

# Warum spherical harmonics?

Johannes Hahn

Andrea Hanke

20. Mai 2021

## Inhaltsverzeichnis

<b>0 Einführung</b>	<b>1</b>
<b>1 Warum Tensoren?</b>	<b>1</b>
1.1 Wiederholung: Vektorräume . . . . .	1
1.1.1 The tensor product . . . . .	3
1.2 The notion of meaningful linear operations with tensors - light introduction to invariant theory . . . . .	5
1.2.1 Operations on one tensor . . . . .	6
1.2.2 Operations between two tensors . . . . .	7
1.3 Symmetric tensor space . . . . .	8
1.4 Level 1 invariant theory: Irreducible and invariant subspaces of the symmetric tensor space . . . . .	9
1.5 Level 2 invariant theory: Linear and Bilinear Maps between Irreducible, invariant subspaces of the symmetric tensor space . . . . .	12
<b>2 Warum Darstellungstheorie?</b>	<b>14</b>

## 0 Einführung

### 1 Warum Tensoren?

#### 1.1 Wiederholung: Vektorräume

You should be familiar with vector spaces. Typical examples include  $\mathbb{R}^3$  or the space of polynomials up to a maximal degree  $n$ . Let us recall the definition of a vector space:

##### 1.1 Definition (Vektorräume):

Sei  $K$  ein Körper. Ein  $K$ -Vektorraum  $(V, +, \cdot)$  besteht aus

- einer Menge  $V$ ,
- einer Abbildung  $+: V \times V \rightarrow V, (v, w) \mapsto v + w$ , genannt (Vektor)addition und

- einer Abbildung  $\cdot : K \times V \rightarrow V, (\lambda, v) \mapsto \lambda v$ , genannt Skalarmultiplikation.

die die folgenden Bedingungen erfüllen:

(V1)  $(V, +)$  ist eine abelsche Gruppe. Das neutrale Element nennt man den Nullvektor und schreibt man fast immer als 0.

(V2) Assoziativität der Skalarmultiplikation:

$$\forall \lambda, \mu \in K \forall v \in V : (\lambda \mu)v = \lambda(\mu v)$$

(V3) Distributivität in  $v$ :

$$\forall \lambda \in K \forall v, w \in V : \lambda(v + w) = \lambda v + \lambda w$$

(V4) Distributivität in  $\lambda$ :

$$\forall \lambda, \mu \in K \forall v \in V : (\lambda + \mu)v = \lambda v + \mu v$$

(V5) Normierung:  $\forall v \in V : 1_K \cdot v = v$

## 1.2 Definition (Vektorräume):

Ein *Vektorraum über einem Körper  $F$* , kurz  *$F$ -Vektorraum* oder gar – wenn der Körper klar ist oder keine Rolle spielt – nur *Vektorraum* ist eine Menge  $V$  zusammen mit zwei Abbildungen, genannt  $+$  und  $\cdot$ , die die unten gelisteten Axiome erfüllen.

The first operation, called vector addition or simply addition  $+: V \times V \rightarrow V$ , takes any two vectors  $\mathbf{v}$  and  $\mathbf{w}$  and assigns to them a third vector which is commonly written as  $\mathbf{v} + \mathbf{w}$ , and called the sum of these two vectors. (The resultant vector is also an element of the set  $V$ .) The second operation, called scalar multiplication  $\cdot : F \times V \rightarrow V$  takes any scalar  $a$  and any vector  $\mathbf{v}$  and gives another vector  $a\mathbf{v}$ . (Similarly, the vector  $a\mathbf{v}$  is an element of the set  $V$ . Scalar multiplication is not to be confused with the scalar product, also called inner product or dot product, which is an additional structure present on some specific, but not all vector spaces. Scalar multiplication is a multiplication of a vector by a scalar; the other is a multiplication of two vectors producing a scalar.)

Elements of  $V$  are commonly called vectors. Elements of  $F$  are commonly called scalars. To qualify as a vector space, the set  $V$  and the operations of addition and multiplication must adhere to a number of requirements called axioms. These are listed in the table below, where  $\mathbf{u}$ ,  $\mathbf{v}$  and  $\mathbf{w}$  denote arbitrary vectors in  $V$ , and  $a$  and  $b$  denote scalars in  $F$ .

The above definition has already hinted at an operation, that a tensor space may lack: A bilinear multiplication of two vectors  $\cdot : V \times V \rightarrow V$ . We can formally define the properties of such a binary operation:

<b>!Axiom</b>	
!Associativity of addition	
!Commutativity of addition	
!Identity element of addition	There exists $\mathbf{0} \in V$
!Inverse elements of addition	For every $\mathbf{v} \in V$ there exists $-\mathbf{v} \in V$
!Compatibility of scalar multiplication with field multiplication	
!Identity element of scalar multiplication	
!Distributivity of scalar multiplication with respect to vector addition	
!Distributivity of scalar multiplication with respect to field addition	

Tabelle 1.1: Properties of a Vector space

### 1.3 Definition (Bilinear multiplication in a vector space):

Let  $F$  be a field, and let  $V$  be a vector space over  $F$ . Denote with  $\cdot$  an additional binary operation,  $\cdot : V \times V \rightarrow V$  (i.e. if  $\mathbf{v}$  and  $\mathbf{w}$  are any two elements of  $V$ ,  $\mathbf{v} \cdot \mathbf{w}$  is the product of  $\mathbf{v}$  and  $\mathbf{w}$  and also lies in  $V$ ). If this operation fulfills all properties in the following table for all elements  $\mathbf{u}, \mathbf{v}, \mathbf{w} \in V$ ,  $a, b \in F$ , then we call it a bilinear multiplication of two vectors.

