Dimensional analysis on differential manifolds [draft]

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Some notes on dimensional analysis on differential manifolds, with an eye on general relativity and the Einstein equation.
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1 ***

'Dimensional analysis remains a controversial and somewhat obscure subject. We do not attempt a complete presentation here.'[1]

There seem to be insecurity and wrong ideas among some students and even researchers in relativity, regarding the dimensions of tensors, of tensor components, and of dimensional constants in equations. I've met, for example, with the statement that the components of a tensor should all have the same dimension; and with calculations of the dimensions of curvature tensors starting from coordinates with dimensions of length. That statement is wrong, and that procedure is unnecessary.

Several factors probably cause or contribute to such difficulties. Modern texts in Lorentzian and general relativity commonly use natural units. They say that to find the dimension of some constant in a tensorial equations it's sufficient to compare the dimensions of the tensors in the equation. But this is not so immediate, because some tensors don't have universally agreed dimensions – prime example the 4-metric tensor. Older texts often use coordinates with dimension of length. They even multiply a timelike coordinate or some tensorial components by c, thus giving the impression that coordinates should always be lengths and that the components of a tensor would all have the same dimension.

In this note I want to clarify some misconceptions about dimensional analysis in differential manifolds, and to illustrate a simple way of reasoning to solve dimensional-analysis doubts and problems. This way

[1] Truesdell et al. 1960 Appendix § 7 footnote 4.

of reasoning relies on the coordinate-free, *intrinsic* view of tensors and other differential-geometrical objects.

Let's start from more general facts about dimensional analysis on differential manifolds.

For dimensional analysis I use ISO conventions and notation. I sometimes use notation such as $\boldsymbol{T}_{\boldsymbol{\cdot}}^{\ \boldsymbol{\cdot}}$ to indicate that the tensor $\boldsymbol{T}$ is covariant in its first slot and contravariant in its second; I call this a "co-contra-variant tensor".

[check[2]]

2 Intrinsic view of differential-geometric objects: brief reminder

From the intrinsic point of view, a tensor is defined by its geometric properties. For example, a vector field $\boldsymbol{v} \equiv \boldsymbol{v}(\,\cdot\,)$ is an object that operates on functions defined on the manifold, yielding new functions, with the properties $\boldsymbol{v}(af + bg) = a\boldsymbol{v}(f) + b\boldsymbol{v}(g)$ and $\boldsymbol{v}(fg) = \boldsymbol{v}(f)g + f\boldsymbol{v}(g)$ for all functions f, g and reals a, b. A covector field (1-form) $\boldsymbol{\omega}$ is an object that operates on vector fields, yielding functions ('duality'), with the property $\boldsymbol{\omega}(f\boldsymbol{u} + g\boldsymbol{v}) = f\boldsymbol{\omega}(\boldsymbol{u}) + g\boldsymbol{\omega}(\boldsymbol{v})$ for all vector fields $\boldsymbol{u}$, $\boldsymbol{v}$ and functions f, g. The sum of vector or covector fields, and their products by functions – let's call this 'linearity' – are defined in an obvious way. Tensors are constructed from these objects.

A system of coordinates (x^i) is just a set of linearly independent functions. This set gives rise to a set of vectors fields $\left(\frac{\partial}{\partial x^i}\right)$ and to a set of covector fields $(\mathrm{d}x^i)$ by the obvious requirements that $\frac{\partial}{\partial x^i}(x^j) = \delta_i^{\ j}$ and $\mathrm{d}x^i\left(\frac{\partial}{\partial x^j}\right) = \delta^i_{\ j}$. These two sets can be used as bases to express all other vectors and covectors as linear combinations. A vector field $\boldsymbol{v}$ can thus be written as

$$\boldsymbol{v} \equiv \sum_i v^i \frac{\partial}{\partial x^i} \equiv v^i \frac{\partial}{\partial x^i}, \tag{1}$$

where the *functions* $v^i := \boldsymbol{v}(x^i)$ are its components with respect to the basis $\left(\frac{\partial}{\partial x^i}\right)$. Analogously for a covector field.

