

An OpenMath Content Dictionary for Tensor Concepts

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Abstract

We introduce a new OpenMath content dictionary named “tensor1” containing symbols for the expression of tensor formulas. These symbols support the expression of non-Cartesian coordinates and invariant, multilinear expressions in the context of coordinate transformations. While current OpenMath symbols support the expression of linear algebra formulas using matrices and vectors, we find that there is an underlying assumption of Cartesian, or *standard*, coordinates that makes the expression of general tensor formulas difficult, if not impossible. In introducing these new OpenMath symbols for the expression of tensor formulas, we attempt to maintain, as much as possible, consistency with prior OpenMath symbol definitions for linear algebra.¹

1 Introduction

In scientific and engineering disciplines there are many uses of tensor notation. A principal reason for the need for tensors is that the laws of physics are best formulated as tensor equations. Tensor equations are used for two reasons: first, the physical laws of greatest interest are those that may be stated in a form that is independent of the choice of coordinates, and secondly; expressing the laws of physics differently for each choice of coordinates becomes cumbersome to maintain. While from a theoretical perspective it is desirable to be able to express the laws of physics in a form that is independent of coordinate frame, the application of those laws to the prediction of the dynamics of physical objects requires that we do ultimately specify the values in some coordinate frame. Much of this discussion might be moot were scientists and engineers to confine themselves to one frame, e.g., Cartesian coordinates, but such is not the case. Non-Cartesian coordinates are useful for curved geometries and because closed form solutions to applied models in classical physics, which rely on the separation of variables method of solving partial differential equations, often exist

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in them. For example, the Laplace equation is separable in thirteen coordinate systems [1]. One may also take as a definition of need that these concepts are included in the ISO standards defining the necessary mathematical symbols in the International System (SI) of Quantities and Units [2].

While we specify the new OpenMath symbols for tensor concepts, we attempt to maintain consistency with pre-existing OpenMath symbols [3]. The symbols within OpenMath content dictionaries support the expression of a wealth of mathematical concepts. Determining whether or not additional symbols are needed requires consideration based upon both necessity and convenience. Advancing new symbols using arguments based upon mathematical necessity only implies that a proof is at hand showing that a particular concept cannot be expressed using existing OpenMath symbols. Since such proofs would be difficult, if not impossible, in practice, convincing arguments for new symbols are more likely to be made based on a combination of practical economy, practical necessity, and convenience: this is certainly the case here. The symbols we introduce are motivated by the need for easily and directly capturing the relevant semantics in the expression of tensor formulas.

OpenMath symbols exist for the specification of matrices and vectors. These are documented in the content dictionaries `linalg1`, `linalg2`, `linalg3`, `linalg4`, `linalg5`, and two dictionaries named `linalg6`. Within these dictionaries there are two representations: one for row vectors and one for column vectors, with the row representation being labeled “official” in preference to the column representation. In the row vector representation a matrix is a column of rows, and in the column vector representation it is a row of columns. We find that the two representations, i.e., the row representation of vectors and the column representation of vectors, appear to be alternative, equivalent representations, related by a transpose operation, rather than dual representations, such as vectors and covectors where row and column representations of a vector are related via a general metric tensor. We also find, from the few examples given and from the general lack of reference to bases, that the row and column vector semantics appear to assume use of the *standard*, or Cartesian, basis only, and, in particular, with a simple Euclidean metric. For example, the scalar product is given as $\mathbf{u} \cdot \mathbf{v} = \sum_i u_i v_i$. In the row representation, the vector components resulting from a matrix-vector multiplication appear as the results of scalar products between matrix rows and a row vector, i.e., a scalar product takes as its arguments two vectors from the same vector space. Given these observations, it is not clear that in using these existing representations it is easy, or even possible, to express the semantics of tensors as they are typically used by engineers and scientists. For these reasons we introduce symbols that are expressly to be used for specifying tensor formulas.

2 Tensor Review

To motivate our choice of OpenMath symbols for specifying tensors, we briefly review some tensor basics. By definition, a tensor is a multilinear mapping that

maps vectors and covectors to a scalar field. A tensor is itself an element of the space defined by a tensor product of covector and vector spaces. Among scientists and engineers, tensor formulas are commonly written using their indexed *components*.