Note, that commutativity is a not required property of a bilinear multiplication (hence the distinction between right and left distributivity). Depending on the situation, the multiplication may or may not have to fulfill the requirement of associativity.

Typical examples for vector spaces, that are equipped with a bilinear multiplication, include:  $\mathbb{R}^3$  with the cross product,  $\mathbb{R}^{n \times n}$  with the matrix product. A vector space that is typically not equipped with a bilinear multiplication is the space of polynomials up to degree  $n$ , since multiplying two polynomials can result in a polynomial of higher degree than  $n$ . However, we can extend this vector space to the space of all polynomials  $P$ .  $P$  is easily equipped with a bilinear multiplication (defined as you would expect the multiplication of two polynomials to work), which even happens to be commutative.

The concept of a vector space equipped with a bilinear multiplication has its own name:

### 1.4 Definition (Algebra):

Let  $F$  be a field, and let  $V$  be a vector space over  $F$ . If  $V$  can be equipped with a bilinear multiplication, then  $V$  is an algebra over  $F$ .

An algebra over  $F$  is sometimes also called an  $F$ -algebra, and  $F$  is called the base field of  $V$ . The binary multiplication is often simply referred to as multiplication in  $V$ .

### 1.1.1 The tensor product

Let us now look at a new kind of multiplication  $\otimes$  between two vectors  $\mathbf{u}, \mathbf{v} \in \mathbb{R}^3$ : The tensor product. There are many ways of motivating and defining it, but for our purposes we shall be satisfied by starting with a bilinear, associative, non-commutative multiplication of two vector spaces  $\otimes : U \times V \rightarrow U \otimes V$  whose result is called a tensor and written as  $\mathbf{U} \otimes \mathbf{V}$  (spoken "Ü tensor V").

$$\otimes : U \times V \rightarrow U \otimes V, \mathbf{u} \times \mathbf{v} \mapsto \mathbf{u} \otimes \mathbf{v}$$

$U \otimes V$  is in itself a vector space (the so called tensor space) of dimensionality

$$\dim U \otimes V = \dim U \cdot \dim V.$$

Choosing basis sets for  $U$  and  $V$ ,  $B_U = \{\mathbf{b}_i^u | i = 1, \dots, \dim U\}$  and  $B_V = \{\mathbf{b}_i^v | i = 1, \dots, \dim V\}$  respectively, allows to immediately choose a basis for  $U \otimes V$ :

$$\{\mathbf{b}_i^u \otimes \mathbf{b}_j^v | i = 1, \dots, \dim U, j = 1, \dots, \dim V\}.$$

Similar to denoting the coordinates of a vector  $v \in V$  e.g. as  $v_i$ , we can express the coordinates of a tensor with respect to the above basis as  $t_{ij}$ .

Given a tensor

$$t = \mathbf{u} \otimes \mathbf{v},$$

one may multiply it with yet another vector  $\mathbf{w}$ , resulting in a product with more terms (i.e. vectors)

$$f = \mathbf{u} \otimes \mathbf{v} \otimes \mathbf{w}$$

and so on. This is similar to the multiplication of polynomials. Indeed, just like polynomials have degrees, tensors can be of different order. The order of a tensor is determined by the number of vectors that are multiplied with each other, the tensor  $t$  is of order 2, the tensor  $f$  is of order 3. This nomenclature applies to tensor spaces as well,  $V \otimes W$  is a tensor space of second order. We are practically exclusively interested in tensor spaces of  $k$ -th order of only one vector space  $V$ , i.e.

$$\underbrace{V \otimes V \otimes \dots \otimes V}_{k \text{ times}},$$

which can be denoted as  $V^{\otimes k}$ . For our purposes we choose  $V = \mathbb{R}^n$  with mostly  $n = 3$ .

**1.5 (Tensor algebra):** Much like the space of all polynomials is an algebra, the vector space of the sum of all tensor products of a vector space  $V$ ,

$$\mathcal{T} : \bigoplus_{i=0}^{\infty} V^{\otimes i},$$

is equipped with the multiplication  $\otimes$  and hence is an algebra.

**1.6 Definition** (Elementary Tensor):

An elementary tensor is a tensor that can be expressed as a single product of vectors, e.g.  $v_1 \otimes v_2$ , (as opposed to a sum of products, e.g.  $v_1 \otimes v_2 - v_2 \otimes v_1$ ). In the following definitions we will often use elementary tensors, the linear continuation for sums of elementary tensors is always implied.

