (a0.a1) & (a0.a2) & 0 & 0 \\ (a0.a1) & (a1.a1) & (a1.a2) & 0 & 0 \\ (a0.a2) & (a1.a2) & (a2.a2) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 \\ 0 & 0 & 0 & 2 & 0 \end{bmatrix} \quad (1.32)$$

for the `cf3d` (conformal 3-d) geometric algebra.

Here we have specified that **n** and **nbar** are orthogonal to all the **a**'s,  $(\mathbf{n}.\mathbf{n}) = (\mathbf{nbar}.\mathbf{nbar}) = 0$ , and  $(\mathbf{n}.\mathbf{nbar}) = 2$ . Using **#** in the metric definition string just tells the program to use the default symbol for that value.

When `Ga` is called multivector representations of the basis local to the program are instantiated. For the case of an orthogonal 3-d vector space that means the symbolic vectors named `a0`, `a1`, and `a2` are created. We can instantiate the geometric algebra and obtain the basis vectors with -

```
o3d = Ga('a_1 a_2 a_3',g=[1,1,1])
(a_1,a_2,a_3) = o3d.mv()
```

or use the `Ga.build()` function -

```
(o3d,a_1,a_2,a_3) = Ga.build('a_1 a_2 a_3',g=[1,1,1])
```

Note that the python variable name for a basis vector does not have to correspond to the name give in `Ga()` or `Ga.build()`, one may wish to use a shortened python variable name to reduce programming (typing) errors, for example one could use -

```
(o3d,a1,a2,a3) = Ga.build('a_1 a_2 a_3',g=[1,1,1])
```

or

```
(st4d,g0,g1,g2,g3) = Ga.build('gamma_0 gamma_1 gamma_2 gamma_3',\
                                g=[1,-1,-1,-1])
```

for Minkowski spacetime.

If the latex printer is used `e1` would print as  $e_1$  and `g1` as  $\gamma_1$ .

Additionally `Ga()` and `Ga.build()` has simplified options for naming a set of basis vectors and for inputing an othogonal basis. If one wishes to name the basis vectors  $e_x$ ,  $e_y$ , and  $e_z$  then set `basis='e*x|y|z'` or to name  $\gamma_t$ ,  $\gamma_x$ ,  $\gamma_y$ , and  $\gamma_z$  then set `basis='gamma*t|x|y|z'`. For the case of an othogonal basis if the signature of the vector space is (1,1,1) (Euclidian 3-space) set `g=[1,1,1]` or if it is (1,-1,-1,-1) (Minkowski 4-space) set `g=[1,-1,-1,-1]`. If `g` is a function of position then `g` can be entered as a *sympy* matrix with *sympy* functions as the entries of the matrix or as a list of functions for the case of a orthogonal metric. In the case of spherical coordinates we have `g=[1,r**2,r**2*sin(th)**2]`.

### 1.3 Representation and Reduction of Multivector Bases

In our symbolic geometric algebra all multivectors can be obtained from the symbolic basis vectors we have input, via the different operations available to geometric algebra. The first

problem we have is representing the general multivector in terms of the basis vectors. To do this we form the ordered geometric products of the basis vectors and develop an internal representation of these products in terms of python classes. The ordered geometric products are all multivectors of the form  $a_{i_1}a_{i_2}\dots a_{i_r}$  where  $i_1 < i_2 < \dots < i_r$  and  $r \leq n$ . We call these multivectors bases and represent them internally with noncommutative symbols so for example  $a_1a_2a_3$  is represented by

```
Symbol('a_1*a_2*a_3', commutative=False)
```

In the simplest case of two basis vectors `a_1` and `a_2` we have a list of bases

```
self.bases = [[Symbol('a_1', commutative=False),\
                Symbol('a_2', commutative=False)],\
               [Symbol('a_1*a_2', commutative=False)]]
```

For the case of the basis blades we have

```
self.blades = [[Symbol('a_1', commutative=False),\
                    Symbol('a_2', commutative=False)],\
                [Symbol('a_1^a_2', commutative=False)]]
```

For all grades/pseudo-grades greater than one (vectors) the `*` in the name of the base symbol is replaced with a `^` in the name of the blade symbol so that for all basis bases and blades of grade/pseudo-grade greater than one there are different symbols for the corresponding bases and blades.

The index tuples for the bases of each pseudo grade and each grade for the case of dimension 3 is

```
self.indexes = (((0,),(1,),(2,)),((0,1),(0,2),(1,2)),((0,1,2)))
```

Then the noncommutative symbol representing each base is constructed from each index tuple. For example for `self.indexes[1][1]` the symbol is `Symbol('a_1*a_3', commutative=False)`.

In the case that the metric tensor is diagonal (orthogonal basis vectors) both base and blade bases are identical and fewer arrays and dictionaries need to be constructed.

## 1.4 Base Representation of Multivectors

In terms of the bases defined as noncommutative *sympy* symbols the general multivector is a linear combination (scalar *sympy* coefficients) of bases so that for the case of two bases the most general multivector is given by -

```
A = A_0+A__1*self.bases[1][0]+A__2*self.bases[1][1]
    +A__12*self.bases[2][0]
```

If we have another multivector **B** to multiply with **A** we can calculate the product in terms of a linear combination of bases if we have a multiplication table for the bases.

## 1.5 Blade Representation of Multivectors

Since we can now calculate the symbolic geometric product of any two multivectors we can also calculate the blades corresponding to the product of the symbolic basis vectors using the formula

$$A_r \wedge b = \frac{1}{2} (A_r b - (-1)^r b A_r), \quad (1.33)$$

where  $A_r$  is a multivector of grade  $r$  and  $b$  is a vector. For our example basis the result is shown in Table 1.3. The important thing to notice about Table 1.3 is that it is a triangular

```
1 = 1
a0 = a0
a1 = a1
a2 = a2
a0^a1 = {-(a0.a1)}1+a0a1
a0^a2 = {-(a0.a2)}1+a0a2
a1^a2 = {-(a1.a2)}1+a1a2
a0^a1^a2 = {-(a1.a2)}a0+{(a0.a2)}a1+{-(a0.a1)}a2+a0a1a2
```

Table 1.3: Bases blades in terms of bases.

(lower triangular) system of equations so that using a simple back substitution algorithm we can solve for the pseudo bases in terms of the blades giving Table 1.4. Using Table 1.4 and simple substitution we can convert from a base multivector representation to a blade representation. Likewise, using Table 1.3 we can convert from blades to bases.

```

1 = 1
a0 = a0
a1 = a1
a2 = a2
a0a1 = {(a0 . a1)}1 + a0^a1
a0a2 = {(a0 . a2)}1 + a0^a2
a1a2 = {(a1 . a2)}1 + a1^a2
a0a1a2 = {(a1 . a2)}a0 + {-(a0 . a2)}a1 + {(a0 . a1)}a2 + a0^a1^a2

```

Table 1.4: Bases in terms of basis blades.

Using the blade representation it becomes simple to program functions that will calculate the grade projection, reverse, even, and odd multivector functions.

Note that in the multivector class `Mv` there is a class variable for each instantiation, `self.is_blade_rep`, that is set to `False` for a base representation and `True` for a blade representation. One needs to keep track of which representation is in use since various multivector operations require conversion from one representation to the other.

When the geometric product of two multivectors is calculated the module looks to see if either multivector is in blade representation. If either is the result of the geometric product is converted to a blade representation. One result of this is that if either of the multivectors is a simple vector (which is automatically a blade) the result will be in a blade representation. If `a` and `b` are vectors then the result `a*b` will be `(a.b)+a^b` or simply `a^b` if `(a.b) = 0`.

## 1.6 Outer and Inner Products, Left and Right Contractions

In geometric algebra any general multivector  $A$  can be decomposed into pure grade multivectors (a linear combination of blades of all the same order) so that in a  $n$ -dimensional vector space

$$A = \sum_{r=0}^n A_r \quad (1.34)$$

The geometric product of two pure grade multivectors  $A_r$  and  $B_s$  has the form

$$A_r B_s = \langle A_r B_s \rangle_{|r-s|} + \langle A_r B_s \rangle_{|r-s|+2} + \cdots + \langle A_r B_s \rangle_{r+s} \quad (1.35)$$

where  $\langle \rangle_t$  projects the  $t$  grade components of the multivector argument. The inner and outer products of  $A_r$  and  $B_s$  are then defined to be

$$A_r \cdot B_s = \langle A_r B_s \rangle_{|r-s|} \quad (1.36)$$

$$A_r \wedge B_s = \langle A_r B_s \rangle_{r+s} \quad (1.37)$$

and

$$A \cdot B = \sum_{r,s \geq 0} A_r \cdot B_s \quad (1.38)$$

$$A \wedge B = \sum_{r,s} A_r \wedge B_s \quad (1.39)$$

Likewise the right ( $\rfloor$ ) and left ( $\lceil$ ) contractions are defined as

$$A_r \rfloor B_s = \begin{cases} \langle A_r B_s \rangle_{r-s} & r \geq s \\ 0 & r < s \end{cases} \quad (1.40)$$

$$A_r \lceil B_s = \begin{cases} \langle A_r B_s \rangle_{s-r} & s \geq r \\ 0 & s < r \end{cases} \quad (1.41)$$

and

$$A \rfloor B = \sum_{r,s} A_r \rfloor B_s \quad (1.42)$$

$$A \lceil B = \sum_{r,s} A_r \lceil B_s \quad (1.43)$$

In the `Mv` class we have overloaded the `^` operator to represent the outer product so that instead of calling the outer product function we can write `mv1^mv2`. Due to the precedence rules for python it is *absolutely essential* to enclose outer products in parenthesis.

In the `Mv` class we have overloaded the `|` operator for the inner product, `>` operator for the right contraction, and `<` operator for the left contraction. Instead of calling the inner product function we can write `mv1|mv2`, `mv1>mv2`, or `mv1<mv2` respectively for the inner product, right contraction, or left contraction. Again, due to the precedence rules for python it is *absolutely essential* to enclose inner products and/or contractions in parenthesis.



## 1.7 Reverse of Multivector

If  $A$  is the geometric product of  $r$  vectors

$$A = a_1 \dots a_r \quad (1.44)$$

Then the reverse of  $A$  designated  $A^\dagger$  is defined by

$$A^\dagger \equiv a_r \dots a_1. \quad (1.45)$$

The reverse is simply the product with the order of terms reversed. The reverse of a sum of products is defined as the sum of the reverses so that for a general multivector  $A$  we have

$$A^\dagger = \sum_{i=0}^N \langle A \rangle_i^\dagger \quad (1.46)$$

but

$$\langle A \rangle_i^\dagger = (-1)^{\frac{i(i-1)}{2}} \langle A \rangle_i \quad (1.47)$$

which is proved by expanding the blade bases in terms of orthogonal vectors and showing that eq. (1.47) holds for the geometric product of orthogonal vectors.

The reverse is important in the theory of rotations in  $n$ -dimensions. If  $R$  is the product of an even number of vectors and  $RR^\dagger = 1$  then  $RaR^\dagger$  is a composition of rotations of the vector  $a$ . If  $R$  is the product of two vectors then the plane that  $R$  defines is the plane of the rotation. That is to say that  $RaR^\dagger$  rotates the component of  $a$  that is projected into the plane defined by  $a$  and  $b$  where  $R = ab$ .  $R$  may be written  $R = e^{\frac{\theta}{2}u}$ , where  $\theta$  is the angle of rotation and  $u$  is a unit blade ( $u^2 = \pm 1$ ) that defines the plane of rotation.

## 1.8 Reciprocal Frames

If we have  $M$  linearly independent vectors (a frame),  $a_1, \dots, a_M$ , then the reciprocal frame is  $a^1, \dots, a^M$  where  $a_i \cdot a^j = \delta_i^j$ ,  $\delta_i^j$  is the Kronecker delta (zero if  $i \neq j$  and one if  $i = j$ ). The reciprocal frame is constructed as follows:

$$E_M = a_1 \wedge \dots \wedge a_M \quad (1.48)$$

$$E_M^{-1} = \frac{E_M}{E_M^2} \quad (1.49)$$

Then

$$a^i = (-1)^{i-1} (a_1 \wedge \dots \wedge \check{a}_i \wedge \dots \wedge a_M) E_M^{-1} \quad (1.50)$$

where  $\check{a}_i$  indicates that  $a_i$  is to be deleted from the product. In the standard notation if a vector is denoted with a subscript the reciprocal vector is denoted with a superscript. The set of reciprocal vectors will be calculated if a coordinate set is given when a geometric algebra is instantiated since they are required for geometric differentiation.

## 1.9 Manifolds and Submanifolds

A  $m$ -dimensional *vector* manifold<sup>1</sup>,  $\mathcal{M}$ , is defined by a coordinate tuple (tuples are indicated by the vector accent “ $\vec{\phantom{x}}$ ”)

$$\vec{x} = (x^1, \dots, x^m), \quad (1.51)$$

and the differentiable mapping ( $U^m$  is an  $m$ -dimensional subset of  $\mathbb{R}^m$ )

$$\mathbf{e}^{\mathcal{M}}(\vec{x}) : U^m \subseteq \mathbb{R}^m \rightarrow \mathcal{V}, \quad (1.52)$$

where  $\mathcal{V}$  is a vector space with an inner product<sup>2</sup>  $(\cdot)$  and is of  $\dim(\mathcal{V}) \geq m$ .

Then a set of basis vectors for the tangent space of  $\mathcal{M}$  at  $\vec{x}$ ,  $\mathcal{T}_{\vec{x}}(\mathcal{M})$ , are

$$\mathbf{e}_i^{\mathcal{M}} = \frac{\partial \mathbf{e}^{\mathcal{M}}}{\partial x^i} \quad (1.53)$$

and

$$g_{ij}^{\mathcal{M}}(\vec{x}) = \mathbf{e}_i^{\mathcal{M}} \cdot \mathbf{e}_j^{\mathcal{M}}. \quad (1.54)$$

A  $n$ -dimensional ( $n \leq m$ ) submanifold  $\mathcal{N}$  of  $\mathcal{M}$  is defined by a coordinate tuple

$$\vec{u} = (u^1, \dots, u^n), \quad (1.55)$$

and a differentiable mapping

$$\vec{x}(\vec{u}) : U^n \subseteq \mathbb{R}^n \rightarrow U^m \subseteq \mathbb{R}^m, \quad (1.56)$$

which induces a mapping

$$\mathbf{e}^{\mathcal{M}}(\vec{x}(\vec{u})) : U^n \subseteq \mathbb{R}^n \rightarrow \mathcal{V}. \quad (1.57)$$

Then the basis vectors for the tangent space  $\mathcal{T}_{\vec{u}}(\mathcal{N})$  are (using  $\mathbf{e}^{\mathcal{N}}(\vec{u}) = \mathbf{e}^{\mathcal{M}}(\vec{x}(\vec{u}))$  and the chain rule)

$$\mathbf{e}_i^{\mathcal{N}}(\vec{u}) = \frac{\partial \mathbf{e}^{\mathcal{N}}(\vec{u})}{\partial u^i} = \frac{\partial \mathbf{e}^{\mathcal{M}}(\vec{x})}{\partial x^j} \frac{\partial x^j}{\partial u^i} = \mathbf{e}_j^{\mathcal{M}}(\vec{x}(\vec{u})) \frac{\partial x^j}{\partial u^i}, \quad (1.58)$$

---

<sup>1</sup>By the manifold embedding theorem any  $m$ -dimensional manifold is isomorphic to a  $m$ -dimensional vector manifold [http://en.wikipedia.org/wiki/Whitney\\_embedding\\_theorem](http://en.wikipedia.org/wiki/Whitney_embedding_theorem).