2.1 Coordinate Frames

To begin the discussion, we note that an arbitrary point in n -dimensional space, $\mathbf{R}^n$, is typically specified by its n Cartesian, or *standard*, coordinates, x^i . The point's *position vector*, is then written as $\mathbf{r} = \sum_i x^i \mathbf{e}_i$, where the $\mathbf{e}_i$ are orthonormal Cartesian basis vectors and are constant, i.e., not a function of the coordinates, for a given Cartesian frame. Using the original Cartesian frame, alternative coordinates may be defined as functions of the Cartesian coordinates in the original frame, e.g., $x'^i = x'^i(x^1, \dots, x^n)$, which may be nonlinear in the x^i .

Spatial coordinates are sometimes expressed as indexed quantities, such as (x^1, x^2, x^3) , or having individual names, such as (x, y, z) . In presentation, different kinds of indexes may appear much the same, but in content markup we must be more discriminating. For example, vector components are one kind of indexed quantity. It would be a mistake, however, to consider the tuple of spatial coordinates to be a vector in the general case. While it may seem to be a vector in Cartesian coordinates, i.e., a position vector, this is not the case in, for example, polar coordinates. For general coordinates the vector addition of coordinate position tuples does not appear to have a defined meaning, i.e., the meaning of

$$\text{coordinates}(\text{Point1}) + \text{coordinates}(\text{Point2}) = \text{coordinates}(\text{Point3})$$

is not preserved under general coordinate transformation.

Considering this, the most we should say is that the variables describing the coordinates of an arbitrary point in a space comprise an n -tuple. This appears to be similar to the notion of an OpenMath *context* [4], i.e., an n -tuple of variables. Consequently, while we need to represent x^i , it is inappropriate to do this using the `vector_selector` symbol, the vector component accessor defined in the OpenMath `linalg1` content dictionary. For this reason we introduce the *tuple* and *tuple_selector* symbols. The symbol, `tuple`, is an n -ary function that returns an n -tuple of its arguments in the order that they are presented. The symbol, `tuple_selector`, takes two arguments, an n -tuple, and an index, a natural number less than or equal to n , and returns the indexed element.

Since the Cartesian frame is most often used, including in the definition of coordinate transformations and the definition of non-Cartesian frames, we find it useful to have symbols to express the base concepts of Cartesian coordinates. We propose the symbol *Cartesian* which takes a single argument, a natural number, and returns the Cartesian coordinate, of a right-handed Cartesian frame, corresponding to the value of the argument. The standard representation of Cartesian 3-space may then be represented by either

$$\text{tuple}(x, y, z) = \text{tuple}(\text{Cartesian}(1), \text{Cartesian}(2), \text{Cartesian}(3))$$

or as

$\text{tuple_selector}(i, \mathbf{x}) = \text{Cartesian}(i)$.

Coordinate transformations may then be defined as functions on the Cartesian coordinates.

The full meaning of the Cartesian coordinate variables comes from their combination with the basis vectors for the Cartesian frame. The commonly used orthonormal basis vectors for the Cartesian frame are given by the symbol *unit_Cartesian*, i.e., `unit_Cartesian` takes a single natural number as its argument and returns the corresponding unit vector, say, $\mathbf{e}_i$. Other representations are easily assigned, such as

$\text{tuple}(\hat{i}, \hat{j}, \hat{k}) = \text{tuple}(\text{unit_Cartesian}(1), \text{unit_Cartesian}(2), \text{unit_Cartesian}(3))$.