**1.7 Definition** (Casimir Element or  $\delta_{ij}$ -Tensor):

Let  $\Omega_V$  denote the symmetric, isotropic 2-tensor of the vector space  $V$  of dimensionality  $k$ . With any complete orthonormal basis set  $\{\mathbf{b}_1, \dots, \mathbf{b}_k\}$  for  $V$ ,  $\Omega_V$  can be expressed as

$$\Omega_V = \sum_{i=1}^k \mathbf{b}_i \otimes \mathbf{b}_i \quad (1)$$

Since we will mostly work with  $V = \mathbb{R}^3$  with some orthonormal basis set  $\{\mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3\}$ , the corresponding  $\Omega_V$  shall be written as  $\Omega$ ,

$$\Omega := \Omega_{\mathbb{R}^3} = \sum_{i=1}^3 \mathbf{b}_i \otimes \mathbf{b}_i.$$

**1.8 Lemma:**

The Casimir element does not depend on the choice of the orthonormal basis for  $V$ , i.e. it is indeed isotropic.

*Beweis.* Take  $B := \{e_1, \dots, e_d\}$ ,  $\tilde{B} := \{\tilde{e}_1, \dots, \tilde{e}_d\}$  to be two orthonormal basis sets and the basis transformation  $\phi : V \rightarrow V, v \mapsto \sum_{i=1}^d \langle v, \tilde{e}_i \rangle \tilde{e}_i$ . Then  $s_{ij} = \langle e_j, \tilde{e}_i \rangle$  are the entries of an orthogonal matrix and we have

$$\begin{aligned} \Omega_V &= \sum_{i=1}^d e_i \otimes e_i \\ \implies \phi(\Omega_V) &= \phi\left(\sum_{i=1}^d e_i \otimes e_i\right) \\ &= \sum_{i=1}^d \phi(e_i) \otimes \phi(e_i) \\ &= \sum_{j=1}^d \left(\sum_{i=1}^d \langle e_j, \tilde{e}_i \rangle \tilde{e}_i\right) \otimes \left(\sum_{i=1}^d \langle e_j, \tilde{e}_i \rangle \tilde{e}_i\right) \\ &= \sum_{i=1}^d \sum_{i'=1}^d \underbrace{\left(\sum_{j=1}^d \langle e_j, \tilde{e}_i \rangle \cdot \langle e_j, \tilde{e}_{i'} \rangle\right)}_{=(SST)_{ii'}=1_{ii'}=\delta_{ii'}} \tilde{e}_i \otimes \tilde{e}_{i'} \end{aligned}$$

$$= \sum_{i=1}^d \tilde{e}_i \otimes \tilde{e}_i = \Omega_V$$

□

## 1.2 The notion of meaningful linear operations with tensors - light introduction to invariant theory

In the context of our physical world, we can use tensors to measure quantities. A possibly familiar example is stress within a material or gas, which is measured with a tensor of second order. The fundamental property we expect from all quantities that we measure, is that they are independent of the orientation of the orthonormal coordinate system - rotating, inverting or mirroring the basis vectors should not change the value of the properties we are interested in (though this may change the numbers with which we express that quantity). A velocity vector for example should always point in the same direction, regardless of whether its coordinates are  $(3, 4, 0)^T$  or  $(0, 0, 5)^T$ . The same goes for its length or the determinant of a matrix.

### 1.9 Definition (Orthogonal Group $O^3$ ):

Let  $O^3$  be the set of all orthogonal matrices

$$O^3 := \{r \in \mathbb{R}^{3 \times 3} : |\det r| = 1\}.$$

All of the operations described above can be described with a corresponding matrix in  $O^3$ . Furthermore, equipped with the typical matrix-matrix multiplication,  $O^3$  fulfills all requirements of a group - hence the name orthogonal group.  $O^3$  has infinitely many elements, but is still compact - allowing for the notion of taking an average over the whole group.

### 1.10 Definition (Action of $O^3$ on the tensor space):

An element  $r \in O^3$  acts on a vector  $v \in \mathbb{R}^3$  via the matrix-vector product  $r \cdot v$ , resulting in the rotation or mirroring of the given vector. This is extended to tensors - An element  $r \in O^3$  acts on a tensor in  $\mathcal{T}$  through the matrix-vector multiplication of each factor of that tensor:

$$r(\cdot) : \mathcal{T} \rightarrow \mathcal{T}$$

$$v_1 \otimes \cdots \otimes v_n \mapsto r(v_1 \otimes \cdots \otimes v_n) := r \cdot v_1 \otimes \cdots \otimes r \cdot v_n.$$

### 1.11 Definition (Orthogonal Group $O_{\mathbf{n}}^2$ as subgroup of $O^3$ ):

Let  $\mathbf{n} \in \mathbb{R}^3$ .  $O_{\mathbf{n}}^2$  is the subgroup of  $O^3$ , that acts like the identity on  $\mathbf{n}$ ,

$$O_{\mathbf{n}}^2 := \{r \in O^3 | r(\mathbf{n}) = \mathbf{n}\}.$$

$O_{\mathbf{n}}^2$  is the embedding of  $\mathbb{R}^2$  and  $O^2 := \{r \in \mathbb{R}^{2 \times 2} : |\det r| = 1\}$  as a plane  $E$  into  $\mathbb{R}^3$  with  $E \perp \mathbf{n}$ .

**1.12 Definition** ( $O^3$ -Invariant linear map of the tensor space):

A linear map  $f : \mathcal{T} \rightarrow \mathcal{T}$  is called compatible (or invariant) with respect to  $O^3$ , iff for all actions  $r \in O^3$  and for any tensor  $T \in \mathcal{T}$  the relationship

$$f \circ r(T) = r \circ f(T)$$

holds. This precisely expresses the above notion of independency (or invariancy) of a quantity or tensor of the choice of coordinate system.

