

# Differential Geometry on Submanifolds

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## 1 Introduction

To formulate the ADM formalism, one not only requires Hamiltonian field theory and the Dirac-Bergmann algorithm, but also a means of defining a foliation of spacetime—thereby introducing a preferred time direction for evolution. This involves a precise formulation of what a foliation is, the construction and interpretation of its associated normal vector field, and, more broadly, a systematic treatment of differential geometry on submanifolds. Submanifolds carry a variety of important geometric structures: an induced metric, projected covariant derivatives, intrinsic as well as extrinsic curvature, and decompositions of the ambient curvature in terms of intrinsic and extrinsic contributions. These will all play a central role in what follows.

## 2 Basics

### 2.1 Definition of a Submanifold

In the following,  $\mathcal{M}$  will denote a ((pseudo-)Riemannian)  $m$ -manifold, and  $x^\mu$  local coordinates on it. We denote the components of the metric tensor on  $\mathcal{M}$  by  $g_{\mu\nu}(x)$ , with  $\mu, \nu, \dots$  indicating coordinate indices ranging from  $1, \dots, m$ . The metric tensor defines a line element on  $\mathcal{M}$ ,

$$ds^2 = g = g_{\mu\nu} dx^\mu \otimes dx^\nu. \quad (2.1.1)$$

A *submanifold* of  $\mathcal{M}$  is a subset  $\mathcal{S} \subset \mathcal{M}$  that is itself a manifold, say of dimension  $s = \dim \mathcal{S} \leq m$ . Here it is understood that the topological structure on  $\mathcal{S}$  is the induced subtopology from  $\mathcal{M}$ . Additional structures, such as the induced metric, connections and curvature, we will introduce gradually in the following sections.

We call the quantity

$$\text{codim}_{\mathcal{M}} \mathcal{S} = \dim \mathcal{M} - \dim \mathcal{S} \quad (2.1.2)$$

the *codimension* of  $\mathcal{S}$ . This is a simple but useful notion that conveys “how many dimensions less” the submanifold has in comparison to the ambient manifold  $\mathcal{M} \supset \mathcal{S}$ , which sometimes is more important than the dimension itself.

For example, a *hypersurface* is, by definition, a submanifold  $\mathcal{S} \subset \mathcal{M}$  of codimension 1, and will be particularly important in the development of foliations and the ADM formalism. A simple way of generating (smooth) hypersurfaces is by considering a function  $f : \mathcal{M} \rightarrow \mathbb{R}$  and constructing a level surface as

$$\mathcal{S} = f^{-1}(\{0\}) = \{p \in \mathcal{M} \mid f(p) = 0\} \subset \mathcal{M}. \quad (2.1.3)$$

For  $\mathcal{S}$  defined in this way to be a proper, smooth submanifold, 0 has to be a regular value of  $f$ . This means that

$$df|_{\mathcal{S}} \neq 0 \quad (2.1.4)$$

or in words, the differential (or equivalently, the gradient) of  $f$  must not vanish on  $\mathcal{S}$ .

More generally, given a collection of smooth functions  $f_i : \mathcal{M} \rightarrow \mathbb{R}$  for  $i = 1, \dots, k$ , the common level set

$$\mathcal{S} = \bigcap_i f_i^{-1}(\{0\}) \quad (2.1.5)$$

is a submanifold of codimension  $k$ , provided the  $f_i$  are functionally independent,  $\mathcal{S}$  is non-empty and 0 is a regular value of the map  $f = (f_1, \dots, f_k)$ .

### 2.2 Induced Metric

So far, we have established that a submanifold  $\mathcal{S} \subset \mathcal{M}$  inherits its topological structure from the subspace topology induced by  $\mathcal{M}$ . This makes  $\mathcal{S}$  a topological manifold. However, since we are studying submanifolds of a (pseudo-)Riemannian manifold, it should come as no surprise that we also wish for  $\mathcal{S}$  to carry a (pseudo-)Riemannian structure.

As a manifold in its own right,  $\mathcal{S}$  admits local coordinates  $y^i$ , where  $i = 1, \dots, s = \dim \mathcal{S}$ . In principle, endowing  $\mathcal{S}$  with a (pseudo-)Riemannian metric is straightforward: one simply picks a symmetric tensor field  $\gamma \in T\mathcal{S} \otimes T\mathcal{S}$  with the desired signature and defines the corresponding line element

$$d\bar{s}^2 = \gamma = \gamma_{ij} dy^i \otimes dy^j. \quad (2.2.1)$$

While this makes  $\mathcal{S}$  a (pseudo-)Riemannian manifold, it does so independently of the geometry on the ambient manifold  $\mathcal{M} \supset \mathcal{S}$ —it disregards the structure already present on  $\mathcal{M}$ .

Yet  $\mathcal{S}$  is fully contained in  $\mathcal{M}$ ; any point  $p \in \mathcal{S}$  is also a point of  $\mathcal{M}$ . That much is obvious—but it matters, because the metric on  $\mathcal{M}$  carries geometric information we may wish to preserve. What, after all, does a metric provide? In particular, it can be used to assign lengths to curves. If we consider a path lying in  $\mathcal{S}$ , then this path is also a path in  $\mathcal{M}$ . Naturally, we would want its length to be the same whether we compute it using the metric  $ds^2 = g$  of the ambient manifold or the metric  $d\bar{s}^2 = \gamma$  of the submanifold.

This requirement reflects a choice, but a canonical one: the geometry of  $\mathcal{S}$  should arise from that of  $\mathcal{M}$  by restriction, not by arbitrary redefinition. That is, the structures on  $\mathcal{M}$  should be *induced* on  $\mathcal{S}$ , not constructed from scratch.

Requiring that all lengths of curves in  $\mathcal{S}$  agree under both metrics leads to the precise condition that

$$d\bar{s}^2 = ds^2|_{\mathcal{S}}. \quad (2.2.2)$$

This is no longer just a heuristic, but an equation—it specifies how the metric on the submanifold must be related to the metric of the ambient space.

Though precise, the definition in relation (2.2.2) is not especially practical for computations. Every time we wish to measure the length of a path on  $\mathcal{S}$ , we must return to the structure on  $\mathcal{M}$  and consult what *it* “thinks” the length is. We would prefer to treat  $\mathcal{S}$  as a manifold in its own right, without this constant indirection via  $\mathcal{M}$ . To achieve that, we need explicit knowledge of the components  $\gamma_{ij}$  of the *induced metric* on  $\mathcal{S}$ —the symmetric tensor satisfying

$$\gamma_{ij} dy^i \otimes dy^j = d\bar{s}^2 \stackrel{!}{=} ds^2|_{\mathcal{S}} = (g_{\mu\nu} dx^\mu \otimes dx^\nu)|_{\mathcal{S}}. \quad (2.2.3)$$

The remainder of this section is devoted to deriving a general formula for  $\gamma_{ij}$  in terms of the ambient metric  $g_{\mu\nu}$ .

To do so, observe that for any point  $p \in \mathcal{S}$ , we have two coordinate systems at our disposal: the intrinsic coordinates  $y^i(p)$  on  $\mathcal{S}$ , and the ambient coordinates  $x^\mu(p)$  from  $\mathcal{M}$ . More formally, since  $\mathcal{S} \subset \mathcal{M}$ , we obtain an *injective coordinate map*

$$y^i \mapsto x^\mu(y^i), \quad (2.2.4)$$

expressing the ambient coordinates as functions of the submanifold coordinates. This has a consequence for the differential of  $x^\mu$  restricted to  $\mathcal{S}$ , namely

$$dx^\mu|_{\mathcal{S}} = d(x^\mu(y^i))|_{\mathcal{S}} = \frac{\partial x^\mu}{\partial y^i} dy^i \equiv E_i^\mu dy^i, \quad (2.2.5)$$

where we defined the so-called *pushforward matrix* or *vielbein*

$$E_i^\mu = \frac{\partial x^\mu}{\partial y^i}. \quad (2.2.6)$$

Using this relation, we can rewrite the restriction of the line element as

$$\begin{aligned}
\gamma_{ij} dy^i \otimes dy^j &= d\bar{s}^2 = ds^2|_{\mathcal{S}} \\
&= (g_{\mu\nu} dx^\mu \otimes dx^\nu)|_{\mathcal{S}} \\
&= g_{\mu\nu} (x^\mu(y^i)) E_i^\mu dy^i \otimes E_j^\nu dy^j \\
&= (E_i^\mu E_j^\nu g_{\mu\nu}) dy^i \otimes dy^j
\end{aligned} \tag{2.2.7}$$

From this, we identify the components of the induced metric as

$$\gamma_{ij} = E_i^\mu E_j^\nu g_{\mu\nu}|_{\mathcal{S}} = \frac{\partial x^\mu}{\partial y^i} \frac{\partial x^\nu}{\partial y^j} g_{\mu\nu}|_{\mathcal{S}}. \tag{2.2.8}$$

This gives a general formula for the induced metric on a submanifold, expressed in terms of the ambient metric and a choice of compatible<sup>1</sup> coordinate systems on both  $\mathcal{M}$  and  $\mathcal{S}$ .

This expression for  $\gamma_{ij}$  guarantees that the length of any path measured intrinsically on  $\mathcal{S}$ , via the line element  $d\bar{s}^2$ , matches the length computed externally in the ambient manifold via  $ds^2$ . It is, of course, a coordinate-dependent representation—whereas the earlier definition in equation (2.2.2) was fully coordinate-independent.

### 2.3 Example Submanifold: $S^2 \subset \mathbb{R}^3$

Before diving into more abstract constructions, let us ground our intuition with a concrete example of a manifold and a natural submanifold. To this end, we consider the flat Euclidean space  $\mathcal{M} = \mathbb{R}^3$ , with cartesian coordinates  $x^\mu = (x, y, z) \in \mathbb{R}^3$  and endowed with the Euclidean metric

$$ds^2 = dx^2 + dy^2 + dz^2 \quad \Leftrightarrow \quad g_{\mu\nu} = \delta_{\mu\nu}. \tag{2.3.1}$$

As our submanifold  $\mathcal{S}$ , we consider the 2-sphere  $S^2$ , defined by

$$S^2 = \{(x, y, z) \in \mathbb{R}^3 \mid x^2 + y^2 + z^2 = 1\}. \tag{2.3.2}$$

It is clear that this is a submanifold, as it is the preimage of  $\{0\}$  under the map

$$f(x, y, z) = x^2 + y^2 + z^2 - 1, \tag{2.3.3}$$

which has 0 as a regular value, i.e., the gradient vanishes nowhere where  $f(x, y, z) = 0$ .

The 2-sphere is most conveniently parameterised by two angular coordinates  $y^i = (\theta, \varphi) \in (0, \pi) \times (0, 2\pi)$ , with the embedding into the ambient space  $\mathbb{R}^3$  given by

$$\begin{aligned}
x(\theta, \varphi) &= \sin \theta \cos \varphi, \\
y(\theta, \varphi) &= \sin \theta \sin \varphi, \\
z(\theta, \varphi) &= \cos \theta.
\end{aligned} \tag{2.3.4}$$

We now compute the induced metric on  $S^2$  using two methods: first by means of the pushforward matrix, and then in a more direct way involving differentials of the above relations.

The components of  $E_i^\mu = \frac{\partial x^\mu}{\partial y^i}$  are given by

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<sup>1</sup>Obviously, the coordinate charts must overlap appropriately and be smooth enough for the construction to be valid.

$$\begin{aligned}
E_\theta^x &= \frac{\partial x}{\partial \theta} = \cos \theta \cos \varphi, & E_\varphi^x &= \frac{\partial x}{\partial \varphi} = -\sin \theta \sin \varphi, \\
E_\theta^y &= \frac{\partial y}{\partial \theta} = \cos \theta \sin \varphi, & E_\varphi^y &= \frac{\partial y}{\partial \varphi} = \sin \theta \cos \varphi, \\
E_\theta^z &= \frac{\partial z}{\partial \theta} = -\sin \theta, & E_\varphi^z &= \frac{\partial z}{\partial \varphi} = 0.
\end{aligned} \tag{2.3.5}$$

This allows us to compute the components of the induced metric as

$$\begin{aligned}
\gamma_{\theta\theta} &= E_\theta^\mu E_\theta^\mu \delta_{\mu\nu} = E_\theta^x E_\theta^x + E_\theta^y E_\theta^y + E_\theta^z E_\theta^z \\
&= \cos^2 \theta \cos^2 \varphi + \cos^2 \theta \sin^2 \varphi + \sin^2 \theta \\
&= 1,
\end{aligned} \tag{2.3.6}$$

$$\begin{aligned}
\gamma_{\varphi\varphi} &= E_\varphi^\mu E_\varphi^\mu \delta_{\mu\nu} = E_\varphi^x E_\varphi^x + E_\varphi^y E_\varphi^y + E_\varphi^z E_\varphi^z \\
&= \sin^2 \theta \sin^2 \varphi + \sin^2 \theta \cos^2 \varphi \\
&= \sin^2 \theta,
\end{aligned} \tag{2.3.7}$$

$$\begin{aligned}
\gamma_{\theta\varphi} &= \gamma_{\varphi\theta} = E_\theta^x E_\varphi^x + E_\theta^y E_\varphi^y + E_\theta^z E_\varphi^z \\
&= -\sin \theta \cos \theta \sin \varphi \cos \varphi + \sin \theta \cos \theta \sin \varphi \cos \varphi \\
&= 0.
\end{aligned} \tag{2.3.8}$$

Using this, the induced line element becomes

$$d\bar{s}^2 = \gamma_{ij} dy^i \otimes dy^j = d\theta \otimes d\theta + \sin^2 \theta d\varphi \otimes d\varphi \tag{2.3.9}$$

—an anticipated result, the standard metric on  $S^2$ .

We now briefly go over how one can compute the induced metric slightly more directly by considering the differentials of the embeddings (2.3.4). These differentials read

$$\begin{aligned}
dx|_{S^2} &= \cos \theta \cos \varphi d\theta - \sin \theta \sin \varphi d\varphi, \\
dy|_{S^2} &= \cos \theta \sin \varphi d\theta + \sin \theta \cos \varphi d\varphi, \\
dz|_{S^2} &= -\sin \theta d\theta.
\end{aligned} \tag{2.3.10}$$

We can then simply insert these relations into the Euclidean line element (2.3.1) to find (writing  $dx^\mu \otimes dx^\nu$  as  $dx^\mu dx^\nu$  for brevity)

$$\begin{aligned}
d\bar{s}^2 &= ds^2|_{S^2} = dx^2|_{S^2} + dy^2|_{S^2} + dz^2|_{S^2} \\
&= (\cos \theta \cos \varphi d\theta - \sin \theta \sin \varphi d\varphi)^2 \\
&\quad + (\cos \theta \sin \varphi d\theta + \sin \theta \cos \varphi d\varphi)^2 \\
&\quad + (-\sin \theta d\theta)^2 \\
&= \cos^2 \theta \cos^2 \varphi d\theta^2 - \cancel{2 \cos \theta \sin \theta \cos \varphi \sin \varphi d\theta d\varphi} + \sin^2 \theta \sin^2 \varphi d\varphi^2 \\
&\quad + \cos^2 \theta \sin^2 \varphi d\theta^2 + \cancel{2 \cos \theta \sin \theta \cos \varphi \sin \varphi d\theta d\varphi} + \sin^2 \theta \cos^2 \varphi d\varphi^2 \\
&\quad + \sin^2 \theta d\theta^2 \\
&= (\cos^2 \theta (\cos^2 \varphi + \sin^2 \varphi) + \sin^2 \theta) d\theta^2 + \sin^2 \theta (\sin^2 \varphi + \cos^2 \varphi) d\varphi^2 \\
&= d\theta^2 + \sin^2 \theta d\varphi^2.
\end{aligned} \tag{2.3.11}$$

This alternative method avoids explicitly constructing the pushforward matrix, relying instead on computing the differentials of the embedding directly and inserting them into the ambient metric —though of course, fully equivalent to the first approach. *Which* of the two approaches is better comes down to being mostly situational, and of course, personal preference.

## 3 Tangent Spaces, Pushforwards, Pullbacks, and Projections

### 3.1 Preliminaries: Maps Between Manifolds and Their Derivatives

Before diving into the formalism of pushforwards and pullbacks, which is the goal of this section, let us first understand the geometric motivation behind them.

Suppose we have two smooth manifolds  $\mathcal{M}$  and  $\mathcal{N}$ , with dimensions  $m$  and  $n$ , and  $\varphi : \mathcal{M} \rightarrow \mathcal{N}$  a smooth map between them. This map assigns to every point  $p \in \mathcal{M}$  a point  $\varphi(p) \in \mathcal{N}$ . But more than just matching up points,  $\varphi$  also relates the local *geometry* near those points.

To illustrate this, imagine a flexible sheet of paper ( $\mathcal{M}$ ) that we smoothly press onto another, possibly curved surface  $\mathcal{N}$ . Every point on the paper ends up on some point of the surface, but the way the paper bends or stretches as it moves gives us more than just a positional correspondence—it tells us how *directions* and *infinitesimal displacements* on  $\mathcal{M}$  are transformed under the map. For example, a tiny arrow drawn on the paper (a tangent vector) will point in some new direction when the paper is curved onto the surface.

This is the essence of what the pushforward captures: it tells us how tangent vectors on  $\mathcal{M}$ —representing directions of motion away from a point—are mapped to tangent vectors on  $\mathcal{N}$ . Formally, the *pushforward* of  $\varphi$ , denoted by  $\varphi_*$ , is a map between tangent spaces,

$$\varphi_* : T_p \mathcal{M} \rightarrow T_{\varphi(p)} \mathcal{N}. \quad (3.1.1)$$

We will now make this precise.

**Definition:** (Pushforward) We begin by recalling what we want to construct: given a smooth map  $\varphi : \mathcal{M} \rightarrow \mathcal{N}$ , we aim to associate to any vector  $X \in T_p \mathcal{M}$  a vector  $\varphi_* X \in T_{\varphi(p)} \mathcal{N}$ , which we call the *pushforward* of  $X$  under  $\varphi$ . This should represent the idea of how the direction  $X$  “looks” after the map  $\varphi$  has distorted the space onto  $\mathcal{N}$ .

But how do we compare directions at two different points of two different manifolds? We use the fact that vectors act on functions as differential operators—they are directional derivatives. A vector  $X \in T_p \mathcal{M}$  acting on a function on  $\mathcal{M}$  tells us how it changes as we move in the direction of  $X$ . Similarly,  $\varphi_* X \in T_{\varphi(p)} \mathcal{N}$  should tell us how a function on  $\mathcal{N}$  changes in the “corresponding direction” under  $\varphi$ .

Here’s the key trick: we cannot directly evaluate how  $X$  acts on a function on  $\mathcal{N}$ , because  $X$  lives on  $\mathcal{M}$ . But we *can* make any function on  $\mathcal{N}$  into a function on  $\mathcal{M}$  by composing it with  $\varphi$ . That is, given any smooth function  $f : \mathcal{N} \rightarrow \mathbb{R}$ , the composition  $f \circ \varphi : \mathcal{M} \rightarrow \mathbb{R}$  is a new function defined on  $\mathcal{M}$  to which we *can* apply  $X$ .

The function  $f \circ \varphi$  is, in essence, just  $f$ , but with the codomain rearranged according to  $\varphi$ . The function values don’t change—only *where* in the domain they are sampled from does. This captures the distortion  $\varphi$  induces: how orientation, stretching, or compression affect the function’s appearance when viewed on  $\mathcal{M}$ . So taking  $X[f \circ \varphi]$  tells us how  $f$  changes along the image of the direction  $X$  under the map  $\varphi$ .

This leads us naturally to the definition

$$(\varphi_* X)[f] := X[f \circ \varphi], \quad \forall f \in C^\infty(\mathcal{N}). \quad (3.1.2)$$

That is,  $\varphi_* X$  is the unique vector at  $\varphi(p)$  whose action on any function  $f$  on  $\mathcal{N}$  agrees with the action of  $X$  on the pulled-back version of  $f$ . This expression captures exactly what the pushforward is doing: it tells us how to “translate” a directional derivative on  $\mathcal{M}$  to one on  $\mathcal{N}$ , while preserving how it affects functions.