<sup>2</sup>This product is not necessarily positive definite.

and

$$g_{ij}^{\mathcal{N}}(\vec{u}) = \frac{\partial x^k}{\partial u^i} \frac{\partial x^l}{\partial u^j} g_{kl}^{\mathcal{M}}(\vec{x}(\vec{u})). \quad (1.59)$$

Going back to the base manifold,  $\mathcal{M}$ , note that the mapping  $\mathbf{e}^{\mathcal{M}}(\vec{x}) : U^n \subseteq \mathbb{R}^n \rightarrow \mathcal{V}$  allows us to calculate an unnormalized pseudo-scalar for  $\mathcal{T}_{\vec{x}}(\mathcal{M})$ ,

$$I^{\mathcal{M}}(\vec{x}) = \mathbf{e}_1^{\mathcal{M}}(\vec{x}) \wedge \dots \wedge \mathbf{e}_m^{\mathcal{M}}(\vec{x}). \quad (1.60)$$

With the pseudo-scalar we can define a projection operator from  $\mathcal{V}$  to the tangent space of  $\mathcal{M}$  by

$$P_{\vec{x}}(\mathbf{v}) = (\mathbf{v} \cdot I^{\mathcal{M}}(\vec{x})) (I^{\mathcal{M}}(\vec{x}))^{-1} \quad \forall \mathbf{v} \in \mathcal{V}. \quad (1.61)$$

In fact for each tangent space  $\mathcal{T}_{\vec{x}}(\mathcal{M})$  we can define a geometric algebra  $\mathcal{G}(\mathcal{T}_{\vec{x}}(\mathcal{M}))$  with pseudo-scalar  $I^{\mathcal{M}}$  so that if  $A \in \mathcal{G}(\mathcal{V})$  then

$$P_{\vec{x}}(A) = (A \cdot I^{\mathcal{M}}(\vec{x})) (I^{\mathcal{M}}(\vec{x}))^{-1} \in \mathcal{G}(\mathcal{T}_{\vec{x}}(\mathcal{M})) \quad \forall A \in \mathcal{G}(\mathcal{V}) \quad (1.62)$$

and similarly for the submanifold  $\mathcal{N}$ .

If the embedding  $\mathbf{e}^{\mathcal{M}}(\vec{x}) : U^n \subseteq \mathbb{R}^n \rightarrow \mathcal{V}$  is not given, but the metric tensor  $g_{ij}^{\mathcal{M}}(\vec{x})$  is given the geometric algebra of the tangent space can be constructed. Also the derivatives of the basis vectors of the tangent space can be calculated from the metric tensor using the Christoffel symbols,  $\Gamma_{ij}^k(\vec{u})$ , where the derivatives of the basis vectors are given by

$$\frac{\partial \mathbf{e}_j^{\mathcal{M}}}{\partial x^i} = \Gamma_{ij}^k(\vec{u}) \mathbf{e}_k^{\mathcal{M}}. \quad (1.63)$$

If we have a submanifold,  $\mathcal{N}$ , defined by eq. (1.56) we can calculate the metric of  $\mathcal{N}$  from eq. (1.59) and hence construct the geometric algebra and calculus of the tangent space,  $\mathcal{T}_{\vec{u}}(\mathcal{N}) \subseteq \mathcal{T}_{\vec{x}(\vec{u})}(\mathcal{M})$ .

If the base manifold is normalized (use the hat symbol to denote normalized tangent vectors,  $\hat{\mathbf{e}}_i^{\mathcal{M}}$ , and the resulting metric tensor,  $\hat{g}_{ij}^{\mathcal{M}}$ ) we have  $\hat{\mathbf{e}}_i^{\mathcal{M}} \cdot \hat{\mathbf{e}}_i^{\mathcal{M}} = \pm 1$  and  $\hat{g}_{ij}^{\mathcal{M}}$  does not possess enough information to calculate  $g_{ij}^{\mathcal{N}}$ . In that case we need to know  $g_{ij}^{\mathcal{M}}$ , the metric tensor of the base manifold before normalization. Likewise, for the case of a vector manifold unless the mapping,  $\mathbf{e}^{\mathcal{M}}(\vec{x}) : U^m \subseteq \mathbb{R}^m \rightarrow \mathcal{V}$ , is constant the tangent vectors and metric tensor can only be normalized after the fact (one cannot have a mapping that automatically normalizes all the tangent vectors).

## 1.10 Geometric Derivative

The directional derivative of a multivector field  $F(x)$  is defined by ( $a$  is a vector and  $h$  is a scalar)

$$(a \cdot \nabla_x) F \equiv \lim_{h \rightarrow 0} \frac{F(x + ah) - F(x)}{h}. \quad (1.64)$$

Note that  $a \cdot \nabla_x$  is a scalar operator. It will give a result containing only those grades that are already in  $F$ .  $(a \cdot \nabla_x) F$  is the best linear approximation of  $F(x)$  in the direction  $a$ . Equation (1.64) also defines the operator  $\nabla_x$  which for a set of basis vectors,  $\{e_i\}$ , has the representation (note that the  $e^j$  are reciprocal basis vectors)

$$\nabla_x F = e^j \frac{\partial F}{\partial x^j} \quad (1.65)$$

If  $F_r$  is a  $r$ -grade multivector (if the independent vector,  $x$ , is obvious we suppress it in the notation and just write  $\nabla$ ) and  $F_r = F_r^{i_1 \dots i_r} e_{i_1} \wedge \dots \wedge e_{i_r}$  then

$$\nabla F_r = \frac{\partial F_r^{i_1 \dots i_r}}{\partial x^j} e^j (e_{i_1} \wedge \dots \wedge e_{i_r}) \quad (1.66)$$

Note that  $e^j (e_{i_1} \wedge \dots \wedge e_{i_r})$  can only contain grades  $r - 1$  and  $r + 1$  so that  $\nabla F_r$  also can only contain those grades. For a grade- $r$  multivector  $F_r$  the inner (div) and outer (curl) derivatives are

$$\nabla \cdot F_r = \langle \nabla F_r \rangle_{r-1} = e^j \cdot \frac{\partial F_r}{\partial x^j} \quad (1.67)$$

and

$$\nabla \wedge F_r = \langle \nabla F_r \rangle_{r+1} = e^j \wedge \frac{\partial F_r}{\partial x^j} \quad (1.68)$$

For a general multivector function  $F$  the inner and outer derivatives are just the sum of the inner and outer derivatives of each grade of the multivector function.

## Geometric Derivative on a Manifold

In the case of a manifold the derivatives of the  $e_i$ 's are functions of the coordinates,  $\{x^i\}$ , so that the geometric derivative of a  $r$ -grade multivector field is (Einstein summation convention)

$$\begin{aligned} \nabla F_r &= e^i \frac{\partial F_r}{\partial x^i} = e^i \frac{\partial}{\partial x^i} (F_r^{i_1 \dots i_r} e_{i_1} \wedge \dots \wedge e_{i_r}) \\ &= \frac{\partial F_r^{i_1 \dots i_r}}{\partial x^i} e^i (e_{i_1} \wedge \dots \wedge e_{i_r}) + F_r^{i_1 \dots i_r} e^i \frac{\partial}{\partial x^i} (e_{i_1} \wedge \dots \wedge e_{i_r}) \end{aligned} \quad (1.69)$$

where the multivector functions  $e^i \frac{\partial}{\partial x^i} (e_{i_1} \wedge \dots \wedge e_{i_r})$  are the connection for the manifold.<sup>3</sup>

The directional (material/convective) derivative,  $(v \cdot \nabla) F_r$  is given by

$$(v \cdot \nabla) F_r = v^i \frac{\partial F_r}{\partial x^i} = v^i \frac{\partial}{\partial x^i} (F_r^{i_1 \dots i_r} e_{i_1} \wedge \dots \wedge e_{i_r})$$

---

<sup>3</sup>We use the Christoffel symbols of the first kind to calculate the derivatives of the basis vectors and the product rule to calculate the derivatives of the basis blades where ([http://en.wikipedia.org/wiki/Christoffel\\_](http://en.wikipedia.org/wiki/Christoffel_)

$$= v^i \frac{\partial F_r^{i_1 \dots i_r}}{\partial x^i} (e_{i_1} \wedge \dots \wedge e_{i_r}) + v^i F_r^{i_1 \dots i_r} \frac{\partial}{\partial x^i} (e_{i_1} \wedge \dots \wedge e_{i_r}), \quad (1.70)$$

so that the multivector connection functions for the directional derivative are  $\frac{\partial}{\partial x^i} (e_{i_1} \wedge \dots \wedge e_{i_r})$ . Be careful and note that  $(v \cdot \nabla) F_r \neq v \cdot (\nabla F_r)$  since the dot and geometric products are not associative with respect to one another ( $v \cdot \nabla$  is a scalar operator).

## Normalizing Basis for Derivatives

The basis vector set,  $\{e_i\}$ , is not in general normalized. We define a normalized set of basis vectors,  $\{\hat{e}_i\}$ , and reciprocal basis vectors,  $\{\hat{e}^i\}$ , by

$$\hat{e}_i = \frac{e_i}{\sqrt{|e_i|^2}} = \frac{e_i}{|e_i|}, \quad (1.71)$$

$$\hat{e}^i = \frac{e^i}{\sqrt{|(e^i)^2|}} = \frac{e^i}{|e^i|}. \quad (1.72)$$

This works for all  $e_i^2 \neq 0$ . Note that  $\hat{e}_i^2 = \pm 1$  and  $(\hat{e}^i)^2 = \pm 1$ . Using the definition of reciprocal vectors we obtain the relationship between  $|e_i|$  and  $|e^i|$ ,

$$\begin{aligned} e^i \cdot e_j &= \delta_j^i \\ |e^i| \hat{e}^i \cdot |e_j| \hat{e}_j &= \delta_j^i \\ |e^i| |e_i| &= 1 \\ |e^i| &= \frac{1}{|e_i|}. \end{aligned}$$

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symbols)

$$\Gamma_{ijk} = \frac{1}{2} \left( \frac{\partial g_{jk}}{\partial x^i} + \frac{\partial g_{ik}}{\partial x^j} - \frac{\partial g_{ij}}{\partial x^k} \right),$$

and

$$\frac{\partial e_j}{\partial x^i} = \Gamma_{ijk} e^k.$$

The Christoffel symbols of the second kind,

$$\Gamma_{ij}^k = \frac{1}{2} g^{kl} \left( \frac{\partial g_{li}}{\partial x^j} + \frac{\partial g_{lj}}{\partial x^i} - \frac{\partial g_{ij}}{\partial x^l} \right),$$

could also be used to calculate the derivatives in term of the original basis vectors, but since we need to calculate the reciprocal basis vectors for the geometric derivative it is more efficient to use the symbols of the first kind.

Thus the geometric derivative for a set of normalized basis vectors is (we assume that  $F_r = F_r^{i_1 \dots i_r} \hat{e}_{i_1} \wedge \dots \wedge \hat{e}_{i_r}$ )

$$\nabla F_r = \mathbf{e}^i \frac{\partial F_r}{\partial x^i} = \frac{\hat{\mathbf{e}}^i}{|\mathbf{e}_i|} \frac{\partial F_r}{\partial x^i} = \frac{\partial F_r^{i_1 \dots i_r}}{\partial x^i} \frac{\hat{\mathbf{e}}^i}{|\mathbf{e}_i|} (\hat{e}_{i_1} \wedge \dots \wedge \hat{e}_{i_r}) + F_r^{i_1 \dots i_r} \frac{\hat{\mathbf{e}}^i}{|\mathbf{e}_i|} \frac{\partial}{\partial x^i} (\hat{e}_{i_1} \wedge \dots \wedge \hat{e}_{i_r}). \quad (1.73)$$

Additionally, one can calculate the connection of the normalized basis as follows

$$\begin{aligned} \frac{\partial \mathbf{e}_i}{\partial x^j} &= \frac{\partial(|\mathbf{e}_i| \hat{\mathbf{e}}_i)}{\partial x^j} = \Gamma_{jik} \mathbf{e}^k, \\ \frac{\partial |\mathbf{e}_i|}{\partial x^j} \hat{\mathbf{e}}_i + |\mathbf{e}_i| \frac{\partial \hat{\mathbf{e}}_i}{\partial x^j} &= \Gamma_{jik} \mathbf{e}^k, \\ \frac{\partial |\mathbf{e}_i|}{\partial x^j} \hat{\mathbf{e}}_i + |\mathbf{e}_i| \frac{\partial \hat{\mathbf{e}}_i}{\partial x^j} &= \frac{1}{|\mathbf{e}_k|} \Gamma_{jik} \hat{\mathbf{e}}^k, \\ \frac{\partial \hat{\mathbf{e}}_i}{\partial x^j} &= \frac{1}{|\mathbf{e}_i|} \left( \frac{1}{|\mathbf{e}_k|} \Gamma_{jik} \hat{\mathbf{e}}^k - \frac{\partial |\mathbf{e}_i|}{\partial x^j} \hat{\mathbf{e}}_i \right), \\ &= \frac{1}{|\mathbf{e}_i| |\mathbf{e}_k|} \Gamma_{jik} \hat{\mathbf{e}}^k - \frac{1}{|\mathbf{e}_i|} \frac{\partial |\mathbf{e}_i|}{\partial x^j} \hat{\mathbf{e}}_i, \\ &= \frac{1}{|\mathbf{e}_i| |\mathbf{e}_k|} \Gamma_{jik} \hat{\mathbf{e}}^k - \frac{1}{2g_{ii}} \frac{\partial g_{ii}}{\partial x^j} \hat{\mathbf{e}}_i. \end{aligned} \quad (1.74)$$

## Linear Differential Operators

First a note on partial derivative notation. We shall use the following notation for a partial derivative where the manifold coordinates are  $x_1, \dots, x_n$ :

$$\frac{\partial^{j_1 + \dots + j_n}}{\partial x_1^{j_1} \dots \partial x_n^{j_n}} = \partial_{j_1 \dots j_n}. \quad (1.75)$$

If  $j_k = 0$  the partial derivative with respect to the  $k^{th}$  coordinate is not taken. If the  $j_k = 0$  for all  $1 \leq k \leq n$  then the partial derivative operator is the scalar one. If we consider a partial derivative where the  $x$ 's are not in normal order such as

$$\frac{\partial^{j_1 + \dots + j_n}}{\partial x_{i_1}^{j_1} \dots \partial x_{i_n}^{j_n}},$$

and the  $i_k$ 's are not in ascending order. The derivative can always be put in the form in eq (1.75) since the order of differentiation does not change the value of the partial derivative (for the smooth functions we are considering). Additionally, using our notation the product of two partial derivative operations is given by

$$\partial_{i_1 \dots i_n} \partial_{j_1 \dots j_n} = \partial_{i_1 + j_1, \dots, i_n + j_n}. \quad (1.76)$$

A general general multivector linear differential operator is a linear combination of multivectors and partial derivative operators denoted by (in all of this section we will use the Einstein summation convention)

$$D \equiv D^{i_1 \dots i_n} \partial_{i_1 \dots i_n}. \quad (1.77)$$

Equation (1.77) is the normal form of the differential operator in that the partial derivative operators are written to the right of the multivector coefficients and do not operate upon the multivector coefficients. The operator of eq (1.77) can operate on multivector functions, returning a multivector function via the following definitions.