For the full presentation of the intrinsic view I recommend the excellent texts by Choquet-Bruhat et al. (1996), Boothby (2003), and on the physics and general-relativity side Burke (1980 ch. 2), Bossavit (1991), Misner et al. (1973 ch. 9), Gourgoulhon (2012 ch. 2), Penrose et al. (2003 ch. 4).

2 Aldersley 1977.

3 Coordinates

From a physical point of view, a coordinate is just a function that associates a value of a physical quantity with every event in a region (the domain of the coordinate chart) of spacetime. Together with the other coordinates, such function allows us to uniquely identify every event within that region. Any physical quantity will do: the distance from something, the time elapsed since something, an angle, an energy density, the strength of a magnetic flux, a temperature, and so on. A coordinate can thus have any dimensions: length L, time T, angle 1, energy density $\mathsf{E} \coloneqq \mathsf{L}^{-1}\mathsf{M}\mathsf{T}^{-2}$, magnetic flux $\Phi \coloneqq \mathsf{L}^{2}\mathsf{M}\mathsf{T}^{-2}\mathsf{I}^{-1}$, temperature Θ, and so on.

The dimensions of the coordinates don't matter, as we'll now see.

4 Tensors

Consider a system of coordinates (x^i) with dimensions (X_i), and the ensuing sets of covector fields (1-form) $\mathrm{d}x^i$ and of vector fields $\left(\frac{\partial}{\partial x^i}\right)$, bases for the cotangent and tangent spaces. Their tensor products are bases for the tangent spaces of higher tensor types.

The differential $\mathrm{d}x^i$ traditionally has the same dimension as x^i: $\dim(\mathrm{d}x^i) = \mathsf{X}_i$, and the operator $\frac{\partial}{\partial x^i}$ traditionally has the inverse dimension: $\dim \frac{\partial}{\partial x^i} = {\mathsf{X}_i}^{-1}$. We'll see later that these conventions are self-consistent.

For our discussion let's take a concrete example: a contra-co-tensor field $\boldsymbol{A} \equiv \boldsymbol{A}^{\bullet}{}_{\bullet}$. The discussion generalizes to tensors of other types in an obvious way.

The tensor $\boldsymbol{A}$ can be expanded in terms of the basis vectors and covectors, as mentioned in § 2:

$$\boldsymbol{A} = A^i{}_j \, \frac{\partial}{\partial x^i} \otimes \mathrm{d}x^j \equiv A^0{}_0 \, \frac{\partial}{\partial x^0} \otimes \mathrm{d}x^0 + A^0{}_1 \, \frac{\partial}{\partial x^0} \otimes \mathrm{d}x^1 + \cdots. \tag{2}$$

Each function

$$A^i{}_j \coloneqq \boldsymbol{A}\Big(\mathrm{d}x^i, \frac{\partial}{\partial x^j}\Big) \tag{3}$$

is a component of the tensor in this coordinate system.

To make dimensional sense, all terms in the sum (2) must have the same dimension. This is possible only if the generic component ${A^i}_j$ has dimension

$$\dim({A^i}_j) = \mathsf{A}\,\mathsf{X}_i\,{\mathsf{X}_j}^{-1}, \tag{4}$$

where A is common to all components. Suppose for example that we're using coordinates with dimensions

$$\dim(x^0) = \Theta, \quad \dim(x^1) = \mathsf{L}, \quad \dim(x^2) = \mathsf{L}, \quad \dim(x^3) = \mathsf{L}^{-1}\mathsf{M}\mathsf{T}^{-2}; \tag{5}$$

then the components of $\boldsymbol{A}$ have dimensions

$$\bigl(\dim({A^i}_j)\bigr) = \mathsf{A}\begin{pmatrix} 1 & \mathsf{L}^{-1}\Theta & \mathsf{L}^{-1}\Theta & \mathsf{L}\mathsf{M}^{-1}\mathsf{T}^{2}\Theta \\ \mathsf{L}\Theta^{-1} & 1 & 1 & \mathsf{L}^{2}\mathsf{M}^{-1}\mathsf{T}^{2} \\ \mathsf{L}\Theta^{-1} & 1 & 1 & \mathsf{L}^{2}\mathsf{M}^{-1}\mathsf{T}^{2} \\ \mathsf{L}^{-1}\mathsf{M}\mathsf{T}^{-2}\Theta^{-1} & \mathsf{L}^{-2}\mathsf{M}\mathsf{T}^{-2} & \mathsf{L}^{-2}\mathsf{M}\mathsf{T}^{-2} & 1 \end{pmatrix}. \tag{6}$$