This is all very abstract, so let us make it more concrete with an analogy. Let us think of  $\mathcal{M}$  as the flat Mercator map, a rectangle showing latitude and longitude lines. Then, we think of  $\mathcal{N}$  as the actual globe, a 2-sphere. The map  $\varphi : \mathcal{M} \rightarrow \mathcal{N}$  we envision as the wrapping map, which tells us how to take the rectangle and bend it into a globe. Suppose  $f$  assigns temperature values across the globe—a real-valued function on  $\mathcal{N}$ . Then  $f \circ \varphi$  is the pulled-back function: it contains the same information, the same temperature values, but now shown on the Mercator map instead of the globe. This function  $f \circ \varphi$  lets us look at the globe's data  $f$  as if it lived on the Mercator map. We then ask: how does the temperature change when moving along some vector  $X$  on that map? This is what  $X[f \circ \varphi]$  computes: how the pulled-back temperature map changes as we follow  $X$  on the rectangle.

Now, on the globe, there should be a corresponding direction,  $\varphi_* X$ , along which the same change occurs—after all, we have the same function values, just arranged differently. This is the direction we have to move towards on the sphere to see the same change in temperature. This should not just happen for this one temperature map—for any function  $f$  on the globe, the pushforward  $\varphi_* X$  must give us the corresponding direction whose action on  $f$  replicates the directional derivative seen on the Mercator map. And that is what the definition (3.1.2) encodes.

For explicit calculations, it is typically more convenient to move away from the abstract, coordinate-independent definition (3.1.2), and instead adopt a coordinate-based approach. To this end, let  $p \in \mathcal{M}$  a point, with local coordinates  $y^\alpha$  around  $p$ , and let  $x^\mu$  be local coordinates on  $\mathcal{N}$  around the image point  $\varphi(p)$ . Then  $\varphi$  induces a local map between coordinate systems,

$$x^\mu(y^\alpha) \equiv x^\mu(\varphi(p(y^\alpha))) : \mathbb{R}^m \rightarrow \mathbb{R}^n, \quad (3.1.3)$$

which is differentiable in the standard sense. That is, composing the chart inverse on  $\mathcal{M}$ , the map  $\varphi$ , and the chart on  $\mathcal{N}$ , we obtain a smooth map between subsets of Euclidean space.

To derive the coordinate expression for the pushforward, consider the coordinate bases

$$\left\{ \partial_\alpha = \frac{\partial}{\partial y^\alpha} \right\} \text{ of } \mathcal{M} \quad \text{and} \quad \left\{ \partial_\mu = \frac{\partial}{\partial x^\mu} \right\} \text{ of } \mathcal{N}. \quad (3.1.4)$$

A vector  $X \in T_p \mathcal{M}$  can be written as  $X = X^\alpha \partial_\alpha$ , and its pushforward as  $\varphi_* X = (\varphi_* X)^\mu \partial_\mu$ . The definition (3.1.2) then becomes to

$$\begin{aligned} (\varphi_* X)^\mu \frac{\partial}{\partial x^\mu} f(x) &= X^\alpha \frac{\partial}{\partial y^\alpha} f(x(y)) \\ &= X^\alpha \frac{\partial x^\mu}{\partial y^\alpha} \frac{\partial}{\partial x^\mu} f(x(y)), \end{aligned} \quad (3.1.5)$$

where we applied the standard multidimensional chain rule on the right-hand side. We may hence identify the components of the pushforward  $\varphi_* X$  as

$$(\varphi_* X)^\mu = \frac{\partial x^\mu}{\partial y^\alpha} X^\alpha \quad (3.1.6)$$

This shows that the pushforward acts linearly on the components of the vector, via the Jacobian matrix

$$(\varphi_*)^\mu{}_\alpha = \frac{\partial x^\mu}{\partial y^\alpha} = \frac{\partial}{\partial y^\alpha} x^\mu(\varphi(p(y^\alpha))), \quad (3.1.7)$$

i.e.

$$(\varphi_* X)^\mu = (\varphi_*)^\mu{}_\alpha X^\alpha. \quad (3.1.8)$$



This expression makes the pushforward entirely concrete: it is simply a linear transformation of the vector components under the coordinate ap induced by  $\varphi$ . In terms of implementation and computation, it behaves exactly like a Jacobian—and it reproduces the familiar coordinate transformation rule for vector components when  $\varphi : \mathcal{M} \rightarrow \mathcal{M}$  is a diffeomorphism.

**Definition** (Canonical Pairing) For a vector  $X \in T_p\mathcal{M}$  and a 1-form  $\omega \in T_p^*\mathcal{M}$ , we define their *canonical pairing* (sometimes called an inner product)

$$\langle \cdot, \cdot \rangle_{\mathcal{M}} : T_p^*\mathcal{M} \times T_p\mathcal{M} \rightarrow \mathbb{R} \quad (3.1.9)$$

by

$$\langle \omega, X \rangle_{\mathcal{M}} \equiv \omega(X). \quad (3.1.10)$$

Here,  $\omega(X)$  denotes the natural pairing between a covector and a vector—i.e., the evaluation of the linear map  $\omega : T_p\mathcal{M} \rightarrow \mathbb{R}$  on the argument  $X \in T_p\mathcal{M}$ . In coordinate components, this reads  $\omega(X) = \omega_\mu X^\mu$ . Notice that this pairing is defined independently of any metric structure. We will use it below to define the pullback  $\varphi^*$ , a dual operation to the pushforward, acting on cotangent spaces.

**Definition** (Pullback) We define the *pullback* associated to  $\varphi$  as the unique linear map

$$\varphi^* : T_{\varphi(p)}^*\mathcal{N} \rightarrow T_p^*\mathcal{M} \quad (3.1.11)$$

satisfying

$$\langle \varphi^*\omega, X \rangle_{\mathcal{M}} = \langle \omega, \varphi_*X \rangle_{\mathcal{N}}, \quad \forall X \in T_p\mathcal{M}, \quad \omega \in T_{\varphi(p)}^*\mathcal{N}. \quad (3.1.12)$$

That is, the pairing between a covector and a vector is preserved under the pushforward-pullback action of  $\varphi$ . This is a natural requirement: having defined how directions deform under  $\varphi$ , we want to ensure that objects measuring those directions (i.e. 1-forms) adapt in a compatible way. Equivalently, this can be written as

$$(\varphi^*\omega)(X) = \omega(\varphi_*X), \quad \forall X \in T_p\mathcal{M}, \quad \omega \in T_{\varphi(p)}^*\mathcal{N}. \quad (3.1.13)$$

Another perspective is the following: a 1-form projects a component from a vector. But if the vector is altered—say, by a pushforward—then extracting the “same” component now requires a different projection. The pullback gives us precisely this adjusted 1-form: one that reproduces the same scalar when applied to the original vector as the original 1-form applied to the pushforward.

As with the pushforward, let us now extract a coordinate-based expression for the pullback. This case turns out to be even simpler. Using the same coordinate setup—local coordinates  $y^\alpha$  around  $p \in \mathcal{M}$ , and  $x^\mu$  around  $\varphi(p) \in \mathcal{N}$ —we express

$$X = X^\alpha \partial_\alpha, \quad \omega = \omega_\mu dx^\mu. \quad (3.1.14)$$

We begin by expanding the left-hand side of the definition (3.1.12),

$$\langle \varphi^*\omega, X \rangle_{\mathcal{M}} = (\varphi^*\omega)_\alpha X^\alpha. \quad (3.1.15)$$

On the right-hand side, we compute the action of  $\omega$  on the pushforward of  $X$ ,

$$\langle \omega, \varphi_*X \rangle_{\mathcal{N}} = \omega_\mu (\varphi_*X)^\mu = \omega_\mu (\varphi_*)^\mu_\alpha X^\alpha. \quad (3.1.16)$$

Equating both sides and using the arbitrariness of  $X^\alpha$ , we identify the components of the pullback:

$$(\varphi^*\omega)_\alpha = (\varphi_*)^\mu_\alpha \omega_\mu = \frac{\partial x^\mu}{\partial y^\alpha} \omega_\mu. \quad (3.1.17)$$

In words: the pullback transforms a 1-form using the same Jacobian matrix as the pushforward acts with on vectors, but the roles of the indices reversed—covariant versus contravariant transformation. Equivalently, the pullback acts via the transpose of the Jacobian of  $\varphi$ , in keeping with the duality between tangent and cotangent spaces.

**Remark** *Pullbacks of Vectors?* We have seen the pushforward as a map

$$\varphi_* : T_p\mathcal{M} \rightarrow T_{\varphi(p)}\mathcal{N}. \quad (3.1.18)$$

A natural question is whether this relationship can be reversed: can we pull back vectors from  $T_{\varphi(p)}\mathcal{N}$  to  $T_p\mathcal{M}$ ?

In general, the answer is no. Algebraically, this follows from the fact that  $\varphi_*$  is not necessarily invertible. As a linear map, invertibility requires its component representation

$$(\varphi_*)^\mu_\alpha = \frac{\partial x^\mu}{\partial y^\alpha} \quad (3.1.19)$$

to be an invertible matrix. This is only possible if  $\dim \mathcal{M} = \dim \mathcal{N}$ , since otherwise the Jacobian is rectangular and hence cannot be inverted. And even when the dimensions match, the Jacobian must be non-singular (i.e. its determinant must be nonzero). Thus,  $\varphi_*$  is only invertible when  $\varphi$  is a diffeomorphism—a smooth bijective map with smooth inverse.

This is the algebraic reasoning. Fortunately, there's also geometric intuition to support it. The pushforward tracks how a direction away from  $p \in \mathcal{M}$  translates to a direction away from  $\varphi(p) \in \mathcal{N}$ , consistent with the local deformation  $\varphi$  induces. In that process, we may preserve the number of independent directions, or lose some—but we can never gain new ones. The rank of a linear map  $\varphi_* : \mathbb{R}^m \rightarrow \mathbb{R}^n$  is at most  $m$ , so if  $n > m$ , its image lies in a proper subspace of  $\mathbb{R}^n$ . In other words, a pushforward cannot invent new degrees of freedom.

In the best-case scenario  $\dim \text{im } \varphi_* = m$ , we retain full information and the map  $\varphi_*$  is invertible. But if information is lost—i.e. if  $\varphi_*$  collapses multiple directions into the same image—then we can no longer recover those original directions when attempting to go back. We do not know how to “blow it back up again”—that is, how to reconstruct the full-dimensional direction space of  $T_p\mathcal{M}$ . A helpful instance to picture is a pushforward collapsing  $T_p\mathcal{M}$  onto a lower-dimensional plane inside  $T_{\varphi(p)}\mathcal{N}$ ; there is no way to lift this back up uniquely.

Therefore, in general, it is not possible to pull back vectors from  $T_{\varphi(p)}\mathcal{N}$  to  $T_p\mathcal{M}$ .

**Generalisation to Tensors** Now that we know how we should associate vectors and 1-forms/covectors on two manifolds  $\mathcal{M}$  and  $\mathcal{N}$  between which we have an association of points given by  $\varphi : \mathcal{M} \rightarrow \mathcal{N}$ , we can generalise to tensors. Due to the difference in “functorial direction” between the pushforward and pullback, it is not possible to define a combined map for arbitrary, mixed tensors. For fully covariant or fully contravariant tensors, however, it is possible—or, if  $\varphi$  is a diffeomorphism. This latter case we will not consider, though—this is because it essentially reduces to a change of coordinates.

Let us begin with the pullback of covariant tensors  $T \in T_{\varphi(p)}^{0,s}\mathcal{N}$ . Such a tensor can be written as

$$T = T_{\mu_1 \dots \mu_s} dx^{\mu_1} \otimes \dots \otimes dx^{\mu_s}, \quad (3.1.20)$$

which allows us to naturally pair it with  $s$  vectors  $X_{(i)} \in T_{\varphi(p)}\mathcal{N}$  to form a scalar

$$T(X_{(1)}, \dots, X_{(s)}) = T_{\mu_1 \dots \mu_s} X_{(1)}^{\mu_1} \dots X_{(s)}^{\mu_s}. \quad (3.1.21)$$

To ensure compatibility between  $T$  and its pullback  $\varphi^*T \in T_p^{0,s}\mathcal{M}$ , we impose that for all vectors  $X_{(1)}, \dots, X_{(s)} \in T_p\mathcal{M}$ , we have

$$(\varphi^*T)(X_{(1)}, \dots, X_{(s)}) = T(\varphi_*X_{(1)}, \dots, \varphi_*X_{(s)}) \quad (3.1.22)$$

In words, we require the pullback of  $T$  to “have the same opinion” about a set of vectors as the original tensor has about their pushforwards—which it should, if they are to encode the “same” tensorial structure on the two spaces related by  $\varphi$ . It shouldn’t matter whether we ask  $\varphi^*T$  on the original vectors for a scalar value, or first squish the space around and then ask the same question to  $T$ , with the correspondents  $\varphi_*X_{(i)}$  as arguments.

Of course, this definition can also be given in terms of coordinate components. Expanding both sides of the equation, we get

$$(\varphi^*T)_{\alpha_1 \dots \alpha_s} X_{(1)}^{\alpha_1} \dots X_{(s)}^{\alpha_s} = T_{\mu_1 \dots \mu_s} (\varphi_*)^{\mu_1}_{\alpha_1} X_{(1)}^{\alpha_1} \dots (\varphi_*)^{\mu_s}_{\alpha_s} X_{(s)}^{\alpha_s}. \quad (3.1.23)$$

This identifies the components of the pullback as

$$(\varphi^*T)_{\alpha_1 \dots \alpha_s} = (\varphi_*)^{\mu_1}_{\alpha_1} \dots (\varphi_*)^{\mu_s}_{\alpha_s} T_{\mu_1 \dots \mu_s}. \quad (3.1.24)$$

Hence, the pullback simply acts multilinearly on all indices by contraction with the pushforward matrix  $(\varphi_*)^\mu_\alpha$ .

We now move to the pushforward for contravariant objects, i.e. of tensors  $T \in T_p^{r,0}\mathcal{M}$ . These can be represented as

$$T = T^{\alpha_1 \dots \alpha_r} \partial_{\alpha_1} \otimes \dots \otimes \partial_{\alpha_r} \quad (3.1.25)$$

in terms of the coordinate basis  $\partial_{\alpha_1} = \frac{\partial}{\partial y^{\alpha_1}}$ . Such a tensor is a multilinear map, taking  $r$  1-forms  $\omega^{(i)} \in T_p^*\mathcal{M}$  and mapping them to the scalar

$$\begin{aligned} T(\omega^{(1)}, \dots, \omega^{(r)}) &= T^{\alpha_1 \dots \alpha_r} \omega^{(1)}(\partial_{\alpha_1}) \dots \omega^{(r)}(\partial_{\alpha_r}) \\ &= T^{\alpha_1 \dots \alpha_r} \omega_{\alpha_1}^{(1)} \dots \omega_{\alpha_r}^{(r)}. \end{aligned} \quad (3.1.26)$$

We define the pushforward  $\varphi_*T \in T_{\varphi(p)}^{r,0}\mathcal{N}$  as the unique tensor satisfying

$$T(\varphi^*\omega^{(1)}, \dots, \varphi^*\omega^{(r)}) = (\varphi_*T)(\omega^{(1)}, \dots, \omega^{(r)}) \quad \forall \omega^{(i)} \in T_{\varphi(p)}^*\mathcal{N}. \quad (3.1.27)$$

In words: The pushforward  $\varphi_*T$  “says” the same about the  $\omega^{(i)}$  as the original tensor  $T$  would have to say about their pullbacks. In terms of coordinates, we verify that this really is just the multilinear extension of what happens to vectors: Inserting coordinate expressions for both sides we get

$$T^{\alpha_1 \dots \alpha_r} (\varphi_*)^{\mu_1}_{\alpha_1} \omega_{\mu_1}^{(1)} \dots (\varphi_*)^{\mu_r}_{\alpha_r} \omega_{\mu_r}^{(r)} = (\varphi_*T)^{\mu_1 \dots \mu_r} \omega_{\mu_1}^{(1)} \dots \omega_{\mu_r}^{(r)}. \quad (3.1.28)$$

We may thus identify the components of  $\varphi_*T$  as

$$(\varphi_*T)^{\mu_1 \dots \mu_r} = (\varphi_*)^{\mu_1}_{\alpha_1} \dots (\varphi_*)^{\mu_r}_{\alpha_r} T^{\alpha_1 \dots \alpha_r}, \quad (3.1.29)$$

which is simply just the index-wise transformation with the pushforward matrix  $(\varphi_*)^\mu_\alpha$ .

### 3.2 Special Case: Submanifolds and the Pushforward as Inclusion

Now that we have established some general theory of smooth maps between manifolds—along with their associated pushforwards and pullbacks—we are ready to specialise to a particularly important class: the inclusion maps of submanifolds. Given a submanifold  $\mathcal{S} \subset \mathcal{M}$ , the inclusion map  $\iota : \mathcal{S} \rightarrow \mathcal{M}$  allows us to view  $\mathcal{S}$  as embedded in the ambient space  $\mathcal{M}$

This setup will naturally recover familiar constructions from Riemannian geometry. Most notably, we will see that the induced metric on the submanifold arises as the pullback of the ambient metric under  $\iota$ . Framed this way, the induced geometry of submanifolds is revealed to be not an isolated trick, but part of the broader formalism of pullbacks—shedding light on how submanifold geometry fits seamlessly into the general machinery of differential geometry.

**Definition** (Inclusion Map for Submanifolds) Let  $\mathcal{M}$  be an  $m$ -dimensional manifold and  $\mathcal{S} \subset \mathcal{M}$  an  $s$ -dimensional submanifold. We call the map

$$\iota : \mathcal{S} \rightarrow \mathcal{M}, \quad p \mapsto p \quad (3.2.1)$$

the *inclusion map* or simply *inclusion* of  $\mathcal{S}$  into  $\mathcal{M}$ .

At first glance, this may not seem particularly interesting—it merely sends each point to itself. But despite its simplicity,  $\iota$  is a smooth map between manifolds, and as such, all the machinery developed previously (pushforward, pullback, tensor behaviour) can and does apply. This makes the inclusion map a powerful conceptual tool, especially when studying how geometric or tensorial structures on the ambient manifold  $\mathcal{M}$  restrict or induce structure on the submanifold  $\mathcal{S}$ . So, let us now examine  $\iota$  through this lens.

**The Pushforward  $\iota_*$**  Firstly, let us examine the pushforward  $\iota_*$ . Before diving into concrete definitions, it helps to build some intuition. In general, the pushforward  $\varphi_*$  of a smooth map  $\varphi : \mathcal{M} \rightarrow \mathcal{N}$  maps tangent vectors from  $T_p\mathcal{M}$  to  $T_{\varphi(p)}\mathcal{N}$ , capturing how directions around  $p$  deform under  $\varphi$ .

In our case,  $\varphi = \iota$  is the inclusion of a submanifold  $\mathcal{S} \subset \mathcal{M}$ . Since  $\iota(p) = p$ , the point itself remains unchanged, and so do the local relationships between points. A tangent vector  $X \in T_p\mathcal{S}$  should therefore remain to be the same geometric object under the pushforward, just now interpreted as living inside the larger ambient space  $T_p\mathcal{M}$ . We are thus led to expect that  $\iota_*$  simply embeds  $T_p\mathcal{S}$  into  $T_p\mathcal{M}$ .

This is what we will now make precise. For that, we consider the pushforward  $\iota_*X$  of some vector  $X \in T_p\mathcal{S}$ . By definition, for any function  $f \in C^\infty(\mathcal{M})$ , its action is given by

$$(\iota_*X)[f] = X[f \circ \iota]. \quad (3.2.2)$$

Since  $\iota(p) = p$  for all  $p \in \mathcal{S}$ , the composition  $f \circ \iota$  is simply the restriction of  $f$  to the submanifold, i.e.  $f|_{\mathcal{S}}$ . That is,

$$(\iota_*X)[f] = X[f|_{\mathcal{S}}]. \quad (3.2.3)$$

This shows that  $\iota_*X \in T_p\mathcal{M}$  acts on ambient functions  $f \in C^\infty(\mathcal{M})$  exactly as  $X \in T_p\mathcal{S}$  acts on their restrictions to  $\mathcal{S}$ . In other words, the pushforward simply embeds the vector  $X$  into the ambient tangent space in a way that preserves its actions on functions.