$F$  as (Einstein summation convention)

$$D \circ F = D^{j_1 \dots j_n} \circ \partial_{j_1 \dots j_n} F, \quad (1.78)$$

or

$$F \circ D = F \circ D^{j_1 \dots j_n} \partial_{j_1 \dots j_n}, \quad (1.79)$$

where the  $D^{j_1 \dots j_n}$  are multivector functions and  $\circ$  is any of the multivector multiplicative operations.

Equations (1.78) and (1.79) are not the most general multivector linear differential operators, the most general would be

$$D(F) = D^{j_1 \dots j_n} (\partial_{j_1 \dots j_n} F), \quad (1.80)$$

where  $D^{j_1 \dots j_n}()$  are linear multivector functionals.

The definition of the sum of two differential operators is obvious since any multivector operator,  $\circ$ , is a bilinear operator ( $(D_A + D_B) \circ F = D_A \circ F + D_B \circ F$ ), the product of two differential operators  $D_A$  and  $D_B$  operating on a multivector function  $F$  is defined to be ( $\circ_1$  and  $\circ_2$  are any two multivector multiplicative operations)

$$(D_A \circ_1 D_B) \circ_2 F \equiv (D_A^{i_1 \dots i_n} \circ_1 \partial_{i_1 \dots i_n} (D_B^{j_1 \dots j_n} \partial_{j_1 \dots j_n} F)) \circ_2 F. \quad (1.81)$$

Thus for a pure operator product  $D_A \circ D_B$  we have

$$D_A \circ D_B = (D_A^{i_1 \dots i_n} \circ_1 \partial_{i_1 \dots i_n} (D_B^{j_1 \dots j_n} \partial_{j_1 \dots j_n})) \quad (1.82)$$

and the form of eq (1.82) is the same as eq (1.78). The basis of eq (1.82) is that the  $\partial$  operator operates on all object to the right of it as products so that the generalized product rule must be used in all differentiations (product rule for higher order partial derivatives if needed). Since eq (1.82) puts the product of two differential operators in standard form we can also evaluate  $F \circ_2 (D_A \circ_1 D_B)$ .

We now must distinguish between the following cases. If  $D$  is a differential operator and  $F$  a multivector function should  $D \circ F$  and  $F \circ D$  return a differential operator or a multivector. In order to be consistent with the standard vector analysis we have  $D \circ F$  return a multivector and  $F \circ D$  return a differential operator. Then we define the complementary differential operator  $\bar{D}$  which is identical to  $D$  except that  $\bar{D} \circ F$  returns a differential operator according to eq (1.82)<sup>4</sup> and  $F \circ \bar{D}$  returns a multivector according to eq (1.79).

A general differential operator is built from repeated applications of the basic operator building blocks  $(\bar{\nabla} \circ A)$ ,  $(A \circ \bar{\nabla})$ ,  $(\bar{\nabla} \circ \bar{\nabla})$ , and  $(A \pm \bar{\nabla})$ . Both  $\nabla$  and  $\bar{\nabla}$  are represented by the operator but are flagged to produce the appropriate result. The two operators are displayed as

$$\nabla = e^i \frac{\partial}{\partial x^i}, \quad (1.83)$$

$$\bar{\nabla} = \frac{\partial}{\partial x^i} e^i. \quad (1.84)$$

Note that in the product of differential operators both operators must be either right acting ( $\nabla$ ) or left acting ( $\bar{\nabla}$ ) with a resulting operator that is right acting or left acting. Mixing left acting and right acting operators is ambiguous.

In the our notation the directional derivative operator is  $a \cdot \nabla$ , the Laplacian  $\nabla \cdot \nabla$  and the expression for the Riemann tensor,  $R_{jkl}^i$ , is

$$(\nabla \wedge \nabla) e^i = \frac{1}{2} R_{jkl}^i (e^j \wedge e^k) e^l. \quad (1.85)$$

If we wish a quantum mechanical type commutator define

$$[x, \nabla] \equiv x \nabla - \nabla x, \quad (1.86)$$

or if we wish to simulate the dot notation (Doran and Lasenby)

$$\dot{F} \dot{\nabla} = F \bar{\nabla}. \quad (1.87)$$

The linear differential operator is represented as a list of tuples. The first member of the tuple is a multivector and the second element is a partial differential operator (**Pdop** class). The partial differential operator is a dictionary wrapped in the **Pdop** class where the keys of the dictionary are the variables one is differentiating with respect to and the key values integers that represent the number of times each differentiation is to be performed. For example we have the correspondence

$$\frac{\partial^4}{\partial x \partial y \partial z^2} \leftrightarrow \{x:1, y:1, z:2\}. \quad (1.88)$$

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<sup>4</sup>In this case  $D_B^{j_1 \dots j_n} = F$  and  $\partial_{j_1 \dots j_n} = 1$ .



The member functions of **Pdop** allow the operator to correctly operate on multivectors and other **Pdop**'s for both first order and higher order derivatives. The order of the derivative is the sum of the key values in the dictionary. If the order is greater than one the **Pdop** is factored into **Pdop**'s of order one that are successively applied to the argument being differentiated. The object that then represents a multivector differential operator (wrapped in the **Dop** class) is then

$$[(A_0, P_0), \dots, (A_r, P_r)], \quad (1.89)$$

where the  $A_i$ 's are multivectors and the  $P_i$ 's are partial differential operators. The member functions of the **Dop** class create an algebra of linear multivector differential operators where the multiplication operator for class members can be any of the multivector multiplicative operators ( $*$ ,  $\wedge$ ,  $\lrcorner$ ,  $\lhd$ , and  $\rhd$ ). Additionally, each instantiation of **Dop** has a flag to indicate whether the operator acts on the left or the right.

For displaying a **Dop** an additional class, **Sdop**, is used. **Sdop** is a scalar differential operator class and it is used to print **Dop**'s as the sum of the products of basis blades and scalar differential operators. Thus if  $A$  is a vector then  $A\nabla$  would be displayed as

$$A^x \frac{\partial}{\partial x} + A^y \frac{\partial}{\partial y} + A^z \frac{\partial}{\partial z} + \mathbf{e}_x \wedge \mathbf{e}_y \left( -A^y \frac{\partial}{\partial x} + A^x \frac{\partial}{\partial y} \right) + \mathbf{e}_x \wedge \mathbf{e}_z \left( -A^z \frac{\partial}{\partial x} + A^x \frac{\partial}{\partial z} \right) + \mathbf{e}_y \wedge \mathbf{e}_z \left( -A^z \frac{\partial}{\partial y} + A^y \frac{\partial}{\partial z} \right).$$

Instead of (internal representation as in eq (1.89))

$$(A^x - \mathbf{e}_x \wedge \mathbf{e}_y A^y - \mathbf{e}_x \wedge \mathbf{e}_z A^z) \frac{\partial}{\partial x} + (A^y + \mathbf{e}_x \wedge \mathbf{e}_y A^x - \mathbf{e}_y \wedge \mathbf{e}_z A^z) \frac{\partial}{\partial y} + (A^z + \mathbf{e}_x \wedge \mathbf{e}_z A^x + \mathbf{e}_y \wedge \mathbf{e}_z A^y) \frac{\partial}{\partial z}.$$

For those interested in quantum mechanics note that if  $\mathbf{X} = x\mathbf{e}_x + y\mathbf{e}_y + z\mathbf{e}_z$  then

$$\mathbf{X} \wedge \nabla = \mathbf{e}_x \wedge \mathbf{e}_y \left( -y \frac{\partial}{\partial x} + x \frac{\partial}{\partial y} \right) + \mathbf{e}_x \wedge \mathbf{e}_z \left( -z \frac{\partial}{\partial x} + x \frac{\partial}{\partial z} \right) + \mathbf{e}_y \wedge \mathbf{e}_z \left( -z \frac{\partial}{\partial y} + y \frac{\partial}{\partial z} \right)$$

and the components of  $\mathbf{X} \wedge \nabla$  are the quantum mechanical angular momentum operators to within a multiplicative constant (in the geometric algebra formulation of mechanics angular momentum is a bivector and not an pseudo vector as in the standard vector treatment).

## 1.11 Linear Transformations/Outermorphisms

In the tangent space of a manifold,  $\mathcal{M}$ , (which is a vector space) a linear transformation is the mapping  $\underline{T}: \mathcal{T}_{\underline{x}}(\mathcal{M}) \rightarrow \mathcal{T}_{\underline{x}}(\mathcal{M})$  (we use an underline to indicate a linear transformation) where for all  $x, y \in \mathcal{T}_{\underline{x}}(\mathcal{M})$  and  $\alpha \in \mathbb{R}$  we have

$$\underline{T}(x + y) = \underline{T}(x) + \underline{T}(y) \quad (1.90)$$

$$\underline{T}(\alpha x) = \alpha \underline{T}(x) \quad (1.91)$$

The outermorphism induced by  $\underline{T}$  is defined for  $x_1, \dots, x_r \in \mathcal{T}_{\vec{x}}(\mathcal{M})$  where  $r \leq \dim(\mathcal{T}_{\vec{x}}(\mathcal{M}))$

$$\underline{T}(x_1 \wedge \dots \wedge x_r) \equiv \underline{T}(x_1) \wedge \dots \wedge \underline{T}(x_r) \quad (1.92)$$

If  $I$  is the pseudo scalar for  $\mathcal{T}_{\vec{x}}(\mathcal{M})$  we also have the following definitions for determinate, trace, and adjoint ( $\overline{T}$ ) of  $\underline{T}$

$$\underline{T}(I) \equiv \det(\underline{T}) I,^5 \quad (1.93)$$

$$\text{tr}(\underline{T}) \equiv \nabla_y \cdot \underline{T}(y),^6 \quad (1.94)$$

$$x \cdot \overline{T}(y) \equiv y \cdot \underline{T}(x). \quad (1.95)$$

If  $\{\mathbf{e}_i\}$  is a basis for  $\mathcal{T}_{\vec{x}}(\mathcal{M})$  then we can represent  $\underline{T}$  with the matrix  $\underline{T}_i^j$  used as follows (Einstein summation convention as usual) -

$$\underline{T}(\mathbf{e}_i) = \underline{T}_i^j \mathbf{e}_j. \quad (1.96)$$

In eq. (1.96) the matrix,  $\underline{T}_i^j$ , only has it's usual meaning if the  $\{\mathbf{e}_i\}$  form an orthonormal Euclidan basis (Minkowski spaces not allowed). Equations (1.93) through (1.95) become

$$\det(\underline{T}) = \underline{T}(\mathbf{e}_1 \wedge \dots \wedge \mathbf{e}_n) (\mathbf{e}_1 \wedge \dots \wedge \mathbf{e}_n)^{-1}, \quad (1.97)$$

$$\text{tr}(\underline{T}) = \underline{T}_i^i, \quad (1.98)$$

$$\overline{T}_j^i = g^{il} g_{jp} \underline{T}_l^p. \quad (1.99)$$

## 1.12 Multilinear Functions (Tensors)

### Multiliner Functions

A multivector multilinear function<sup>7</sup> is a multivector function  $T(A_1, \dots, A_r)$  that is linear in each of it arguments<sup>8</sup> (it could be implicitly non-linearly dependent on a set of additional arguments such as the postion coordinates, but we only consider the linear arguments).  $T$  is a *tensor* of

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<sup>5</sup>Since  $\underline{T}$  is linear we do not require  $I^2 = \pm 1$ .

<sup>6</sup>In this case  $y$  is a vector in the tangent space and not a coordinate vector so that the basis vectors are *not* a function of  $y$ .

<sup>7</sup>We are following the treatment of Tensors in section 3–10 of [2].

<sup>8</sup>We assume that the arguments are elements of a vector space or more generally a geometric algebra so that the concept of linearity is meaningful.

degree  $r$  if each variable  $A_j$  is restricted to the vector space  $\mathcal{V}_n$ . More generally if each  $A_j \in \mathcal{G}(\mathcal{V}_n)$  (the geometric algebra of  $\mathcal{V}_n$ ), we call  $T$  an *extensor* of degree- $r$  on  $\mathcal{G}(\mathcal{V}_n)$ .

If the values of  $T(a_1, \dots, a_r)$  ( $a_j \in \mathcal{V}_n \forall 1 \leq j \leq r$ ) are  $s$ -vectors (pure grade  $s$  multivectors in  $\mathcal{G}(\mathcal{V}_n)$ ) we say that  $T$  has grade  $s$  and rank  $r + s$ . A tensor of grade zero is called a *multilinear form*.

In the normal definition of tensors as multilinear functions the tensor is defined as a mapping

$$T : \bigotimes_{i=1}^r \mathcal{V}_i \rightarrow \mathfrak{R},$$

so that the standard tensor definition is an example of a grade zero degree/rank  $r$  tensor in our definition.

## Algebraic Operations

The properties of tensors are ( $\alpha \in \mathfrak{R}$ ,  $a_j, b \in \mathcal{V}_n$ ,  $T$  and  $S$  are tensors of rank  $r$ , and  $\circ$  is any multivector multiplicative operation)

$$T(a_1, \dots, \alpha a_j, \dots, a_r) = \alpha T(a_1, \dots, a_j, \dots, a_r), \quad (1.100)$$

$$T(a_1, \dots, a_j + b, \dots, a_r) = T(a_1, \dots, a_j, \dots, a_r) + T(a_1, \dots, b, \dots, a_r), \quad (1.101)$$

$$(T \pm S)(a_1, \dots, a_r) \equiv T(a_1, \dots, a_r) \pm S(a_1, \dots, a_r). \quad (1.102)$$

Now let  $T$  be of rank  $r$  and  $S$  of rank  $s$  then the product of the two tensors is

$$(T \circ S)(a_1, \dots, a_{r+s}) \equiv T(a_1, \dots, a_r) \circ S(a_{r+1}, \dots, a_{r+s}), \quad (1.103)$$

where “ $\circ$ ” is any multivector multiplicative operation.