Finding  $O^3$ -invariant linear maps and being sure, that one has found all possibilities, requires some very interesting and complicated piece of mathematics known as invariant theory. This goes far beyond the scope of this thesis, we will restrict ourselves to introducing and applying the results. The interested reader may start by inquiring for the Brauer algebra.

**1.2.1 Operations on one tensor**

Below is a list of all types of  $O^3$ -invariant linear maps between tensors, defined with the elementary tensor  $v_1 \otimes \cdots \otimes v_n$ . All combinations of them is the full set of  $O^3$ -invariant linear maps between tensors:

**Multiplication with a scalar**  $s \in \mathbb{R}$ . This does not change the degree of the tensor.

**Permutation of the factors of a tensor.** We have seen this in tensors of second degree, where we called it transpose in correspondence to matrices. Formally,  $\sigma \in S_n$  acts on a tensor  $v_1 \otimes \cdots \otimes v_n$ :

$$\sigma(\cdot) : \mathcal{T} \rightarrow \mathcal{T}, v_1 \otimes \cdots \otimes v_n \mapsto v_{\sigma^{-1}(1)} \otimes \cdots \otimes v_{\sigma^{-1}(n)}$$

This does not change the degree of the tensor or any of the vectors  $v_i$ , it only reorders them. When using index notation, this operation is represented by a permutation of indices.

**Taking the trace  $tr$  between two factors of a tensor.** We can pick two vectors of a tensor and replace them with their scalar product:

$$tr_{i;j}(\cdot) : \mathcal{T} \rightarrow \mathcal{T}, v_1 \otimes \cdots \otimes v_i \otimes \cdots \otimes v_j \otimes \cdots \otimes v_n \mapsto \langle v_i, v_j \rangle v_1 \otimes \cdots \otimes v_{i-1} \otimes v_{i+1} \otimes \cdots \otimes v_{j-1} \otimes v_{j+1} \otimes \cdots \otimes v_n$$

This reduces the degree of the tensor by 2. When using index notation, this operation is represented by the sum over two identical indices, which is often abbreviated with Einstein's sum convention.

**Tensor multiplication with the Casimir element  $\Omega$ .**

$$\Omega(\cdot) : \mathcal{T} \rightarrow \mathcal{T}, v_1 \otimes \cdots \otimes v_n \mapsto \Omega \otimes v_1 \otimes \cdots \otimes v_n$$

This increases the degree of the tensor by 2. When using index notation, this operation is represented by the multiplication with  $\delta_{ij}$ .

### 1.2.2 Operations between two tensors

Given two tensors  $u, v \in \mathcal{T}$ , the question of finding invariant linear maps with respect to  $O^3 \mathcal{T} \times \mathcal{T} \rightarrow \mathcal{T}$  is easily reduced to the already described case of operations of one tensor. We just have to identify all possible maps  $\mathcal{T} \otimes \mathcal{T} \rightarrow \mathcal{T} = \mathcal{T} \rightarrow \mathcal{T}$  due to the isomorphism  $\mathcal{T} \times \mathcal{T} \rightarrow \mathcal{T} \cong \mathcal{T} \otimes \mathcal{T} \rightarrow \mathcal{T}$  for bilinear and linear maps. To be more specific: Given two tensors  $u, v$ , take the tensor product  $u \otimes v$  and now apply any combination of the operations described for one tensor. Nevertheless, some operations are very common and worth mentioning.

#### 1.13 Definition (Contraction between two tensors):

Taking one or multiple traces between two tensors is given a special name: Contraction.

$$\begin{aligned} tr_{i;j}(\cdot, \cdot) : \mathcal{T} \times \mathcal{T} &\rightarrow \mathcal{T}, \\ v_1 \otimes \cdots \otimes v_i \otimes \cdots \otimes v_n \otimes u_1 \otimes \cdots \otimes u_i \otimes u_j \otimes \cdots \otimes u_n \\ \mapsto \langle v_i, u_j \rangle v_1 \otimes \cdots \otimes v_{i-1} \otimes v_{i+1} \otimes \cdots \otimes v_n \otimes u_1 \otimes \cdots \otimes u_{j-1} \otimes u_{j+1} \otimes \cdots \otimes u_n \end{aligned}$$

#### 1.14 Definition (Standard scalar product):

The standard scalar product  $\langle \cdot, \cdot \rangle$  between two tensors of same order is defined as the (ordered) full contraction between the two tensors:

$$\begin{aligned} \langle \cdot, \cdot \rangle : V^{\otimes n} \times V^{\otimes n} &\rightarrow \mathbb{R}, \\ \langle u_1 \otimes \cdots \otimes u_n, v_1 \otimes \cdots \otimes v_n \rangle &\mapsto tr_{1,\dots,n;1,\dots,n}(u_1 \otimes \cdots \otimes u_n, v_1 \otimes \cdots \otimes v_n) \\ &= \langle u_1, v_1 \rangle \cdot \langle u_2, v_2 \rangle \cdots \langle u_n, v_n \rangle. \end{aligned}$$