The dimension A, which is also the dimension of the sum (2), is called the *absolute dimension*[3] of the tensor $\boldsymbol{A}$, and we write

$$\dim(\boldsymbol{A}) = \mathsf{A}. \tag{7}$$

This is the intrinsic dimension of the tensor, independent of any coordinate system. It reflects the physical or operational[4] meaning of the tensor. We'll see an example of what this mean in § 8.

Different coordinate systems lead to different dimensions of the *components* of $\boldsymbol{A}$, but its absolute dimension remains the same. Formula (4) for the dimensions of the components is consistent under changes of coordinates. For example, in new coordinates (x'^k) with dimensions $({\mathsf{X}'}_k)$, the new components of $\boldsymbol{A}$ are

$${A'^k}_l = {A^i}_j \, \frac{\partial x'^k}{\partial x^i} \, \frac{\partial x^j}{\partial x'^l} \tag{8}$$

and a quick check shows that $\dim({A'^k}_l) = \mathsf{A}\,{\mathsf{X}'}_k\,{{\mathsf{X}'}_l}^{-1}$, consistent with the general formula (4).

In the following I'll drop the adjective 'absolute' when it's clear from the context.

[3] Dorgelo et al. 1946; Schouten 1989 ch. VI. [4] Bridgman 1958; see also Synge 1960 § A.2; Truesdell et al. 1960 §§ A.3–4.

5 Tensor operations

By the reasoning of the previous section, which simply applies standard dimensional considerations to the basis expansion (2), it's easy to find out the resultant absolute dimension of various operations on tensors and tensor fields.

The tensor product of $\boldsymbol{A}^{\bullet}{}_{\bullet}$ and $\boldsymbol{B}_{\bullet\bullet}{}^{\bullet}$, for example, can be written as the sum

$$\boldsymbol{A} \otimes \boldsymbol{B} = A^{i}{}_{j}\, B_{kl}{}^{m}\, \frac{\partial}{\partial x^{i}} \otimes \mathrm{d}x^{j} \otimes \mathrm{d}x^{k} \otimes \mathrm{d}x^{l} \otimes \frac{\partial}{\partial x^{m}} \tag{9}$$

from which it follows that

$$\dim(A^{i}{}_{j}\, B_{kl}{}^{m}) = \mathsf{A}\,\mathsf{B}\; \mathsf{X}_{i}\, \mathsf{X}_{j}{}^{-1}\, \mathsf{X}_{k}{}^{-1}\, \mathsf{X}_{l}{}^{-1}\, \mathsf{X}_{m} \tag{10}$$

with $\mathsf{A} = \dim(\boldsymbol{A})$ and $\mathsf{B} = \dim(\boldsymbol{B})$. The absolute dimension of $\boldsymbol{A} \otimes \boldsymbol{B}$ is therefore $\mathsf{AB} \equiv \dim(\boldsymbol{A})\ \dim(\boldsymbol{B})$.

Here is then a summary of the dimensional results of the main differential-geometric operators. In brackets I give the section of Choquet-Bruhat et al. (1996) where they are defined.

- *Tensor multiplication* [III.B.5] multiplies dimensions:

$$\dim(\boldsymbol{A} \otimes \boldsymbol{B}) = \dim(\boldsymbol{A})\, \dim(\boldsymbol{B}). \tag{11}$$

- The *contraction* [III.B.5] of the ith and jth slots (one covariant and one contravariant) of a tensor has the same dimension as the tensor:

$$\dim(\mathrm{tr}_{ij}\, \boldsymbol{A}) = \dim(\boldsymbol{A}). \tag{12}$$

Note that this only holds *without* raising or lowering indices.