## Covariant, Contravariant, and Mixed Representations

The arguments (vectors) of the multilinear function can be represented in terms of the basis vectors or the reciprocal basis vectors

$$a_j = a^{ij} e_{ij}, \quad (1.104)$$

$$= a_{ij} e^{ij}. \quad (1.105)$$

Equation (1.104) gives  $a_j$  in terms of the basis vectors and eq (1.105) in terms of the reciprocal basis vectors. The index  $j$  refers to the argument slot and the indices  $i_j$  the components of

the vector in terms of the basis. The Einstein summation convention is used throughout. The covariant representation of the tensor is defined by

$$T_{i_1 \dots i_r} \equiv T(e_{i_1}, \dots, e_{i_r}) \quad (1.106)$$

$$\begin{aligned} T(a_1, \dots, a_r) &= T(a^{i_1} e_{i_1}, \dots, a^{i_r} e_{i_r}) \\ &= T(e_{i_1}, \dots, e_{i_r}) a^{i_1} \dots a^{i_r} \\ &= T_{i_1 \dots i_r} a^{i_1} \dots a^{i_r}. \end{aligned} \quad (1.107)$$

Likewise for the contravariant representation

$$T^{i_1 \dots i_r} \equiv T(e^{i_1}, \dots, e^{i_r}) \quad (1.108)$$

$$\begin{aligned} T(a_1, \dots, a_r) &= T(a_{i_1} e^{i_1}, \dots, a_{i_r} e^{i_r}) \\ &= T(e^{i_1}, \dots, e^{i_r}) a_{i_1} \dots a_{i_r} \\ &= T^{i_1 \dots i_r} a_{i_1} \dots a_{i_r}. \end{aligned} \quad (1.109)$$

One could also have a mixed representation

$$T_{i_1 \dots i_s}^{i_{s+1} \dots i_r} \equiv T(e_{i_1}, \dots, e_{i_s}, e^{i_{s+1}} \dots e^{i_r}) \quad (1.110)$$

$$\begin{aligned} T(a_1, \dots, a_r) &= T(a^{i_1} e_{i_1}, \dots, a^{i_s} e_{i_s}, a_{i_{s+1}} e^{i_{s+1}} \dots, a_{i_r} e^{i_r}) \\ &= T(e_{i_1}, \dots, e_{i_s}, e^{i_{s+1}}, \dots, e^{i_r}) a^{i_1} \dots a^{i_s}, a_{i_{s+1}}, \dots, a_{i_r} \\ &= T_{i_1 \dots i_s}^{i_{s+1} \dots i_r} a^{i_1} \dots a^{i_s}, a_{i_{s+1}}, \dots, a_{i_r}. \end{aligned} \quad (1.111)$$

In the representation of  $T$  one could have any combination of covariant (lower) and contravariant (upper) indices.

To convert a covariant index to a contravariant index simply consider

$$\begin{aligned} T(e_{i_1}, \dots, e^{i_j}, \dots, e_{i_r}) &= T(e_{i_1}, \dots, g^{ij} e_{k_j}, \dots, e_{i_r}) \\ &= g^{ij} T(e_{i_1}, \dots, e_{k_j}, \dots, e_{i_r}) \\ T_{i_1 \dots}^{i_j} \dots i_r &= g^{ij} T_{i_1 \dots i_j \dots i_r}. \end{aligned} \quad (1.112)$$

Similarly one could lower an upper index with  $g_{ij}$ .

## Contraction and Differentiation

The contraction of a tensor between the  $j^{th}$  and  $k^{th}$  variables (slots) is

$$T(a_i, \dots, a_{j-1}, \nabla_{a_k}, a_{j+1}, \dots, a_r) = \nabla_{a_j} \cdot (\nabla_{a_k} T(a_1, \dots, a_r)). \quad (1.113)$$

This operation reduces the rank of the tensor by two. This definition gives the standard results for *metric contraction* which is proved as follows for a rank  $r$  grade zero tensor (the circumflex “ $\circ$ ” indicates that a term is to be deleted from the product).

$$T(a_1, \dots, a_r) = a^{i_1} \dots a^{i_r} T_{i_1 \dots i_r} \quad (1.114)$$

$$\begin{aligned} \nabla_{a_j} T &= e^{l_j} a^{i_1} \dots (\partial_{a^{l_j}} a^{i_j}) \dots a^{i_r} T_{i_1 \dots i_r} \\ &= e^{l_j} \delta_{l_j}^{i_j} a^{i_1} \dots \check{a}^{i_j} \dots a^{i_r} T_{i_1 \dots i_r} \end{aligned} \quad (1.115)$$

$$\begin{aligned} \nabla_{a_m} \cdot (\nabla_{a_j} T) &= e^{k_m} \cdot e^{l_j} \delta_{l_j}^{i_j} a^{i_1} \dots \check{a}^{i_j} \dots (\partial_{a^{k_m}} a^{i_m}) \dots a^{i_r} T_{i_1 \dots i_r} \\ &= g^{k_m l_j} \delta_{l_j}^{i_j} \delta_{k_m}^{i_m} a^{i_1} \dots \check{a}^{i_j} \dots \check{a}^{i_m} \dots a^{i_r} T_{i_1 \dots i_r} \\ &= g^{i_m i_j} a^{i_1} \dots \check{a}^{i_j} \dots \check{a}^{i_m} \dots a^{i_r} T_{i_1 \dots i_j \dots i_m \dots i_r} \\ &= g^{i_j i_m} a^{i_1} \dots \check{a}^{i_j} \dots \check{a}^{i_m} \dots a^{i_r} T_{i_1 \dots i_j \dots i_m \dots i_r} \\ &= (g^{i_j i_m} T_{i_1 \dots i_j \dots i_m \dots i_r}) a^{i_1} \dots \check{a}^{i_j} \dots \check{a}^{i_m} \dots a^{i_r} \end{aligned} \quad (1.116)$$

Equation (1.116) is the correct formula for the metric contraction of a tensor.

If we have a mixed representation of a tensor,  $T_{i_1 \dots i_k \dots i_r}^{i_j}$ , and wish to contract between an upper and lower index ( $i_j$  and  $i_k$ ) first lower the upper index and then use eq (1.116) to contract the result. Remember lowering the index does *not* change the tensor, only the *representation* of the tensor, while contraction results in a *new* tensor. First lower index

$$T_{i_1 \dots i_k \dots i_r}^{i_j} \xrightarrow{\text{Lower Index}} g_{i_j k_j} T_{i_1 \dots i_k \dots i_r}^{k_j} \quad (1.117)$$

Now contract between  $i_j$  and  $i_k$  and use the properties of the metric tensor.

$$\begin{aligned} g_{i_j k_j} T_{i_1 \dots i_k \dots i_r}^{k_j} &\xrightarrow{\text{Contract}} g^{i_j i_k} g_{i_j k_j} T_{i_1 \dots i_k \dots i_r}^{k_j} \\ &= \delta_{k_j}^{i_k} T_{i_1 \dots i_k \dots i_r}^{k_j} \end{aligned} \quad (1.118)$$

Equation (1.118) is the standard formula for contraction between upper and lower indices of a mixed tensor.

Finally if  $T(a_1, \dots, a_r)$  is a tensor field (implicitly a function of position) the tensor derivative is defined as

$$T(a_1, \dots, a_r; a_{r+1}) \equiv (a_{r+1} \cdot \nabla) T(a_1, \dots, a_r), \quad (1.119)$$

assuming the  $a^{i_j}$  coefficients are not a function of the coordinates.

This gives for a grade zero rank  $r$  tensor

$$\begin{aligned} (a_{r+1} \cdot \nabla) T(a_1, \dots, a_r) &= a^{i_{r+1}} \partial_{x^{i_{r+1}}} a^{i_1} \dots a^{i_r} T_{i_1 \dots i_r}, \\ &= a^{i_1} \dots a^{i_r} a^{i_{r+1}} \partial_{x^{i_{r+1}}} T_{i_1 \dots i_r}. \end{aligned} \quad (1.120)$$

## From Vector to Tensor

A rank one tensor is a vector since it satisfies all the axioms for a vector space, but a vector is not necessarily a tensor since not all vectors are multilinear (actually in the case of vectors a linear function) functions. However, there is a simple isomorphism between vectors and rank one tensors defined by the mapping  $v(a) : \mathcal{V} \rightarrow \mathfrak{R}$  such that if  $v, a \in \mathcal{V}$

$$v(a) \equiv v \cdot a. \quad (1.121)$$

So that if  $v = v^i \mathbf{e}_i = v_i \mathbf{e}^i$  the covariant and contravariant representations of  $v$  are (using  $\mathbf{e}^i \cdot \mathbf{e}_j = \delta_j^i$ )

$$v(a) = v_i a^i = v^i a_{i2}. \quad (1.122)$$

## Parallel Transport and Covariant Derivatives

The covariant derivative of a tensor field  $T(a_1, \dots, a_r; x)$  ( $x$  is the coordinate vector of which  $T$  can be a non-linear function) in the direction  $a_{r+1}$  is (remember  $a_j = a_j^k \mathbf{e}_k$  and the  $\mathbf{e}_k$  can be functions of  $x$ ) the directional derivative of  $T(a_1, \dots, a_r; x)$  where all the arguments of  $T$  are parallel transported. The definition of parallel transport is if  $a$  and  $b$  are tangent vectors in the tangent space of the manifold then

$$(a \cdot \nabla_x) b = 0 \quad (1.123)$$

if  $b$  is parallel transported. Since  $b = b^i \mathbf{e}_i$  and the derivatives of  $\mathbf{e}_i$  are functions of the  $x^i$ 's then the  $b^i$ 's are also functions of the  $x^i$ 's so that in order for eq (1.123) to be satisfied we have

$$\begin{aligned} (a \cdot \nabla_x) b &= a^i \partial_{x^i} (b^j \mathbf{e}_j) \\ &= a^i ((\partial_{x^i} b^j) \mathbf{e}_j + b^j \partial_{x^i} \mathbf{e}_j) \\ &= a^i ((\partial_{x^i} b^j) \mathbf{e}_j + b^j \Gamma_{ij}^k \mathbf{e}_k) \\ &= a^i ((\partial_{x^i} b^j) \mathbf{e}_j + b^k \Gamma_{ik}^j \mathbf{e}_j) \\ &= a^i ((\partial_{x^i} b^j) + b^k \Gamma_{ik}^j) \mathbf{e}_j = 0. \end{aligned} \quad (1.124)$$

Thus for  $b$  to be parallel transported we must have

$$\partial_{x^i} b^j = -b^k \Gamma_{ik}^j. \quad (1.125)$$

The geometric meaning of parallel transport is that for an infinitesimal rotation and dilation of the basis vectors (cause by infinitesimal changes in the  $x^i$ 's) the direction and magnitude of the vector  $b$  does not change.

If we apply eq (1.125) along a parametric curve defined by  $x^j(s)$  we have

$$\begin{aligned}\frac{db^j}{ds} &= \frac{dx^i}{ds} \frac{\partial b^j}{\partial x^i} \\ &= -b^k \frac{dx^i}{ds} \Gamma_{ik}^j,\end{aligned}\tag{1.126}$$

and if we define the initial conditions  $b^j(0) \mathbf{e}_j$ . Then eq (1.126) is a system of first order linear differential equations with initial conditions and the solution,  $b^j(s) \mathbf{e}_j$ , is the parallel transport of the vector  $b^j(0) \mathbf{e}_j$ .

An equivalent formulation for the parallel transport equation is to let  $\gamma(s)$  be a parametric curve in the manifold defined by the tuple  $\gamma(s) = (x^1(s), \dots, x^n(s))$ . Then the tangent to  $\gamma(s)$  is given by

$$\frac{d\gamma}{ds} \equiv \frac{dx^i}{ds} \mathbf{e}_i\tag{1.127}$$

and if  $v(x)$  is a vector field on the manifold then

$$\begin{aligned}\left(\frac{d\gamma}{ds} \cdot \nabla_x\right) v &= \frac{dx^i}{ds} \frac{\partial}{\partial x^i} (v^j \mathbf{e}_j) \\ &= \frac{dx^i}{ds} \left( \frac{\partial v^j}{\partial x^i} \mathbf{e}_j + v^j \frac{\partial \mathbf{e}_j}{\partial x^i} \right) \\ &= \frac{dx^i}{ds} \left( \frac{\partial v^j}{\partial x^i} \mathbf{e}_j + v^j \Gamma_{ij}^k \mathbf{e}_k \right) \\ &= \frac{dx^i}{ds} \frac{\partial v^j}{\partial x^i} \mathbf{e}_j + \frac{dx^i}{ds} v^k \Gamma_{ik}^j \mathbf{e}_j \\ &= \left( \frac{dv^j}{ds} + \frac{dx^i}{ds} v^k \Gamma_{ik}^j \right) \mathbf{e}_j \\ &= 0.\end{aligned}\tag{1.128}$$

Thus eq (1.128) is equivalent to eq (1.126) and parallel transport of a vector field along a curve is equivalent to the directional derivative of the vector field in the direction of the tangent to the curve being zero.

If the tensor component representation is contra-variant (superscripts instead of subscripts) we must use the covariant component representation of the vector arguments of the tensor,  $a = a_i \mathbf{e}^i$ . Then the definition of parallel transport gives

$$(a \cdot \nabla_x) b = a^i \partial_{x^i} (b_j \mathbf{e}^j)$$

$$= a^i \left( (\partial_{x^i} b_j) e^j + b_j \partial_{x^i} e^j \right), \quad (1.129)$$

and we need

$$(\partial_{x^i} b_j) e^j + b_j \partial_{x^i} e^j = 0. \quad (1.130)$$

To satisfy equation (1.130) consider the following

$$\begin{aligned} \partial_{x^i} (e^j \cdot e_k) &= 0 \\ (\partial_{x^i} e^j) \cdot e_k + e^j \cdot (\partial_{x^i} e_k) &= 0 \\ (\partial_{x^i} e^j) \cdot e_k + e^j \cdot e_l \Gamma_{ik}^l &= 0 \\ (\partial_{x^i} e^j) \cdot e_k + \delta_l^j \Gamma_{ik}^l &= 0 \\ (\partial_{x^i} e^j) \cdot e_k + \Gamma_{ik}^j &= 0 \\ (\partial_{x^i} e^j) \cdot e_k &= -\Gamma_{ik}^j \end{aligned} \quad (1.131)$$

Now dot eq (1.130) into  $e_k$  giving

$$\begin{aligned} (\partial_{x^i} b_j) e^j \cdot e_k + b_j (\partial_{x^i} e^j) \cdot e_k &= 0 \\ (\partial_{x^i} b_j) \delta_j^k - b_j \Gamma_{ik}^j &= 0 \\ (\partial_{x^i} b_k) &= b_j \Gamma_{ik}^j. \end{aligned} \quad (1.132)$$

Thus if we have a mixed representation of a tensor

$$T(a_1, \dots, a_r; x) = T_{i_1 \dots i_s}^{i_{s+1} \dots i_r}(x) a^{i_1} \dots a^{i_s} a_{i_{s+1}} \dots a_{i_r}, \quad (1.133)$$

the covariant derivative of the tensor is

$$\begin{aligned} (a_{r+1} \cdot D) T(a_1, \dots, a_r; x) &= \frac{\partial T_{i_1 \dots i_s}^{i_{s+1} \dots i_r}}{\partial x^{r+1}} a^{i_1} \dots a^{i_s} a_{i_{s+1}} \dots a_{i_r}^r a^{i_{r+1}} \\ &+ \sum_{p=1}^s \frac{\partial a^{i_p}}{\partial x^{i_{r+1}}} T_{i_1 \dots i_s}^{i_{s+1} \dots i_r} a^{i_1} \dots \check{a}^{i_p} \dots a^{i_s} a_{i_{s+1}} \dots a_{i_r} a^{i_{r+1}} \\ &+ \sum_{q=s+1}^r \frac{\partial a_{i_q}}{\partial x^{i_{r+1}}} T_{i_1 \dots i_s}^{i_{s+1} \dots i_r} a^{i_1} \dots a^{i_s} a_{i_{s+1}} \dots \check{a}_{i_q} \dots a_{i_r} a^{i_{r+1}} \\ &= \frac{\partial T_{i_1 \dots i_s}^{i_{s+1} \dots i_r}}{\partial x^{r+1}} a^{i_1} \dots a^{i_s} a_{i_{s+1}} \dots a_{i_r}^r a^{i_{r+1}} \\ &- \sum_{p=1}^s \Gamma_{i_{r+1} l_p}^{i_p} T_{i_1 \dots i_p \dots i_s}^{i_{s+1} \dots i_r} a^{i_1} \dots a^{l_p} \dots a^{i_s} a_{i_{s+1}} \dots a_{i_r} a^{i_{r+1}} \end{aligned}$$



$$+ \sum_{q=s+1}^r \Gamma_{i_{r+1}i_q}^{l_q} T_{i_1 \dots i_s}^{i_{s+1} \dots i_q \dots i_r} a^{i_1} \dots a^{i_s} a_{i_{s+1}} \dots a_{l_q} \dots a_{i_r} a^{i_{r+1}}. \quad (1.134)$$