We therefore conclude that the pushforward acts as the canonical inclusion of tangent spaces,

$$\iota_* : T_p\mathcal{S} \rightarrow T_p\mathcal{M}, \quad X \mapsto X, \quad \text{for all } p \in \mathcal{S}. \quad (3.2.4)$$

That is, we naturally identify each tangent space  $T_p\mathcal{S}$  with a subspace of the ambient tangent space  $T_p\mathcal{M}$ , and the map  $\iota_*$  serves as a pointwise injective linear embedding.

Let us now consider how the pushforward looks in coordinate components. To this end, let  $p \in \mathcal{S} \subset \mathcal{M}$ , and suppose  $y^i$ ,  $i = 1, \dots, s$  and  $x^\mu$ ,  $1, \dots, m$ , are local coordinates around  $p$  on  $\mathcal{S}$  and  $\mathcal{M}$ , respectively. We consider the pushforward of a vector  $X \in T_p\mathcal{S}$ , written in the coordinate basis  $\partial_i = \frac{\partial}{\partial y^i}$  as

$$X = X^i \partial_i \quad (3.2.5)$$

From the general theory of pushforwards established in the previous section, its image under the inclusion  $\iota$  is given by

$$\iota_* X = (\iota_* X)^\mu \partial_\mu = (\iota_*)^\mu_i X^i \partial_\mu \quad (3.2.6)$$

where  $\partial_\mu = \frac{\partial}{\partial x^\mu}$  is the coordinate basis of  $T_p \mathcal{M}$ , and the pushforward matrix  $(\iota_*)^\mu_i$  is given by the Jacobian matrix

$$(\iota_*)^\mu_i = \frac{\partial x^\mu}{\partial y^i}. \quad (3.2.7)$$

This is the same object we previously denoted by  $E^\mu_i$  in equation (2.2.6), and we now return to that notation. Thus, the pushforward becomes

$$\iota_* X = (E^\mu_i X^i) \partial_\mu \Leftrightarrow (\iota_* X)^\mu = E^\mu_i X^i. \quad (3.2.8)$$

**The Pullback  $\iota^*$**  We now turn to the pullback  $\iota^* : T_p^* \mathcal{M} \rightarrow T_p^* \mathcal{S}$  associated with the immersion  $\iota : \mathcal{S} \rightarrow \mathcal{M}$ . By definition, for any  $X \in T_p \mathcal{S}$  and  $\omega \in T_p^* \mathcal{M}$ , it satisfies

$$\langle \iota^* \omega, X \rangle_{\mathcal{S}} = \langle \omega, \iota_* X \rangle_{\mathcal{M}}. \quad (3.2.9)$$

In terms of components, this reads

$$(\iota^* \omega)_i X^i = \omega_\mu (\iota_* X)^\mu = \omega_\mu E^\mu_i X^i, \quad (3.2.10)$$

from which we identify the components of the pullback as

$$(\iota^* \omega)_i = E^\mu_i \omega_\mu. \quad (3.2.11)$$

**The Induced Metric** As we have seen in the previous section, we can also define the pushforward and pullback for purely contra- or covariant tensors, by applying the transformation with  $E^\mu_i$  to each index separately. This arose from the requirement of compatibility under the map between manifolds of the multilinear map a tensor defines. A tensor of particular interest to differential geometry is the metric. Since it is a  $(0, 2)$ -tensor, it is purely covariant, and we can apply the pullback to the metric on  $\mathcal{M}$  to get a tensor on  $\mathcal{S}$ . Intuition would tell us that this is the induced metric, but let us go through this calmly. The metric on  $\mathcal{M}$  is the symmetric tensor

$$ds^2 = g = g_{\mu\nu} dx^\mu \otimes dx^\nu. \quad (3.2.12)$$

It is a symmetric bilinear map of two vectors  $A, B \in T_p \mathcal{M}$  to  $\mathbb{R}$ , with

$$g(A, B) = g_{\mu\nu} dx^\mu(A) dx^\nu(B) = g_{\mu\nu} A^\mu B^\nu. \quad (3.2.13)$$

Its pullback  $\iota^* g$  is defined by the relationship

$$(\iota^* g)(X, Y) = g(\iota_* X, \iota_* Y), \quad X, Y \in T_p \mathcal{S}. \quad (3.2.14)$$

Let us briefly interpret this, then we move to the coordinate expression which will match the induced metric we derived in Section 2.2. Equation (3.2.14) tells us that the the pullback  $\iota^* g$  is a symmetric bilinear map that simply uses the metric on  $\mathcal{M}$  to measure the pushforwards  $\iota_* X$  and  $\iota_* Y$ . Recall, however, that we had previously found  $\iota_* X$  and  $\iota_* Y$  to be nothing more than the natural embeddings of  $X$  and  $Y$  in  $T_p \mathcal{M}$ . So, in essence, the equation states that  $(\iota^* g)$  simply returns the same value as  $g$  would, if  $X$  and  $Y$  were to be seen as vectors in  $T_p \mathcal{M}$ , which they can as  $T_p \mathcal{S}$  is embedded in it as a subspace. This narrative of “asking the ambient metric what it thinks and reproducing that” is precisely the reasoning we used in Section 2.2 to motivate its definition—but now, we have rediscovered it in a much more general context, in that of pushforwards and pullbacks associated to smooth maps between manifolds.

Going through the component expressions, we find

$$\begin{aligned} (\iota^*g)(X, Y) &= g(\iota_*X, \iota_*Y) = g_{\mu\nu}E^\mu_i E^\nu_j X^i Y^j \\ &= (g_{\mu\nu}E^\mu_i E^\nu_j)X^i Y^j = \gamma_{ij}X^i Y^j = \gamma(X, Y). \end{aligned} \quad (3.2.15)$$

This confirms explicitly that  $\iota^*g = \gamma$ ; in other words, the induced metric on  $\mathcal{S}$  is simply the pullback of the metric from the ambient manifold  $\mathcal{M}$ . We have come full circle: the geometric idea that guided our definition of the induced metric has now emerged naturally from algebraic considerations grounded in a broader theoretical framework. That coherence gives us confidence to admit the idea into our formal foundations—when algebra and intuition converge, we are likely on the right path.

### 3.3 The Left-Inverse: Projections onto Tangent Spaces

We have previously remarked that for a general pushforward

$$\varphi_* : T_p\mathcal{M} \rightarrow T_{\varphi(p)}\mathcal{N} \quad (3.3.1)$$

associated with a smooth map  $\varphi : \mathcal{M} \rightarrow \mathcal{N}$ , it is in general not possible to define an inverse

$$(\varphi_*)^{-1} : T_{\varphi(p)}\mathcal{N} \rightarrow T_p\mathcal{M}. \quad (3.3.2)$$

However, if  $\varphi_*$  is injective, then it *is* possible to define a *left-inverse*. A particularly relevant case where this holds is that of immersion maps, such as

$$\varphi = \iota : \mathcal{S} \rightarrow \mathcal{M}, \quad (3.3.3)$$

where we have previously seen that the associated pushforward

$$\iota_* : T_p\mathcal{S} \rightarrow T_p\mathcal{M} \quad (3.3.4)$$

is an injective linear embedding.

Let us now examine this in detail. We may define a (non-unique) left-inverse<sup>2</sup>

$$(\iota_*)^{-1} : T_p\mathcal{M} \rightarrow T_p\mathcal{S} \quad (3.3.5)$$

as a linear map satisfying

$$(\iota_*)^{-1} \circ \iota_* = \text{id}_{T_p\mathcal{S}}. \quad (3.3.6)$$

Though this constrains  $(\iota_*)^{-1}$  fully on  $\text{im}(\iota_*)$ , its action on the complement of  $\text{im}(\iota_*)$  remains arbitrary—hence we have no uniqueness.

In components, using the same coordiante systems as before, let us expand both sides of this identity for a vector  $X \in T_p\mathcal{S}$ . On the right-hand side, we get

$$\text{id}_{T_p\mathcal{S}} X = X = X^i \partial_i = \delta_j^i X^j \partial_i \quad (3.3.7)$$

For the left-hand side, we use the component expression for the pushforward to find

$$((\iota_*)^{-1} \circ \iota_*)(X) = (\iota_*)^{-1}(\iota_*X) = (\iota_*)^{-1}(E^\mu_i X^i \partial_\mu) = ((\iota_*)^{-1})^j_\mu E^\mu_i X^i \partial_j. \quad (3.3.8)$$

where we have defined

$$E^i_\mu = ((\iota_*)^{-1})^i_\mu \quad (3.3.9)$$

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<sup>2</sup>We use the notation  $(\cdot)^{-1}$  here to indicate just a left- and not a proper inverse.

as the component representation of the left-inverse. Equating both sides allows us to express equation (3.3.6) as

$$E^i_\mu E^\mu_j X^j \partial_i = \delta^i_j X^j \partial_i. \quad (3.3.10)$$

By arbitrariness of  $X$ , we conclude the matrix identity

$$E^i_\mu E^\mu_j = \delta^i_j. \quad (3.3.11)$$

This is exactly the condition for  $E^i_\mu$  to be a left-inverse of  $E^\mu_i$  in the standard sense of matrix algebra. Notice that this implies that both the ranks of  $E^\mu_i$  and  $E^i_\mu$  must be  $s = \dim \mathcal{S} = \text{rank } \delta^i_j$ .

The left-inverse  $(\iota_*)^{-1}$  might not appear very useful, since all it does is allow us to form an identity on  $T_p \mathcal{S}$ . We can, however, attempt to use it as a right-inverse, to define the map

$$P \equiv \iota_* \circ (\iota_*)^{-1} : T_p \mathcal{M} \rightarrow \text{im}(\iota_*) \subset T_p \mathcal{M}. \quad (3.3.12)$$

Clearly, the component representation of this map acting on  $X \in T_p \mathcal{M}$  is

$$P(X) = (\iota_* \circ (\iota_*)^{-1})(X^\mu \partial_\mu) = (E^\mu_i E^i_\nu X^\nu) \partial_\mu = (P^\mu_\nu X^\nu) \partial_\mu, \quad (3.3.13)$$

with the components of  $P$  denoted by  $P^\mu_\nu \equiv E^\mu_i E^i_\nu$ . Since  $P$  is a linear map, and

$$P^2 = \iota_* \circ \underbrace{(\iota_*)^{-1} \circ \iota_*}_{=\text{id}_{T_p \mathcal{S}}} \circ (\iota_*)^{-1} = \iota_* \circ (\iota_*)^{-1} = P, \quad (3.3.14)$$

we infer that  $P$  is a projection map. Moreover, since we have  $\text{rank } P = \text{rank } \iota_* = \dim \mathcal{S} = s$ , we infer that

$$P : T_p \mathcal{M} \rightarrow \text{im}(\iota_*) \quad (3.3.15)$$

is a projector of  $T_p \mathcal{M}$  onto the embedding  $\text{im}(\iota_*)$  of  $T_p \mathcal{S}$  in  $T_p \mathcal{M}$ .

Recall that the left-inverse  $(\iota_*)^{-1}$  is non-unique—it depends on the choice of complement to  $\text{im}(\iota_*)$  during its construction. Without proof, we claim that it is always possible to choose it such that  $P$  satisfies the condition

$$g(P(X), Y) = g(X, P(Y)), \quad X, Y \in T_p \mathcal{M}, \quad (3.3.16)$$

turning  $P$  into an orthogonal projection.

In words, what  $P$  tells us is the following: For any vector  $X \in T_p \mathcal{M}$ , the associated  $P(X) \in \text{im}(\iota_*)$  represents the part of  $X$  that aligns with the tangent space  $T_p \mathcal{S}$  of the submanifold. This construction of  $P$  allows us to split any vector  $X \in T_p \mathcal{M}$  into two parts: a component tangent to the submanifold  $\mathcal{S}$ , and a component orthogonal to it. That is,

$$X = P(X) + (X - P(X)) \quad (3.3.17)$$

where  $P(X) \in \text{im}(\iota_*)$  and  $X - P(X) \in \text{im}(\iota_*)^\perp$ .

What we should take away from this section is the following. The left-inverse  $(\iota_*)^{-1}$  is not particularly interesting on its own, as it is inherently non-unique—its definition depends on an arbitrary choice of complement to  $\text{im}(\iota_*)$ . However, it does enable the construction a projection  $P : T_p \mathcal{M} \rightarrow \text{im}(\iota_*)$ , which can be made into an orthogonal projection by condition (3.3.16), equivalent to the symmetry condition<sup>3</sup>

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<sup>3</sup> $g(P(X), Y) = g_{\mu\nu} P^\mu_\lambda X^\lambda Y^\nu = P_{\mu\nu} X^\mu Y^\nu = P_{\nu\mu} X^\mu Y^\nu = \dots$

$$P_{\mu\nu} = P_{\nu\mu} \quad (3.3.18)$$

where  $P_{\mu\nu} = g_{\mu\lambda} P^\lambda{}_\nu$ . This condition ensures that  $P$  is self-adjoint with respect to the metric  $g$ , and hence defines an orthogonal projection.

When  $P$  is symmetric in this sense, we can interpret it as specifying an orthogonal splitting of the tangent space,

$$T_p\mathcal{M} = \underbrace{\text{im}(\iota_*)}_{\text{tangent to } \mathcal{S}} \oplus \underbrace{\ker(P)}_{\text{normal to } \mathcal{S}}, \quad (3.3.19)$$

where the symbol  $\oplus$  indicates a direct sum of mutually orthogonal subspaces. The image of  $\iota_*$  thus spans the tangent space to the submanifold  $\mathcal{S}$  (or rather, its embedding in  $T_p\mathcal{M}$ ), while the kernel of  $P$  corresponds to vectors in  $T_p\mathcal{M}$  orthogonal to  $\mathcal{S}$ —i.e., the *normal directions*.

### 3.4 Ambient Metric Decomposition and the Pullback of $P_{\mu\nu}$

In the previous section, we saw that for  $P$  to define an *orthogonal* projection, its components must be symmetric with respect to the metric  $g$ . Since the metric tensor itself is symmetric, this hints at the possibility of a decomposition of  $g$  in terms of  $P$  and a complementary projection  $Q$ . The goal of this section is to examine the properties and consequences of such a decomposition.

The symmetry condition for  $P$  was previously written in components as

$$P_{\mu\nu} = P_{\nu\mu}, \quad \text{with} \quad P_{\mu\nu} = g_{\mu\lambda} P^\lambda{}_\nu, \quad (3.4.1)$$

but this can be expressed more naturally in coordinate-free language, which we now introduce.

To do so, we reinterpret  $P$ , originally a  $(1,1)$ -tensor (a linear map on  $T_p\mathcal{M}$ ) as a  $(0,2)$ -tensor by lowering one index using the metric. That is, we define the bilinear form  $\tilde{P}$

$$\tilde{P}(X, Y) = g(P(X), Y), \quad (3.4.2)$$

for all  $X, Y \in T_p\mathcal{M}$ . In components, this reads

$$\tilde{P}(X, Y) = (g_{\mu\lambda} P^\lambda{}_\nu) X^\mu Y^\nu \quad (3.4.3)$$

so the components of  $\tilde{P}$  are precisely what we earlier denoted  $P_{\mu\nu}$ —the object that must be symmetric. Thus, the requirement of symmetry of  $P$  turns into

$$\tilde{P}(X, Y) = \tilde{P}(Y, X), \quad X, Y \in T_p\mathcal{M}. \quad (3.4.4)$$

We will retain the tilde notation for  $\tilde{P}$  throughout this section for clarity. However, it should be understood that identifications between  $(1,1)$ - and  $(0,2)$ -tensors via the metric are always possible, and we may implicitly make such conversions in later sections, slightly abusing notation for brevity.

Having worked out a coordinate-independent symmetry condition for  $P$ , let us now approach the decomposition of the metric in terms of  $\tilde{P}$ . We introduce it as

$$g(X, Y) = \tilde{P}(X, Y) + \tilde{Q}(X, Y), \quad X, Y \in T_p\mathcal{M} \quad (3.4.5)$$

where  $\tilde{Q}$ , trivially given by

$$\tilde{Q}(X, Y) = g(X, Y) - \tilde{P}(X, Y), \quad X, Y \in T_p\mathcal{M}, \quad (3.4.6)$$

is necessarily symmetric as well—due to symmetry of both  $\tilde{P}$  and  $g$ . The components of  $\tilde{Q}$  (and its associated  $(1,1)$ -tensor  $Q$ ) are given by



$$\tilde{Q}_{\mu\nu} = g_{\mu\nu} - P_{\mu\nu} \Leftrightarrow Q^\mu{}_\nu = g^{\mu\lambda}\tilde{Q}_{\lambda\nu} = \delta^\mu_\nu - P^\mu{}_\nu. \quad (3.4.7)$$

Notice that hence,  $Q(X) = X - P(X)$  is nothing but the projection of  $X$  onto the normal space  $\ker(P)$  in the decomposition (3.3.19), and  $\tilde{Q}$  its associated bilinear form. The projections  $P$  and  $Q$  are orthogonally complete, as we have (this is easily verifiable by plugging in definitions)

$$P + Q = \text{id}_{T_p\mathcal{M}}, \quad P \circ Q = Q \circ P = 0. \quad (3.4.8)$$

What we learned thus far is the following: Writing the metric in terms of  $\tilde{P}$  and collecting the remaining parts into  $\tilde{Q}$  naturally decomposes it into a projection onto the embedding of  $T_p\mathcal{S}$  into  $T_p\mathcal{M}$  and its orthogonal complement—the *normal space*  $N_p\mathcal{S} \equiv \ker(P)$ .

Having decomposed the metric, we now consider its pullback onto  $\mathcal{S}$ . Since we have established  $\iota^*g = \gamma$ , i.e., that the ambient metric pulls back to the induced metric, it is natural to ask: which part of  $\gamma$  arises from  $\tilde{P}$ , and which from  $\tilde{Q}$ ? We approach this question from two perspectives: firstly, via a coordinate-independent formulation; then, secondly, by a component-based calculation.

By linearity of  $\iota^*$ , and since  $\iota^*g = \gamma$ , it is sufficient to compute  $\iota^*\tilde{P}$ —this immediately gives us the pullback of  $\tilde{Q}$  via  $\iota^*\tilde{Q} = \gamma - \iota^*\tilde{P}$ . We compute this now; let  $X, Y \in T_p\mathcal{S}$ —then, by definition,

$$\begin{aligned} (\iota^*\tilde{P})(X, Y) &= \tilde{P}(\iota_*X, \iota_*Y) = g(P(\iota_*X), \iota_*Y) = g\left(\underbrace{(\iota_* \circ (\iota_*)^{-1} \circ \iota_*)}_{=\text{id}_{T_p\mathcal{S}}}X, \iota_*Y\right) \\ &= g(\iota_*X, \iota_*Y) = (\iota^*g)(X, Y) = \gamma(X, Y); \\ \Rightarrow \quad \iota^*\tilde{Q} &= \gamma - \gamma = 0. \end{aligned} \quad (3.4.9)$$

In summary, we have found

$$\gamma = \iota^*g = \iota^*\tilde{P} \quad (3.4.10)$$

—hence, the pullback  $\iota^*g$  depends only on the tangential part  $\tilde{P}$ —the normal contribution  $\tilde{Q}$  vanishes under pullback. Notice that  $\text{rank } P = \text{rank } \gamma = \dim \mathcal{S}$ ; in light of the above, this implies that  $\gamma$  and  $\tilde{P}$  represent the same bilinear map on  $T_p\mathcal{S}$  and its embedding  $\text{im}(\iota_*) \subset T_p\mathcal{M}$ .