### 1.3 Symmetric tensor space

#### 1.15 Definition (Symmetric tensors):

A tensor  $v$  of  $n$ -th order is called symmetric, iff for all permutations  $\sigma \in S_n$  holds:

$$\sigma(v) = v.$$

The space spanned by all symmetric tensors of degree  $n$ ,  $\text{Sym } n$ , is an invariant subspace of the tensor space due to the completely decoupled nature of the actions of  $S_n$  and  $O^3$  on a tensor. We can take any tensor and project it onto this subspace by taking the average of all possible permutations:

$$\begin{aligned} q : \mathbb{R}^{3^{\otimes n}} &\rightarrow \text{Sym } n \\ q(v_1 \otimes \cdots \otimes v_n) &\mapsto \frac{1}{n!} \sum_{\sigma \in S_n} v_{\sigma(1)} \otimes \cdots \otimes v_{\sigma(n)} \end{aligned}$$

and linear extension. In index notation this is denoted by round brackets surrounding the indices.  $\text{Sym } n$  is of dimension  $\frac{1}{2}(n+1)(n+2)$ .



□ It is easy to show for the standard scalar product on  $\mathbb{R}^{\otimes n}$ , that for all  $v, u \in \mathbb{R}^{\otimes n}$  the following identity holds:

$$\langle q(v), q(u) \rangle = \langle v, q(u) \rangle = \langle q(v), u \rangle. \quad (2)$$

**1.16 Definition** (Trace and contraction of symmetric tensors):

Since for symmetric tensors all the positions  $i, j (i \neq j)$  of the two vectors that are used to take the trace  $tr_{i,j}$  (contraction) are equivalent to each other, we can use a notation that only shows the relevant information: The number of traces (contractions) taken of one tensor (between two tensors).

$k$ -fold trace of a symmetric tensor:

$$\begin{aligned} tr^k(\cdot) : \text{Sym } n &\rightarrow \text{Sym } n - 2k, \\ tr^k(s) &\mapsto tr_{1,3,5,\dots,2k-1;2,4,6,\dots,2k}(s) \end{aligned}$$

$k$ -fold contraction between two symmetric tensors:

$$\begin{aligned} tr^k(\cdot, \cdot) : \text{Sym } n \times \text{Sym } m &\rightarrow \text{Sym } n - k \otimes \text{Sym } m - k, \\ tr^k(s, t) &\mapsto tr_{1,2,3,\dots,k;1,2,3,\dots,k}(s, t) \end{aligned}$$

Due to the polynomial nature of the ansatz for the distribution function, we will almost exclusively work with symmetric tensor spaces (reference chapter ?? to see why). Casually spoken,  $O^3$  imposes a specific structure on  $\text{Sym } n$ , which brings us to the next section.

## 1.4 Level 1 invariant theory: Irreducible and invariant subspaces of the symmetric tensor space

**1.17 Definition** (Invariant subspaces):

A subspace  $U$  of any vector space  $V$  is called invariant with respect to the action of a group  $G$ , or  $G$ -invariant, iff for all  $r \in G$  and for all  $u \in U$ , the action of  $r$  on  $u$  still is in  $U$ ,  $r(u) \in U$  or equivalently:  $\forall r \in G : r(U) = U$ .

**1.18 Beispiel** ( $O_{\mathbf{n}}^2$ -invariant subspaces of  $\mathbb{R}^3$ ):

We pick  $\mathbb{R}^3$  as vector space and the subgroup  $O_{\mathbf{n}}^2 \subset O^3$  along with a direction  $n \in \mathbb{R}^3$ , for which by definition  $\forall r \in O_{\mathbf{n}}^2 : r(n) = n$ . Then the subspace  $\mathbf{n} = \{\alpha \mathbf{n} | \alpha \in \mathbb{R}\}$  is a one-dimensional invariant subspace, since

$$\forall r \in O_{\mathbf{n}}^2, \forall \alpha \in \mathbb{R} : r(\alpha \mathbf{n}) = \alpha r(\mathbf{n}) = \alpha \mathbf{n}.$$

Given an  $O^3$ -compatible scalar product, we can define the plane  $E \subset \mathbb{R}^3$  orthogonal to  $\mathbf{n}$  and decompose  $\mathbb{R}^3$  into

$$\mathbb{R}^3 = \mathbf{n} \oplus E.$$

It is easily shown that  $E$  is also an invariant, 2-dimensional subspace under the action of  $O_{\mathbf{n}}^2$ .

**1.19 Beispiel** ( $O^3$ -invariant subspaces of the tensor space):

These are subspaces  $U \subset \mathcal{T}$  that fulfill  $\forall r \in O^3 : r(U) = U$ . One such subspace is the above described space of symmetric tensors, which is of relatively large dimensionality for high  $n$ . Another example of an invariant subspace would be  $\Omega \subset \text{Sym } 2$  with a dimensionality of 1. One may wonder, if  $\text{Sym } n$  can be further decomposed into "smallest", invariant subspaces, and if such a decomposition is unique.

