

Tensor Bible

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Introduction

before, big picture, what is a tensor, algebraic object describing multilinear relationship between algebraic objects [1]

Chapter 1

Vectors

Ironically enough, this was the hardest section to write. It is easy to get lost in abstraction and pedantics.

I think that the best way to start is with vectors. Tensors are always defined relative to some kind of vector space. Scalars are so-called zeroth-order tensors, vectors are so-called first-order tensors, and any other kind of tensor can be constructed from these.

1.1 Vector Space

examples of vector spaces

1.2 Dual Space

1.2.1 Isometric Isomorphism

Riesz representation and dealing with complex vector spaces

1.3 Inner Product and Norm

norm is also a metric

1.4 Vector Spaces in Continuum Mechanics

construction of euclidean geometry but don't get to lost

R^n is a Euclidean geometry, also cartesian coordinates

note on how velocity

also fields which are functions

1.5 Getting Started

For all intents and purposes of continuum mechanics, it is sufficient to start with a Euclidean space, usually two- or three-dimensional, described by a Cartesian coordinate system, because this can be used to describe the physical world at our scale quite well.

1.5.1 Notation

Scalars are simply written as a letter, usually lower-case (a). Vectors are bolded (\mathbf{a}). When hand-written, they may have an arrow on top (\vec{a}) or a single underline (\underline{a}). Unit vectors, with a magnitude 1, may be

marked with a circumflex ($\hat{\mathbf{a}}$). Higher-order tensors are bolded and usually upper-case (\mathbf{A}). When written, they may have a number of underlines equal to their order.

1.6 Bases and Components

We start with some right-handed orthonormal basis $\{\hat{\mathbf{e}}_i\}_{i=1}^n$ for an n -dimensional Euclidean vector space \mathbb{R}^n . If these align with a Cartesian coordinate frame, or when a Cartesian coordinate frame is defined to line up with them, they're called the canonical basis, i.e. the standard one. Using the geometric definitions for the dot and cross product, the following relations exist between the basis vectors, represented in shorthand by the Kronecker delta δ and Levi-Civita symbol ϵ .

These products are both bilinear. The dot product commutes, and the cross product anti-commutes.

$$\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_j = \delta_{ij} := \begin{cases} 1, & i = j, \\ 0, & i \neq j. \end{cases} \quad (1.1)$$

$$(\hat{\mathbf{e}}_i \times \hat{\mathbf{e}}_j) \cdot \hat{\mathbf{e}}_k = \epsilon_{ijk} := \begin{cases} 1, & (i, j, k) = (1, 2, 3), (2, 3, 1), \text{ or } (3, 1, 2), \\ -1, & (i, j, k) = (3, 2, 1), (2, 1, 3), \text{ or } (1, 3, 2), \\ 0, & \text{otherwise.} \end{cases} \quad (1.2)$$

Since any basis set is linearly independent and spans the vector space, any vector in the space may be represented in terms of such a basis. The coefficients of the linear combination are called components. It is important to note that these are not the same as coordinates, especially for non-Cartesian coordinate systems.

$$\mathbf{a} = \sum_{i=1}^n a_i \hat{\mathbf{e}}_i \quad (1.3)$$

1.6.1 Cobasis

If the chosen basis is not orthonormal with respect to some inner product and corresponding induced norm, then there is some more nuance. Sidestepping the excess mental infrastructure of the dual space and Riesz representation, the cobasis of some basis $\{\mathbf{f}_i\}_{i=1}^n$, marked with a superscript as $\{\mathbf{f}^i\}_{i=1}^n$, is another basis for the same space, which is bi-orthonormal to the basis.

$$\mathbf{f}^i \cdot \mathbf{f}_j = \mathbf{f}_j \cdot \mathbf{f}^i = \delta_{ij} \quad (1.4)$$

Notation for components in a non-orthonormal basis is more complicated. The contravariant components of the basis use superscripts, and the covariant components of the cobasis use subscripts. This may seem backwards, but this is the convention that was developed.

$$\mathbf{a} = \sum_{i=1}^n \tilde{a}^i \mathbf{f}_i \quad (1.5)$$

$$\mathbf{a} = \sum_{i=1}^n \tilde{a}_i \mathbf{f}^i \quad (1.6)$$

Contra in contravariant refers to how the components scale inversely with the basis vectors. For example, if a basis is changed from inches to feet, the components used to represent a vector will shrink to represent the same length. On the other hand, the covariant components would increase.