Let us now repeat the same calculation in components. We find

$$\begin{aligned} (\iota^*\tilde{P})_{ij} &= E^\mu{}_i E^\nu{}_j P_{\mu\nu} = E^\mu{}_i E^\nu{}_j g_{\mu\lambda} P^\lambda{}_\nu = E^\mu{}_i E^\nu{}_j g_{\mu\lambda} E^\lambda{}_k E^k{}_\nu \\ &= E^\mu{}_i \delta_j^k E^\lambda{}_k g_{\mu\lambda} = E^\mu{}_i E^\nu{}_j g_{\mu\nu} = \gamma_{ij}. \end{aligned} \quad (3.4.11)$$

This reproduces the identity (3.4.10) in terms of components as

$$\gamma_{ij} = E^\mu{}_i E^\nu{}_j g_{\mu\nu} = E^\mu{}_i E^\nu{}_j P_{\mu\nu}. \quad (3.4.12)$$

This result offers a clear structural interpretation of the induced metric  $\gamma$ : it is precisely the tangential part of the ambient metric  $g$ , isolated by projection through  $P$  and realised by the pullback. The normal component  $Q$  plays no role in the geometry intrinsic to the submanifold, as expected— $\gamma$  contains only the information relevant to distances and angles *within*  $\mathcal{S}$ . What initially appeared as a simple construction now reveals itself as a direct manifestation of the geometry of orthogonal decomposition.

## 4 Bundles

This section aims to introduce the notion of various types of *bundles* one can define on a smooth manifold. Though this is not strictly necessary to study submanifolds, it seems like it would be

a useful digression to prepare for the differential geometry lecture in Part III, so I will go over it briefly here.

## 4.1 Vector Bundles: Intuition and Definitions

So far, when we discussed vectorial (or tensorial) objects, our expressions have been entirely pointwise. We have considered, for example, maps from  $T_p\mathcal{M}$  to  $T_{\varphi(p)}\mathcal{N}$ , where  $\mathcal{N}$  is another manifold and  $\varphi : \mathcal{M} \rightarrow \mathcal{N}$  is a smooth map between them. These are relations between tangent spaces at individual points.

However, since there exists a tangent space at every point  $p \in \mathcal{M}$ , it is natural to seek a way to *assemble* or *bundle together* all these tangent spaces into a single structure. Intuitively, we take the manifold  $\mathcal{M}$  and, at each point, attach the tangent space at that point. This yields a new, higher-dimensional manifold-like object that encodes all the tangent spaces and their relation to points in  $\mathcal{M}$ . This construction is known as the *tangent bundle*.

Of course, this is a loose and purely intuitive description. In this section, we aim to make rigorous the idea of “attaching a vector space to each point of a manifold” by introducing the notion of a *vector bundle*. In the next section, we will see that the tangent (and cotangent) bundles are special instances of this general concept.

**Definition** (Vector Bundle) Let  $\mathcal{M}$  be a smooth manifold of dimension  $m$ . A *smooth real vector bundle* of rank  $n$  over  $\mathcal{M}$  is a triple  $(\mathcal{E}, \pi, \mathcal{M})$ , where:

1.  $\mathcal{E}$  is a smooth manifold of dimension  $n + m$ , called the *total space*.
2.  $\pi : \mathcal{E} \rightarrow \mathcal{M}$  is a smooth surjective map, called the *bundle projection*.
3. For each  $p \in \mathcal{M}$ , the *fibre*  $\mathcal{E}_p \equiv \pi^{-1}(\{p\})$  is equipped with the structure of a real vector space of dimension  $n$ .
4. We have *local triviality*, i.e. for each  $p \in \mathcal{M}$  there exists an open neighbourhood  $U \subset \mathcal{M}$  of  $p$  and a diffeomorphism

$$\Phi : \pi^{-1}(U) \rightarrow U \times \mathbb{R}^n \quad (4.1.1)$$

such that

- $\Phi$  is a fibre-preserving vector space isomorphism on fibres, meaning that for each  $q \in U$ ,

$$\Phi|_{\mathcal{E}_q} : \mathcal{E}_q \rightarrow \{q\} \times \mathbb{R}^n \simeq \mathbb{R}^n \quad (4.1.2)$$

is a vector space isomorphism.

- the diagram

$$\begin{array}{ccc} \mathcal{E} \supset \pi^{-1}(U) & \xrightarrow{\Phi} & U \times \mathbb{R}^n \\ \pi \downarrow & \swarrow P_1 & \\ U & & \end{array} \quad (4.1.3)$$

commutes, where  $P_1$  is the projection onto the first component of the cartesian product  $((a, b) \mapsto a)$

Let us now go through this definition calmly, and explain the meaning and intuition behind each of the constructions separately.

Firstly, we should give a summary of what a vector bundle is supposed to be. Intuitively, a vector bundle over  $\mathcal{M}$  is a smooth family of vector spaces  $\{\mathcal{E}_p\}_{p \in \mathcal{M}}$ , smoothly parameterised by  $\mathcal{M}$ , such that near each point, the collection of fibres looks like a product  $U \times \mathbb{R}^n$ . This means we can locally identify each fibre with  $\mathbb{R}^n$  in a way that varies smoothly with the base point, and respects the vector space operations.

Now, let us go over each part of the definition in detail.

1. *Total Space*: The total space  $\mathcal{E}$  can be viewed as the union of all the vector spaces at each point. Formally, it is the disjoint union of all fibres,

$$\mathcal{E} = \bigsqcup_{p \in \mathcal{M}} \mathcal{E}_p. \quad (4.1.4)$$

This is an  $(m+n)$ -dimensional manifold, since the base manifold has dimension  $\mathcal{M}$ , and attaching an  $n$ -dimensional vector space at each point increases the dimension by  $n$ .

Very loosely, one might imagine this as dragging a window (the vector space) across a screen (the manifold) in Windows XP, with the bug that leaves behind a smeared trail of it. As you drag it, the trail being formed represents this union of all these smeared copies (counting overlapping regions appropriately), which is what is known as the total space.

2. *Bundle Projection*: A point in  $\mathcal{E}$  encodes two pieces of information: a point  $p \in \mathcal{M}$ , and a vector attached to it, describing a *direction from*  $p$ . The bundle projection's job is simple: it takes such a pair and tells us to which point on the base manifold it belongs.

It must be surjective, so that each point  $p \in \mathcal{M}$  has a corresponding vector space attached to it. If it were not surjective, there would exist some  $p$  for which no vectors are associated, contradicting the idea of “attaching a vector space at each point”.

3. *Fibres*: The fibre at  $p \in \mathcal{M}$  is the collection of all vectors attached or associated to  $p$ , i.e. its preimage under the bundle projection  $\pi$ . More precisely,

$$\mathcal{E}_p = \pi^{-1}(\{p\}). \quad (4.1.5)$$

Since we want to attach not just *any* kind of fibre, but specifically an  $n$ -dimensional vector space, we impose the additional requirement that each fibre  $\mathcal{E}_p$  carries the structure of a real vector space of dimension  $n$ .

4. *Local Triviality*: This is likely the most convoluted part of the definition, but can also be broken down intuitively. What local triviality demands is that *locally*, in some neighbourhood  $U \subset \mathcal{M}$  of  $p \in \mathcal{M}$ , the total space  $\mathcal{E}$  “looks like” the space  $U \times \mathbb{R}^n$ . This is the simplest way of “attaching vector spaces to each point”—the cartesian product does exactly that. In more formal terms, “looks like” is replaced by the notion of the diffeomorphism  $\Phi$ . Since  $\mathbb{R}^n$  is the concrete representation of the attached vector space, we would also like the fibres  $\mathcal{E}_q$ ,  $q \in U$  to map to  $\mathbb{R}^n$  under  $\Phi$  in a way that respects the algebraic structure—hence the condition on  $\Phi|_{\mathcal{E}_q}$ . The requirement that the diagram (4.1.3) commutes then further ensures that the fibres get attached to the correct points on  $\mathcal{M}$ .

Now that we have defined vector bundles, let us introduce a notion that makes use of it. Specifically, we consider so-called *smooth sections* of vector bundles. A smooth section is, intuitively speaking, the selection of one vector in the fibre  $\mathcal{E}_p$  at each  $p \in \mathcal{M}$ , in a way that creates a smooth surface in the total space  $\mathcal{E}$ . Such a surface can be viewed as a vector field, since it maps each point on the manifold to one vector in its fibre.

**Definition** (Smooth Section) Let  $\mathcal{M}$  be a smooth manifold and  $(\mathcal{E}, \pi, \mathcal{M})$  a smooth real vector bundle over  $\mathcal{M}$ . A *smooth section* of  $\mathcal{E}$  is a smooth map

$$\sigma : \mathcal{M} \rightarrow \mathcal{E} \quad (4.1.6)$$

such that

$$\pi \circ \sigma = \text{id}_{\mathcal{M}} \quad (4.1.7)$$

In other words, for each  $p \in \mathcal{M}$ , the map  $\sigma$  selects a vector  $\sigma(p) \in \mathcal{E}_p$  lying in the fibre over  $p$ , and this assignment varies smoothly with  $p$ . In particular, for  $\pi \circ \sigma$  to be the identity on  $\mathcal{M}$ ,  $\sigma$  must be injective.

We denote the set of all smooth sections of  $\mathcal{E}$  by

$$\begin{aligned} \Gamma(\mathcal{E}) &= \{\sigma : \mathcal{M} \rightarrow \mathcal{E} \mid \pi \circ \sigma = \text{id}_{\mathcal{M}}, \sigma \text{ smooth}\}, \\ &= \{\sigma : \mathcal{M} \rightarrow \mathcal{E} \mid \sigma \text{ smooth section on } \mathcal{E}\}. \end{aligned} \quad (4.1.8)$$

This is a real vector space under pointwise addition and scalar multiplication. In the case where  $\mathcal{E} = T\mathcal{M}$  is the tangent bundle (which we introduce in the next section),  $\Gamma(T\mathcal{M})$  is the space of smooth vector fields on  $\mathcal{M}$ .

We are now prepared for the next section, in which we will define the tangent and cotangent bundles  $T\mathcal{M}$  and  $T^*\mathcal{M}$ , and use smooth sections to give an alternative perspective on vector fields and differential 1-forms.

## 4.2 The Tangent and Cotangent Bundles

In this section, we introduce the two most important vector bundles in differential geometry: the tangent bundle  $T\mathcal{M}$  and the cotangent bundle  $T^*\mathcal{M}$ . In essence, these are the special cases where one chooses the fibres  $\mathcal{E}_p$  of a vector bundle to be the (co)-tangent spaces  $T_p\mathcal{M}$  and  $T_p^*\mathcal{M}$ , respectively—but let us now introduce this rigorously.

**Definition** (Tangent Bundle) Let  $\mathcal{M}$  be a smooth manifold of dimension  $m$  and denote by  $T_p\mathcal{M}$  its tangent space at any point  $p \in \mathcal{M}$ . Define the  $2m$ -dimensional total space  $T\mathcal{M}$  by the disjoint union

$$T\mathcal{M} = \bigsqcup_{p \in \mathcal{M}} T_p\mathcal{M}. \quad (4.2.1)$$

We define the bundle projection

$$\pi : T\mathcal{M} \rightarrow \mathcal{M} \quad (4.2.2)$$

as the map

$$\pi(p, v) = p, \quad (4.2.3)$$

choosing to write elements of  $T\mathcal{M}$  as pairs  $(p, v)$  with  $v \in T_p\mathcal{M}$ .

**Remarks:** A few direct consequences follow from this construction:

- *Fibres:* The fibre over a point  $p \in \mathcal{M}$  is given by

$$(T\mathcal{M})_p = \pi^{-1}(\{p\}) = T_p\mathcal{M}, \quad (4.2.4)$$

meaning that we are indeed attaching the tangent space  $T_p\mathcal{M}$  to each point  $p$ .

- *Local triviality and charts on  $T\mathcal{M}$ :* Given a coordinate chart  $(U, x^\mu)$  on  $\mathcal{M}$ , we can define a chart on the preimage  $\pi^{-1}(U) \subset T\mathcal{M}$  by identifying

$$\pi^{-1}(U) \simeq U \times \mathbb{R}^m, \quad (p, V) \mapsto (x^{\mu(p)}, V^{\mu}), \quad (4.2.5)$$

where  $V^{\mu}$  are the components of the tangent vector  $V = V^{\mu} \partial_{\mu}$  in the coordinate basis induced by  $x^{\mu}$ . This provides  $T\mathcal{M}$  with a smooth manifold structure of dimension  $2m$ .

- *Zero section:* We may define the zero section

$$\sigma_0 : \mathcal{M} \rightarrow T\mathcal{M}, \quad p \mapsto (p, 0), \quad (4.2.6)$$

or, in coordinates,

$$x^{\mu} \mapsto (x^{\mu}, 0), \quad (4.2.7)$$

where 0 denotes the zero vector in  $T_p\mathcal{M}$ . This map is a smooth embedding, and its image forms a submanifold of  $T\mathcal{M}$  diffeomorphic to  $\mathcal{M}$  itself.

Intuitively, this makes perfect sense: if we attach a vector space to each point of the manifold in such a way that their origins coincide with the base points, then the collection of those origins sweeps out a copy of  $\mathcal{M}$  embedded inside  $T\mathcal{M}$ .

- *Vector fields as section:* Any smooth vector field on  $\mathcal{M}$ , i.e. a smooth assignment  $X : p \mapsto X_p \in T_p\mathcal{M}$ , is precisely a smooth section of the tangent bundle,

$$X : \mathcal{M} \rightarrow T\mathcal{M}, \quad \text{with} \quad \pi \circ X = \text{id}_{\mathcal{M}}. \quad (4.2.8)$$

That is,  $X \in \Gamma(T\mathcal{M})$ . This is the prototypical example of a smooth section, and shows how the familiar notion of a vector field fits directly into the general formalism of vector bundles.

**Definition** (Cotangent Bundle) The definition of the cotangent bundle is analogous to that of the tangent bundle, with the distinction being that we use

$$T^*\mathcal{M} = \bigsqcup_{p \in \mathcal{M}} T_p^*\mathcal{M} \quad (4.2.9)$$

as our total space, and the bundle projection

$$\pi : T^*\mathcal{M} \rightarrow \mathcal{M} \quad (4.2.10)$$

now given by the map

$$\pi(p, \omega) = p, \quad (4.2.11)$$

writing elements of  $T^*\mathcal{M}$  as pairs  $(p, \omega)$  with  $\omega \in T_p^*\mathcal{M}$ . The same remarks as for the tangent bundle hold, with the occasional change of terminology from vectors to 1-forms.

### 4.3 Bundle Maps and Vector Bundle Morphisms

Now that we have introduced the notion of vector bundles as well as concrete (and important) examples thereof, the tangent bundle  $T\mathcal{M}$  and the cotangent bundle  $T^*\mathcal{M}$ , we can begin considering maps between them. A map between two tangent bundles becomes particularly interesting if it respects the algebraic structure of the fibres—i.e., if it maps vectors in one fibre linearly to vectors in another. Such maps we will refer to as *bundle morphisms*. We now first introduce the more general concept of a bundle map, and then impose the additional algebraic structure to define the notion of bundle morphisms.

**Definition** (Bundle Map) Let  $\mathcal{M}, \mathcal{N}$  be smooth manifolds and  $(\mathcal{E}, \pi_{\mathcal{M}}, \mathcal{M})$  as well as  $(\mathcal{F}, \pi_{\mathcal{N}}, \mathcal{N})$  vector bundles on them. Further, let

$$\varphi : \mathcal{M} \rightarrow \mathcal{N} \quad (4.3.1)$$

be a smooth map from one manifold to the other. We call a map

$$\Phi : \mathcal{E} \rightarrow \mathcal{F} \quad (4.3.2)$$

a *bundle map* if the following diagram commutes:

$$\begin{array}{ccc} \mathcal{E} & \xrightarrow{\Phi} & \mathcal{F} \\ \pi_{\mathcal{M}} \downarrow & & \downarrow \pi_{\mathcal{N}} \\ \mathcal{M} & \xrightarrow{\varphi} & \mathcal{N} \end{array} \quad (4.3.3)$$

This is equivalent to the condition that

$$\pi_{\mathcal{N}} \circ \Phi = \varphi \circ \pi_{\mathcal{M}}. \quad (4.3.4)$$

Without further interpretation, the definition above may seem opaque—so let us walk through it and develop some intuition. Consider an element  $(p, X) \in \mathcal{E}$ , where  $p \in \mathcal{M}$  and  $X \in \mathcal{E}_p$ , the fibre over  $p$ . We examine the two sides of the condition (4.3.4) act on such a point.

Starting with the right-hand side, we have

$$(\varphi \circ \pi_{\mathcal{M}})(p, X) = \varphi(\pi_{\mathcal{M}}(p, X)) = \varphi(p). \quad (4.3.5)$$

this means we first project  $(p, X)$  onto its base point  $p \in \mathcal{M}$  via  $\pi_{\mathcal{M}}$ , then apply  $\varphi$  to obtain a point in  $\mathcal{N}$ .

Now for the left-hand side:

$$(\pi_{\mathcal{N}} \circ \Phi)(p, X) = \pi_{\mathcal{N}}(\Phi(p, X)) = \pi_{\mathcal{N}}(q, Y) = q. \quad (4.3.6)$$

Here, we write  $\Phi(p, X)$  as some pair  $(q, Y) \in \mathcal{F}$ , and  $\pi_{\mathcal{N}}$  returns the base point  $q \in \mathcal{N}$ .

Thus, the commutativity condition simplifies to

$$q = \varphi(p). \quad (4.3.7)$$

In other words, a bundle map  $\Phi$  must map  $(p, X) \in \mathcal{E}$  to  $(\varphi(p), Y) \in \mathcal{F}$ ; the base point of the image is determined entirely by the underlying map  $\varphi$ . The vector part  $Y$  can be chosen freely (within the fibre over  $\varphi(p)$ ), but the association between fibres is rigidly tied to that between base points.

A third, equivalent way to phrase this is to say that  $\Phi$  maps each fibre  $\mathcal{E}_p$  into the fibre  $\mathcal{F}_{\varphi(p)}$ . That is,

$$\Phi|_{\mathcal{E}_p} : \mathcal{E}_p \rightarrow \mathcal{F}_{\varphi(p)}. \quad (4.3.8)$$

The content of the definition is precisely this: a bundle map over  $\varphi$  is one that maps vectors attached to a point  $p \in \mathcal{M}$  into vectors attached to  $\varphi(p) \in \mathcal{N}$ , without violating the structure of the fibration.

Besides the structure of the fibration, a vector bundle has additional algebraic structure that one could demand to be preserved; each fibre is a vector space, and we could demand a bundle map to respect it by imposing linearity. This notion, called *bundle morphisms*, is what we now define rigorously.

**Definition** (Vector Bundle Morphism) Let  $\mathcal{M}, \mathcal{N}$  be smooth manifolds, and let  $(\mathcal{E}, \pi_{\mathcal{M}}, \mathcal{M})$  and  $(\mathcal{F}, \pi_{\mathcal{N}}, \mathcal{N})$  be smooth real vector bundles over them. Suppose we are given a smooth map  $\varphi : \mathcal{M} \rightarrow \mathcal{N}$  and a bundle map  $\Phi : \mathcal{E} \rightarrow \mathcal{F}$  covering  $\varphi$ , i.e.

$$\pi_{\mathcal{N}} \circ \Phi = \varphi \circ \pi_{\mathcal{M}}. \quad (4.3.9)$$

We say that  $\Phi$  is a *vector bundle morphism* (over  $\varphi$ ) if, for each  $p \in \mathcal{M}$ , the induced map on the fibres

$$\Phi|_{\mathcal{E}_p} : \mathcal{E}_p \rightarrow \mathcal{F}_{\varphi(p)} \quad (4.3.10)$$

is a linear map of vector spaces.

Intuitively, a vector bundle morphism over  $\varphi$  can be seen as a fibrewise linear transformation that “respects the base”: it transforms each vector in a fibre over  $p \in \mathcal{M}$  to a vector in the fibre over  $\varphi(p) \in \mathcal{N}$ , via a linear map.

While there are many abstract vector bundle morphisms one could define and study, there is a particularly natural one associated with a smooth map  $\varphi : \mathcal{M} \rightarrow \mathcal{N}$  that we have already encountered: the pushforward. Though we initially introduced the pushforward  $\varphi_* : T_p\mathcal{M} \rightarrow T_{\varphi(p)}\mathcal{N}$  as a pointwise linear map between tangent spaces, it readily extends to a global vector bundle morphism.