- The *transposition* (swapping) of the ith and jth slots of a tensor has the same dimension as the tensor:

$$\dim(\boldsymbol{A}^{\intercal ij}) = \dim(\boldsymbol{A}). \tag{13}$$

- The *Lie bracket* [III.B.3] of two vectors has the product of their dimensions:

$$\dim([\boldsymbol{u}, \boldsymbol{v}]) = \dim(\boldsymbol{u})\, \dim(\boldsymbol{v}). \tag{14}$$

- The *Lie derivative* [III.C.2] of a tensor with respect to a vector field has the product of the dimensions of the tensor and of the vector:

$$\dim(\mathrm{L}_{\boldsymbol{v}} \boldsymbol{A}) = \dim(\boldsymbol{v})\, \dim(\boldsymbol{A}). \tag{15}$$

Regarding operations on differential forms:

• The *exterior product* [IV.A.1] of two differential forms multiplies their dimensions:

$$\dim(\boldsymbol{\omega} \wedge \boldsymbol{\tau}) = \dim(\boldsymbol{\omega}) \dim(\boldsymbol{\tau}). \tag{16}$$

• The *interior product* [IV.A.4] of a vector and a form multiplies their dimensions:

$$\dim(\mathrm{i}_{\boldsymbol{v}} \boldsymbol{\omega}) = \dim(\boldsymbol{v}) \dim(\boldsymbol{\omega}). \tag{17}$$

• The *exterior derivative* [IV.A.2] of a form has the same dimension of the form:

$$\dim(\mathrm{d}\boldsymbol{\omega}) = \dim(\boldsymbol{\omega}). \tag{18}$$

This can be proven using the identity $\mathrm{d}\,\mathrm{i}_{\boldsymbol{v}} + \mathrm{i}_{\boldsymbol{v}}\,\mathrm{d} = \mathrm{L}_{\boldsymbol{v}}$ or similar identities[5] together with eqs (15) and (17).

• The *integral* [IV.B.1] of a form over a submanifold has the same dimension as the form:

$$\dim\Bigl(\int_c \boldsymbol{\omega}\Bigr) = \dim(\boldsymbol{\omega}). \tag{19}$$

6 Connection, covariant derivative, curvature tensors

Consider an arbitrary connection[6] with covariant derivative ∇. For the moment we don't assume the presence of any metric structure.

The *covariant derivative* of the product $f\boldsymbol{v}$ of a function and a vector satisfies[7]

$$\nabla(f\boldsymbol{v}) = \mathrm{d}f \otimes \boldsymbol{v} + f\nabla\boldsymbol{v}. \tag{20}$$

The first summand, from formulae (18) and (11), has dimension $\dim(f)\dim(\boldsymbol{v})$; for dimensional consistency this must also be the dimension of the second summand. Thus

$$\dim(\nabla\boldsymbol{v}) = \dim(\boldsymbol{v}). \tag{21}$$

It follows that the *directional covariant derivative* has dimension

$$\dim(\nabla_{\boldsymbol{u}}\boldsymbol{v}) = \dim(\boldsymbol{u}) \dim(\boldsymbol{v}), \tag{22}$$

and by its derivation properties[8] we see that formula (21) extends from vectors to tensors of arbitrary type.

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5 Curtis et al. 1985 ch. 9 p. 180 Theorem 9.78. 6 Choquet-Bruhat et al. 1996 § V.B.
7 Choquet-Bruhat et al. 1996 § V.B.1. 8 Choquet-Bruhat et al. 1996 § V.B.1 p. 303.

In the coordinate system (x^i), the action of the covariant derivative is carried by the *connection coefficients* or Christoffel symbols $(\Gamma^i_{\ jk})$ defined by

$$\nabla \frac{\partial}{\partial x^k} = \Gamma^i_{\ jk}\ \mathrm{d}x^j \otimes \frac{\partial}{\partial x^i}. \tag{23}$$

From this equation and the previous ones it follows that these coefficients have dimensions

$$\dim(\Gamma^i_{\ jk}) = \mathsf{X}_i\,\mathsf{X}_j^{\ -1}\,\mathsf{X}_k^{\ -1}. \tag{24}$$