If one goes further into the weeds of tensor-world, there is a whole shorthand system of upstairs and downstairs indices used for tensors defined by a certain combination of bases and cobases. However, in continuum-world, one can fudge over all of these nuances by choosing to use an orthonormal basis, which is conveniently its own cobasis.

1.6.2 Independence of Basis

That freedom of choice is an important idea behind this tensor system. Up until this point, you were probably used to seeing vectors and matrices as lists and tables of numbers. Start with a unit vector $(1, 0)$. Rotate the coordinate frame 45 degrees clockwise and you get $(\sqrt{2}/2, \sqrt{2}/2)$. This would seem like a new and unequal vector, since $(1, 0) \neq (\sqrt{2}/2, \sqrt{2}/2)$.

Writing them in terms of components of particular bases allows for more abstraction and flexibility. The vector is no longer the tuple per se, but is represented by a tuple in the context of a particular reference frame. The vector and the physical quantity it represents stay the same conceptually, regardless of the frame of reference: $\mathbf{a} = \sum_{i=1}^n a_i \hat{\mathbf{e}}_i = \sum_{i=1}^n \tilde{a}^i \mathbf{f}_i = \sum_{i=1}^n \tilde{a}_i \mathbf{f}^i$. Only components vary. So we can say for the prior example, labeling the coordinate frames as A and B, $(1, 0)_A = (\sqrt{2}/2, \sqrt{2}/2)_B$. Operations and properties like an inner product, cross product, norm should stay the same, too. However, it may not necessarily be that $\mathbf{a} \cdot \mathbf{b} = \sum_{i=1}^n \tilde{a}^i \tilde{b}^i$, because the dot product is defined geometrically, not algebraically.

1.6.3 Computing Components

differentiate coordinates and components

1.6.4 Curvilinear Coordinates

same vector using different coordinates

1.7 Kronecker Delta and Levi-Civita Symbol Identities

The Kronecker Delta and Levi-Civita Symbol have the following identities which are useful in proof.

$$a = b \quad \text{Proof ?? (1.7)}$$

$$a = b \quad \text{Proof ?? (1.8)}$$

$$\epsilon_{pqs}\epsilon_{nrs} = \delta_{pn}\delta_{qr} - \delta_{pr}\delta_{qn} \quad \text{Proof ?? (1.9)}$$

$$\epsilon_{pqs}\epsilon_{rqs} = 2\delta_{pr} \quad \text{Proof ?? (1.10)}$$

1.8 Einstein Notation

Chapter 2

Tensor Algebra

aaa

2.1 Dyads and Dyadics

tensor product spaces
order and covector-vector degree

2.2 Contractions

2.3 Equivalence to Linear Algebra

isomorphic to linear algebra if appropriate combination of basis/cobasis
linearity
coordinate vs non coordinate basis
components
deltas and epsilons, symbols, only up to rank 2, etc
einstein notation
tensor as operator
basis independence
isomorphism
definitions contrived to fulfill certain properties
using dyadic symbol and not
defining property of dyadic, compare to linear algebra
simple properties of each product (distributive, associative, commutative) that may depend on the operands
linear algebra comparison
computing in canonical basis
introducing the dot product
introducing the cross product
introducing the dyadic product
specifically takes two vectors
non commutative
scalar rule
simple contractions
double contractions
change of basis
invariants of vectors and tensors
symmetric, skew-symmetric

complex numbers

operations between tensors (to fit with vectors)