To see this, consider the map

$$\Phi : T\mathcal{M} \rightarrow T\mathcal{N}, \quad (p, X) \mapsto (\varphi(p), \varphi_*X), \quad p \in \mathcal{M}, X \in T_p\mathcal{M}. \quad (4.3.11)$$

This construction maps each element of the tangent bundle  $T\mathcal{M}$  to the tangent bundle  $T\mathcal{N}$  by pushing forward the vector  $X$  and sending its base point  $p$  to  $\varphi(p)$ . It is easy to check that this satisfies the bundle map condition

$$\pi_{\mathcal{N}} \circ \Phi = \varphi \circ \pi_{\mathcal{M}}, \quad (4.3.12)$$

and that the fibrewise maps  $\Phi|_{T_p\mathcal{M}} = \varphi_* : T_p\mathcal{M} \rightarrow T_{\varphi(p)}\mathcal{N}$  are linear. Hence,  $\Phi$  defines a (vector) bundle morphism from  $T\mathcal{M}$  to  $T\mathcal{N}$  over  $\varphi$ .

## 4.4 The Normal Bundle and Orthogonal Decomposition

In this section, we explore how the tangent bundle  $T\mathcal{S}$  of a submanifold  $\mathcal{S} \subset \mathcal{M}$  can be understood as a subbundle of the restriction of the tangent bundle  $T\mathcal{M}$  to  $\mathcal{S}$ . Further, we define the normal bundle  $N\mathcal{S}$  and explain how the pointwise projections  $P$  and  $Q$ , as introduced earlier, extend naturally to smooth vector bundle morphisms between  $T\mathcal{M}|_{\mathcal{S}}$ ,  $T\mathcal{S}$  and  $N\mathcal{S}$ . While this may seem like an unnecessary abstraction at first glance, it will turn out to offer geometric clarity and prepare us for later constructions involving intrinsic curvature.

**Definition** (Restriction of vector bundles to submanifolds) Let  $\mathcal{M}$  be a smooth manifold of dimension  $m$ , and let  $\mathcal{S} \subset \mathcal{M}$  be a submanifold of dimension  $s < m$ . Given a vector bundle  $(\mathcal{E}, \pi, \mathcal{M})$  over  $\mathcal{M}$ , its *restriction to  $\mathcal{S}$*  is defined as the triple

$$(\mathcal{E}|_{\mathcal{S}}, \pi|_{\mathcal{S}}, \mathcal{S}), \quad \text{where } \mathcal{E}|_{\mathcal{S}} \equiv \pi^{-1}(\mathcal{S}) \subset \mathcal{E}. \quad (4.4.1)$$

This construction simply discards all fibres of  $\mathcal{E}$  lying over points  $p \in \mathcal{M} \setminus \mathcal{S}$ , retaining only the portion of the bundle sitting above  $\mathcal{S}$ .

As a key example, consider the tangent bundle  $T\mathcal{M}$ . Its restriction to  $\mathcal{S}$ , denoted by  $T\mathcal{M}|_{\mathcal{S}}$ , consists of the collection of tangent spaces  $T_p\mathcal{M}$  for  $p \in \mathcal{S}$ . This restricted bundle is not the same as the tangent bundle of  $\mathcal{S}$ —the fibres of  $T\mathcal{M}|_{\mathcal{S}}$  are  $m$ -dimensional, while the fibres of  $T\mathcal{S}$  are only  $s$ -dimensional.

However, the inclusion map  $\iota : \mathcal{S} \rightarrow \mathcal{M}$  induces a smooth injective bundle morphism

$$\iota_* : T\mathcal{S} \rightarrow T\mathcal{M}|_{\mathcal{S}} \quad (4.4.2)$$

which embeds each fibre  $T_p\mathcal{S} \subset T_p\mathcal{M}$  for  $p \in \mathcal{S}$ . As a result,  $T\mathcal{S}$  is realised as a smooth vector subbundle of  $T\mathcal{M}|_{\mathcal{S}}$ . This perspective will be useful not only for defining and understanding the normal bundle but also for lifting previously pointwise constructions—such as the projections  $P$  and  $Q$ —into global morphisms between bundles.

Recall that for any submanifold  $\mathcal{S} \subset \mathcal{M}$  of a (pseudo-)Riemannian manifold  $\mathcal{M}$ , we obtain a canonical orthogonal decomposition of the tangent space at each point  $p \in \mathcal{S}$ ,

$$T_p\mathcal{M} = T_p\mathcal{S} \oplus N_p\mathcal{S}, \quad (4.4.3)$$

where  $T_p\mathcal{S} \subset T_p\mathcal{M}$  is identified via the pushforward  $\iota_*$  of the inclusion  $\iota : \mathcal{S} \rightarrow \mathcal{M}$ , and the normal space  $N_p\mathcal{S}$  is defined as the orthogonal complement

$$N_p\mathcal{S} = (T_p\mathcal{S})^\perp \subset T_p\mathcal{M}. \quad (4.4.4)$$

Note that  $\dim N_p\mathcal{S} = \text{codim}_{\mathcal{M}} \mathcal{S}$ , so that  $\dim T_p\mathcal{S} + \dim N_p\mathcal{S} = \dim T_p\mathcal{M}$ .

Just as bundling the tangent spaces  $T_p\mathcal{S}$  yields the tangent bundle  $T\mathcal{S}$ , we may bundle the normal spaces to obtain a smooth vector bundle over  $\mathcal{S}$ . We now define this more precisely.

**Definition** (Normal bundle) Let  $\mathcal{S} \subset \mathcal{M}$  be an embedded submanifold of a (pseudo-)Riemannian manifold  $\mathcal{M}$ . The *normal bundle*  $N\mathcal{S}$  is the smooth vector bundle over  $\mathcal{S}$  defined by

$$N\mathcal{S} \equiv \bigsqcup_{p \in \mathcal{S}} N_p\mathcal{S}, \quad \pi : N\mathcal{S} \rightarrow \mathcal{S}, \quad (p, X) \mapsto p, \quad (4.4.5)$$

choosing the normal spaces at each  $p \in \mathcal{S}$  as the fibres.

Since the decomposition

$$T_p\mathcal{M} = T_p\mathcal{S} \oplus N_p\mathcal{S} \quad (4.4.6)$$

is orthogonal and varies smoothly with  $p$ , the total bundle  $T\mathcal{M}|_{\mathcal{S}}$  likewise decomposes as a direct sum of vector bundles,

$$T\mathcal{M}|_{\mathcal{S}} = T\mathcal{S} \oplus N\mathcal{S}. \quad (4.4.7)$$

Here, the direct sum  $\oplus$  is understood as the fibrewise orthogonal sum within each  $T_p\mathcal{M}$ .

Let us make a final addition to the bundle perspective we have been building in this section. Specifically, let us consider how the orthogonal projections

$$\begin{aligned} P : T_p\mathcal{M} &\rightarrow \text{im}(P) = T_p\mathcal{S} \quad \text{and} \\ Q : T_p\mathcal{M} &\rightarrow \text{im}(Q) = \ker(P) = N_p\mathcal{S} \end{aligned} \quad (4.4.8)$$

are lifted from their pointwise definitions to smooth vector bundle morphisms. Since these projections were defined for each  $p \in \mathcal{S}$  using the orthogonal decomposition (4.4.6) and since this splitting varies smoothly over  $\mathcal{S}$ , we obtain globally defined, smooth bundle morphisms

$$P : T\mathcal{M}|_{\mathcal{S}} \rightarrow T\mathcal{S}, \quad Q : T\mathcal{M}|_{\mathcal{S}} \rightarrow N\mathcal{S}, \quad (4.4.9)$$

which act fibrewise as the orthogonal projections onto  $T_p\mathcal{S}$  and  $N_p\mathcal{S}$ , respectively. Both  $P$  and  $Q$  are idempotent ( $P^2 = P$ ,  $Q^2 = Q$ ) and satisfy

$$\ker P = \text{im } Q \quad \text{and} \quad \ker Q = \text{im } P, \quad (4.4.10)$$

pointwise. This allows us to view the splitting (4.4.7) not merely as a statement about individual tangent spaces, but as a decomposition of vector bundles, mediated by smooth projections.



## 5 Foliations

### 5.1 Motivation and Definition of Foliations

In the previous sections, we introduced and examined submanifolds of (pseudo-)Riemannian manifolds in detail, including the tensorial structures they inherit—such as the induced metric. Rather than focusing on isolated submanifolds, we now turn our attention to decompositions of an entire manifold  $\mathcal{M}$  into a smooth family of non-intersecting submanifolds. Such decompositions, often referred to as foliations, arise naturally in a variety of settings. In the ADM formalism, for instance, foliating spacetime into spacelike hypersurfaces allows one to isolate a direction of dynamical evolution—typically a timelike one. In other contexts, such as the study of flows or congruences, one may be interested in decompositions into curves or integral lines.

Either way, the concept of splitting a manifold into lower-dimensional submanifolds is fundamental, and we now develop it in the form of *foliations*. In this section, we focus on the case of hypersurfaces, i.e., submanifolds of codimension 1. Such a foliation can be described as a one-parameter family  $\Sigma_{t_0} \subset \mathcal{M}$  of hypersurfaces labelled by the parameter  $t_0 \in \mathbb{R}$ .

**Definition (Foliation)** Let  $\mathcal{M}$  be a smooth manifold. A *foliation of codimension 1* is a family  $\{\Sigma_{t_0}\}_{t_0 \in \mathbb{R}}$  of smooth, embedded hypersurfaces  $\Sigma_{t_0} \subset \mathcal{M}$  such that

$$\Sigma_{t_0} \cap \Sigma_{t'_0} = \emptyset \quad \text{for } t_0 \neq t'_0, \quad \text{and} \quad \mathcal{M} = \bigsqcup_{t_0 \in \mathbb{R}} \Sigma_{t_0}. \quad (5.1.1)$$

The hypersurfaces  $\Sigma_{t_0}$  are referred to as the *leaves* of the foliation.

This definition, while clean, hides a more powerful and flexible characterisation. Since the leaves are disjoint and cover all of  $\mathcal{M}$ , each point  $p \in \mathcal{M}$  lies in a unique leaf  $\Sigma_{t_0}$ . We can therefore associate to each point its corresponding label  $t_0$ , giving rise to a map

$$t : \mathcal{M} \rightarrow \mathbb{R}, \quad t(p) = t_0 \text{ such that } p \in \Sigma_{t_0}. \quad (5.1.2)$$

This defines a smooth scalar field on  $\mathcal{M}$ , and the leaves of the foliation may then be expressed as the family of level sets

$$\Sigma_{t_0} = t^{-1}(t_0). \quad (5.1.3)$$

In order for each  $\Sigma_{t_0}$  to be a smooth hypersurface, we require  $t_0$  to be a regular value of  $t$ . For this to hold for all  $t_0$ , we demand  $t$  be a *submersion*, i.e.

$$dt \neq 0 \quad \text{everywhere.} \quad (5.1.4)$$

We thus arrive at an equivalent perspective: a codimension-1 foliation of  $\mathcal{M}$  may be defined by a scalar field  $t : \mathcal{M} \rightarrow \mathbb{R}$  whose differential is nowhere vanishing. Its level sets then define the leaves of the foliation.

This point of view has practical consequences. Given a chart  $(x^\mu, U)$ , a (local) foliation may be defined by holding one coordinate constant:

$$\Sigma_{t_0} = \{p \in U \mid x^{\mu_0}(p) = t_0\}, \quad (5.1.5)$$

which trivially satisfies  $dx^{\mu_0} \neq 0$  since  $x^{\mu_0}$  is a coordinate function.

Conversely, if a scalar field  $t(x^\mu)$  defines a foliation via  $dt \neq 0$ , then  $t$  can be extended to a local coordinate chart. That is, there exist coordinates  $y^\mu = (t, y^i)$ ,  $i = 1, \dots, \dim \mathcal{M} - 1$ , such that each  $\Sigma_t$  is locally given by fixing  $t$  and varying the  $y^i$ . Such coordinate systems are called (*weakly*)

*adapted coordinates* for the foliation induced by  $t$ , and we will make use of them in the coordinate-based derivations that follow.

## 5.2 The Normal 1-Form and Normal Vector Field

The choice of a foliation of a manifold  $\mathcal{M}$  naturally gives rise to a host of associated mathematical objects, each playing its own role in its geometry. Among the most central of these is the normal vector field, together with its corresponding one-form. In what follows, we shall first build some intuition for why such an object may be constructed, before proceeding to define it rigorously.

As we have seen previously, a submanifold  $\mathcal{S} \subset \mathcal{M}$  induces, at each point  $p \in \mathcal{S}$ , a decomposition

$$T_p \mathcal{M} = T_p \mathcal{S} \oplus N_p \mathcal{S}, \quad (5.2.1)$$

splitting the tangent space of  $\mathcal{M}$  into components tangent and normal to  $\mathcal{S}$ . However, this decomposition is inherently local to  $\mathcal{S}$ ; at points  $p \in \mathcal{M}$  outside of  $\mathcal{S}$ , the notions  $T_p \mathcal{S}$  and  $N_p \mathcal{S}$  have no meaning. Hence one cannot define a vector field on  $\mathcal{M}$  with the property that it is normal to  $\mathcal{S}$  everywhere—this statement simply does not make sense away from  $\mathcal{S}$ .

A foliation  $\Sigma = \{\Sigma_t\}_{t \in \mathbb{R}}$  changes this picture dramatically. Given such a foliation, every point  $p \in \mathcal{M}$  belongs to a unique leaf  $\Sigma_{t(p)}$ , for a unique  $t(p) \in \mathbb{R}$ . Consequently, we may write

$$T_p \mathcal{M} = T_p \Sigma_{t(p)} \oplus N_p \Sigma_{t(p)}, \quad (5.2.2)$$

thereby defining a decomposition into tangent and normal directions at *every* point of  $\mathcal{M}$ . In other words, a foliation allows us to speak globally about directions that are tangent or normal to the slices  $\Sigma_t$ , since every point of  $\mathcal{M}$  lies on precisely one such submanifold.

At this point it is natural to briefly revisit the notion of vector bundles. Using the decomposition (5.2.2), we may define two vector bundles over  $\mathcal{M}$  that together decompose the tangent bundle  $T\mathcal{M}$ . Namely,

$$T\Sigma = \bigsqcup_{p \in \mathcal{M}} T_p \Sigma_{t(p)}, \quad N\Sigma = \bigsqcup_{p \in \mathcal{M}} N_p \Sigma_{t(p)}, \quad (5.2.3)$$

equipped with their canonical projections onto  $\mathcal{M}$ , yield the tangent bundle and normal bundle of the foliation, respectively. It is then immediate that the tangent bundle of the manifold decomposes as

$$T\mathcal{M} = T\Sigma \oplus N\Sigma. \quad (5.2.4)$$

We may now also formalise the notion of a *normal vector field*. Recall that a vector field on  $\mathcal{M}$  is a smooth section of the tangent bundle  $T\mathcal{M}$ . Given the decomposition (5.2.4) we call a vector field *tangent* to the foliation  $\Sigma$  if it is a smooth section of  $T\Sigma$ , and *normal* to  $\Sigma$  if it is a smooth section of  $N\Sigma$ . In more elementary terms, a vector field  $X$  is tangent (respectively normal), if at each point  $p \in \mathcal{M}$ , the vector  $X(p)$  lies in the subspace  $T_p \Sigma_t$  (respectively,  $N_p \Sigma_t$ ) associated to the unique slice  $\Sigma_t$  containing  $p$ .

In our specific case of a codimension-one foliation, the normal spaces  $N_p \Sigma_{t(p)}$  are one-dimensional at every point. This observation is powerful: it implies that any vector field normal to the foliation can be written as a scalar multiple of a single, globally defined, nowhere-vanishing basis vector field. Concretely, we may express any such field  $X$  as

$$X = \lambda n^\sharp, \quad (5.2.5)$$

where  $n^\sharp$  denotes a chosen normal vector field, and  $\lambda$  is a smooth scalar function on  $\mathcal{M}$ . The use of the musical isomorphism in this notation is deliberate: rather than constructing  $n^\sharp$  directly, it

is often more natural to begin with a normal one-form  $n$ , and then obtain the vector field  $n^\sharp$  via the defining identity

$$g(n^\sharp, X) = n(X) \quad \forall X \quad \Leftrightarrow \quad (n^\sharp)^\mu = n^\mu = g^{\mu\nu} n_\nu. \quad (5.2.6)$$

If the normal subspaces  $N_p \Sigma_{t(p)}$  are timelike (or spacelike) everywhere, then we may impose a canonical normalisation to fix  $n^\sharp$  uniquely (up to sign),

$$g(n^\sharp, n^\sharp) = \begin{cases} -1, & \text{timelike,} \\ +1, & \text{spacelike.} \end{cases} \quad (5.2.7)$$

This condition pins down a distinguished unit normal vector field. However, we have not yet addressed how to construct such a form or field in practice.

Let us now turn to this task. For a vector field  $n^\sharp$  to be normal to the foliation  $\Sigma$ , it must satisfy

$$g(n^\sharp, X) = 0, \quad \forall X \in T_p \Sigma_{t(p)} \quad (5.2.8)$$

at every point  $p \in \mathcal{M}$ ; that is,  $n^\sharp$  must be orthogonal to all vectors tangent to the slice  $\Sigma_t$  through  $p$ . By the defining property of the musical isomorphism, this is equivalent to requiring

$$n(X) = 0 \quad \forall X \in T_p \Sigma_{t(p)} \quad (5.2.9)$$

i.e. the 1-form  $n$  must annihilate all tangent vectors to the foliation.

This insight significantly simplifies the problem in adapted coordinates. Let  $x^\mu = (t, y^i)$  be a coordinate chart adapted to the foliation, so that each slice  $\Sigma_t$  is locally given by  $t = \text{const.}$ , and the  $y^i$  serve as coordinates on each leaf. Then the tangent space to  $\Sigma_t$  at  $p$  is spanned by the coordinate basis vectors

$$T_p \Sigma_{t(p)} = \text{span} \left\{ \partial_i = \frac{\partial}{\partial y^i} \mid i = 1, \dots, \dim \mathcal{M} - 1 \right\}. \quad (5.2.10)$$

We thus seek a 1-form  $n$  satisfying

$$n(\partial_i) = 0 \quad i = 1, \dots, \dim \mathcal{M} - 1. \quad (5.2.11)$$

The standard coordinate duality relation

$$dx^\mu(\partial_\nu) = \delta^\mu_\nu \quad (5.2.12)$$

immediately suggests a solution: the 1-form

$$n = \alpha dt \quad (5.2.13)$$

clearly satisfies condition (5.2.11), as

$$n(\partial_i) = \alpha dt(\partial_i) = \delta_i^t = 0. \quad (5.2.14)$$

Here,  $\alpha$  is a smooth scalar field on  $\mathcal{M}$ , to be determined by a normalisation condition. If we require  $n^\sharp$  to be unit-normalised, this yields the relation

$$\pm 1 = g(n^\sharp, n^\sharp) = g^{\mu\nu} n_\mu n_\nu = \alpha^2 g^{tt} \quad \Leftrightarrow \quad g^{tt} = \frac{\pm 1}{\alpha^2}. \quad (5.2.15)$$

Moreover, the components of  $n^\sharp$  can be written in terms of the metric as well,

$$(n^\sharp)^\mu = n^\mu = g^{\mu\nu} n_\nu = \alpha g^{\mu\nu} \delta_\nu^t = \alpha g^{\mu t}. \quad (5.2.16)$$

In hindsight, it is only natural that the function  $t : \mathcal{M} \rightarrow \mathbb{R}$  which defines the foliation  $\Sigma$  plays a central role in the construction of the normal form. After all, moving along the gradient of  $t$  corresponds to moving between leaves, so it makes sense that for an arbitrary set of coordinates  $\bar{x}^\alpha$ ,

$$dt = \partial_\alpha t d\bar{x}^\alpha \quad (5.2.17)$$

somehow encodes the normal direction.