From eq (1.134) we obtain the components of the covariant derivative to be

$$\frac{\partial T_{i_1 \dots i_s}^{i_{s+1} \dots i_r}}{\partial x^{r+1}} - \sum_{p=1}^s \Gamma_{i_{r+1}l_p}^{i_p} T_{i_1 \dots i_p \dots i_s}^{i_{s+1} \dots i_r} + \sum_{q=s+1}^r \Gamma_{i_{r+1}i_q}^{l_q} T_{i_1 \dots i_s}^{i_{s+1} \dots i_q \dots i_r}. \quad (1.135)$$

The component free form of the covariant derivative (the one used to calculate it in the code) is

$$\mathcal{D}_{a_{r+1}} T(a_1, \dots, a_r; x) \equiv a_{r+1} \cdot \nabla T - \sum_{k=1}^r T(a_1, \dots, (a_{r+1} \cdot \nabla) a_k, \dots, a_r; x). \quad (1.136)$$



# Chapter 2

## Module Components

The geometric algebra module consists of the following files and classes

File	Classes	Usage
<code>metric.py</code>	<code>Metric</code>	Instantiates metric tensor and derivatives of basis vectors. Normalized basis if required.
<code>ga.py</code>	<code>Ga</code>	Instantiates geometric algebra (inherits <code>Metric</code> ), generates bases, blades, multiplication tables, reciprocal basis, and left and right geometric derivative operators.
	<code>Sm</code>	Instantiates geometric algebra for submanifold (inherits <code>Ga</code> ).
<code>mv.py</code>	<code>Mv</code>	Instantiates multivector.
	<code>Dop</code>	Instantiates linear multivector differential operator.
	<code>Pdop</code>	Instantiates partial differential operator.
	<code>Sdop</code>	Instantiates linear scalar differential operator.
<code>lt.py</code>	<code>Lt</code>	Instantiates multivector linear transformation.
<code>printer.py</code>	<code>Eprint</code>	Starts enhanced text printing on ANSI terminal (requires <code>ansicon</code> on Windows).
	<code>GaPrinter</code>	Text printer for all geometric algebra classes (inherits from <code>sympy StringPrinter</code> ).
	<code>GaLatexPrinter</code>	L <sup>A</sup> T <sub>E</sub> Xprinter for all geometric algebra classes (inherits from <code>sympy LatexPrinter</code> ).

## 2.1 Instantiating a Geometric Algebra

The geometric algebra class is instantiated with

```
Ga(basis, g=None, coords=None, X=None, norm=False, debug=False)
```

The `basis` and `g` parameters were described in section 1.2. If the metric is a function of position, if we have multivector fields, or we wish to calculate geometric derivatives (differential operators) a coordinate set, `coords`, is required. `coords` is a list of *sympy* symbols. For the case of instantiating a 3-d geometric algebra in spherical coordinates we could use

```
(r, th, phi) = coords = symbols('r,theta,phi', real=True)
basis = 'e_r e_theta e_phi'
g = [1, r**2, r**2*sin(th)**2]
sp3d = Ga(basis,g=g,coords=coords,norm=True)
```

The input `X` allows the metric to be input as a vector manifold. `X` is a list of functions of `coords` of dimension,  $m$ , equal to or greater than the number of coordinates. If `g=None` it is assumed that `X` is a vector in an  $m$ -dimensional orthonormal Euclidian vector space. If it is wished the embedding vector space to be non-Euclidian that condition is specified with `g`. For example if we wish the embedding space to be a 5-dimensional Minkowski space then `g=[-1,1,1,1,1]`. Then the `Ga` class uses `X` to calculate the manifold basis vectors as a function of the coordinates and from them the metric tensor.<sup>1</sup>

If `norm=True` the basis vectors of the manifold are normalized so that the absolute values of the squares of the basis vectors are one. *It is suggested that one only use this option for diagonal metric tensors, and even there due so with caution, due to the possible problems with taking the square root of a general sympy expression (one that has an unknown sign).*

If `debug=True` the data structures required to initialize the `Ga` class are printed out.

To get the basis vectors for `sp3d` we would have to use the member function `Ga.mv()` in the form

```
(er,eth,ephi) = sp3d.mv()
```

---

<sup>1</sup>Since `X` or the metric tensor can be functions of coordinates the vector space that the geometric algebra is constructed from is not necessarily flat so that the geometric algebra is actually constructed on the tangent space of the manifold which is a vector space.

In addition to the basis vectors, if coordinates are defined for the geometric algebra, the left and right geometric derivative operators are calculated and accessed with the `Ga` member function `grads()`.

`Ga.grads()`

`Ga.grads()` returns a tuple with the left and right geometric derivative operators. A typical usage would be

```
(grad, rgrad) = sp3d.grads()
```

for the spherical 3-d geometric algebra. The left derivative ( $\text{grad} = \nabla$ ) and the right derivative ( $\text{rgrad} = \bar{\nabla}$ ) have been explained in section 1.10. Again the names `grad` and `rgrad` are whatever the user chooses them to be.

an alternative instantiation method is

```
Ga.build(basis, g=None, coords=None, X=None, norm=False, debug=False)
```

The input parameters for `Ga.build()` are the same as for `Ga()`. The difference is that in addition to returning the geometric algebra `Ga.build()` returns the basis vectors at the same time. Using `Ga.build()` in the previous example gives

```
1 (r, th, phi) = coords = symbols('r,theta,phi', real=True)
2 basis = 'e_r e_theta e_phi'
3 g = [1, r**2, r**2*sin(th)**2]
4 (sp3d, er, eth, ephi) = Ga.build(basis, g=g, coord=coords, norm=True)
```

To access the pseudo scalar of the geometric algebra us the member function `I()`.

`Ga.I()`

`Ga.I()` returns the normalized pseudo scalar ( $|I^2| = 1$ ) for the geometric algebra. For example  $I = \text{o3d.I}()$  for the `o3d` geometric algebra.

In general we have defined member fuctions of the `Ga` class that will instantiate objects of other classes since the objects of the other classes are all associated with a particular geometric algebra object. Thus we have

Object	Class	Ga method
multivector	Mv	mv
submanifold	Sm	sm
linear transformation	Lt	lt
differential operator	Dop	dop

for the instantiation of various objects from the `Ga` class. This means that in order to instantiate any of these objects we need only to import `Ga` into our program.

## 2.2 Instantiating a Multivector

Since we need to associate each multivector with the geometric algebra that contains it we use a member function of `Ga` to instantiate every multivector<sup>2</sup> The multivector is instantiated with:

`Ga.mv(name, mode, f=False)`

As an example of both instantiating a geometric algebra and multivectors consider the following code fragment for a 3-d Euclidian geometric algebra.

```
1 from sympy import symbols
2 from ga import Ga
3 (x, y, z) = coords = symbols('x,y,z',real=True)
4 o3d = Ga('e_x e_y e_z', g=[1,1,1], coords=coords)
5 (ex, ey, ez) = o3d.mv()
6 V = o3d.mv('V', 'vector', f=True)
```

First consider the multivector instantiation `V = o3d.mv('V', 'vector', f=True)`. Here a 3-dimensional multivector field that is a function of `x`, `y`, and `z` (`f=True`) is being instantiated. If latex output were used (to be discussed later) the multivector `V` would be displayed as

$$A^x e_x + A^y e_y + A^z e_z \quad (2.1)$$

Where the coefficients of the basis vectors are generalized *sympy* functions of the coordinates. The superscripts<sup>3</sup> are formed from the coordinate symbols or if there are no coordinates from the subscripts of the basis vectors. The types of name and modes available for multivector instantiation are

---

<sup>2</sup>There is a multivector class, `Mv`, but in order to insure that every multivector is associated with the correct geometric algebra we always use the member function `Ga.mv` to instantiate the multivector.

<sup>3</sup>Denoted in text output by `A__x`, etc. so that for text output `A` would be printed as `A__x*e_x+A__y*e_y+A__z*e_z`.

name	mode	result
string s	'scalar'	symbolic scalar of value Symbol(s)
string s	'vector'	symbolic vector
string s	'bivector'	symbolic bivector
string s,n	'grade'	symbolic n-grade multivector
string s	'pseudo'	symbolic pseudoscalar
string s	'spinor'	symbolic even multivector
string s	'mv'	symbolic general multivector
scalar c	None	zero grade multivector with coefficient value c

Line 5 of the previous listing illustrates the case of using the `mv` member function with no arguments. The code does not return a multivector, but rather a tuple or the basis vectors of the geometric algebra `o3d`. The elements of the tuple then can be used to construct multivectors, or multivector fields through the operations of addition, subtraction, multiplication (geometric, inner, and outer products and left and right contraction). As an example we could construct the vector function

```
F = x**2*ex + z*ey + x*y*ez
```

or the bivector function

```
B = z*(ex^ey) + y*(ey^ez) + x*(ex^ez).
```

If one wished to calculate the left and right geometric derivatives of `F` and `B` the required code would be

```
1 (grad,rgrad) = o3d.grads()
2 dF = grad*F
3 dB = grad*B
4 dFr = F*rgrad
5 dBr = B*rgrad.
```

`dF`, `dB`, `dFr`, and `dBr` are all multivector functions. For the code where the order of the operations are reversed

```
1 (grad,rgrad) = o3d.grads()
2 dFop = F*grad
3 dBop = B*grad
4 dFrop = rgrad*F
5 dBrop = rgrad*B.
```

`dFop`, `dBop`, `dFrop`, and `dBrop` are all multivector differential operators (again see section 1.10).

## 2.3 Basic Multivector Class Functions

If we can instantiate multivectors we can use all the multivector class functions as described as follows.

`convert_to_blades(self)`

Convert multivector from the base representation to the blade representation. If multivector is already in blade representation nothing is done.

`convert_from_blades(self)`

Convert multivector from the blade representation to the base representation. If multivector is already in base representation nothing is done.

`diff(self,var)`

Calculate derivative of each multivector coefficient with respect to variable `var` and form new multivector from coefficients.

`dual(self)`

Return dual of multivector which is multivector left multiplied by pseudoscalar `Mv.i` ([2],p22).

`even(self)`

Return the even grade components of the multivector.

`exp(self, hint='+')`

Return exponential of a multivector  $A$  if  $A^2$  is a scalar (if  $A^2$  is not a scalar an error message is generated). If  $A$  is the multivector then  $e^A$  is returned where the default `hint, +`, assumes  $A^2 > 0$  so that

$$e^A = \cosh\left(\sqrt{A^2}\right) + \sinh\left(\sqrt{A^2}\right) \frac{A}{\sqrt{A^2}}.$$



If the mode is not + then  $A^2 < 0$  is assumed so that

$$e^A = \cos\left(\sqrt{-A^2}\right) + \sin\left(\sqrt{-A^2}\right) \frac{A}{\sqrt{-A^2}}.$$

The hint is required for symbolic multivectors  $A$  since in general *sympy* cannot determine if  $A^2$  is positive or negative. If  $A$  is purely numeric the hint is ignored.

`expand(self)`

Return multivector in which each coefficient has been expanded using *sympy* `expand()` function.

`factor(self)`

Apply the *sympy* `factor` function to each coefficient of the multivector.

`Fmt(self, fmt=1, title=None)`

Fuction to print multivectors in different formats where

<code>fmt</code>	Formatting
1	Print entire multivector on one line.
2	Print each grade of multivector on one line.
3	Print each base of multivector on one line.

`title` appends a title string to the beginning of the output. An equal sign in the title string is not required, but is added as a default.

`func(self, fct)`

Apply the *sympy* scalar function `fct` to each coefficient of the multivector.

`grade(self, igrade=0)`

Return a multivector that consists of the part of the multivector of grade equal to `igrade`. If the multivector has no `igrade` part return a zero multivector.

`inv(self)`

Return the inverse of the multivector  $M$  (`M.inv()`) if  $MM^\dagger$  is a nonzero scalar. If  $MM^\dagger$  is not a scalar the program exits with an error message.

`norm(self)`

Return the norm of the multivector  $M$  (`M.norm()`) defined by  $\sqrt{MM^\dagger}$  if  $MM^\dagger$  is a scalar (a *sympy* scalar is returned). If  $MM^\dagger$  is not a scalar the program exits with an error message.

`norm2(self)`

Return the square of the norm of the multivector  $M$  (`M.norm2()`) defined by  $MM^\dagger$  if  $MM^\dagger$  is a scalar (a *sympy* scalar is returned). If  $MM^\dagger$  is not a scalar the program exits with an error message.

`proj(self,bases_lst)`

Return the projection of the multivector  $M$  (`M.proj(bases_lst)`) onto the subspace defined by the list of bases (`bases_lst`).

`scalar(self)`

Return the coefficient (*sympy* scalar) of the scalar part of a multivector.

`simplify(self,mode=simplify)`

`mode` is a *sympy* simplification function of a list/tuple of *sympy* simplification functions that are applied in sequence (if more than one function) each coefficient of the multivector. For example if we wished to applied `trigsimp` and `ratsimp` *sympy* functions to the multivector `F` the code would be

```
Fsimp = F.simplify(mode=[trigsimp,ratsimp]).
```

Actually `simplify` could be used to apply any scalar *sympy* function to the coefficients of the multivector.

`subs(self,x)`

Return multivector where *sympy* subs function has been applied to each coefficient of multivector for argument dictionary/list `x`.

`rev(self)`

Return the reverse of the multivector. See eq. (1.47).

`set_coef(self,grade,base,value)`

Set the multivector coefficient of index `(grade,base)` to `value`.

`trigsimp(self,**kwargs)`

Apply the *sympy* trigonometric simplification fuction `trigsimp` to each coefficient of the multivector. `**kwargs` are the arguments of `trigsimp`. See *sympy* documentation on `trigsimp` for more information.

## 2.4 Basic Multivector Functions

`Com(A,B)`

Calulate commutator of multivectors `A` and `B`. Returns  $(AB-BA)/2$ .

`GAeval(s,pstr=False)`<sup>4</sup>

Returns multivector expression for string `s` with operator precedence for string `s` defined by inputs to function `def_prec()`. if `pstr=True` `s` and `s` with parenthesis added to enforce operator precedence are printed.

`Nga(x,prec=5)`

If `x` is a multivector with coefficients that contain floating point numbers, `Nga()` rounds all these numbers to a precision of `prec` and returns the rounded multivector.

---

<sup>4</sup>`GAeval` is in the `printer` module.

`ReciprocalFrame(basis,mode='norm')`

If `basis` is a list/tuple of vectors, `ReciprocalFrame()` returns a tuple of reciprocal vectors. If `mode=norm` the vectors are normalized. If `mode` is anything other than `norm` the vectors are unnormalized and the normalization coefficient is added to the end of the tuple. One must divide by the coefficient to normalize the vectors.