- $\phi, \kappa \in \mathbb{R}$
- $\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d} \in \mathbb{R}^n$
- $\mathbf{x}, \mathbf{y} \in \mathbb{R}^m$
- $\boldsymbol{\omega} \in \mathbb{R}^p$
- $\mathbf{u}, \mathbf{v}, \mathbf{w} \in \mathbb{R}^3$
- $\mathbf{Q}, \mathbf{R} \in \mathbb{R}^{m \times m}$
- $\mathbf{S}, \mathbf{T} \in \mathbb{R}^{m \times n}$
- $\mathbf{U} \in \mathbb{R}^{n \times p}$
- $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{3 \times 3}$

INTRODUCING VECTORS

$$\mathbf{S} = \sum_{i=1}^m \sum_{j=1}^n S_{ij} \hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_j \quad (2.1)$$

$$\mathbf{u} \times \mathbf{v} = \sum_{i=1}^3 \sum_{j=1}^3 \sum_{k=1}^3 u_i v_j \epsilon_{ijk} \hat{\mathbf{e}}_k \quad (2.2)$$

(2.3)

INTRODUCING TENSORS

$$(\mathbf{a} \otimes \mathbf{x}) \mathbf{y} := \mathbf{a} (\mathbf{x} \cdot \mathbf{y}) \quad (2.4)$$

$$\mathbf{a} \cdot (\mathbf{b} \otimes \mathbf{x}) := (\mathbf{a} \cdot \mathbf{b}) \mathbf{x} \quad (2.5)$$

$$\mathbf{x} \cdot (\mathbf{y} \otimes \mathbf{a}) \mathbf{b} = \dots \quad \text{Proof ??} \quad (2.6)$$

$$(\mathbf{a} \otimes \mathbf{x})^T := \mathbf{x} \otimes \mathbf{a} \quad (2.7)$$

$$\text{tr}(\mathbf{a} \otimes \mathbf{b}) := \mathbf{a} \cdot \mathbf{b} \quad (2.8)$$

$$(\mathbf{a} \otimes \mathbf{x})(\mathbf{y} \otimes \boldsymbol{\omega}) = (\mathbf{x} \cdot \mathbf{y})(\mathbf{a} \otimes \boldsymbol{\omega}) \quad \text{Proof ??} \quad (2.9)$$

$$(\mathbf{a} \otimes \mathbf{x}) : (\mathbf{b} \otimes \mathbf{y}) := (\mathbf{a} \cdot \mathbf{b})(\mathbf{x} \cdot \mathbf{y}) \quad (2.10)$$

$$\mathbf{a} \otimes \mathbf{x} = \sum_{i=1}^n \sum_{j=1}^m a_i x_j \hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_j \quad (2.11)$$

(2.12)

CONTRACTIONS

$$\mathbf{a} \cdot \mathbf{b} = \sum_{i=1}^n a_i b_i \quad \text{Proof A.1 (2.13)}$$

$$\mathbf{S}\mathbf{a} = \mathbf{S} \cdot \mathbf{a} = \sum_{i=1}^m \sum_{j=1}^n S_{ij} a_j \hat{\mathbf{e}}_i \quad \text{Proof A.2 (2.14)}$$

$$\mathbf{x} \cdot \mathbf{S} = \sum_{i=1}^m \sum_{k=1}^n x_i S_{ik} \hat{\mathbf{e}}_k \quad \text{Proof A.3 (2.15)}$$

$$\mathbf{S}\mathbf{U} = \sum_{i=1}^m \sum_{j=1}^n \sum_{\ell=1}^p S_{ij} U_{j\ell} (\hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_\ell) \quad \text{Proof A.4 (2.16)}$$

$$\mathbf{S} : \mathbf{T} = \sum_{i=1}^m \sum_{j=1}^n S_{ij} T_{ij} \quad \text{Proof A.5 (2.17)}$$