Basis vectors, $\mathbf{g}_i$, for transformed coordinates, x'^i , are given by

$$\mathbf{g}_i = \sum_j \frac{\partial x^j}{\partial x'^i} \mathbf{e}_j.$$

2.2 Vectors and Covectors

To describe tensors we must also give prior description to vectors and covectors. A vector, $\mathbf{v}$, may be specified by components v^i with respect to an arbitrary, ordered, vector space basis, $(\mathbf{g}_1, \dots, \mathbf{g}_n)$, as $\mathbf{v} = \sum_i v^i \mathbf{g}_i$. These basis vectors, $\mathbf{g}_i$, are generally the tangent vectors with respect to the spatial coordinates, e.g., x^i . In curvilinear coordinates these general basis vectors are clearly functions of the coordinates. A dual, covector space may be defined relative to a given vector space. A dual space is defined as a set of linear functionals on the vector space and is spanned by a set of basis elements, $(\mathbf{g}^1, \dots, \mathbf{g}^n)$, such that $\mathbf{g}^i(\mathbf{g}_j) = \delta^i_j$, where δ^i_j is the Kronecker tensor. The symbol, *Kronecker_tensor*, has components, δ^i_j , equal to one when $i = j$ and zero otherwise.

The presentation of the indexes, either raised or lowered, on basis vectors, basis covectors, vector components, or covector components, generally indicates how the components transform. With a transformation of coordinates, indexed tensor quantities transform either *covariantly*, as do the basis vectors, $\mathbf{g}_i$, or they transform *contravariantly*, as do vector components, v^i , or, for example, coordinate differentials, dx^i . Transforming from coordinates x^i to coordinates x'^i , the covariant transformation is defined by the transformation of the basis vectors:

$$\mathbf{g}'_i = \sum_k \frac{\partial x^k}{\partial x'^i} \mathbf{g}_k.$$

The contravariant transformation of a vector's components is given by:

$$v'^i = \sum_k \frac{\partial x'^i}{\partial x^k} v^k.$$

The covariant transformation of the components of a covector, u , is given by

$$u'_j = \sum_k \frac{\partial x^k}{\partial x'^j} u_k.$$

Vectors whose components transform contravariantly, and their covectors, whose components transform covariantly, are tensors. Many, but not all, vector quantities are tensors. For example, the coordinates themselves, x^i , are referred to as the components of a *position vector* (in Cartesian coordinates), $\mathbf{x}$ or $\mathbf{r}$, which is *not* a tensor. (We have already noted that the position vector in Cartesian coordinates, defined as a tuple of position coordinates, does not generally preserve its meaning after coordinate transformation).

In general, tensors may be created by tensor (outer) products of vectors and covectors, contracted products of tensors, and sums of tensors of the same order. Order one tensors are contravariant or covariant vectors, while order zero tensors are scalars. The order of a higher order tensor is just the necessary number of vectors and covectors multiplied together, using the tensor product, to create it.

For the purpose of describing tensor formulas in content markup, we introduce the OpenMath symbols *tensor_selector*, *contra_index*, and *covar_index*, which are applied to a natural number, returning the appropriate index. In standard tensor notation, a contravariant index is represented as a superscripted index and a covariant index is represented as a subscripted index. The *contra_index* and *covar_index* symbols are so named because characterizing the indexes of tensor quantities as being contravariant or covariant captures the semantics.

In engineering and scientific applications standard matrix-vector multiplication is consistent with tensor notation when interpreted as a matrix multiplying a column vector from the left, resulting in a column vector. Each of the components of the result are arrived at by applying the rows of the matrix to the column vector being multiplied. It is consistent with this common usage to identify the components of a column vector using the contravariant, superscripted index as a row index, and to identify the components of a row vector using the covariant, subscripted index as a column index. The matrix-vector multiplication is then represented as $u^i = \sum_j M_j^i v^j$. It is common in tensor notation to suppress the explicit summation in such an expression using the Einstein Summation Convention.

While it is common to implicitly assume the use of standard, or Cartesian coordinates, in which case the distinction between superscripts and subscripts appears superfluous, this is not so with tensor notation: a vector may be specified by its components relative to some general, non-Cartesian basis. As pointed out above, the basis vectors of an arbitrary, ordered basis of a vector space transform covariantly, hence they are indexed using the symbol, *covar_index*. Similarly, the basis covectors, derived from the same arbitrary, ordered basis of the vector space, transform contravariantly, hence they are indexed using the symbol, *contra_index*.

We introduce, then, the *basis_selector* symbol as a binary operator, taking as its arguments:

- 1) an ordered basis, a tuple of linearly independent vectors that spans some vector space;
 - 2) either a *covar_index* or *contra_index* symbol applied to a natural number.
- The *basis_selector* operator returns a basis vector of the vector space when a *covar_index* symbol is passed and returns a basis covector of the dual vector space when a *contra_index* is passed.