**1.20 Definition** (Irreducible (and invariant) subspaces):

A subspace  $U$  of any vector space  $V$  is called irreducible with respect to the action of a group  $G$ , or  $G$ -irreducible, iff it is invariant and there is no invariant subspace  $W \subset U$  with the properties  $W \neq U$  and  $W \neq 0$ . If a subspace  $U$  is invariant and  $\dim U = 1$ , then it is also irreducible, however an irreducible subspace can be of dimension larger than 1.

Two irreducible subspaces  $U_1, U_2, U_1 \neq U_2$  of a vector space  $V$  are orthogonal to each other with respect to any scalar product of  $V$  that is compatible with the action of the group  $G$ . We can project from the full vector space onto an irreducible subspace. Due to the universal orthogonality, such a projection is always unique up to a constant (or a zero).

**1.21 Beispiel** ( $O_{\mathbf{n}}^2$ -irreducible subspaces of  $\mathbb{R}^3$ ):

We already know that  $E$  and  $\mathbf{n}$  are invariant subspaces. Since  $\dim \mathbf{n} = 1$ ,  $\mathbf{n}$  is also an irreducible subspace. For the 2-dimensional  $E$  we cannot find a lower-dimensional invariant subspace, since

$$\exists r \in O_{\mathbf{n}}^2 : \forall \mathbf{v} \neq 0 \in E, \forall \alpha \in \mathbb{R} : r(\mathbf{v}) \neq \alpha \mathbf{v}.$$

This means that  $E$  is irreducible as well and that we have found all  $O_{\mathbf{n}}^2$ -irreducible subspaces of  $\mathbb{R}^3$ .

**1.22 Beispiel** ( $O_{\mathbf{n}}^2$ -irreducible subspaces of  $\text{Sym } n$ ):

We note:

$$\text{Sym } n = q \left( (\mathbb{R}^3)^{\otimes n} \right).$$

Insert the splitting of  $\mathbb{R}^3$  into  $E$  and  $\mathbf{n}$ :

$$\begin{aligned} \text{Sym } n &= q \left( \left( E \oplus \mathbf{n} \right)^{\otimes n} \right) \\ &= \bigoplus_{i=0}^n q \left( E^{\otimes i} \otimes (\mathbf{n})^{\otimes n-i} \right) \end{aligned}$$

The orthogonality between  $E$  and  $\mathbf{n}$  leads to an orthogonality between each of these tensor spaces, the invariancy of each  $q \left( E^{\otimes i} \otimes (\mathbf{n})^{\otimes n-i} \right)$  follows from the invariancy

of the "building blocks"  $E$  and  $\mathbf{n}$ . However, for general  $n, i$  these subspaces are not irreducible. For instance we find that the invariant tensor  $q(\Omega_E^{\otimes j})$  spans a 1-dimensional (and therefore irreducible) subspace of  $q(E^{\otimes 2j})$ . In general, since  $q(E^{\otimes i} \otimes (\mathbf{n})^{\otimes n-i}) \cong q(E^{\otimes i}) \cong i$ , finding all irreducible subspaces of  $i$  immediately leads to all irreducible subspaces of  $q(E^{\otimes i} \otimes (\mathbf{n})^{\otimes n-i})$ .

**1.23 (Invariant tensors):** Sometimes one may work with a tensor  $T$  that is invariant with respect to a group  $G$ , i.e.  $\forall r \in G : r(T) = T$ . For example:

- $G = S_n$ . Then all tensors  $T \in \text{Sym } n$  are invariant
- $G = O^3$ . Then all tensors  $T \in (\mathbb{R}^3)^{\otimes 2i}$  that are a linear combination of permutations  $\Omega^{\otimes i}$  are invariant. If in addition  $T \in \text{Sym } 2i$ :  $T = \alpha q(\Omega^{\otimes i})$ ,  $\alpha \in \mathbb{R}$ .
- $G = O_n^2$  and  $T \in \text{Sym } n$ . Not all tensors in  $q(E^{\otimes m})$  are invariant, in fact the only invariant tensors are  $\alpha q(\Omega_E^{\otimes i})$ ,  $\alpha \in \mathbb{R} \implies m = 2i$ . All tensors in  $\mathbf{n}$  are invariant, so an  $O_n^2$ -invariant, symmetric tensor must come from the subspace spanned by  $\{q(\Omega_E^{\otimes i} \otimes \mathbf{n}^{\otimes n-2i})\}$ , i.e.

$$T = \sum_{i=0}^{\frac{n}{2}} \alpha_i q(\Omega_E^{\otimes i} \mathbf{n}^{\otimes n-2i}), \alpha_i \in \mathbb{R}. \quad (3)$$

Notice, that not all tensors from an invariant subspace are themselves invariant. Even that a tensor lies in an irreducible subspace is no guarantee that the tensor itself is invariant.

#### 1.24 Beispiel ( $O^3$ -irreducible subspaces of $\text{Sym } n$ ):

It turns out, that  $\text{Sym } n$  can be expressed as the direct sum of  $\lfloor \frac{n}{2} \rfloor + 1$   $O^3$ -irreducible subspaces (i.e.  $\text{Sym } n$  is semi-simple). Most of these subspaces are of dimensionality greater than 1. Furthermore, these irreducible subspaces are pairwise orthogonal with respect to any scalar product of the  $\text{Sym } n$  that is compatible with  $O^3$  (which is a rather redundant requirement, since we wouldn't want to choose a scalar product that is not compatible with  $O^3$  anyway).