2.4 Miscellaneous Operations

2.4.1 Change of Basis

2.5 Helpful Identities

$$\mathbf{S}\mathbf{a} = \mathbf{a} \cdot (\mathbf{S}^T) \quad \text{Proof ?? (2.18)}$$

$$(\mathbf{x} \cdot \mathbf{S}) \cdot \mathbf{a} = \mathbf{x} \cdot (\mathbf{S}\mathbf{a}) \quad \text{Proof ?? (2.19)}$$

$$(\mathbf{S}^T) : \mathbf{V} = \mathbf{S} : (\mathbf{V}^T) \quad \text{Proof ?? (2.20)}$$

Chapter 3

Tensor Calculus

differentiate nabla and grad

in different coordinate systems

expand to field...define operations...basis changes locally

algebraic and geometric definitions which conveniently coincide for a euclidean geometry described by a cartesian coordinate system

INTRODUCING NABLA OPERATOR

3.1 Introducing Nabla

$$\nabla := \sum_{i=1}^m \frac{\partial}{\partial x_i} \hat{\mathbf{e}}_i \quad (3.1)$$

$$\nabla[\dots] = \nabla \otimes [\dots] := \sum_{i=1}^m \frac{\partial}{\partial x_i} [\hat{\mathbf{e}}_i \otimes \dots] \quad (3.2)$$

$$\nabla \cdot [\dots] := \sum_{i=1}^m \frac{\partial}{\partial x_i} [\hat{\mathbf{e}}_i \cdot \dots] \quad (3.3)$$

$$\nabla \times [\dots] := \sum_{i=1}^m \frac{\partial}{\partial x_i} [\hat{\mathbf{e}}_i \times \dots] \quad (3.4)$$

3.2 Gradient

$$\nabla \phi = \dots \quad \text{Proof ?? (3.5)}$$

$$\nabla \mathbf{a} = \dots \quad \text{Proof ?? (3.6)}$$

$$\nabla \mathbf{S} = \dots \quad \text{Proof ?? (3.7)}$$

$$\text{grad } \phi = \dots \quad (3.8)$$

$$\text{grad } \mathbf{a} = \dots \quad (3.9)$$

$$\text{grad } \mathbf{S} = \dots \quad (3.10)$$

$$(3.11)$$

3.2.1 Gradient Product Rules

First Order Value, Zeroth Order Operand

$$\nabla(\phi\kappa) = \phi\nabla\kappa + \kappa\nabla\phi \quad \text{Proof ?? (3.12)}$$

$$\nabla(a \cdot b) = (\nabla b)a + (\nabla a)b *** \quad \text{Proof ?? (3.13)}$$

$$\nabla(S : T) = (\nabla T) : S + (\nabla S) : T \quad \text{Proof ?? (3.14)}$$

Second Order Value, First Order Operand

$$\nabla(\phi a) = \dots \quad \text{Proof ?? (3.15)}$$

$$\nabla(Sa) = \dots \quad \text{Proof ?? (3.16)}$$

$$\nabla(y \cdot S) = \dots \quad \text{Proof ?? (3.17)}$$

$$\nabla(D : S) = \dots \quad \text{Proof ?? (3.18)}$$

$$\nabla(S : D) = \dots \quad \text{Proof ?? (3.19)}$$

$$\nabla(u \times v) = \dots \quad \text{Proof ?? (3.20)}$$

Third Order Value, Second Order Operand

$$\nabla(\phi S) = \dots \quad \text{Proof ?? (3.21)}$$

$$\nabla(a \otimes y) = \dots \quad \text{Proof ?? (3.22)}$$

$$\nabla(SU) = \dots \quad \text{Proof ?? (3.23)}$$

$$\nabla(D \cdot a) = \dots \quad \text{Proof ?? (3.24)}$$

$$\nabla(y \cdot D) = \dots \quad \text{Proof ?? (3.25)}$$

3.3 Divergence

$$\nabla \cdot a = \dots \quad \text{Proof ?? (3.26)}$$

$$\nabla \cdot S = \dots \quad \text{Proof ?? (3.27)}$$

$$\operatorname{div} a = \dots \quad \text{Proof ?? (3.28)}$$

$$\operatorname{div} S = \dots \quad \text{Proof ?? (3.29)}$$

3.3.1 Divergence Product Rules

Zeroth Order Value, First Order Operand

$$\nabla \cdot (\phi a) = \phi \nabla \cdot a + a \cdot \nabla \phi \quad \text{Proof A.6 (3.30)}$$