This construction of  $n$  as being proportional to  $dt$  was rather simple in coordinates. Keeping with the spirit of these notes, though, we should also show the equivalence

$$dt_p(X) = 0 \iff X \in T_p \Sigma_{t(p)} \quad (5.2.18)$$

in a coordinate-independent way. This is not that hard, and gives some additional geometric intuition as it makes use of the definition of tangent spaces in terms of derivatives along curves.

*Proof:* (of eq. (5.2.18)) We first prove the implication “ $\Leftarrow$ ”. Let  $X \in T_p \Sigma_{t(p)}$ . Then there exists a smooth curve  $\gamma : (-\varepsilon, \varepsilon) \rightarrow \Sigma_{t(p)} \subset \mathcal{M}$  with  $\gamma(0) = p$  and  $\dot{\gamma}(0) = X$ , such that for any  $f \in C^\infty(\mathcal{M})$ ,

$$X[f] = \frac{d}{ds} f(\gamma(s))|_{s=0}. \quad (5.2.19)$$

In particular,

$$dt(X) = X[t] = \frac{d}{ds} t(\gamma(s)) = \frac{d}{ds} t(p) = 0, \quad (5.2.20)$$

since  $\gamma(s) \in \Sigma_t = t^{-1}(t(p))$  implies  $t(\gamma(s)) = t(p)$  identically (and hence is constant).

For the converse, note that  $dt \neq 0$  everywhere by construction, and  $\text{codim } T_p \Sigma_t(p) = 1$ . Hence, for any vector  $X \in T_p \mathcal{M} \setminus T_p \Sigma_{t(p)}$ , we must have  $dt(X) \neq 0$ , otherwise  $dt_p$  would vanish on all of  $T_p \mathcal{M}$ , contradicting  $dt \neq 0$ . This implies

$$T_p \Sigma_{t(p)} = \ker(dt_p), \quad (5.2.21)$$

which establishes the equivalence.  $\square$

We can even take the pointwise identification (5.2.21) one step further. To this end, let us define the notion of a kernel of a differential 1-form  $\omega \in \Gamma(T^* \mathcal{M})$ . At any point  $p$ , we have

$$\ker(\omega_p) = \{X \in T_p \mathcal{M} \mid \omega_p(X) = 0\}, \quad (5.2.22)$$

the standard definition of the kernel from linear algebra. We can extend this to the entire differential form  $\omega$  by attaching to each point in  $\mathcal{M}$  the corresponding subspace  $\ker(\omega_p) \subset T_p \mathcal{M}$ , yielding the subbundle

$$\ker(\omega) \equiv \bigsqcup_{p \in \mathcal{M}} \ker(\omega_p) \subset T\mathcal{M}, \quad (5.2.23)$$

together with the canonical projection map onto  $\mathcal{M}$ . It is now straightforward to see that when choosing  $\omega = dt$ , due to the identification (5.2.21) we find

$$\ker(dt) = T\Sigma \subset T\mathcal{M}. \quad (5.2.24)$$

The tangent bundle of a foliation  $\Sigma$  generated by the level sets of a scalar function  $t : \mathcal{M} \rightarrow \mathbb{R}$  is hence simply the kernel of the 1-form  $dt$  associated to it by the exterior derivative.

### 5.3 Hypersurface-Orthogonal Distributions

In the previous section, we defined what it means for a vector field to be normal to a foliation  $\Sigma$  generated by a scalar function  $t \in C^\infty(\mathcal{M})$  with  $dt \neq 0$  everywhere. In particular, we constructed an explicit example of such a vector field  $n^\sharp$  by setting

$$n = \alpha dt \quad \text{such that} \quad g(n^\sharp, n^\sharp) = \pm 1. \quad (5.3.1)$$

This addressed the question “Given a foliation, can we find a vector field that is normal to it everywhere?”.

In this section, we turn that question around: “Given a vector field, does there exist a foliation to which it is everywhere normal?”. This leads us to the notion of *hypersurface-orthogonal* vector fields—those that are locally normal to a family of hypersurfaces. Without proof, we will also give the so-called *Frobenius condition* which can be used to check this property directly.

**Definition** (Hypersurface-Orthogonal Vector Fields) Let  $X \in \Gamma(T\mathcal{M})$  be a smooth vector field on a smooth manifold  $\mathcal{M}$ . We say that  $X$  is *hypersurface-orthogonal* if, for every point  $p \in \mathcal{M}$ , there exists a neighbourhood  $U \subset \mathcal{M}$  of  $p$  and a local foliation  $\Sigma = \{\Sigma_t\}_{t \in \mathbb{R}}$  of  $U$  with the property that

$$g(X_p, Y) = 0 \quad \text{for all } Y \in T_p \Sigma_{t(p)}. \quad (5.3.2)$$

In words:  $X$  is hypersurface-orthogonal if, at every point, it is orthogonal to the leaves of some local foliation.

Though geometrically intuitive, this definition of hypersurface-orthogonality is rather difficult to verify in practice. We now derive an equivalent *analytic* criterion that allows us to check whether a given vector field  $X \in \Gamma(T\mathcal{M})$  is hypersurface-orthogonal.

The derivation proceeds in a few steps:

- First, recall that any local foliation  $\Sigma = \{\Sigma_t\}$  defined on an open set  $U \subset \mathcal{M}$  can be represented by a smooth function  $\varphi : U \rightarrow \mathbb{R}$  with  $d\varphi \neq 0$ , whose level sets define the leaves as  $\Sigma_{\varphi(p)} = \varphi^{-1}(\varphi(p))$ . Conversely, any such function defines a local foliation by level sets. In the previous section, we saw that the tangent spaces to the leaves are given by the pointwise kernels of the differential,

$$\ker(d\varphi_p) = T_p \Sigma_{\varphi(p)} \quad (5.3.3)$$

- A vector field  $X$  is orthogonal to the foliation if and only if for all  $Y \in T_p \mathcal{M}$

$$0 = g(X_p, Y) = X_p^\flat(Y) \Leftrightarrow Y \in T_p \Sigma_{\varphi(p)}, \quad (5.3.4)$$

i.e.  $X_p^\flat$  annihilates all vectors tangent to the leaf through  $p$ . But by equation (5.3.3), those tangent vectors are precisely the kernel of  $d\varphi_p$ . Hence, the two kernels must agree,

$$\ker(X_p^\flat) = \ker(d\varphi_p). \quad (5.3.5)$$

- Since both  $X_p^\flat$  and  $d\varphi_p$  are non-vanishing 1-forms, they must be pointwise proportional,

$$X_p^\flat \propto d\varphi_p. \quad (5.3.6)$$

That is, there exists a smooth function  $\lambda$  such that

$$X^\flat = \lambda d\varphi \quad (5.3.7)$$

on  $U$ .

We have thus shown that  $X$  is hypersurface-orthogonal if and only if, for every point  $p \in \mathcal{M}$ , there exist smooth functions  $\varphi, \lambda \in C^\infty(U)$  on a neighbourhood  $U \subset \mathcal{M}$  of  $p$  such that

$$X^\flat = \lambda d\varphi. \quad (5.3.8)$$

This provides a concrete and (more) checkable analytic characterisation of hypersurface-orthogonality.

Equation (5.3.8) is a condition on the 1-form  $X^\flat$  associated to the vector field  $X$ . Conversely, one can also say that if a 1-form  $\omega$  can locally (say, on  $U \subset \mathcal{M}$ ) be expressed as

$$\omega = \lambda d\varphi, \quad \lambda, \varphi \in C^\infty(U), \quad (5.3.9)$$

then the associated vector field  $X = \omega^\sharp$  is hypersurface-orthogonal. An immediate example is when  $\omega = dx^{\mu_0}$  is the differential of a fixed coordinate  $x^{\mu_0}$ , which trivially has the above form and hence generates the hypersurface-orthogonal vector field

$$X = \omega^\sharp = (dx^{\mu_0})^\sharp = g^{\mu_0\nu} \partial_\nu, \quad (5.3.10)$$

which is orthogonal to the foliation generated by fixing the coordinate  $x^{\mu_0}$ , i.e.

$$\Sigma_t = \{p \in U \subset \mathcal{M} \mid x^{\mu_0}(p) = t\}. \quad (5.3.11)$$

However, there are many vector fields or 1-forms for which it is nontrivial to determine whether a representation as in condition (5.3.8) exists. In such cases, the so-called *Frobenius condition* comes into play, which we formulate (but not prove) below.

**Theorem** (Frobenius Condition) Let  $\mathcal{M}$  be a smooth manifold,  $U \subset \mathcal{M}$  an open neighbourhood, and  $\omega$  a differential 1-form on  $U$ . Then,  $\omega$  admits a local expression of the form

$$\omega = \lambda d\varphi \quad (5.3.12)$$

for some  $\lambda, \varphi \in C^\infty(U)$  if and only if the condition

$$\omega \wedge d\omega = 0 \quad (5.3.13)$$

holds.

This is now a purely computational way to verify whether a vector field  $X$  is hypersurface-orthogonal—in components, this condition reads

$$0 \stackrel{!}{=} X^\flat \wedge dX^\flat = X_\mu dx^\mu \wedge (\partial_\nu X_\lambda) dx^\nu \wedge dx^\lambda = X_\mu \partial_\nu X_\lambda dx^\mu \wedge dx^\nu \wedge dx^\lambda, \quad (5.3.14)$$

which yields the standard identity

$$X_{[\mu} \nabla_\nu X_{\lambda]} \stackrel{!}{=} 0. \quad (5.3.15)$$

Notice that we were able to replace partial by covariant derivatives due to the antisymmetrisation, which removes the (here torsion-free) connection components from the expression.

As announced, we will not prove the Frobenius condition here, at least not the difficult implication that  $\omega \wedge d\omega = 0$  guarantees a decomposition into  $\omega = \lambda d\varphi$ . To make the claim somewhat more plausible, though, we can opt to briefly examine the converse direction, which is immediate from a direct computation—let us assume  $\omega = \lambda d\varphi$ , and plug in:

$$\omega \wedge d\omega = \lambda d\varphi \wedge d(\lambda d\varphi) = \lambda d\varphi \wedge d\lambda \wedge d\varphi = 0, \quad (5.3.16)$$

where the last equality holds by anti-symmetry of the wedge product.

## 5.4 Decomposition of the Metric under Foliation

In many applications such as ADM, it is essential to decompose a metric in terms of its contributions tangential and normal to the leaves of a foliation. In this section, we approach this decomposition from multiple angles, both from a coordinate-independent and -dependent perspective.

### 5.4.1 Coordinate-Independent Perspective

We begin by recalling from Section 5.2 that given a foliation  $\Sigma = \{\Sigma_t\}$  of a (pseudo-)Riemannian manifold  $\mathcal{M}$ , the tangent bundle can be decomposed as

$$T\mathcal{M} = T\Sigma \oplus N\Sigma. \quad (5.4.1)$$

This decomposition is implemented by the corresponding bundle maps

$$P : T\mathcal{M} \rightarrow T\Sigma, \quad Q : T\mathcal{M} \rightarrow N\Sigma \quad (5.4.2)$$

—pointwise, these are simply the orthogonal projections

$$P_p : T_p\mathcal{M} \rightarrow T_p\Sigma_{t(p)}, \quad Q_p : T_p\mathcal{M} \rightarrow N_p\Sigma_{t(p)}, \quad p \in \mathcal{M}. \quad (5.4.3)$$

For any vector field  $X \in \Gamma(T\mathcal{M})$ , we have

$$X = P(X) + Q(X) \quad (5.4.4)$$

where  $P(X) \in \Gamma(T\Sigma)$  and  $Q(X) \in \Gamma(N\Sigma)$ .

Alternatively, in the pointwise view, for any  $X_p \in T_p\mathcal{M}$ , it holds that

$$X_p = P_p(X_p) + Q_p(X_p), \quad (5.4.5)$$

such that  $P_p(X_p) \in T_p\Sigma_{t(p)}$  and  $Q_p(X_p) \in N_p\Sigma_{t(p)}$ , and hence

$$g(P_p(X_p), Q_p(X_p)) = 0. \quad (5.4.6)$$

Further recall that the associated  $(0, 2)$ -tensors of  $P$  and  $Q$  decompose the metric as

$$g = P + Q. \quad (5.4.7)$$

Having set the stage for orthogonal decompositions of the metric, we now turn to the special case where  $\Sigma$  is a hypersurface foliation generated by  $t \in C^\infty(\mathcal{M})$  with  $dt \neq 0$  everywhere. Our goal is to derive the orthogonal projection  $Q$  onto  $N\Sigma$ , as this will enable us to decompose the metric as  $P + Q$  using  $P = g - Q$ .

To make this decomposition explicit, we now compute the form of  $Q$  in terms of the normal 1-form  $n$  we introduced in Section 5.2. More precisely, it is given by

$$n = \alpha dt, \quad (5.4.8)$$

with  $\alpha \in C^\infty(\mathcal{M})$  fixed by the condition

$$g(n^\sharp, n^\sharp) = \varepsilon = \pm 1, \quad (5.4.9)$$

where the sign  $\varepsilon$  reflects whether  $n^\sharp$  is spacelike or timelike (we do not consider the null case here). Further recall that  $n$  annihilates vectors tangent to  $\Sigma$ , i.e.

$$g(n^\sharp, X) = n(X) = 0 \quad \forall X \in \Gamma(T\Sigma). \quad (5.4.10)$$

Let us consider how  $n$  acts on an arbitrary vector  $X \in \Gamma(N\Sigma)$ . For our case of a hypersurface foliation,  $N\Sigma$  is a vector bundle with one-dimensional fibres. Since  $n^\sharp \in \Gamma(N\Sigma)$  is nowhere vanishing, we can express  $X$  as a scalar multiple of it, i.e.

$$X = \lambda n^\sharp, \quad \text{for some } \lambda \in C^\infty(\mathcal{M}). \quad (5.4.11)$$

This allows us to derive the action of the normal 1-form  $n$  on any  $X \in \Gamma(N\Sigma)$  as

$$n(X) = \lambda n(n^\sharp) = \lambda g(n^\sharp, n^\sharp) = \varepsilon \lambda. \quad (5.4.12)$$

Multiplying this equation by  $\varepsilon n^\sharp$  yields

$$\varepsilon n^\sharp \cdot n(X) = \varepsilon^2 \lambda n^\sharp = X. \quad (5.4.13)$$

Let us briefly digest this last result. It tells us that the map

$$\varepsilon n^\sharp \otimes n : T\mathcal{M} \rightarrow N\Sigma \quad (5.4.14)$$

acts as the identity when restricted to  $N\Sigma$ . Moreover, since  $n$  annihilates any vector in  $\Gamma(T\Sigma)$  and due to the orthogonal decomposition (5.4.1), we conclude that  $\varepsilon n^\sharp \otimes n$  is the orthogonal projection of  $T\mathcal{M}$  onto  $N\Sigma$ . Consequently, we have

$$Q = \varepsilon n^\sharp \otimes n. \quad (5.4.15)$$

The metric hence decomposes as

$$\begin{aligned} g &= P + Q \\ &= (g - \varepsilon n \otimes n) + \varepsilon n \otimes n \\ &= (g - \varepsilon \alpha^2 dt \otimes dt) + \varepsilon \alpha^2 dt \otimes dt \end{aligned} \quad (5.4.16)$$

where we identify

$$P = g - \varepsilon \alpha^2 dt \otimes dt \quad (5.4.17)$$

as the orthogonal projector onto  $T\Sigma$ . Recall that  $P$  is the tangential component of the metric, pulling back to the induced metric on  $\Sigma_t$  as

$$\gamma = \iota^* g = \iota^* P \quad (5.4.18)$$

due to  $\iota^* Q = 0$ .

### 5.4.2 ADM-Type Metric Decomposition in Coordinates

We again assume the (pseudo-)Riemannian manifold  $\mathcal{M}$  to be equipped with a foliation  $\Sigma = \{\Sigma_t\}$  generated by a scalar function  $t \in C^\infty(\mathcal{M})$  with  $dt \neq 0$  everywhere. We use  $t$  as a coordinate, extending it to a full, local coordinate system  $x^\mu = (t, y^i)$ ,  $i = 1, \dots, \dim \mathcal{M} - 1$  by transverse coordinates  $y^i$ . Let us again consider the normal 1-form

$$n = \alpha dt, \quad (5.4.19)$$

subject to the condition

$$g(n^\sharp, n^\sharp) = \varepsilon. \quad (5.4.20)$$

Our goal will be to write the metric  $g$  in terms of the components of  $n^\sharp$ —i.e. of the function  $\alpha$  and a vector  $\beta^i$  we will introduce momentarily—as well as the induced metric on the leaves, which has the components

$$\gamma_{ij} \equiv g(\partial_i, \partial_j) = g(\partial_i, \partial_j). \quad (5.4.21)$$



The vector  $n^\sharp$  associated to the normal 1-form can be written in terms of its coordinate components, yielding

$$n^\sharp = \alpha \delta_\mu^t g^{\mu\nu} \partial_\nu = \alpha g^{t\mu} \partial_\mu = \alpha g^{tt} \partial_t + \alpha g^{ti} \partial_i. \quad (5.4.22)$$

Making use of the normalisation condition (5.4.20), we find

$$\varepsilon = g(n^\sharp, n^\sharp) = n(n^\sharp) = \alpha^2 g^{tt} \underbrace{dt(\partial_t)}_{=1} + \alpha^2 g^{ti} \underbrace{dt(\partial_i)}_{=0} = \alpha^2 g^{tt}, \quad (5.4.23)$$

or equivalently,

$$g^{tt} = \frac{\varepsilon}{\alpha^2}. \quad (5.4.24)$$

This is our first direct relationship between  $\alpha$  and a component of the (inverse) metric. Inserting this back into the expansion for  $n^\sharp$  above, we get

$$n^\sharp = \frac{\varepsilon}{\alpha} \partial_t + \alpha g^{ti} \partial_i. \quad (5.4.25)$$

We now introduce the *shift vector*  $\beta^i$  as

$$\beta^i = -\varepsilon \alpha^2 g^{ti}, \quad (5.4.26)$$

where the factor is chosen such one can extract  $\varepsilon/\alpha$  as a common factor in  $n^\sharp$ , i.e.

$$n^\sharp = \frac{\varepsilon}{\alpha} (\partial_t - \beta^i \partial_i). \quad (5.4.27)$$

Equivalently, we may express  $\partial_t$  in terms of  $n^\sharp$  and  $\beta = \beta^i \partial_i$ ,

$$\partial_t = \varepsilon \alpha n^\sharp + \beta. \quad (5.4.28)$$

This allows us to derive both  $g_{tt}$  and  $g_{ti}$  via

$$\begin{aligned} g_{tt} &= g(\partial_t, \partial_t) = \varepsilon^2 \alpha^2 \underbrace{g(n^\sharp, n^\sharp)}_{=\varepsilon} + 2\varepsilon \alpha \underbrace{g(n^\sharp, \beta)}_{=0} + \underbrace{g(\beta, \beta)}_{=\gamma_{ij} \beta^i \beta^j} \\ &= \varepsilon \alpha^2 + \gamma_{ij} \beta^i \beta^j, \\ g_{ti} &= g(\partial_t, \partial_i) = \varepsilon \alpha \underbrace{g(n^\sharp, \partial_i)}_{=0} + g(\beta, \partial_i) = \gamma_{ij} \beta^j \end{aligned} \quad (5.4.29)$$

Here, we made use of the fact that  $n^\sharp$  is normal to the foliation, whereas the  $\partial_i$  and hence also  $\beta$  are tangent to it—or, algebraically,

$$g(n^\sharp, \partial_i) = n(\partial_i) = \alpha \underbrace{dt(\partial_i)}_{=0} = 0. \quad (5.4.30)$$

In summary, the components of the metric are given by

$$g_{tt} = \varepsilon \alpha^2 + \gamma_{ij} \beta^i \beta^j, \quad g_{ti} = \gamma_{ij} \beta^j, \quad g_{ij} = \gamma_{ij}, \quad (5.4.31)$$

or in block matrix form,

$$g_{\mu\nu} = \begin{pmatrix} \varepsilon \alpha^2 + \gamma_{ij} \beta^i \beta^j & \gamma_{ij} \beta^j \\ \gamma_{ij} \beta^j & \gamma_{ij} \end{pmatrix}. \quad (5.4.32)$$

The metric tensor is hence given by

$$g = g_{\mu\nu} dx^\mu \otimes dx^\nu = \varepsilon \alpha^2 dt \otimes dt + \gamma_{ij} (dy^i + \beta^i dt)(dy^j + \beta^j dt). \quad (5.4.33)$$

### Remarks

- *The Lapse:* In the literature, the function  $\alpha$  is known as the *lapse function*. To understand its meaning (assuming  $t$  is a timelike coordinate), consider an observer moving orthogonally to the spatial slices  $\Sigma_t$ , i.e. following the integral curves of the normal vector field  $n^\sharp$ . Since  $n^\sharp$  is normalised, the tangent vector to such a path  $\gamma(\tau)$ , parameterised by proper time  $\tau$ , satisfies

$$\dot{\gamma} = n^\sharp. \quad (5.4.34)$$

Thus, the tangent vector is normal to the foliation, and when computing the elapsed proper time  $d\tau$  between nearby leaves, only the normal part of the metric contributes. Hence, for such a path, we have

$$d\tau^2 = -g = -Q = n \otimes n = \alpha^2 dt^2. \quad (5.4.35)$$

This further implies

$$d\tau = \pm \alpha dt. \quad (5.4.36)$$

In other words, when moving from one hypersurface  $\Sigma_t$  to the next along the normal flow, the lapse function  $\alpha$  gives the rate at which proper time  $\tau$  advances with respect to coordinate time  $t$ . The larger the lapse, the “more” proper time elapses between adjacent slices for such an observer. Naturally, if one moves between slices while also displacing in tangential directions, additional contributions appear—the lapse governs the conversion only for motion orthogonal to the foliation.