For every order  $n$ , we find that the largest irreducible subspace of  $\text{Sym } n$  consists of trace-free tensors.

#### 1.25 Definition (Symmetric trace-free tensors):

A symmetric tensor  $v$  of order  $n > 1$  is called symmetric trace-free, iff  $\text{tr}_{1,2}(v) = 0$ . Tensors of order 1 are always symmetric tracefree. The space spanned by all symmetric trace-free tensors of order  $n$  is denoted as  $n$  and has dimension  $2n + 1$ . On  $n$  all  $O^3$ -compatible scalar products of the tensor space are equivalent to each other (they give the same result up to a constant factor). That has the effect that an orthogonal basis of  $n$  chosen with respect to one scalar product is orthogonal with respect to any other scalar product (as long as both are  $O^3$ -compatible). In index notation, the projection

onto the space of symmetric trace-free tensor is denoted as square brackets around the indices.

The other irreducible subspaces are related to symmetric tracefree tensors:

**1.26 Definition** (Symmetric traceable tensors):

$n, a$  is the space of symmetric tensors of order  $n + 2a$ , that result in a trace-free tensor (of order  $n$ ) after taking  $i$  traces. Equivalently:  $n, a$  is the space of symmetric tensors of order  $n + 2a$ , that can be expressed as the result of taking trace-free tensors (of order  $n$ ), and applying the linear map

$$q \circ \underbrace{\Omega \circ \dots \circ \Omega}_{i \text{ times}}.$$

This means that there is a bijective map between  $n, i$  and  $n$ , i.e.  $n, i$  and  $n$  are isomorph to each other.

**1.27 Lemma** (Decomposition of  $\text{Sym } n$  into its  $O^3$  irreducible subspaces):

Each  $i$  is a building block for subspaces of  $\text{Sym } n, i \leq n$ ,

$$\text{Sym } n = \bigoplus_{i=0}^{\lfloor \frac{n}{2} \rfloor} q \left( \Omega^{\otimes i} \otimes n - 2i \right) = \bigoplus_{i=0}^{\lfloor \frac{n}{2} \rfloor} n - 2i, i$$

When building an orthogonal basis for  $\text{Sym } n$  for a physical problem (i.e.  $O^3$  acts on  $\text{Sym } n$ ), the natural choice is the composition of all orthonormal basis sets from each of the subspaces.

## 1.5 Level 2 invariant theory: Linear and Bilinear Maps between Irreducible, invariant subspaces of the symmetric tensor space

**1.28 Lemma** (Compatible linear Maps between irreducible subspaces (Schur's Lemma)):

Let  $U_1$  and  $U_2$  be two invariant, irreducible subspaces of a vector space. A compatible linear map  $\phi : U_1 \rightarrow U_2$  is only non-zero, iff  $U_1$  and  $U_2$  are isomorph to each other. All non-zero linear maps  $U_1 \rightarrow U_2$  are the same up to a constant.

Applied to the space of all symmetric tensors, we find non-zero,  $O^3$ -compatible linear maps only of the form  $n, a \rightarrow n, b, n, a, b \in \mathbb{N}_0$ .

**1.29 Lemma** ( $O^3$ -compatible, bilinear maps between symmetric trace free tensors):

An  $O^3$ -compatible bilinear map  $\phi^{n\tilde{n}\hat{n}} : \tilde{n} \times \hat{n} \rightarrow n$  can only be non-zero, iff the following conditions apply:

$$\begin{aligned} \tilde{n} + \hat{n} + n &\text{ even} \\ |\tilde{n} - \hat{n}| &\leq n \leq \tilde{n} + \hat{n} \end{aligned}$$

Then  $\phi^{n\tilde{n}\hat{n}}$  is unique (up to a constant).

*Beweis.*  $\phi^{n\tilde{n}\hat{n}}$  is isomorph to an  $O^3$ -compatible linear map  $\varphi^{n\tilde{n}\hat{n}} : \tilde{n} \otimes \hat{n} \rightarrow n$ .  $\varphi$  can only be non-zero, iff there exists a subspace of  $\tilde{n} \otimes \hat{n}$ , that is isomorph to  $n$ , so we are looking for a projection of  $\tilde{n} \otimes \hat{n}$  onto  $n, i$  with condition

$$n + 2i = \tilde{n} + \hat{n} \iff \tilde{n} + \hat{n} + n \text{ even.}$$

Such a projection is always linear, unique, and compatible with  $O^3$ . Due to the isomorphism between  $n$  and  $n, i$ , this makes  $\varphi$  unique up to a constant, if it exists.

Let  $s$  be any tensor of degree  $n$ , and  $t$  be the resulting tensor from the projection of  $t$  onto  $n$ . Projecting a tensor of the form  $\Omega \otimes s$  (or some permutation) onto  $n + 2$  is equivalent to projecting  $t$  onto  $n + 2$ . Since the only linear map from  $n$  to  $n + 2$  is the zero-map, the projection of  $\Omega \otimes s$  onto  $n + 2$  will always result in 0. This imposes the condition

$$n \leq \tilde{n} + \hat{n}$$

onto  $n, \tilde{n}$ , and  $\hat{n}$ .