$$\nabla \cdot (Sa) = S : \nabla a + a \cdot (\nabla \cdot S) \quad \text{Proof ?? (3.31)}$$

$$\nabla \cdot (y \cdot S) = (S^T) : \nabla y + y \cdot (\nabla \cdot (S^T)) \quad \text{Proof ?? (3.32)}$$

$$\nabla \cdot (u \times v) = \dots \quad \text{Proof ?? (3.33)}$$

First Order Value, Second Order Operand

$$\nabla \cdot (\phi S) = \phi \nabla \cdot S + \nabla \phi \cdot S \quad \text{Proof A.7 (3.34)}$$

$$\nabla \cdot (a \otimes y) = a \cdot \nabla y + y \cdot (\nabla \cdot a) \quad \text{Proof ?? (3.35)}$$

$$\nabla \cdot (SU) = S : (\nabla U) + (\nabla \cdot S) U \quad \text{Proof ?? (3.36)}$$

3.4 Curl

$\nabla \times \mathbf{a} = \dots$	Proof ?? (3.37)
$\nabla \times \mathbf{S} = \dots$	Proof ?? (3.38)
$\text{curl } \mathbf{a} = \dots$	(3.39)
$\text{curl } \mathbf{S} = \dots$	(3.40)

3.4.1 Curl Product Rules

First Order Value, First Order Operand

3.5 Laplacian

3.5.1 Laplacian Product Rules

Zeroth Order Value, Zeroth Order Operand

$\nabla^2 (\phi\kappa) = \dots$	Proof ?? (3.41)
$\nabla^2 (\mathbf{a} \cdot \mathbf{b}) = \dots$	Proof ?? (3.42)
$\nabla^2 (\mathbf{S} : \mathbf{T}) = \dots$	Proof ?? (3.43)

First Order Value, First Order Operand

$\nabla^2 (\phi\mathbf{a}) = \dots$	Proof ?? (3.44)
$\nabla^2 (\mathbf{S}\mathbf{a}) = \dots$	Proof ?? (3.45)
$\nabla^2 (\mathbf{y} \cdot \mathbf{S}) = \dots$	Proof ?? (3.46)
$\nabla^2 (\mathbf{u} \times \mathbf{v}) = \dots$	Proof ?? (3.47)

Second Order Value, Second Order Operand

$\nabla^2 (\phi\mathbf{S}) = \dots$	Proof ?? (3.48)
$\nabla^2 (\mathbf{a} \otimes \mathbf{y}) = \dots$	Proof ?? (3.49)
$\nabla^2 (\mathbf{S}\mathbf{U}) = \dots$	Proof ?? (3.50)

3.6 Other Second Derivatives

div of curl = 0
curl of grad = 0

3.7 Function Derivatives

derivative of vector value/input functions
compositions thereof
derivative of determinant, etc
grad div relation

Chapter 4

Kinematics

Topics:

- different frames
- deformation map
- all the different kinds of tensors
- material and spatial fields
- derivatives of material and spatial fields

Chapter 5

Conservation Laws

Topics:

continuum assumptions

general conservation laws: integral and differential, material and spatial
mass

momentum

energy

entropy inequality

5.1 Conservation of Mass

5.1.1 Material Frame

$$\rho_0 = \rho \circ \phi_t J$$

Proof ?? (5.1)

5.1.2 Spatial Frame

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0$$

Proof ?? (5.2)