`ScalarFunction(TheFunction)`

If `TheFunction` is a real `sympy` function a scalar multivector function is returned.

`cross(v1,v2)`

If `v1` and `v2` are 3-dimensional euclidian vectors the vector cross product is returned,  $v_1 \times v_2 = -I(v_1 \wedge v_2)$ .

`def_prec(gd,op_ord='<>|,^,*')`<sup>5</sup>

This is used with the `GAeval()` function to evaluate a string representing a multivector expression with a revised operator precedence. `def_prec()` redefines the operator precedence for multivectors. `def_prec()` must be called in the main program and the argument `gd` must be `globals()`. The argument `op_ord` defines the order of operator precedence from high to low with groups of equal precedence separated by commas. the default precedence `op_ord='<>|,^,*'` is that used by Hestenes ([2],p7,[1],p38).

`dual(M)`

Return the dual of the multivector `M`,  $MI^{-1}$ .

`inv(B)`

If for the multivector `B`,  $BB^\dagger$  is a nonzero scalar, return  $B^{-1} = B^\dagger/(BB^\dagger)$ .

`proj(B,A)`

---

<sup>5</sup>See footnote 4.

Project blade A on blade B returning  $(A|B) B^{-1}$ .

`refl(B,A)`

Reflect blade A in blade B. If **r** is grade of A and **s** is grade of B returns  $(-1)^{s(r+1)} BAB^{-1}$ .

`rot(itheta,A)`

Rotate blade A by 2-blade **itheta**. It is assumed that **itheta\*itheta** > 0 so that the rotation is Euclidian and not hyperbolic so that the angle of rotation is **theta** = **itheta.norm()**. Then in 3-dimensional Euclidian space. **theta** is the angle of rotation (scalar in radians) and **n** is the vector axis of rotation. Returned is the rotor **cos(theta)+sin(theta)\*N** where N is the normalized dual of **n**.

## 2.5 Multivector Differential Operators

The various derivatives of a multivector function are calculated by multiplying the gradient differential operator with the function. The gradient differential operators (left and right) are returned by the `(grad,rgrad) = Ga.grads()` function if coordinates are defined. For example if we have for a 3-D vector space

```
1 X = (x,y,z) = symbols('x y z')
2 o3d = Ga('e*x|y|z',metric='[1,1,1]',coords=X)
3 (ex,ey,ez) = o3d.mv()
4 (grad,rgrad) = o3d.grads()
```

The gradient differential operator is **grad** (actually the user can give it any name he wants to). The left and right derivatives of the multivector function **F = o3d.mv('F','mv',f=True)** are given by multiplying by the left geometric derivative operator and the right geometric derivative operator (**grad** =  $\nabla$  and **rgrad** =  $\bar{\nabla}$ ). Another option is to use the gradient operator members of the geometric algebra directly where we have  $\nabla = \text{o3d.grad}$  and  $\bar{\nabla} = \text{o3d.rgrad}$ .

$$\nabla F = \text{grad} * F \quad (2.2)$$

$$F \bar{\nabla} = F * \text{rgrad} \quad (2.3)$$

$$\nabla \wedge F = \text{grad} \wedge F \quad (2.4)$$

$$F \wedge \bar{\nabla} = F \wedge \text{rgrad} \quad (2.5)$$

$$\nabla \cdot F = \text{grad} | F \quad (2.6)$$

$$F \cdot \bar{\nabla} = F | \text{rgrad} \quad (2.7)$$

$$\nabla \rfloor F = \text{grad} \langle F \quad (2.8)$$

$$F \rfloor \bar{\nabla} = F \langle \text{rgrad} \quad (2.9)$$

$$\nabla \rfloor F = \text{grad} \rangle F \quad (2.10)$$

$$F \rfloor \bar{\nabla} = F \rangle \text{rgrad} \quad (2.11)$$

The preceding code block gives examples of all possible multivector derivatives of the multivector function **F** where the operation returns a multivector function. The complementary operations

$$F \nabla = F * \text{grad} \quad (2.12)$$

$$\bar{\nabla} F = \text{rgrad} * F \quad (2.13)$$

$$F \wedge \nabla = F \wedge \text{grad} \quad (2.14)$$

$$\bar{\nabla} \wedge F = \text{rgrad} \wedge F \quad (2.15)$$

$$F \cdot \nabla = F | \text{grad} \quad (2.16)$$

$$\bar{\nabla} \cdot F = \text{rgrad} | F \quad (2.17)$$

$$F \rfloor \nabla = F \langle \text{grad} \quad (2.18)$$

$$\bar{\nabla} \rfloor F = \text{rgrad} \langle F \quad (2.19)$$

$$F \rfloor \nabla = F \rangle \text{grad} \quad (2.20)$$

$$\bar{\nabla} \rfloor F = \text{rgrad} \rangle F \quad (2.21)$$

all return multivector linear differential operators.

## 2.6 Submanifolds

In general the geometric algebra that the user defines exists on the tangent space of a manifold (see section 1.9). The submanifold class, **Sm**, is derived from the **Ga** class and allows one to define a submanifold of a manifold by defining a coordinate mapping between the submanifold coordinates and the manifold coordinates. What is returned as the submanifold is the geometric algebra of the tangent space of the submanifold. The submanifold for a geometric algebra is instantiated with

```
Ga.sm(map,coords,root='e',norm=False)
```

To define the submanifold we must def a coordinate map from the coordinates of the submanifold to each of the coordinates of the base manifold. Thus the arguments **map** and **coords** are respectively lists of functions and symbols. The list of symbols,

`coords`, are the coordinates of the submanifold and are of length equal to the dimension of the submanifold. The list of functions, `map`, define the mapping from the coordinate space of the submanifold to the coordinate space of the base manifold. The length of `map` is equal to the dimension of the base manifold and each function in `map` is a function of the coordinates of the submanifold. As a concrete example consider the following code.

Listing 2.1: python/submanifold.py

```

1 from sympy import symbols, sin, pi, latex
2 from sympy.galgebra.ga import Ga
3 from sympy.galgebra.printer import Format, xpdf
4
5 Format()
6 coords = (r, th, phi) = symbols('r,theta,phi', real=True)
7 sp3d = Ga('e_r e_th e_ph', g=[1, r**2, r**2*sin(th)**2], \
8         coords=coords, norm=True)
9
10 sph_uv = (u, v) = symbols('u,v', real=True)
11 sph_map = [1, u, v] # Coordinate map for sphere of r = 1
12 sph2d = sp3d.sm(sph_map, sph_uv)
13
14 print r'(u,v)\rightarrow (r,\theta,\phi) = ', latex(sph_map)
15 print 'g = ', latex(sph2d.g)
16 F = sph2d.mv('F', 'vector', f=True) #scalar function
17 f = sph2d.mv('f', 'scalar', f=True) #vector function
18 print r'\nabla f = ', sph2d.grad * f
19 print 'F = ', F
20 print r'\nabla F = ', sph2d.grad * F
21
22 cir_s = s = symbols('s', real=True)
23 cir_map = [pi/8, s]
24 cir1d = sph2d.sm(cir_map, (cir_s,))
25
26 print 'g = ', latex(cir1d.g)
27 h = cir1d.mv('h', 'scalar', f=True)
28 H = cir1d.mv('H', 'vector', f=True)
29 print r'(s)\rightarrow (u,v) = ', latex(cir_map)
30 print 'H = ', H

```

```

31 print latex(H)
32 print r'\nabla h =', cir1d.grad * h
33 print r'\nabla H =', cir1d.grad * H
34 xpdf(filename='submanifold.tex',paper=(6,5),crop=True)

```

The output of this program (using L<sup>A</sup>T<sub>E</sub>X) is

$$\begin{aligned}
(u, v) &\rightarrow (r, \theta, \phi) = [1, \quad u, \quad v] \\
g &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\
\nabla f &= \partial_u f \mathbf{e}_u + \partial_v f \mathbf{e}_v \\
F &= F^u \mathbf{e}_u + F^v \mathbf{e}_v \\
\nabla F &= (\partial_u F^u + \partial_v F^v) + (-\partial_v F^u + \partial_u F^v) \mathbf{e}_u \wedge \mathbf{e}_v \\
g &= [1] \\
(s) &\rightarrow (u, v) = \left[ \frac{\pi}{8}, \quad s \right] \\
H &= H^s \mathbf{e}_s \\
H^s &\mathbf{e}_s \\
\nabla h &= \partial_s h \mathbf{e}_s \\
\nabla H &= \partial_s H^s
\end{aligned}$$

The base manifold, **sp3d**, is a 3-d Euclidian space using standard spherical coordinates. The submanifold **sph2d** of **sp3d** is a spherical surface of radius 1. To take the submanifold operation one step further the submanifold **cir1d** of **sph2d** is a circle in **sph2d** where the latitude of the circle is  $\pi/8$ .

In each case, for demonstration purposes, a scalar and vector function on each manifold is defined (**f** and **F** for the 2-d manifold and **h** and **H** for the 1-d manifold) and the geometric derivative of each function is taken. The manifold mapping and the metric tensor for **cir1d** of **sph2d** are also shown. Note that if the submanifold basis vectors are not normalized the program output is.



$$(u, v) \rightarrow (r, \theta, \phi) = [1, \quad u, \quad v]$$

$$g = \begin{bmatrix} 1 & 0 \\ 0 & \sin^2(u) \end{bmatrix}$$

$$\nabla f = \partial_u f \mathbf{e}_u + \frac{\partial_v f}{\sin^2(u)} \mathbf{e}_v$$

$$F = F^u \mathbf{e}_u + F^v \mathbf{e}_v$$

$$\nabla F = \left( \frac{F^u}{\tan(u)} + \partial_u F^u + \partial_v F^v \right) + \left( \frac{2F^v}{\tan(u)} + \partial_u F^v - \frac{\partial_v F^u}{\sin^2(u)} \right) \mathbf{e}_u \wedge \mathbf{e}_v$$

$$g = \left[ -\frac{\sqrt{2}}{4} + \frac{1}{2} \right]$$

$$(s) \rightarrow (u, v) = \left[ \frac{\pi}{8}, \quad s \right]$$

$$H = H^s \mathbf{e}_s$$

$$H^s \mathbf{e}_s$$

$$\nabla h = (2\sqrt{2} + 4) \partial_s h \mathbf{e}_s$$

$$\nabla H = \partial_s H^s$$

## 2.7 Linear Transformations

The mathematical background for linear transformations is in section 1.11. Linear transformations on the tangent space of the manifold are instantiated with the `Ga` member function `lt` (the actual class being instantiated is `Lt`) as shown in lines 12, 20, 26, and 44 of the code listing `Ltrans.py`. In all of the examples in `Ltrans.py` the default instantiation is used which produces a general (all the coefficients of the linear transformation are symbolic constants) linear transformation. *Note that to instantiate linear transformations coordinates,  $\{\mathbf{e}_i\}$ , must be defined when the geometric algebra associated with the linear transformation is instantiated. This is due to the naming conventions of the general linear transformation (coordinate names are used) and for the calculation of the trace of the linear transformation which requires taking a divergence..* To instantiate a specific linear transformation the usage of `lt()` is `Ga.lt(M,f=False)`

`M` is an expression that can define the coefficients of the linear transformation in various ways defined as follows.

M	Result
string M	Coefficients are symbolic constants with names $M^{x_i x_j}$ where $x_i$ and $x_j$ are the names of the $i^{th}$ and $j^{th}$ coordinates (see output of <code>Ltrans.py</code> ).
list M	If M is a list of vectors equal in length to the dimension of the vector space then the linear transformation is $L(e_i) = M[i]$ . If M is a list of lists of scalars where all lists are equal in length to the dimension of the vector space then the linear transformation is $L(e_i) = M[i][j] e_j$ .
dict M	If M is a dictionary the linear transformation is defined by $L(e_i) = M[e_i]$ . If $e_i$ is not in the dictionary then $L(e_i) = 0$ .
rotor M	If M is a rotor, $MM^\dagger = 1$ , the linear transformation is defined by $L(e_i) = M e_i M^\dagger$ .
multivector function M	If M is a general multivector function, the function is tested for linearity, and if linear the coefficients of the linear transformation are calculated from $L(e_i) = M(e_i)$ .

`f` is `True` or `False`. If `True` the symbolic coefficients of the general linear transformation are instantiated as functions of the coordinates.

The different methods of instantiation are demonstrated in the code `LtransInst.py`

Listing 2.2: `python/LtransInst.py`

```

1 from sympy import symbols, sin, cos, latex, Matrix
2 from ga import Ga
3 from printer import Format, xpdf
4
5 Format()
6 (x, y, z) = xyz = symbols('x,y,z',real=True)
7 (o3d, ex, ey, ez) = Ga.build('e_x e_y e_z', g=[1, 1, 1], coords=xyz)
8
9 A = o3d.lt('A')
10 print r'\mbox{General Instantiation: }A =', A
11 th = symbols('theta',real=True)
12 R = cos(th/2)+(ex^ey)*sin(th/2)
13 B = o3d.lt(R)
14 print r'\mbox{Rotor: }R =', R
15 print r'\mbox{Rotor Instantiation: }B =', B

```

```

16 dict1 = {ex:ey+ez, ez:ey+ez, ey:ex+ez}
17 C = o3d.lt(dict1)
18 print r'\mbox{Dictionary} =', latex(dict1)
19 print r'\mbox{Dictionary Instantiation: }C =', C
20 lst1 = [[1,0,1],[0,1,0],[1,0,1]]
21 D = o3d.lt(lst1)
22 print r'\mbox{List} =', latex(lst1)
23 print r'\mbox{List Instantiation: }D =', D
24 lst2 = [ey+ez, ex+ez, ex+ey]
25 E = o3d.lt(lst2)
26 print r'\mbox{List} =', latex(lst2)
27 print r'\mbox{List Instantiation: }E =', E
28 xpdf(paper=(10,12), crop=True)

```

with output

$$\text{General Instantiation: } A = \begin{bmatrix} L(e_x) = A_{xx}e_x + A_{yx}e_y + A_{zx}e_z \\ L(e_y) = A_{xy}e_x + A_{yy}e_y + A_{zy}e_z \\ L(e_z) = A_{xz}e_x + A_{yz}e_y + A_{zz}e_z \end{bmatrix}$$

$$\text{Rotor: } R = \cos\left(\frac{\theta}{2}\right) + \sin\left(\frac{\theta}{2}\right)e_x \wedge e_y$$

$$\text{Rotor Instantiation: } B = \begin{bmatrix} L(e_x) = \cos(\theta)e_x - \sin(\theta)e_y \\ L(e_y) = \sin(\theta)e_x + \cos(\theta)e_y \\ L(e_z) = e_z \end{bmatrix}$$

$$\text{Dictionary} = \{e_x : e_y + e_z, \quad e_y : e_x + e_z, \quad e_z : e_y + e_z\}$$

$$\text{Dictionary Instantiation: } C = \begin{bmatrix} L(e_x) = 0 \\ L(e_y) = 0 \\ L(e_z) = 0 \end{bmatrix}$$

$$\text{List} = [[1, 0, 1], [0, 1, 0], [1, 0, 1]]$$

$$\text{List Instantiation: } D = \begin{bmatrix} L(e_x) = e_x + e_z \\ L(e_y) = e_y \\ L(e_z) = e_x + e_z \end{bmatrix}$$

$$\text{List} = [e_y + e_z, \quad e_x + e_z, \quad e_x + e_y]$$

$$\text{List Instantiation: } E = \begin{bmatrix} L(e_x) = e_y + e_z \\ L(e_y) = e_x + e_z \\ L(e_z) = e_x + e_y \end{bmatrix}$$

The member fuction of the `Lt` class are

`Lt(A)`

Returns the image of the multivector  $A$  under the linear transformation  $L$  where  $L(A)$  is defined by the linearity of  $L$ , the vector values  $L(\mathbf{e}_i)$ , and the definition  $L(\mathbf{e}_{i_1} \wedge \dots \wedge \mathbf{e}_{i_r}) = L(\mathbf{e}_{i_1}) \wedge \dots \wedge L(\mathbf{e}_{i_r})$ .