- *The Shift:* Given the definition of the normal 1-form,

$$n = \alpha dt, \quad (5.4.37)$$

one might naively expect the associated vector to be proportional to  $\partial_t$ , perhaps something like

$$n^\sharp = \frac{\varepsilon}{\alpha} \partial_t. \quad (5.4.38)$$

However, as we have seen before, the correct expression is

$$n^\sharp = \frac{\varepsilon}{\alpha} (\partial_t - \beta), \quad (5.4.39)$$

which includes an additional component from  $\beta$  along the tangential directions  $\partial_i$ . Since  $n^\sharp$  is normal to the foliation, this tells us that  $\partial_t$  itself is *not* normal in general. The shift vector  $\beta = \beta^i \partial_i$  encodes precisely this discrepancy—it provides the spatial correction needed to turn  $\partial_t$  into a vector normal to the leaves.

Put differently, the shift quantifies the failure of  $\partial_t$  to be orthogonal to the foliation. It tells us how much spatial displacement occurs—within the leaves themselves—when evolving forward in coordinate time. Alternatively, we can re-express this as

$$\partial_t = \varepsilon \alpha n^\sharp + \beta, \quad (5.4.40)$$

making explicit that  $\partial_t$  consists of both a normal and a tangential component. From this viewpoint, the shift is simply the tangential part of the time flow vector  $\partial_t$ .

Motion along the flow of  $\partial_t$  involves keeping the coordinates  $y^i$  fixed. Therefore, the choice of the coordinates  $y^i$  is intimately related to the shift vector  $\beta$ —in particular, as we will see in an upcoming example, the coordinates  $y^i$  can (typically) be chosen such that the shift is zero.

- *Induced Metric vs. Tangential Projector:* We have seen before that under the orthogonal decomposition

$$g = P + Q, \quad (5.4.41)$$

with  $P$  the tangential and  $Q$  the normal projector (or rather, its associated bilinear form), that the induced metric  $\gamma$  is related via

$$\gamma = \iota^* g = \iota^* P + \underbrace{\iota^* Q}_{=0} = \iota^* P. \quad (5.4.42)$$

In most contexts, it is fine to say that  $\gamma = P$ , since they act the same on  $T\Sigma$ . However, it should be kept in mind that  $P$  is a bilinear form on  $T\mathcal{M}$  whereas  $\gamma$  is only defined on  $T\Sigma$ . In other words,  $P$  “knows” how to handle vectors with components in  $N\Sigma$ —namely by mapping those components to zero—while  $\gamma$ , by definition, does not.

This manifests itself when considering the expression (5.4.17) for  $P$  after inserting the ADM decomposition for  $g$ :

$$P = \gamma_{ij}(dy^i + \beta^i dt) \otimes (dy^j + \beta^j dt). \quad (5.4.43)$$

This is in comparison to the induced metric on the leaves, which simply reads

$$\gamma = \gamma_{ij} dy^i \otimes dy^j. \quad (5.4.44)$$

The  $dt$  terms equip  $P$  with the (correct) means to handle  $\partial_t$ , which generically has both tangential ( $\propto \beta$ ) and normal components. The tangential components are what  $P$  needs to isolate, which is why the  $dt$  bits are necessary.

However, note here that  $\partial_t$  lies outside of  $T\Sigma$ . Hence, it is a foreign object to the induced metric  $\gamma$ , and it “does not have to know” how to deal with it—it is safe to discard the  $dt$  pieces. It need not concern itself with vectors pointing “off the leaf”—that is, directions leading from one slice to another—even if they do have tangential components. The induced metric is content with only measuring vectors fully tangential to the leaf.

If the shift is zero, though, then  $P = \gamma$  not just in effect but in substance. One can see this either algebraically, or intuitively as follows: when the shift vanishes, we have  $\partial_t \propto n^\sharp$ , meaning  $\partial_t$  is fully normal. In that case,  $P$  never has to process  $\partial_t$  at all—there is no tangential contribution to extract. Hence, no  $dt$  terms need to appear, and  $P$  reduces directly to  $\gamma$ .

- *Inverse Metric:* Besides the ADM split of the metric, (5.4.33), one frequently needs to use the inverse metric,

$$g^{-1} = g^{\mu\nu} \partial_\mu \otimes \partial_\nu, \quad (5.4.45)$$

as well. Its components are given by

$$g^{tt} = \frac{\varepsilon}{\alpha^2}, \quad g^{ti} = -\frac{\varepsilon}{\alpha^2} \beta^i, \quad g^{ij} = \gamma^{ij} + \frac{\varepsilon}{\alpha^2} \beta^i \beta^j, \quad (5.4.46)$$

where  $\gamma^{ij}$  is inverse to  $\gamma_{ij}$  in the sense that

$$\gamma^{ik} \gamma_{kj} = \delta_j^i. \quad (5.4.47)$$

As a block matrix, this reads

$$g^{\mu\nu} = \begin{pmatrix} \varepsilon/\alpha^2 & -\varepsilon\beta^i/\alpha^2 \\ -\varepsilon\beta^i/\alpha^2 & \gamma^{ij} + \varepsilon\beta^i\beta^j/\alpha^2 \end{pmatrix}. \quad (5.4.48)$$

The inverse metric tensor can hence be written as

$$\begin{aligned} g^{-1} &= \frac{\varepsilon}{\alpha^2} (\partial_t - \beta^i \partial_i) \otimes (\partial_t - \beta^j \partial_j) + \gamma^{ij} \partial_i \otimes \partial_j \\ &= \varepsilon n^\sharp \otimes n^\sharp + \gamma^{ij} \partial_i \otimes \partial_j. \end{aligned} \quad (5.4.49)$$

Notice that also here, we have a separation into a normal and a tangential part.

## 5.5 Example: Foliation of $\mathbb{R}^3 \setminus \{0\}$ into Spheres

At this point, we should consider an example to solidify our grasp of foliations and the ADM decomposition of the metric. To this end, we consider a simple (but still nontrivial) foliation of the manifold  $\mathcal{M} = \mathbb{R}^3 \setminus \{0\}$ , equipped with the flat Euclidean metric

$$g = dx \otimes dx + dy \otimes dy + dz \otimes dz \quad (5.5.1)$$

where  $x, y, z$  are the Cartesian coordinates on  $\mathcal{M}$ . We foliate it into origin-centered spheres of varying radii. Here, we will derive the objects we defined generally in the previous section—the normal 1-form, its associated normal vector, the lapse, the shift, and the ADM decomposition of the metric, as well as the projectors  $P$  and  $Q$  onto the tangent and normal bundles of the foliation.

First, let us define the foliation by introducing the function

$$r : \mathcal{M} \rightarrow \mathbb{R}, \quad r(p) = \sqrt{x^2 + y^2 + z^2}, \quad p = (x, y, z) \quad (5.5.2)$$

and define the leaves of the foliation  $\Sigma = \{\Sigma_r\}$  to be its level sets,

$$\Sigma_{r_0} \equiv \{p \in \mathcal{M} \mid r(p) = r_0\} = r_0 S^2. \quad (5.5.3)$$

Notice that this does indeed define a foliation, since

$$dr = \frac{x}{r} dx + \frac{y}{r} dy + \frac{z}{r} dz \neq 0 \quad (5.5.4)$$

everywhere on  $\mathcal{M}$ —each of the  $\Sigma_r \subset \mathcal{M}$  is a submanifold in its own right.

We begin by analysing the normal 1-form and the associated vector, which also yields an explicit expression for the lapse function  $\alpha$ . In general, the normal 1-form is given by

$$n = \alpha dr. \quad (5.5.5)$$

Since the (inverse) metric in Cartesian coordinates is trivial, we have

$$n^\sharp = \alpha dr^\sharp = \alpha \left( \frac{x}{r} \partial_x + \frac{y}{r} \partial_y + \frac{z}{r} \partial_z \right). \quad (5.5.6)$$

The normalisation condition on  $n$  hence yields

$$\begin{aligned} 1 &\stackrel{!}{=} g(n^\sharp, n^\sharp) = n(n^\sharp) = \alpha^2 dr \left( \frac{x}{r} \partial_x + \frac{y}{r} \partial_y + \frac{z}{r} \partial_z \right) \\ &= \alpha^2 \left( \frac{x^2}{r^2} dx(\partial_x) + \frac{y^2}{r^2} dy(\partial_y) + \frac{z^2}{r^2} dz(\partial_z) \right) \\ &= \frac{\alpha^2}{r^2} \underbrace{(x^2 + y^2 + z^2)}_{=r^2} = \alpha^2, \end{aligned} \quad (5.5.7)$$

which fixes the lapse as  $\alpha^2 = \pm 1$ —we choose the positive sign, i.e.  $\alpha = +1$ . Moreover, we now have the concrete expressions

$$\begin{aligned}
n &= dr = \frac{x}{r} dx + \frac{y}{r} dy + \frac{z}{r} dz, \\
n^\sharp &= \frac{x}{r} \partial_x + \frac{y}{r} \partial_y + \frac{z}{r} \partial_z.
\end{aligned} \tag{5.5.8}$$

Let us now consider the shift vector  $\beta$ . For this, we need to introduce additional coordinates  $q^i$ ,  $i = 1, 2$  to amend  $r$  into a full coordinate system. Naturally, a great candidate for the  $q^i$  are the angles  $\theta, \varphi$  used with spherical coordinates—for now though, let us remain general. What we have now is a relationship between two sets of coordinates,

$$\left. \begin{aligned} r &= r(x, y, z) \\ q^i &= q^i(x, y, z) \end{aligned} \right\} \longleftrightarrow \begin{cases} x = x(r, q^i) \\ y = y(r, q^i) \\ z = z(r, q^i) \end{cases} \tag{5.5.9}$$

Recall from the previous section that the shift  $\beta$  is given by

$$\beta = \partial_r - \underbrace{\varepsilon \alpha}_{=1} n^\sharp = \partial_r - n^\sharp, \tag{5.5.10}$$

quantifying how much tangential motion (since  $\beta = \beta^i \partial_i \in \Gamma(T\Sigma)$ ) displacement along the flow of  $\partial_r$  entails. In terms of the Cartesian coordinate basis  $\{\partial_x, \partial_y, \partial_z\}$ , we may express  $\partial_r$  as

$$\partial_r = \frac{\partial x}{\partial r} \partial_x + \frac{\partial y}{\partial r} \partial_y + \frac{\partial z}{\partial r} \partial_z. \tag{5.5.11}$$

Note that this cannot be simplified further without assumptions on the coordinates  $q^i$ . Either way, we can now explicitly write down the shift as

$$\beta = \partial_r - n^\sharp = \left( \frac{\partial x}{\partial r} - \frac{x}{r} \right) \partial_x + \left( \frac{\partial y}{\partial r} - \frac{y}{r} \right) \partial_y + \left( \frac{\partial z}{\partial r} - \frac{z}{r} \right) \partial_z. \tag{5.5.12}$$

At this point, we cannot really proceed without some sort of assumption on the  $q^i$ . So, let us do this: we require that  $\beta = 0$ . In other words, we want the  $q^i$  to be such that we have zero shift, that  $\partial_r$  is normal to  $T\Sigma$ .

This requires that each of the coefficients of  $\beta$  above must be zero. Notice that

$$\frac{\partial x}{\partial r} - \frac{x}{r} = 0 \iff x(r, q^i) = r f_x(q^i) \tag{5.5.13}$$

for some function  $f_x(q_i)$ , and analogously for  $y$  and  $z$ . Thus, requiring  $\beta = 0$  implies that the coordinates  $x, y, z$  are simply parametrisations of the 2-sphere  $S^2$  scaled linearly by the radius  $r$ . Put differently, if we require  $\beta = 0$ , we must parameterise each of our leaves  $\Sigma_r = rS^2$  with the same coordinates  $q^i$ , simply stretched by the sphere's radius.

All that is left to do now is to choose one's favourite parametrisation of  $S^2$ . Here, we opt to use the standard coordinates  $\theta, \varphi$  which parameterise the 2-sphere of radius  $r$  as

$$\begin{aligned} x &= r \sin \theta \cos \varphi, \\ y &= r \sin \theta \sin \varphi, \\ z &= r \cos \theta. \end{aligned} \tag{5.5.14}$$

We now have our lapse and shift,  $\alpha = 1$  and  $\beta = 0$ —all that remains to be derived are the transverse metric components

$$\gamma_{ij} = g(\partial_i, \partial_j), \quad i, j \in \{\theta, \varphi\}. \tag{5.5.15}$$

The relevant vectors are

$$\begin{aligned}\partial_\theta &= r \cos \theta (\cos \varphi \partial_x + \sin \varphi \partial_y) - r \sin \theta \partial_z, \\ \partial_\varphi &= r \sin \theta (-\sin \varphi \partial_x + \cos \varphi \partial_y).\end{aligned}\tag{5.5.16}$$

A further mechanical computation reveals that

$$\gamma_{\theta\theta} = r^2, \quad \gamma_{\theta\varphi} = 0, \quad \gamma_{\varphi\varphi} = r^2 \sin^2 \theta.\tag{5.5.17}$$

We are now ready to write down the full ADM decomposition of the metric. Inserting into the general result (5.4.33), we find

$$\begin{aligned}g &= \varepsilon \alpha^2 dr \otimes dr + \gamma_{ij} (dq^i + \beta^i dr) (dq^j + \beta^j dr) \\ &= dr \otimes dr + r^2 d\theta \otimes d\theta + r^2 \sin^2 \theta d\varphi \otimes d\varphi\end{aligned}\tag{5.5.18}$$

At this point, one might reasonably point out that we've essentially just recovered the familiar expression for the flat metric in spherical coordinates through a rather elaborate detour. So far, this may seem suspiciously close to reinventing spherical coordinates. That, however, would be a disheartening conclusion after having gone through all this effort—so let us not argue that. Instead, let us appreciate having seen the ADM decomposition machinery at work in a setting where the outcome is familiar, but derived by taking the scenic route. After all, we've just learned that spherical coordinates arise naturally when seeking a zero-shift ADM decomposition of the flat Euclidean metric on concentric spheres. Which, as every self-respecting postgraduate knows, is the entire point of advanced studies: to rediscover well-known results in a more baroque fashion—ideally in a way that makes the undergrads look impressed.

Now that we have derived a particular ADM decomposition of the flat Euclidean metric on  $\mathcal{M} = \mathbb{R}^3 \setminus \{0\}$ , we can also briefly consider the bilinear forms  $P$ ,  $Q$  associated to the orthogonal decomposition

$$T\mathcal{M} = T\Sigma \oplus N\Sigma.\tag{5.5.19}$$

The normal part of the metric,  $Q$ , is simply given by

$$Q = \varepsilon n \otimes n = dr \otimes dr.\tag{5.5.20}$$

Correspondingly, the tangential projection  $P$ —or equivalently (in this case, since  $\beta = 0$ ), the induced metric  $\gamma$  on the leaves—is given by

$$\gamma = P = g - Q = r^2 (d\theta \otimes d\theta + \sin^2 \theta d\varphi \otimes d\varphi).\tag{5.5.21}$$

This is also what one would expect: an appropriately scaled metric on  $S^2$ .

## 6 Covariant Derivatives on Submanifolds

The goal of this section is to define how a connection on a manifold  $\mathcal{M}$  induces a connection on the leaves of a foliation  $\Sigma$  of  $\mathcal{M}$ . To this end, we review the definition of a connection  $\nabla$  as well as how the conditions of vanishing torsion and metric compatibility uniquely single out the Levi-Civita connection. We then proceed to define the induced connection  $\bar{\nabla}$  on a foliation as the projection of  $\nabla$ , and show that if  $\nabla$  is of Levi-Civita type, then so is  $\bar{\nabla}$ .

### 6.1 Review: Affine Connections

Before discussing how a connection on a (pseudo-)Riemannian manifold  $\mathcal{M}$  induces a connection on the submanifolds  $\Sigma_t \subset \mathcal{M}$  that comprise a foliation  $\Sigma$ , we review the definition of affine connections and recall how the conditions of metric compatibility and torsion-freeness uniquely determine the Levi-Civita connection.

Let

$$T^{(r,s)}\mathcal{M} = (T\mathcal{M})^{\otimes r} \otimes (T^*\mathcal{M})^{\otimes s} \quad (6.1.1)$$

denote the *bundle of  $(r, s)$ -tensors on  $\mathcal{M}$* , where the tensor product between vector bundles is to be understood pointwise—i.e., as a tensor product of the fibres at each point. Tensor fields are smooth sections of this bundle; in other words, an  $(r, s)$ -tensor field  $T$  is a section of  $T^{(r,s)}\mathcal{M}$ , that is,  $T \in \Gamma(T^{(r,s)}\mathcal{M})$ . With this notational preface out of the way, we are now ready to give the definition of affine connections.

**Definition** (Affine Connection) Let  $\mathcal{M}$  be a smooth manifold, and consider a linear map

$$\nabla : \Gamma(T^{(r,s)}\mathcal{M}) \rightarrow \Gamma(T^{(r,s+1)}\mathcal{M}) = \Gamma(T^*\mathcal{M} \otimes T^{(r,s)}\mathcal{M}), \quad (6.1.2)$$

which maps  $(r, s)$ -tensors to  $(r, s + 1)$ -tensors.

With the interpretation of a tensor as a multilinear map on a set of vectors  $Y_1, \dots, Y_s \in \Gamma(T\mathcal{M})$  and covectors  $\omega_1, \dots, \omega_r \in \Gamma(T^*\mathcal{M})$ , we introduce the shorthand notation

$$\nabla_X T(\omega_1, \dots, \omega_r, Y_1, \dots, Y_s) = (\nabla T)(X, \omega_1, \dots, \omega_r, Y_1, \dots, Y_s), \quad (6.1.3)$$

which simply indicates that  $\nabla_X$  populates the additional vector argument introduced when passing from  $T$  to  $\nabla T$  with the vector  $X$ .