The *torsion* $\boldsymbol{T}^{\bullet}{}_{\bullet\bullet}$, *Riemann curvature* $\boldsymbol{R}^{\bullet}{}_{\bullet\bullet\bullet}$, and *Ricci curvature* $\boldsymbol{R}_{\bullet\bullet}$ tensors are defined by[9]

$$\boldsymbol{T}(\boldsymbol{u},\boldsymbol{v}) \coloneqq \nabla_{\boldsymbol{u}}\boldsymbol{v} - \nabla_{\boldsymbol{v}}\boldsymbol{u} - [\boldsymbol{u},\boldsymbol{v}], \tag{25}$$

$$\boldsymbol{R}(\boldsymbol{u},\boldsymbol{v})\boldsymbol{w} \coloneqq \nabla_{\boldsymbol{u}}\nabla_{\boldsymbol{v}}\boldsymbol{w} - \nabla_{\boldsymbol{v}}\nabla_{\boldsymbol{u}}\boldsymbol{w} - \nabla_{[\boldsymbol{u},\boldsymbol{v}]}\boldsymbol{w}, \tag{26}$$

$$\boldsymbol{R}_{\bullet\bullet} \coloneqq \mathrm{tr}_{13}\,\boldsymbol{R}^{\bullet}{}_{\bullet\bullet\bullet}. \tag{27}$$

From these definitions, formula (21), and the dimensional properties of tensor product (11) and contraction (12) we see that

$$\dim(\boldsymbol{T}^{\bullet}{}_{\bullet\bullet}) = \dim(\boldsymbol{R}^{\bullet}{}_{\bullet\bullet\bullet}) = \dim(\boldsymbol{R}_{\bullet\bullet}) = 1. \tag{28}$$

The exact contra- and co-variant type used above for these tensors is very important in these equations. If we raise any of their indices using a metric, their dimensions will generally change.

The formulae above are also valid if a metric is defined and the connection is compatible with it. The connection coefficients in this case are defined in terms of the metric tensor, but using the results of §*** it's easy to see that eqs (21), (22), (24), (28) still hold.

7 Curves and integral curves

Consider a curve into spacetime, $c\colon s \mapsto P(s)$, with the parameter s having dimension $\dim(s) = \mathsf{S}$.

If we consider the manifold as "adimensional" (if this makes sense), then the dimensions of the tangent vector $\dot{c}$ to the curve are $\dim(\dot{c}) = [\mathsf{S}^{-1}]$. This follows either from $\dot{c} := \partial x^i[c(s)]/\partial s\ \partial_{x^i}$, or considering that $\dot{c}$ can be interpreted as the push-forward of ∂_s, that is, $c_*(\partial_s)$.

[9] Choquet-Bruhat et al. 1996 § V.B.1.

This has an interesting, quirky implication. Given a vector field $P \mapsto v(P)$ we say that c is an integral curve for it if

$$v[c(s)] = \dot{c}(s).$$

But this equation is only valid if v has dimensions $[\mathrm{S}^{-1}]$. For the general case a constant dimensional factor needs to be introduced in the equation above.

8 Metric tensor

From the above discussion we see that the component g_{ij} of the metric $\boldsymbol{g}$ has dimensions $[\mathrm{Z}\,\mathrm{X}_i\,{\mathrm{X}_j}^{-1}\,{\mathrm{X}_k}^{-1}]$, where $[\mathrm{Z}]$ are the absolute dimensions of the metric. What are these absolute dimensions?

The answer probably depends on how you see the operational meaning of the metric. Here I offer my personal point of view. We can use the metric to measure the "length" of (timelike or spacelike) paths in spacetime. The "length" of a path $c(s)$ with $s \in [a, b]$ is

$$\int_a^b \mathrm{d}s\ \sqrt{\left|g_{ij}[c(s)]\ \dot{c}^i(s)\,\dot{c}^j(s)\right|}.$$

We see that this "length" has dimensions $[\mathrm{Z}^{1/2}]$ and not unexpectedly it doesn't depend on the dimensions of the curve parameter s.