`Lt.det()`

Returns the determinant (a scalar) of the linear transformation,  $L$ , defined by  $\det(L)I = L(I)$ .

`Lt.adj()`

Returns the adjoint (a linear transformation) of the linear transformation,  $L$ , defined by  $a \cdot L(b) = b \cdot \bar{L}(a)$  where  $a$  and  $b$  are any two vectors in the tangent space and  $\bar{L}$  is the adjoint of  $L$ .

`Lt.tr()`

Returns the trace (a scalar) of the linear transformation,  $L$ , defined by  $\text{tr}(L) = \nabla_a \cdot L(a)$  where  $a$  is a vector in the tangent space.

`Lt.matrix()`

Returns the matrix representation (*sympy* `Matrix`) of the linear transformation,  $L$ , defined by  $L(\mathbf{e}_i) = L_{ij}\mathbf{e}_j$  where  $L_{ij}$  is the matrix representation.

The `Ltrans.py` demonstrate the use of the various `Lt` member functions and operators. The operators that can be used with linear transformations are  $+$ ,  $-$ , and  $*$ . If  $A$  and  $B$  are linear transformations,  $V$  a multivector, and  $\alpha$  a scalar then  $(A \pm B)(V) = A(V) \pm B(V)$ ,  $(AB)(V) = A(B(V))$ , and  $(\alpha A)(V) = \alpha A(V)$ .

The `matrix()` member function returns a *sympy* `Matrix` object which can be printed in IPython notebook.

Note that in `Ltrans.py` lines 30 and 49 are commented out since the latex output of those statements would run off the page. The use can uncomment those statements and run the code in the “LaTeX docs” directory to see the output.

Listing 2.3: python/Ltrans.py

```

1 from sympy import symbols, sin, cos, latex
2 from sympy.galgebra.ga import Ga
3 from sympy.galgebra.printer import Format, xpdf
4
5 Format()
6 (x, y, z) = xyz = symbols('x,y,z',real=True)
7 (o3d, ex, ey, ez) = Ga.build('e_x e_y e_z', g=[1, 1, 1], coords=xyz)
8 grad = o3d.grad
9 (u, v) = uv = symbols('u,v',real=True)
10 (g2d, eu, ev) = Ga.build('e_u e_v', coords=uv)
11 grad_uv = g2d.grad
12 A = o3d.lt('A')
13 print '#3d orthogonal ($A,\;\;B$ are linear transformations)'
14 print 'A =', A
15 print r'\f{\operatorname{mat}}{A} =', latex(A.matrix())
16 print '\f{\det}{A} =', A.det()
17 print '\overline{A} =', A.adj()
18 print '\f{\Tr}{A} =', A.tr()
19 print '\f{A}{e_x^e_y} =', A(ex^ey)
20 print '\f{A}{e_x}^{\f{A}{e_y}} =', A(ex)^A(ey)
21 B = o3d.lt('B')
22 print 'A + B =', A + B
23 print 'AB =', A * B
24 print 'A - B =', A - B
25
26 print '#2d general ($A,\;\;B$ are linear transformations)'
27 A2d = g2d.lt('A')
28 print 'A =', A2d
29 print '\f{\det}{A} =', A2d.det()
30 #A2d.adj().Fmt(4, '\overline{A}')
31 print '\f{\Tr}{A} =', A2d.tr()
32 print '\f{A}{e_u^e_v} =', A2d(eu^ev)
33 print '\f{A}{e_u}^{\f{A}{e_v}} =', A2d(eu)^A2d(ev)
34 B2d = g2d.lt('B')
35 print 'B =', B2d
36 print 'A + B =', A2d + B2d
37 print 'AB =', A2d * B2d

```

```

38 print 'A - B =', A2d - B2d
39 a = g2d.mv('a','vector')
40 b = g2d.mv('b','vector')
41 print r'a|\f{\overline{A}}{b}-b|\f{\underline{A}}{a} =',((a|A2d.adj()(b))
42
43 print '#4d Minkowski spaqce (Space Time)'
44 m4d = Ga('e_t e_x e_y e_z', g=[1, -1, -1, -1],coords=symbols('t,x,y,z',re
45 T = m4d.lt('T')
46 print 'g =', m4d.g
47 print r'\underline{T} =',T
48 print r'\overline{T} =',T.adj()
49 #m4d.mv(T.det()).Fmt(4,r'\f{\det}{\underline{T}}')
50 print r'\f{\mbox{tr}}{\underline{T}} =',T.tr()
51 a = m4d.mv('a','vector')
52 b = m4d.mv('b','vector')
53 print r'a|\f{\overline{T}}{b}-b|\f{\underline{T}}{a} =',((a|T.adj()(b))-
54 xpdf(paper=(10,12))

```

The output of this code is (next page):

3d orthogonal ( $A, B$  are linear transformations)

$$A = \begin{cases} L(\mathbf{e}_x) = A_{xx}\mathbf{e}_x + A_{yx}\mathbf{e}_y + A_{zx}\mathbf{e}_z \\ L(\mathbf{e}_y) = A_{xy}\mathbf{e}_x + A_{yy}\mathbf{e}_y + A_{zy}\mathbf{e}_z \\ L(\mathbf{e}_z) = A_{xz}\mathbf{e}_x + A_{yz}\mathbf{e}_y + A_{zz}\mathbf{e}_z \end{cases}$$

$$\text{mat}(A) = \begin{bmatrix} A_{xx} & A_{xy} & A_{xz} \\ A_{yx} & A_{yy} & A_{yz} \\ A_{zx} & A_{zy} & A_{zz} \end{bmatrix}$$

$$\det(A) = A_{xz}(A_{yx}A_{zy} - A_{yy}A_{zx}) - A_{yz}(A_{xx}A_{zy} - A_{xy}A_{zx}) + A_{zz}(A_{xx}A_{yy} - A_{xy}A_{yx})$$

$$\bar{A} = \begin{cases} L(\mathbf{e}_x) = A_{xx}\mathbf{e}_x + A_{xy}\mathbf{e}_y + A_{xz}\mathbf{e}_z \\ L(\mathbf{e}_y) = A_{yx}\mathbf{e}_x + A_{yy}\mathbf{e}_y + A_{yz}\mathbf{e}_z \\ L(\mathbf{e}_z) = A_{zx}\mathbf{e}_x + A_{zy}\mathbf{e}_y + A_{zz}\mathbf{e}_z \end{cases}$$

$$\text{Tr}(A) = A_{xx} + A_{yy} + A_{zz}$$

$$A(\mathbf{e}_x \wedge \mathbf{e}_y) = (A_{xx}A_{yy} - A_{xy}A_{yx})\mathbf{e}_x \wedge \mathbf{e}_y + (A_{xx}A_{zy} - A_{xy}A_{zx})\mathbf{e}_x \wedge \mathbf{e}_z + (A_{yx}A_{zy} - A_{yy}A_{zx})\mathbf{e}_y \wedge \mathbf{e}_z$$

$$A(\mathbf{e}_x) \wedge A(\mathbf{e}_y) = (A_{xx}A_{yy} - A_{xy}A_{yx})\mathbf{e}_x \wedge \mathbf{e}_y + (A_{xx}A_{zy} - A_{xy}A_{zx})\mathbf{e}_x \wedge \mathbf{e}_z + (A_{yx}A_{zy} - A_{yy}A_{zx})\mathbf{e}_y \wedge \mathbf{e}_z$$

$$A + B = \begin{cases} L(\mathbf{e}_x) = (A_{xx} + B_{xx})\mathbf{e}_x + (A_{yx} + B_{yx})\mathbf{e}_y + (A_{zx} + B_{zx})\mathbf{e}_z \\ L(\mathbf{e}_y) = (A_{xy} + B_{xy})\mathbf{e}_x + (A_{yy} + B_{yy})\mathbf{e}_y + (A_{zy} + B_{zy})\mathbf{e}_z \\ L(\mathbf{e}_z) = (A_{xz} + B_{xz})\mathbf{e}_x + (A_{yz} + B_{yz})\mathbf{e}_y + (A_{zz} + B_{zz})\mathbf{e}_z \end{cases}$$

$$AB = \begin{cases} L(\mathbf{e}_x) = (A_{xx}B_{xx} + A_{xy}B_{yx} + A_{xz}B_{zx})\mathbf{e}_x + (A_{yx}B_{xx} + A_{yy}B_{yx} + A_{yz}B_{zx})\mathbf{e}_y + (A_{zx}B_{xx} + A_{zy}B_{yx} + A_{zz}B_{zx})\mathbf{e}_z \\ L(\mathbf{e}_y) = (A_{xx}B_{xy} + A_{xy}B_{yy} + A_{xz}B_{zy})\mathbf{e}_x + (A_{yx}B_{xy} + A_{yy}B_{yy} + A_{yz}B_{zy})\mathbf{e}_y + (A_{zx}B_{xy} + A_{zy}B_{yy} + A_{zz}B_{zy})\mathbf{e}_z \\ L(\mathbf{e}_z) = (A_{xx}B_{xz} + A_{xy}B_{yz} + A_{xz}B_{zz})\mathbf{e}_x + (A_{yx}B_{xz} + A_{yy}B_{yz} + A_{yz}B_{zz})\mathbf{e}_y + (A_{zx}B_{xz} + A_{zy}B_{yz} + A_{zz}B_{zz})\mathbf{e}_z \end{cases}$$

$$A - B = \begin{cases} L(\mathbf{e}_x) = (A_{xx} - B_{xx})\mathbf{e}_x + (A_{yx} - B_{yx})\mathbf{e}_y + (A_{zx} - B_{zx})\mathbf{e}_z \\ L(\mathbf{e}_y) = (A_{xy} - B_{xy})\mathbf{e}_x + (A_{yy} - B_{yy})\mathbf{e}_y + (A_{zy} - B_{zy})\mathbf{e}_z \\ L(\mathbf{e}_z) = (A_{xz} - B_{xz})\mathbf{e}_x + (A_{yz} - B_{yz})\mathbf{e}_y + (A_{zz} - B_{zz})\mathbf{e}_z \end{cases}$$

2d general ( $A, B$  are linear transformations)

$$A = \begin{cases} L(\mathbf{e}_u) = A_{uu}\mathbf{e}_u + A_{vu}\mathbf{e}_v \\ L(\mathbf{e}_v) = A_{uv}\mathbf{e}_u + A_{vv}\mathbf{e}_v \end{cases}$$

$$\det(A) = A_{uu}A_{vv} - A_{uv}A_{vu}$$

$$\text{Tr}(A) = -\frac{(e_u \cdot e_u)(e_v \cdot e_v)A_{uu}}{-(e_u \cdot e_u)(e_v \cdot e_v) + (e_u \cdot e_v)^2} - \frac{(e_u \cdot e_u)(e_v \cdot e_v)A_{vv}}{-(e_u \cdot e_u)(e_v \cdot e_v) + (e_u \cdot e_v)^2} + \frac{(e_u \cdot e_v)^2 A_{uu}}{-(e_u \cdot e_u)(e_v \cdot e_v) + (e_u \cdot e_v)^2} + \frac{(e_u \cdot e_v)^2 A_{vv}}{-(e_u \cdot e_u)(e_v \cdot e_v) + (e_u \cdot e_v)^2}$$

$$A(\mathbf{e}_u \wedge \mathbf{e}_v) = (A_{uu}A_{vv} - A_{uv}A_{vu})\mathbf{e}_u \wedge \mathbf{e}_v$$

$$A(\mathbf{e}_u) \wedge A(\mathbf{e}_v) = (A_{uu}A_{vv} - A_{uv}A_{vu})\mathbf{e}_u \wedge \mathbf{e}_v$$

$$B = \begin{cases} L(\mathbf{e}_u) = B_{uu}\mathbf{e}_u + B_{vu}\mathbf{e}_v \\ L(\mathbf{e}_v) = B_{uv}\mathbf{e}_u + B_{vv}\mathbf{e}_v \end{cases}$$

$$A + B = \begin{cases} L(\mathbf{e}_u) = (A_{uu} + B_{uu})\mathbf{e}_u + (A_{vu} + B_{vu})\mathbf{e}_v \\ L(\mathbf{e}_v) = (A_{uv} + B_{uv})\mathbf{e}_u + (A_{vv} + B_{vv})\mathbf{e}_v \end{cases}$$

$$AB = \begin{cases} L(\mathbf{e}_u) = (A_{uu}B_{uu} + A_{uv}B_{vu})\mathbf{e}_u + (A_{vu}B_{uu} + A_{vv}B_{vu})\mathbf{e}_v \\ L(\mathbf{e}_v) = (A_{uu}B_{uv} + A_{uv}B_{vv})\mathbf{e}_u + (A_{vu}B_{uv} + A_{vv}B_{vv})\mathbf{e}_v \end{cases}$$

$$A - B = \begin{cases} L(\mathbf{e}_u) = (A_{uu} - B_{uu})\mathbf{e}_u + (A_{vu} - B_{vu})\mathbf{e}_v \\ L(\mathbf{e}_v) = (A_{uv} - B_{uv})\mathbf{e}_u + (A_{vv} - B_{vv})\mathbf{e}_v \end{cases}$$

$$a \cdot \bar{A}(b) - b \cdot \underline{A}(a) = 0$$

4d Minkowski space (Space Time)

$$g = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

$$\underline{T} = \begin{cases} L(\mathbf{e}_t) = T_{tt}\mathbf{e}_t + T_{xt}\mathbf{e}_x + T_{yt}\mathbf{e}_y + T_{zt}\mathbf{e}_z \\ L(\mathbf{e}_x) = T_{tx}\mathbf{e}_t + T_{xx}\mathbf{e}_x + T_{yx}\mathbf{e}_y + T_{zx}\mathbf{e}_z \\ L(\mathbf{e}_y) = T_{ty}\mathbf{e}_t + T_{xy}\mathbf{e}_x + T_{yy}\mathbf{e}_y + T_{zy}\mathbf{e}_z \\ L(\mathbf{e}_z) = T_{tz}\mathbf{e}_t + T_{xz}\mathbf{e}_x + T_{yz}\mathbf{e}_y + T_{zz}\mathbf{e}_z \end{cases}$$

$$\bar{T} = \begin{cases} L(\mathbf{e}_t) = T_{tt}\mathbf{e}_t - T_{tx}\mathbf{e}_x - T_{ty}\mathbf{e}_y - T_{tz}\mathbf{e}_z \\ L(\mathbf{e}_x) = -T_{xt}\mathbf{e}_t + T_{xx}\mathbf{e}_x + T_{xy}\mathbf{e}_y + T_{xz}\mathbf{e}_z \\ L(\mathbf{e}_y) = -T_{yt}\mathbf{e}_t + T_{yx}\mathbf{e}_x + T_{yy}\mathbf{e}_y + T_{yz}\mathbf{e}_z \\ L(\mathbf{e}_z) = -T_{zt}\mathbf{e}_t + T_{zx}\mathbf{e}_x + T_{zy}\mathbf{e}_y + T_{zz}\mathbf{e}_z \end{cases}$$

$$\text{tr}(\underline{T}) = T_{tt} + T_{xx} + T_{yy} + T_{zz}$$

$$a \cdot \bar{T}(b) - b \cdot \underline{T}(a) = 0$$

## 2.8 Instantiating a Multi-linear Functions (Tensors)

The mathematical background for multi-linear functions is in section 1.12. To instantiate a multi-linear function use

```
Mlt(self, f, Ga, nargs=None, fct=False)
```

Where the arguments are

- f** Either a string for a general tensor (this option is included mainly for debugging of the `Mlt` class) or a multi-linear function of manifold tangent vectors (multi-vectors of grade one) to scalar. For example one could generate a custom python function such as shown in `TensorDef.py`.
- Ga** Geometric algebra that tensor is associated with.
- nargs** If **f** is a string then **nargs** is the number of vector arguments of the tensor. If **f** is anything other than a string **nargs** is not required since `Mlt` determines the number of vector arguments from **f**.
- fct** if **f** is a string then **fct=True** forces the tensor to be a tensor field (function of the coordinates. If **f** anything other than a string **fct** is not required since `Mlt` determines whether the tensor is a tensor field from **f**.