5.2 Conservation of Momentum

5.2.1 Material Frame

5.2.2 Spatial Frame

5.3 Conservation of Energy

5.3.1 Material Frame

5.3.2 Spatial Frame

5.4 Combined Equations

5.4.1 Material Frame

$$\begin{aligned}
 \rho_0 &= \rho \circ \phi_t J && \text{Proof ?? (5.3)} \\
 \rho_0 \frac{dV}{dt} &= \operatorname{div}_{\mathbf{x}} \mathbf{P} + \rho_0 \mathbf{B} && \text{Proof ?? (5.4)} \\
 \mathbf{S} &= \mathbf{S}^T && \text{Proof ?? (5.5)} \\
 \rho_0 \frac{dI}{dt} + \operatorname{div}_{\mathbf{x}} \mathbf{Q} &= \rho_0 \mathbf{R} + \mathbf{S} : \mathbf{D} && \text{Proof ?? (5.6)} \\
 \rho_0 \frac{dN}{dt} + \operatorname{div}_{\mathbf{x}} \frac{\mathbf{Q}}{\Theta} &\geq \rho_0 \frac{R}{\Theta} && \text{Proof ?? (5.7)}
 \end{aligned}$$

5.4.2 Spatial Frame

$$\begin{aligned}
 a &= b && \text{Proof ?? (5.8)} \\
 \frac{\partial(\rho \mathbf{v})}{\partial t} + \operatorname{div}(\rho \mathbf{v} \otimes \mathbf{v}) &= \operatorname{div} \boldsymbol{\sigma} + \rho \mathbf{b} && \text{Proof ?? (5.9)} \\
 \boldsymbol{\sigma} &= \boldsymbol{\sigma}^T && \text{Proof ?? (5.10)} \\
 \frac{\partial(\rho e)}{\partial t} + \operatorname{div}(\rho e \mathbf{v}) &= \operatorname{div}(\boldsymbol{\sigma} \mathbf{v}) + \rho r + \rho \mathbf{b} \cdot \mathbf{b} - \operatorname{div} \mathbf{q} && \text{Proof ?? (5.11)} \\
 \frac{\partial(\rho \eta)}{\partial t} + \operatorname{div}(\rho \eta \mathbf{v}) + \operatorname{div} \frac{\mathbf{q}}{\Theta} - \rho r &\geq 0 && \text{Proof ?? (5.12)} \\
 &&& (5.13)
 \end{aligned}$$

5.5 Advection Diffusion Reaction Equation

$$\begin{aligned}
 \frac{\partial c}{\partial t} + \nabla \cdot (\mathbf{v}c - \mathbf{D} \nabla c) &= R && \text{Proof ?? (5.14)} \\
 \frac{\partial \mathbf{c}}{\partial t} + \nabla \cdot (\mathbf{v} \otimes \mathbf{c} - \mathcal{D} : \nabla \mathbf{c}) &= R && \text{Proof ?? (5.15)}
 \end{aligned}$$

Chapter 6

Solid Mechanics

general
elastic waves

6.1 Elastic Wave Equations

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} - \operatorname{div} \boldsymbol{\sigma} = 0 \quad \text{Proof ?? (6.1)}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} = (\lambda + 2\mu) \operatorname{grad}(\operatorname{div} \mathbf{u}) - \mu \operatorname{curl}^2 \mathbf{u} \quad \text{hm (6.2)}$$

(6.3)

Chapter 7

Fluid Mechanics

full navier stokes
incompressible
rans
stokes flow
euler equations
acoustic equations
my special acoustic equations
shallow water equations

7.1 Shallow Water Equations

conservative, non-conservative,

$$\frac{\partial(\rho\eta)}{\partial t} + \operatorname{div}(\rho\eta\mathbf{u}) = 0 \quad \text{Proof ?? (7.1)}$$

$$\frac{\partial(\rho\eta\mathbf{u})}{\partial t} + \operatorname{div}\left(\rho\eta\mathbf{u} \otimes \mathbf{u} + \frac{1}{2}\rho g\eta^2 \mathbf{I}\right) = 0 \quad \text{Proof ?? (7.2)}$$

$$\frac{\partial(\rho\eta)}{\partial t} + \nabla \cdot (\rho\eta\mathbf{u}) = 0 \quad \text{Proof ?? (7.3)}$$

$$\frac{\partial(\rho\eta\mathbf{u})}{\partial t} + \nabla \cdot (\rho\eta\mathbf{u} \otimes \mathbf{u}) + \nabla \frac{1}{2}\rho g\eta^2 = 0 \quad \text{Proof ?? (7.4)}$$