If the path is timelike, this "length" can be measured by a clock having that path as worldline – it's its proper time. Thus, for me $[\mathrm{Z}^{1/2}] = [\mathrm{T}]$, a time, and therefore the absolute dimensions of the metric tensor are time squared:

$$\dim(\boldsymbol{g}) = [\mathrm{T}^2].$$

I believe that these dimensions also make sense for spacelike paths: in this case we would have to measure the "length" by dividing it in very small pieces and using radar coordinates on each piece. So we're measuring the "length" by checking clocks, to see how long it takes for the light to bounce back: time [T], again.

By our usual argument it's possible to see that the Riemann curvature tensor $\boldsymbol{R}^{\bullet}{}_{\bullet\bullet\bullet}$, the Ricci tensor $\boldsymbol{R}_{\bullet\bullet}$, and the Einstein tensor $\boldsymbol{G}_{\bullet\bullet}$ are adimensional – [1] – and the scalar curvature has dimensions $[\mathrm{T}^{-2}]$. Note that the Riemann and Ricci tensors (with the contra/co-variant type specified above) do not require a metric for their definition, but an affine connection. They are adimensional no matter what dimensions we give the metric. By construction the (fully co-variant) Einstein tensor is always adimensional, too.

An important operation done with the metric:

- "lowering an index" of a tensor multiplies its dimensions by $[\mathrm{T}^2]$, and "rising an index" multiplies them by $[\mathrm{T}^{-2}]$ (if you agree with my discussion above).

** Stress-energy-momentum tensor **

What are the absolute dimensions of the co-contra-variant stress-energy-momentum tensor $\boldsymbol{T}_{\bullet}{}^{\bullet}$? We must look for an operational meaning here too. I'll try to sketch an informal argument that reflects my point of view. The argument can be made more rigorous but that would take too long to do here.

The dynamics equation $\nabla \cdot \boldsymbol{T} = 0$ holds in general-relativistic (thermo)mechanics, and also in Newtonian (thermo)mechanics when no body forces and no body heating are present. In Newtonian mechanics it's the formal combination of the balances of momentum density and energy density – which incidentally have the same dimensions $[\mathrm{M}\,\mathrm{L}^{-1}\,\mathrm{T}^{-3}]$, energy/(volume × time).

The divergence of the stress-energy-momentum gives us a 4-force density, just like the 3-divergence of the stress gives us a force density. Please check Misner &al (1973), chap. 14, for a very interesting discussion of these matters, and also Eckart (1940) and Burke (1980, 1987).

Further, the 4-force is an object that, integrated over a path, gives us an energy density (cf Milne 1951 chap. IV, and Burke again). The integral of a force in Newtonian mechanics is the work done by the force. In general-relativistic mechanics, the timelike component of the 4-force additionally gives us the increase in energy owing to heating (Eckart 1940).

So $\nabla \cdot \boldsymbol{T} \equiv T_i{}^j{}_{;j}\,\mathrm{d}x^i$ has the dimensions of energy density, $[\mathrm{M}\,\mathrm{L}^{-1}\mathrm{T}^{-2}]$. The *co-contra-variant* stress-energy-momentum $\boldsymbol{T}_{\bullet}{}^{\bullet}$ has therefore the same dimensions. But the *co-co-variant* tensor, obtained by contraction with the metric, $\boldsymbol{T}_{\bullet\bullet} \equiv \boldsymbol{T} \cdot \boldsymbol{g}$, has dimensions of energy density times squared time: $[\mathrm{M}\,\mathrm{L}^{-1}]$, a mass over length.

Einstein's constant κ therefore relates a dimensionless quantity and a mass over length:

$$\boldsymbol{G}_{\bullet\bullet} = \kappa \boldsymbol{T}_{\bullet\bullet}\ .$$

Its dimension must be [$\mathrm{M}^{-1}\,\mathrm{L}$], and it's easily seen that these are the dimensions of G/c^2. So I'm one of those people (like Fock 1964 p. 199) who define

$$\kappa = 8\pi G/c^2.$$

[10]

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10 Whitney 1968a,b.

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('de *X*' is listed under D, 'van *X*' under V, and so on, regardless of national conventions.)

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