2.3 Higher Order Tensors

To write expressions using tensor components, we use the symbol, `tensor_selector`. The `tensor_selector` symbol returns a scalar and takes three arguments:

- 1) a tensor;
- 2) a tuple of `contra_index` and `covar_index` symbols, and, finally;
- 3) a frame, an ordered set of basis vectors.

The sum total of indexes used, both `contra_index`'s and `covar_index`'s, must be the same as the order of the tensor. The contravariant and covariant indexes, taken together, are totally ordered, and refer to a matrix of tensor components, which are assumed to be in 'row-major' order, regardless of whether the indexes are `contra_index`'s or `covar_index`'s. By use of the term row-major order, we do not attribute any special meaning to whether an index is considered a row index or a column index, rather we merely mean that for the serial traversal of an arbitrarily dimensioned array used to store an indexed quantity, the rightmost index varies fastest. The assumption of this convention allows the unambiguous assignment of indexed matrix component values to indexed tensor components.

The scalar returned by `tensor_selector` is the tensor component. For example, the contravariant components of a vector are identified by applying `tensor_selector` to the vector and a `contra_index`. Components of higher order tensors are identified by use of multiple `contra_index` and `covar_index` symbols. The final argument, the frame, is necessary when one needs to specify a tensor expression that is dependent on the basis or on multiple bases, as in a transformation expression. As tensor formulas are commonly made without regard to basis, often no basis is required, and so any single, consistent basis is sufficient in this case, such as Cartesian. It is also suggested that a special value, called "unspecified", might be used.

A general tensor is usually indicated with a capital letter. Its coordinates may be represented using a sequence of `contra_index` and / or `covar_index` symbols. The tensor itself may be represented by taking the product

$$\mathbf{T} = \sum_{ij} T^{ij} \mathbf{g}_i \mathbf{g}_j.$$

The Einstein summation convention is normally implicitly applied to the product of two tensors whose components are represented with matching contravariant and covariant indexes. In content markup this summation should be explicit since there is otherwise no content markup to indicate the fact that these indexes are bound variables.

Finally, we define a couple more symbols for specific tensor and vector quantities. First, there is the *metric_tensor* which defines the geometric features of the vector space, such as length. Its components are represented as g_{ij} , a symmetric, non-degenerate, covariant, bilinear form defined by $(ds)^2 = g_{ij} dx'^i dx'^j$, where ds is the differential length element and dx'^i are the differential changes in spatial coordinates. This is a generalization of the simple Euclidean metric given by the scalar product. Covariant components and contravariant components of a vector, or row and column representations of a vector, are related by $v_i = \sum_j g_{ij} v^j$ and squared length, or squared norm, of a vector is $|\mathbf{v}|^2 = \sum_{ij} g_{ij} v^i v^j = \sum_j v_j v^j$.

Lastly, we define the *Levi-Civita* symbol, the so-called permutation tensor. It takes one argument, the dimension of the space. Its components may be indexed with the `contra_index` and `/` or `covar_index` symbols.

2.4 Conclusion

We have introduced a number of OpenMath symbols for the expression of tensor formulas. They are `tuple`, `tuple_selector`, `Cartesian`, `unit_Cartesian`, `Kronecker_tensor`, `basis_selector`, `tensor_selector`, `contra_index`, `covar_index`, `metric_tensor`, and `Levi-Civita`. Using the `tuple`, `tuple_selector`, `Cartesian`, and `unit_Cartesian` symbols we can build finite dimensioned Cartesian frames and define differentiable coordinate transformations to define other frames. Using `Kronecker_tensor`, `basis_selector`, `tensor_selector`, `contra_index`, and `covar_index`, we can define tensor spaces on those frames, assign values to tensor components, and write tensor formulas. The formulas may be within a single frame or between frames. Finally, with the metric tensor we can specify non-Euclidean metrics and using the `Levi-Civita` symbol we can express vector cross products and the curl operation in vector component form. These symbols are being submitted as a content dictionary named `tensor1` to the online OpenMath repository.

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