7.1.1 Closures and Assumptions

diffusive wave equations
bernoulli
groundwater darcy flow

Appendix A

Proofs

Proof A.1 (Equation 2.13)

$$\begin{aligned}
 \mathbf{a} \cdot \mathbf{b} &= \left(\sum_{i=1}^n a_i \hat{\mathbf{e}}_i \right) \cdot \left(\sum_{j=1}^n b_j \hat{\mathbf{e}}_j \right) \\
 &= \sum_{i=1}^n \sum_{j=1}^n a_i b_j \hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_j \\
 &= \sum_{i=1}^n a_i b_i
 \end{aligned}
 \tag{A.2}$$

Using 1.3 (A.1)

Using 1.1 (A.3)

Proof A.2 (Equation 2.14)

$$\begin{aligned}
 \mathbf{S}\mathbf{a} &= \left(\sum_{i=1}^m \sum_{j=1}^n S_{ij} \hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_j \right) \left(\sum_{k=1}^n a_k \hat{\mathbf{e}}_k \right) \\
 &= \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^n S_{ij} a_k (\hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_j) \hat{\mathbf{e}}_k \\
 &= \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^n S_{ij} a_k \hat{\mathbf{e}}_i (\hat{\mathbf{e}}_j \cdot \hat{\mathbf{e}}_k) \\
 &= \sum_{i=1}^m \sum_{j=1}^n S_{ij} a_j \hat{\mathbf{e}}_i
 \end{aligned}$$

Using 2.1, 1.3 (A.4)

Using 2.4 (A.6)

Using 1.1 (A.7)

Proof A.3 (Equation 2.15)

$$\begin{aligned}
 \mathbf{x} \cdot \mathbf{S} &= \left(\sum_{i=1}^n x_i \hat{\mathbf{e}}_i \right) \cdot \left(\sum_{j=1}^m \sum_{k=1}^n S_{jk} \hat{\mathbf{e}}_j \otimes \hat{\mathbf{e}}_k \right) \\
 &= \sum_{i=1}^n \sum_{j=1}^m \sum_{k=1}^n x_i S_{jk} \hat{\mathbf{e}}_i \cdot (\hat{\mathbf{e}}_j \otimes \hat{\mathbf{e}}_k) \\
 &= \sum_{i=1}^n \sum_{j=1}^m \sum_{k=1}^n x_i S_{jk} (\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_j) \hat{\mathbf{e}}_k \\
 &= \sum_{i=1}^n \sum_{k=1}^n x_i S_{ik} \hat{\mathbf{e}}_k
 \end{aligned}$$

Using 1.3, 2.1 (A.8)

Using 2.5 (A.10)

Using 1.1 (A.11)

Proof A.4 (Equation 2.16)

$$\mathbf{S}\mathbf{U} = \left(\sum_{i=1}^m \sum_{j=1}^n S_{ij} \hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_j \right) \left(\sum_{k=1}^n \sum_{\ell=1}^p U_{k\ell} \hat{\mathbf{e}}_k \otimes \hat{\mathbf{e}}_\ell \right) \quad \text{Using 2.1 (A.12)}$$

$$= \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^n \sum_{\ell=1}^p S_{ij} U_{k\ell} (\hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_j) (\hat{\mathbf{e}}_k \otimes \hat{\mathbf{e}}_\ell) \quad (\text{A.13})$$

$$= \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^n \sum_{\ell=1}^p S_{ij} U_{k\ell} (\hat{\mathbf{e}}_j \cdot \hat{\mathbf{e}}_k) (\hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_\ell) \quad \text{Using 2.9 (A.14)}$$

$$= \sum_{i=1}^m \sum_{j=1}^n \sum_{\ell=1}^p S_{ij} U_{j\ell} (\hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_\ell) \quad \text{Using 1.1 (A.15)}$$