Listing 2.4: python/TensorDef.py

```

1
2 import sys
3 from sympy import symbols,sin,cos
4 from sympy.galgebra.printer import Format,xpdf,Get_Program,Print_Function
5 from sympy.galgebra.ga import Ga
6 from sympy.galgebra.lt import Mlt
7
8 coords = symbols('t x y z',real=True)
9 (st4d,g0,g1,g2,g3) = Ga.build('gamma*t|x|y|z',g=[1,-1,-1,-1],coords=coord
10
11 A = st4d.mv('T','bivector')
12
13 def TA(a1,a2):
14     global A
15     return A | (a1 ^ a2)
16
17 T = Mlt(TA,st4d) # Define multi-linear function
```



```

18
19 print T

```

## 2.9 Basic Multilinear Function Class Functions

If we can instantiate multilinear functions we can use all the multilinear function class functions as described as follows. See section 1.12 for the mathematical description of each operation.

`self(kargs)`

Calling function to evaluates multilinear function for **kargs** list of vector arguments and returns a value. Note that a sympy scalar is returned, *not* a multilinear function.

`self.contract(slot1,slot2)`

Returns contraction of tensor between **slot1** and **slot2** where **slot1** is the index of the first vector argument and **slot2** is the index of the second vector argument of the tensor. For example if we have a rank two tensor,  $T(\mathbf{a}_1, \mathbf{a}_2)$ , then `T.contract(1,2)` is the contraction of  $T$ . For this case since there are only two slots there can only be one contraction.

`self.pdiff(slot)`

Returns gradient of tensor,  $T$ , with respect to slot vector. For example if the tensor is  $T(a_1, a_2)$  then `T.pdiff(2)` is  $\nabla_{a_2} T$ . Since  $T$  is a scalar function, `T.pdiff(2)` is a vector function.

`self.cderiv()`

Returns covariant derivative of tensor field. If  $T$  is a tensor of rank  $k$  then `T.cderiv()` is a tensor of rank  $k + 1$ . The operation performed is defined in section 1.12.

## 2.10 Standard Printing

Printing of multivectors is handled by the module `printer` which contains a string printer class derived from the *sympy* string printer class and a latex printer class derived from the *sympy* latex

printer class. Additionally, there is an **Eprint** class that enhances the console output of *sympy* to make the printed output multivectors, functions, and derivatives more readable. **Eprint** requires an ansi console such as is supplied in linux or the program **ansicon** ([github.com/adoxa/ansicon](https://github.com/adoxa/ansicon)) for windows which replaces **cmd.exe**.

For a windows user the simplest way to implement **ansicon** is to use the **geany** editor and in the Edit→Preferences→Tools menu replace **cmd.exe** with **ansicon.exe** (be sure to supply the path to **ansicon**).

If **Eprint** is called in a program (linux) when multivectors are printed the basis blades or bases are printed in bold text, functions are printed in red, and derivative operators in green.

For formatting the multivector output there is the member function

```
Fmt(self,fmt=1,title=None)
```

**Fmt** is used to control how the multivector (**Mv**) is printed with the argument **fmt**. If **fmt=1** the entire multivector is printed on one line. If **fmt=2** each grade of the multivector is printed on one line. If **fmt=3** each component (base) of the multivector is printed on one line. If a **title** is given then **title=multivector** is printed. If the usual print command is used the entire multivector is printed on one line.

For formatting the tensor (**Mlt**) output there is the member function

```
Fmt(self,cnt=1,title=None)
```

**Fmt** is used to control how the tensor is printed with the argument **cnt**. If **cnt=1** the each tensor component is printed on one line. If **fmt=n** *n* tensor components are printed on one line. If a **title** is given then **title=tensor** is printed. If the usual print command is used one tensor component is printed on one line. If **cnt** is greater or equal to the number of tensor components then the entire tensor is printed on one line.

## 2.11 Latex Printing

For latex printing one uses one functions from the **ga** module and one function from the **printer** module. The functions are

```
Format(Fmode=True,Dmode=True,ipy=False)
```

This function from the `ga` module turns on latex printing with the following options

Argument	Value	Result
Fmode	True	Print functions without argument list, $f$
	False	Print functions with standard <i>sympy</i> latex formatting, $f(x, y, z)$
Dmode	True	Print partial derivatives with condensed notation, $\partial_x f$
	False	Print partial derivatives with standard <i>sympy</i> latex formatting $\frac{\partial f}{\partial x}$
ipy	False	Redirect print output to file for post-processing by latex
	True	Do not redirect print output. This is used for IPython with MathJax

```
xpdf(filename=None,paper=(14,11),crop=False,png=True,prog=True,debug=False)
```

This function from the `printer` module post-processes the output captured from print statements, writes the resulting latex strings to the file `filename`, processes the file with `pdflatex`, and displays the resulting pdf file. All latex files except the pdf file are deleted. If `debug = True` the file `filename` is printed to standard output for debugging purposes and `filename` (the tex file) is saved. If `filename` is not entered the default filename is the root name of the python program being executed with `.tex` appended. The `paper` option defines the size of the paper sheet for latex. The format for the `paper` is

<code>paper=(w,h)</code>	<code>w</code> is paper width in inches and <code>h</code> is paper height in inches
<code>paper='letter'</code>	paper is standard letter size 8.5 in $\times$ 11 in
<code>paper='landscape'</code>	paper is standard letter size but 11 in $\times$ 8.5 in

The default of `paper=(14,11)` was chosen so that long multivector expressions would not be truncated on the display.

If the `crop` input is `True` the linux `pdfcrop` program is used to crop the pdf output (if output is one page). This only works for linux installations (where `pdfcrop` is installed).

If the `png` input is `True` the linux `convert` program from the `imagemagick` will produce a high quality `png` file as output (this requires the script `Pdf2Png` in the `galgebra/utilities` directory to be in the executables path).

If the `prog` input is `True` the python program generating the LaTeX output will be inserted at the beginning of the `pdf` output file using the LaTeX `listlisting` package.

The `xpdf` function requires that latex and a pdf viewer be installed on the computer.

*xpdf is not required when printing latex in IPython notebook.*

As an example of using the latex printing options when the following code is executed

```

1  from printer import Format, xpdf
2  from ga import Ga
3  Format()
4  g3d = Ga('e*x|y|z')
5  A = g3d.mv('A', 'mv')
6  print r'\bm{A} =', A
7  A.Fmt(2, r'\bm{A}')
8  A.Fmt(3, r'\bm{A}')
9  xpdf()

```

The following is displayed

$$\begin{aligned}
 \mathbf{A} &= A + A^x \mathbf{e}_x + A^y \mathbf{e}_y + A^z \mathbf{e}_z + A^{xy} \mathbf{e}_x \wedge \mathbf{e}_y + A^{xz} \mathbf{e}_x \wedge \mathbf{e}_z + A^{yz} \mathbf{e}_y \wedge \mathbf{e}_z + A^{xyz} \mathbf{e}_x \wedge \mathbf{e}_y \wedge \mathbf{e}_z \\
 \mathbf{A} &= A \\
 &\quad + A^x \mathbf{e}_x + A^y \mathbf{e}_y + A^z \mathbf{e}_z \\
 &\quad + A^{xy} \mathbf{e}_x \wedge \mathbf{e}_y + A^{xz} \mathbf{e}_x \wedge \mathbf{e}_z + A^{yz} \mathbf{e}_y \wedge \mathbf{e}_z \\
 &\quad + A^{xyz} \mathbf{e}_x \wedge \mathbf{e}_y \wedge \mathbf{e}_z \\
 \mathbf{A} &= A \\
 &\quad + A^x \mathbf{e}_x \\
 &\quad + A^y \mathbf{e}_y \\
 &\quad + A^z \mathbf{e}_z \\
 &\quad + A^{xy} \mathbf{e}_x \wedge \mathbf{e}_y \\
 &\quad + A^{xz} \mathbf{e}_x \wedge \mathbf{e}_z \\
 &\quad + A^{yz} \mathbf{e}_y \wedge \mathbf{e}_z \\
 &\quad + A^{xyz} \mathbf{e}_x \wedge \mathbf{e}_y \wedge \mathbf{e}_z
 \end{aligned}$$

For the cases of derivatives the code is

```

1  from printer import Format, xpdf
2  from ga import Ga
3
4  Format()
5  X = (x,y,z) = symbols('x y z')
6  o3d = Ga('e_x e_y e_z', g=[1,1,1], coords=X)
7
8  f = o3d.mv('f', 'scalar', f=True)

```

```

9      A = o3d.mv('A','vector',f=True)
10     B = o3d.mv('B','grade2',f=True)
11
12     print r'\bm{A} =',A
13     print r'\bm{B} =',B
14
15     print 'grad*f =',o3d.grad*f
16     print r'grad|\bm{A} =',o3d.grad|A
17     (o3d.grad*A).Fmt(2,r'grad*\bm{A}')
18
19     print r'-I*(grad^\bm{A}) =',-o3g.mv_I*(o3d.grad^A)
20     (o3d.grad*B).Fmt(2,r'grad*\bm{B}')
21     print r'grad^\bm{B} =',o3d.grad^B
22     print r'grad|\bm{B} =',o3d.grad|B
23
24     xpdf()

```

and the latex displayed output is ( $f$  is a scalar function)

$$\mathbf{A} = A^x \mathbf{e}_x + A^y \mathbf{e}_y + A^z \mathbf{e}_z$$

$$\mathbf{B} = B^{xy} \mathbf{e}_x \wedge \mathbf{e}_y + B^{xz} \mathbf{e}_x \wedge \mathbf{e}_z + B^{yz} \mathbf{e}_y \wedge \mathbf{e}_z$$

$$\nabla f = \partial_x f \mathbf{e}_x + \partial_y f \mathbf{e}_y + \partial_z f \mathbf{e}_z$$

$$\nabla \cdot \mathbf{A} = \partial_x A^x + \partial_y A^y + \partial_z A^z$$

$$\begin{aligned} \nabla \mathbf{A} = & \partial_x A^x + \partial_y A^y + \partial_z A^z \\ & + (-\partial_y A^x + \partial_x A^y) \mathbf{e}_x \wedge \mathbf{e}_y + (-\partial_z A^x + \partial_x A^z) \mathbf{e}_x \wedge \mathbf{e}_z + (-\partial_z A^y + \partial_y A^z) \mathbf{e}_y \wedge \mathbf{e}_z \end{aligned}$$

$$-I(\nabla \wedge \mathbf{A}) = (-\partial_z A^y + \partial_y A^z) \mathbf{e}_x + (\partial_z A^x - \partial_x A^z) \mathbf{e}_y + (-\partial_y A^x + \partial_x A^y) \mathbf{e}_z$$

$$\begin{aligned} \nabla \mathbf{B} = & (-\partial_y B^{xy} - \partial_z B^{xz}) \mathbf{e}_x + (\partial_x B^{xy} - \partial_z B^{yz}) \mathbf{e}_y + (\partial_x B^{xz} + \partial_y B^{yz}) \mathbf{e}_z \\ & + (\partial_z B^{xy} - \partial_y B^{xz} + \partial_x B^{yz}) \mathbf{e}_x \wedge \mathbf{e}_y \wedge \mathbf{e}_z \end{aligned}$$

$$\nabla \wedge \mathbf{B} = (\partial_z B^{xy} - \partial_y B^{xz} + \partial_x B^{yz}) \mathbf{e}_x \wedge \mathbf{e}_y \wedge \mathbf{e}_z$$

$$\nabla \cdot \mathbf{B} = (-\partial_y B^{xy} - \partial_z B^{xz}) \mathbf{e}_x + (\partial_x B^{xy} - \partial_z B^{yz}) \mathbf{e}_y + (\partial_x B^{xz} + \partial_y B^{yz}) \mathbf{e}_z$$

This example also demonstrates several other features of the latex printer. In the case that strings are input into the latex printer such as `r'grad*\bm{A}'`, `r'grad^\bm{A}'`, or `r'grad*\bm{A}'`. The text symbols `grad`, `^`, `|`, and `*` are mapped by the `xpdf()` post-processor as follows if the string contains an `=`.

original	replacement	displayed latex
<code>grad*A</code>	<code>\bm{\nabla}A</code>	$\nabla A$
<code>A^B</code>	<code>A\wedge B</code>	$A \wedge B$
<code>A B</code>	<code>A\cdot B</code>	$A \cdot B$
<code>A*B</code>	<code>AB</code>	$AB$
<code>A&lt;B</code>	<code>A\lfloor B</code>	$A \lfloor B$
<code>A&gt;B</code>	<code>A\rfloor B</code>	$A \rfloor B$

If the first character in the string to be printed is a `%` none of the above substitutions are made before the latex processor is applied. In general for the latex printer strings are assumed to be in a math environment (`equation` or `align`) unless the first character in the string is a `#`.<sup>6</sup>

Except where noted the conventions for latex printing follow those of the latex printing module of *sympy*. This includes translating *sympy* variables with Greek name (such as `alpha`) to the equivalent Greek symbol ( $\alpha$ ) for the purpose of latex printing. Also a single underscore in the variable name (such as `"X_j"`) indicates a subscript ( $X_j$ ), and a double underscore (such as `"X_k"`) a superscript ( $X^k$ ). The only other change with regard to the *sympy* latex printer is that matrices are printed full size (`equation displaystyle`).

---

<sup>6</sup>Preprocessing do not occur for the Ipython notebook and the string post processing commands `%` and `#` are not used in this case.

# Bibliography

- [1] Chris Doran and Anthony Lasenby, “Geometric Algebra for Physicists,” Cambridge University Press, 2003. <http://www.mrao.cam.ac.uk/~clifford>
- [2] David Hestenes and Garret Sobczyk, “Clifford Algebra to Geometric Calculus,” Kluwer Academic Publishers, 1984. <http://modelingnts.la.asu.edu>