In chapter 1.2.1 we listed all types of linear,  $O^3$ -compatible maps,  $\varphi^{n\tilde{n}\hat{n}}$  must be a combination of these. The only map that decreases the order of a given tensor is taking the trace of that tensor. For a tensor of the specific form  $\tilde{n} \otimes \hat{n}$ , taking the trace within the first  $\tilde{n}$  or the last  $\hat{n}$  factors will always be zero. The only traces that yield a non-zero result are those taken between the first  $\tilde{n}$  and the last  $\hat{n}$  factors, i.e.  $k$ -fold contractions between the two arguments of  $\phi$ . Since the two arguments are each symmetric, all  $k$ -fold contractions between them are equivalent. The number of traces  $k$  with a non-zero result we can take of a tensor from the space  $\tilde{n} \otimes \hat{n}$  is limited by  $\tilde{n}$  and  $\hat{n}$ ,  $k \leq \min \tilde{n}, \hat{n}$ . Since  $n = \tilde{n} + \hat{n} - 2k$ , that imposes the condition on  $n$ :

$$n \geq \tilde{n} + \hat{n} - 2 \min(\tilde{n}, \hat{n}) = \max(\tilde{n} - \hat{n}, \hat{n} - \tilde{n}) = |\tilde{n} - \hat{n}|.$$

□

### 1.30 Lemma ( $O^3$ -compatible, bilinear maps between symmetric tensors):

Every  $O^3$ -compatible bilinear map  $\psi : \text{Sym } \tilde{m} \times \text{Sym } \hat{m} \rightarrow \text{Sym } m$  with  $m, \tilde{m}, \hat{m} \in \mathbb{N}_0$  can be expressed as the sum of  $O^3$ -compatible bilinear maps between all combinations of invariant, irreducible subspaces of  $\text{Sym } \tilde{m}$ ,  $\text{Sym } \hat{m}$ , and  $\text{Sym } m$ . With

$$m = n + 2a, \quad \tilde{m} = \tilde{n} + 2b, \quad \hat{m} = \hat{n} + 2c \quad \tilde{n}, b, \hat{n}, c, n, a \in \mathbb{N}_0$$

we can write

$$\begin{aligned}
\psi : \text{Sym } \tilde{m} \times \text{Sym } \hat{m} &\rightarrow \text{Sym } m \\
&= \bigoplus_{b=0}^{\lfloor \frac{\tilde{m}}{2} \rfloor} \tilde{n}, b \times \bigoplus_{c=0}^{\lfloor \frac{\hat{m}}{2} \rfloor} \hat{n}, c \rightarrow \bigoplus_{a=0}^{\lfloor \frac{m}{2} \rfloor} n, a \\
&= \bigoplus_{b=0}^{\lfloor \frac{\tilde{m}}{2} \rfloor} \bigoplus_{c=0}^{\lfloor \frac{\hat{m}}{2} \rfloor} \bigoplus_{a=0}^{\lfloor \frac{m}{2} \rfloor} \tilde{n}, b \times \hat{n}, c \rightarrow n, a \\
&=: \bigoplus_{b=0}^{\lfloor \frac{\tilde{m}}{2} \rfloor} \bigoplus_{c=0}^{\lfloor \frac{\hat{m}}{2} \rfloor} \bigoplus_{a=0}^{\lfloor \frac{m}{2} \rfloor} \psi_{abc}^{n\tilde{n}\hat{n}}
\end{aligned}$$

Each of the  $\psi_{abc}^{n\tilde{n}\hat{n}}$  are unique up to a constant and only non-zero, iff the following conditions apply:

$$\begin{aligned}
&\tilde{n} + \hat{n} + n \text{ even} \\
&|\tilde{n} - \hat{n}| \leq n \leq \tilde{n} + \hat{n}.
\end{aligned}$$

Given a set of all maps  $\psi_{abc}^{n\tilde{n}\hat{n}}$ , two  $\psi$  can only differ in the constants multiplied with those maps. Furthermore, due to the isomorphism between  $n$  and  $n, i$ , all  $\psi_{abc}^{n\tilde{n}\hat{n}}$  are isomorph to a map  $Q^{n\tilde{n}\hat{n}} : \tilde{n} \otimes \hat{n} \rightarrow n$ , which is unique up to a constant. Given a set of all maps  $Q^{n\tilde{n}\hat{n}}$ , two tensors of the form  $U := q(\Omega^{\otimes b} \otimes u)$  and  $V := q(\Omega^{\otimes b} \otimes v)$  with  $u \in \tilde{n}, v \in \hat{n}$ , we can express any  $\psi_{abc}^{n\tilde{n}\hat{n}}(U, V)$  as

$$\psi_{abc}^{n\tilde{n}\hat{n}} \left( q \left( \Omega^{\otimes b} \otimes u \right), q \left( \Omega^{\otimes b} \otimes v \right) \right) = S_{abc}^{n\tilde{n}\hat{n}} \cdot q \left( \Omega^{\otimes a} \otimes Q^{n\tilde{n}\hat{n}}(u, v) \right). \quad (4)$$

The only degree of freedom for  $O^3$ -compatible, bilinear maps  $\psi$  between symmetric tensors lies in the choice for the constants  $S_{abc}^{n\tilde{n}\hat{n}}$ .

## 2 Warum Darstellungstheorie?