Proof A.5 (Equation 2.17)

$$\mathbf{S} : \mathbf{T} = \left(\sum_{i=1}^m \sum_{j=1}^n S_{ij} \hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_j \right) : \left(\sum_{k=1}^n \sum_{\ell=1}^m T_{k\ell} \hat{\mathbf{e}}_k \otimes \hat{\mathbf{e}}_\ell \right) \quad \text{Using 2.1 (A.16)}$$

$$= \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^n \sum_{\ell=1}^m S_{ij} T_{k\ell} (\hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_j) : (\hat{\mathbf{e}}_k \otimes \hat{\mathbf{e}}_\ell) \quad (\text{A.17})$$

$$= \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^n \sum_{\ell=1}^n S_{ij} T_{k\ell} (\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_k) (\hat{\mathbf{e}}_j \cdot \hat{\mathbf{e}}_\ell) \quad \text{Using 2.10 (A.18)}$$

$$= \sum_{i=1}^m \sum_{j=1}^n S_{ij} T_{ij} \quad \text{Using 1.1 (A.19)}$$

(A.20)

Proof A.6 (Equation 3.30)

$$\boldsymbol{\nabla} \cdot (\phi \mathbf{a}) = \sum_{i=1}^n \frac{\partial}{\partial x_i} \left[\hat{\mathbf{e}}_i \cdot \left(\phi \sum_{j=1}^n a_j \hat{\mathbf{e}}_j \right) \right] \quad \text{Using 3.3, 1.3 (A.21)}$$

$$= \sum_{i=1}^n \sum_{j=1}^n \frac{\partial \phi a_j}{\partial x_i} (\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_j) \quad (\text{A.22})$$

$$= \sum_{i=1}^n \frac{\partial \phi a_i}{\partial x_i} \quad \text{Using 1.1 (A.23)}$$

$$= \sum_{i=1}^n \left(\phi \frac{\partial a_i}{\partial x_i} + a_i \frac{\partial \phi}{\partial x_i} \right) \quad (\text{A.24})$$

$$= \phi \boldsymbol{\nabla} \cdot \mathbf{a} + \mathbf{a} \cdot \boldsymbol{\nabla} \phi \quad \text{Using 3.26, 2.13, 3.5 (A.25)}$$

Proof A.7 (Equation 3.34)

$$\nabla \cdot (\phi \mathbf{S}) = \left(\sum_{i=1}^m \hat{\mathbf{e}}_i \frac{\partial}{\partial x_i} \right) \cdot \left(\phi \sum_{j=1}^m \sum_{k=1}^n S_{jk} \hat{\mathbf{e}}_j \otimes \hat{\mathbf{e}}_k \right) \quad \text{Using 3.3, 2.1 (A.26)}$$

$$= \sum_{i=1}^m \sum_{j=1}^m \sum_{k=1}^n \frac{\partial (\phi S_{jk})}{\partial x_i} \hat{\mathbf{e}}_i \cdot (\hat{\mathbf{e}}_j \otimes \hat{\mathbf{e}}_k) \quad (\text{A.27})$$

$$= \sum_{i=1}^m \sum_{j=1}^m \sum_{k=1}^n \left(\phi \frac{\partial S_{jk}}{\partial x_i} + S_{jk} \frac{\partial \phi}{\partial x_i} \right) (\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_j) \hat{\mathbf{e}}_k \quad \text{Using 2.5 (A.28)}$$

$$= \sum_{i=1}^m \sum_{k=1}^n \phi \frac{\partial S_{ik}}{\partial x_i} \hat{\mathbf{e}}_k + S_{ik} \frac{\partial \phi}{\partial x_i} \hat{\mathbf{e}}_k \quad \text{Using 1.1 (A.29)}$$

$$= \phi \nabla \cdot \mathbf{S} + \nabla \phi \cdot \mathbf{S} \quad \text{Using 3.27, 3.5, 2.15 (A.30)}$$

Bibliography

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