We call  $\nabla$  an *affine connection* or *covariant derivative* if it satisfies:

1. Reduction to the exterior derivative on functions  $\varphi \in C^\infty(\mathcal{M})$ ,

$$\nabla \varphi = d\varphi, \quad (6.1.4)$$

2. Tensorial Leibniz rule,

$$\nabla(T \otimes S) = (\nabla T) \otimes S + T \otimes (\nabla S), \quad (6.1.5)$$

3. and compatibility with contraction<sup>4</sup> of a contra- and a covariant index,

$$\nabla(\text{tr}_j^i T) = \text{tr}_j^i(\nabla T). \quad (6.1.6)$$

This is a rather abstract (though likely familiar, if you got this far in these notes) definition, which benefits from building some intuition. Let us make a few remarks:

- **Connection as Derivative** The first axiom is the most concrete—requiring that the connection reduce to the exterior derivative when acting on functions immediately introduces a differential structure to  $\nabla$ . In this context, it makes sense to consider the associated map  $\nabla_X$  for a vector field  $X \in \Gamma(T\mathcal{M})$ , and observe what it reduces to on a smooth function  $\varphi \in C^\infty(\mathcal{M})$ . By definition,

$$\nabla_X \varphi = d\varphi(X) = X[\varphi], \quad (6.1.7)$$

so the covariant derivative along  $X$  coincides with the familiar directional derivative. This anchors the definition in standard calculus and motivates the interpretation of  $\nabla$  as a generalisation of differentiation to tensor fields. Since both  $\nabla$  and  $\nabla_X$  map tensors to tensors of the same type (modulo the extra slot), they provide a coordinate-independent extension of the partial derivative which respects the underlying bundle structure.

- **Role of the Connection on Vectors** In components associated to some coordinate system  $x^\mu$ , we may locally expand a vector field  $X \in T\mathcal{M}$  as

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<sup>4</sup>The contraction operator  $\text{tr}_j^i$  acts on a tensor by contracting its  $i$ -th contravariant with the  $j$ -th covariant index when written in components.

$$X = X^\mu \partial_\mu = X^\mu \otimes \partial_\mu. \quad (6.1.8)$$

While the tensor product notation is formally unnecessary here—since we are simply multiplying smooth functions with the coordinate basis vector fields—it clarifies the use of the Leibniz rule in what follows.

It is best to think of  $\nabla$  as acting on  $X$  by acting separately on the component functions  $X^\mu \in C^\infty(\mathcal{M})$  and the basis vector fields  $\partial_\mu$ ,

$$\nabla X = \nabla(X^\mu \otimes \partial_\mu) = dX^\mu \otimes \partial_\mu + X^\mu \otimes \nabla \partial_\mu. \quad (6.1.9)$$

The components  $X^\mu$  are smooth functions, so by the first axiom of the connection,  $\nabla X^\mu = dX^\mu$ . However, the axioms impose no direct condition on  $\nabla \partial_\mu$ . Its role is to restore tensoriality: the first term alone is not a tensor, which we now demonstrate.

Consider the term  $dX^\mu \otimes \partial_\mu$  in components, i.e.

$$dX^\mu \otimes \partial_\mu = (\partial_\nu X^\mu) dx^\nu \otimes \partial_\mu. \quad (6.1.10)$$

Under a coordinate transformation  $x^\mu \rightarrow y^\alpha$  with Jacobians

$$J^\mu_\alpha = \frac{\partial x^\mu}{\partial y^\alpha}, \quad J^\alpha_\mu = \frac{\partial y^\alpha}{\partial x^\mu}, \quad (6.1.11)$$

the transformed components of a vector field read  $X^\alpha = J^\alpha_\mu X^\mu$ . Differentiating yields

$$\partial_\alpha X^\beta = J^\nu_\alpha \partial_\nu (J^\beta_\mu X^\mu) = J^\nu_\alpha J^\beta_\mu \partial_\nu X^\mu + X^\mu (J^\nu_\alpha \partial_\nu J^\beta_\mu). \quad (6.1.12)$$

The first term transforms as expected, but the second term spoils tensoriality—it introduces an inhomogeneous piece. Therefore,

$$dX^\mu \otimes \partial_\mu \text{ is not a tensor.} \quad (6.1.13)$$

This is precisely the failure remedied by the  $X^\mu \otimes \nabla \partial_\mu$  term. Writing out the coordinate-transformed derivative in the new basis leads to

$$(\partial_\alpha X^\beta) dy^\alpha \otimes \partial_\beta = [J^\nu_\alpha J^\beta_\mu \partial_\nu X^\mu + X^\mu (J^\nu_\alpha \partial_\nu J^\beta_\mu)] dx^\nu \otimes \partial_\mu. \quad (6.1.14)$$

We see that the connection term must absorb the inhomogeneous contribution. That is,

$$X^\mu \otimes \nabla \partial_\mu = X^\alpha \otimes \nabla \partial_\alpha + X^\mu (J^\nu_\alpha \partial_\nu J^\beta_\mu) dx^\nu \otimes \partial_\mu. \quad (6.1.15)$$

The final term determines how  $\nabla \partial_\mu$  must transform in order to make  $\nabla X$  a genuine tensor. We will return to this structure momentarily when introducing the connection coefficients explicitly.

- **Connection Coefficients** As we have seen in the previous remark, the object  $\nabla \partial_\mu$  is of particular interest—we should write it in terms of components. To this end, let us introduce additional shorthand notation for covariant derivatives along the coordinate directions  $\partial_\mu$ , as

$$\nabla_\mu \equiv \nabla_{\partial_\mu}. \quad (6.1.16)$$

From the derivations in the previous remark, it is clear that the object  $\nabla \partial_\nu$ , in terms of coordinates, must be of the form

$$\nabla \partial_\nu = (\nabla_\mu \partial_\nu) \otimes dx^\mu = \Gamma^\lambda_{\mu\nu} dx^\mu \otimes \partial_\lambda, \quad \text{for coefficients } \Gamma^\lambda_{\mu\nu} \in C^\infty(\mathcal{M}). \quad (6.1.17)$$

This implicitly defines the *connection coefficients*  $\Gamma^\lambda_{\mu\nu}$  through



$$\Gamma_{\mu\nu}^\lambda \partial_\lambda = \nabla_\mu \partial_\nu. \quad (6.1.18)$$

Fully explicitly, they are given by

$$\Gamma_{\mu\nu}^\lambda = dx^\lambda(\nabla_\mu \partial_\nu). \quad (6.1.19)$$

Using these coefficients, we can write the action of the connection on a vector  $X = X^\mu \partial_\mu \in \Gamma(TM)$  concretely as

$$\begin{aligned} \nabla X &= \nabla(X^\nu \partial_\nu) = dX^\nu \otimes \partial_\nu + X^\nu \nabla \partial_\nu \\ &= (\partial_\mu X^\lambda) dx^\mu \otimes \partial_\lambda + (X^\nu \Gamma_{\mu\nu}^\lambda) dx^\mu \otimes \partial_\lambda \\ &= (\partial_\mu X^\lambda + \Gamma_{\mu\nu}^\lambda X^\nu) dx^\mu \otimes \partial_\lambda. \end{aligned} \quad (6.1.20)$$

Along the coordinate directions, this turns into

$$\nabla_\mu X = (\partial_\mu X^\lambda + \Gamma_{\mu\nu}^\lambda X^\nu) \partial_\lambda. \quad (6.1.21)$$

This is nothing but the partial derivative of  $X$ , amended by a term linear in  $X$  that ensures tensoriality of  $\nabla X$ .

- **Interpretation of the Connection** In light of our previous remark that the connection along some vector  $X \in \Gamma(TM)$  is a covariant generalisation of the directional derivative along  $X$ , we can give an interpretation to the equality

$$\nabla_\mu \partial_\nu = \Gamma_{\mu\nu}^\lambda \partial_\lambda. \quad (6.1.22)$$

On the left-hand side, we compute a generalised directional derivative along the coordinate direction  $\partial_\mu$ . In other words, we ask ourselves: how does the basis vector  $\partial_\nu$  change as we move along the direction  $\partial_\mu$ ? This question is answered by the right-hand side, which tells us, for the given combination of  $\mu$  and  $\nu$ , what the rate of change is, in terms of a linear combination of the coordinate basis vectors. So, the component  $\Gamma_{\mu\nu}^\lambda$  encodes information about “by how much of  $\partial_\lambda$  does  $\partial_\nu$  change when moving along the flow of  $\partial_\mu$ ?”. A connection hence imposes a relationship between vectors in infinitesimally neighbouring tangent spaces.

A priori, there exists no canonical way to relate vectors at different points of the manifold—that is, to compare vectors in distinct tangent spaces and transport them around the manifold. While the transformation law of the connection coefficients is constrained by the requirement that  $\nabla T$  be tensorial for all tensors  $T$ , the connection itself remains arbitrary otherwise. However, by imposing additional (natural) conditions on  $\nabla$ , one can uniquely determine a distinguished connection: the *Levi-Civita connection*. We will pursue this in the next section.

- **Coordinate Transformation Behaviour** From equation (6.1.15) it can be derived that under a coordinate transformation  $x^\mu \rightarrow y^\alpha$ , the connection coefficients

$$dx^\lambda(\nabla_\mu \partial_\nu) = \Gamma_{\mu\nu}^\lambda \quad (6.1.23)$$

must transform as

$$\Gamma_{\mu\nu}^\lambda \rightarrow \Gamma_{\beta\gamma}^\alpha = J_\lambda^\alpha J_\beta^\mu J_\gamma^\nu \Gamma_{\mu\nu}^\lambda + J_\lambda^\alpha \partial_\beta J_\gamma^\lambda. \quad (6.1.24)$$

The second term is what makes the connection coefficients transform non-tensorially. Unlike the first term, which is the usual triple contraction with (inverse) Jacobians for a  $(1, 2)$ -tensor, the inhomogeneous second term violates tensorial transformation behaviour.

- **Action on Arbitrary Tensors** Since we know how  $\nabla$  acts on the coordinate basis vector fields  $\partial_\mu$ , we can readily extend it to any contravariant tensor  $T \in \Gamma(T^{(r,0)}\mathcal{M})$  by using the Leibniz rule,

$$\begin{aligned}\nabla T &= \nabla(T^{\mu_1 \dots \mu_r} \partial_{\mu_1} \otimes \dots \otimes \partial_{\mu_r}) \\ &= dT^{\mu_1 \dots \mu_r} \otimes \partial_{\mu_1} \otimes \dots \otimes \partial_{\mu_r} + T^{\mu_1 \dots \mu_r} (\nabla \partial_{\mu_1}) \otimes \partial_{\mu_2} \otimes \dots \otimes \partial_{\mu_r} + \dots \\ &= \left( \partial_\nu T^{\mu_1 \dots \mu_r} + \Gamma^{\mu_1}_{\nu\lambda} T^{\lambda \mu_2 \dots \mu_r} + \dots + \Gamma^{\mu_r}_{\nu\lambda} T^{\mu_1 \dots \mu_{r-1} \nu} \right) dx^\nu \otimes \partial_{\mu_1} \otimes \dots \otimes \partial_{\mu_r}.\end{aligned}\tag{6.1.25}$$

In essence, every contravariant index produces a term where the connection coefficients are contracted with the tensor components, as by the Leibniz rule,  $\nabla$  acts on each of the basis vectors once.

For tensors that are not purely contravariant, i.e. general tensors  $T \in \Gamma(T^{(r,s)}\mathcal{M})$ , however, the general basis expansion reads

$$T^{\mu_1 \dots \mu_r}_{\nu_1 \dots \nu_s} \partial_{\mu_1} \otimes \dots \otimes \partial_{\mu_r} \otimes dx^{\nu_1} \otimes \dots \otimes dx^{\nu_s}.\tag{6.1.26}$$

To be able to extend the action of  $\nabla$  for general tensors—as above, by means of the Leibniz rule—we must know what

$$\nabla dx^\mu\tag{6.1.27}$$

evaluates to. This is where the (so far unused!) third axiom comes into play, the compatibility with contractions: together with the Leibniz rule, it is possible to derive an explicit expression for the above from what we already know. Consider an arbitrary vector  $X = X^\mu \partial_\mu \in \Gamma(T\mathcal{M})$  as well as an arbitrary 1-form  $\omega = \omega_\mu dx^\mu \in \Gamma(T^*\mathcal{M})$ . Clearly, since  $\omega(X) \in C^\infty(\mathcal{M})$ , we have

$$\text{tr}_2^1 \nabla(\omega \otimes X) = \nabla(\omega(X)) = d(\omega(X)) = d(\omega_\mu X^\mu).\tag{6.1.28}$$

Let us take a closer look at the left-hand side. We can derive

$$\begin{aligned}\text{tr}_2^1 \nabla(\omega \otimes X) &= \text{tr}_2^1 \nabla(\omega_\mu X^\nu dx^\mu \otimes \partial_\nu) \\ &= \text{tr}_2^1 [d(\omega_\mu X^\nu) \otimes dx^\mu \otimes \partial_\nu + \omega_\mu X^\nu ((\nabla dx^\mu) \otimes \partial_\nu + dx^\mu \otimes \nabla \partial_\nu)] \\ &= d(\omega_\mu X^\mu) + \omega_\mu X^\nu \text{tr}_2^1 ((\nabla dx^\mu) \otimes \partial_\nu + dx^\mu \otimes \nabla \partial_\nu).\end{aligned}\tag{6.1.29}$$

Inserting this back into equation (6.1.28) above and canceling the exterior derivative terms, by arbitrariness of  $\omega_\mu$  and  $X^\mu$  we get

$$\text{tr}_2^1 [(\nabla dx^\mu) \otimes \partial_\nu] = -\text{tr}_2^1 [dx^\mu \otimes \nabla \partial_\nu].\tag{6.1.30}$$

Evaluating this along a coordinate direction  $\partial_\lambda$ , we find

$$\begin{aligned}\text{tr}_1^1 [\nabla_\lambda dx^\mu \otimes \partial_\nu] &= -\text{tr}_1^1 [dx^\mu \otimes \nabla_\lambda \partial_\nu] = -\text{tr}_1^1 [dx^\mu \otimes \Gamma^\rho_{\lambda\nu} \partial_\rho] \\ &= -\Gamma^\rho_{\lambda\nu} dx^\mu (\partial_\rho) = -\Gamma^\rho_{\lambda\nu} \delta_\rho^\mu = -\Gamma^\mu_{\lambda\nu}.\end{aligned}\tag{6.1.31}$$

The left hand side simplifies as

$$\text{tr}_1^1 [\nabla_\lambda dx^\mu \otimes \partial_\nu] = (\nabla_\lambda dx^\mu)(\partial_\nu),\tag{6.1.32}$$

which implies that overall,

$$\nabla_\lambda dx^\mu = -\Gamma^\mu_{\lambda\nu} dx^\nu.\tag{6.1.33}$$

Thus, in summary,  $\nabla$  acts on the coordinate basis vectors and 1-forms as

$$\begin{aligned}\nabla \partial_\mu &= \Gamma^\lambda_{\nu\mu} dx^\nu \otimes \partial_\lambda, \\ \nabla dx^\mu &= -\Gamma^\mu_{\nu\lambda} dx^\nu \otimes dx^\lambda,\end{aligned}\tag{6.1.34}$$

or, along a coordinate direction  $\partial_\mu$ ,

$$\begin{aligned}\nabla_\mu \partial_\nu &= \Gamma^\lambda_{\mu\nu} \partial_\lambda, \\ \nabla_\mu dx^\nu &= -\Gamma^\nu_{\mu\lambda} dx^\lambda.\end{aligned}\tag{6.1.35}$$

This, together with the axiom that  $\nabla\varphi = d\varphi$  (or  $\nabla_\mu\varphi = \partial_\mu\varphi$ ), allows one to evaluate the action of  $\nabla$  (or  $\nabla_\mu$ ) on arbitrary tensors.

To reiterate: the expressions for  $\nabla_\mu \partial_\nu$  and  $\nabla_\mu dx^\nu$  above inform us what the rate of change of the basis vectors  $\partial_\nu$  and 1-forms  $dx^\nu$  are as one moves along the coordinate direction  $\partial_\mu$ .

## 6.2 Review: Levi-Civita Connection

Now that we have introduced the general notion of a connection—a way of encoding the change of basis vectors and 1-forms as one moves through a manifold—we turn to the most prominent example: the *Levi-Civita connection*, which is uniquely determined by two conditions. These are:

1. Vanishing torsion,
2. Metric compatibility.

We will now introduce both conditions rigorously and examine their consequences for the connection coefficients  $\Gamma^\lambda_{\mu\nu}$ , which ultimately leads to the *Christoffel Symbols*, which are the coefficients of the Levi-Civita connection.

**Vanishing Torsion** A connection provides us with a means of comparing vectors at nearby points and describing how they change as we move infinitesimally along a given direction. Given two vector fields  $X, Y \in \Gamma(TM)$ , the covariant derivatives  $\nabla_X Y$  and  $\nabla_Y X$  describe how  $Y$  changes along the flow of  $X$ , and how  $X$  changes along the flow of  $Y$ , respectively.

On a flat space, one can think of the vectors  $X, Y, X + \alpha\nabla_Y X$ , and  $Y + \alpha\nabla_X Y$  as forming a parallelogram for infinitesimal  $\alpha$ , assuming  $[X, Y] = 0$ . However, on a general manifold with arbitrary connection, this parallelogram may fail to close. There are two distinct reasons for this failure:

1. The flow paths of  $X$  and  $Y$  do not commute, i.e., following  $X$  then  $Y$  leads to a different point than following  $Y$  then  $X$ . This is encoded by the Lie bracket  $[X, Y]$ .
2. The change in the transported vector fields differs, i.e.,  $\nabla_X Y \neq \nabla_Y X$ . This is an intrinsic feature of the connection.

The *torsion* is designed to isolate the second phenomenon: it captures the failure of symmetry in the connection itself, independent of the non-commutativity of the vector fields.

**Definition (Torsion)** Let  $\mathcal{M}$  be a smooth manifold, and  $\nabla$  a connection on  $\mathcal{M}$ . The torsion is the vector-valued map defined by

$$T : \Gamma(TM) \otimes \Gamma(TM), \quad T(X, Y) = \nabla_X Y - \nabla_Y X - [X, Y].\tag{6.2.1}$$

The first two terms,  $\nabla_X Y - \nabla_Y X$ , measure the asymmetry of the connection, but also include contributions from the possible non-closure of paths due to non-commuting vector fields. The Lie bracket  $[X, Y]$  encodes this latter effect—by subtracting it, we isolate the connection's contribution to the failure of the parallelogram to close, i.e., the torsion.

If  $T = 0$ , the connection is said to be *torsion-free*. To make this condition explicit, and to check its consequences on the connection coefficients, we now express the torsion in terms of components. Take  $X = X^\mu \partial_\mu$ ,  $Y = Y^\nu \partial_\nu$ ; then

$$\begin{aligned}
T(X, Y) &= X^\mu \nabla_\mu (Y^\nu \partial_\nu) - (X^\mu \partial_\mu Y^\nu) \partial_\nu - (X \leftrightarrow Y) \\
&= X^\mu \left( \cancel{(\partial_\mu Y^\nu)} \partial_\nu + Y^\nu \underbrace{\nabla_\mu \partial_\nu}_{=\Gamma_{\mu\nu}^\lambda \partial_\lambda} \right) - \cancel{(X^\mu \partial_\mu Y^\nu)} \partial_\nu - (X \leftrightarrow Y) \\
&= X^\mu Y^\nu \Gamma_{\mu\nu}^\lambda \partial_\lambda - (X \leftrightarrow Y) \\
&= X^\mu Y^\nu (\Gamma_{\mu\nu}^\lambda - \Gamma_{\nu\mu}^\lambda)
\end{aligned} \tag{6.2.2}$$

Note that subtracting the Lie bracket was essential to remove contributions from non-commutativity of the vector fields  $X$  and  $Y$ .

The torsion thus has the following properties:

1. It is antisymmetric:  $T(X, Y) = -T(Y, X)$ ;
2. It is  $C^\infty(\mathcal{M})$ -linear in both arguments;
3. It can be written in terms of components as

$$T(X, Y) = X^\mu Y^\nu T_{\mu\nu}^\lambda \partial_\lambda \quad \text{where} \quad T_{\mu\nu}^\lambda = T_{[\mu\nu]}^\lambda = \Gamma_{\mu\nu}^\lambda - \Gamma_{\nu\mu}^\lambda, \tag{6.2.3}$$

and is therefore proportional to the anti-symmetric part of the connection coefficients in the lower indices;

4. It is tensorial, since the transformation behaviour under  $x^\mu \rightarrow y^\alpha$  is given by

$$T_{\mu\nu}^\lambda \propto \Gamma_{[\mu\nu]}^\lambda \rightarrow \Gamma_{[\beta\gamma]}^\alpha = J_\lambda^\alpha J_\beta^\mu J_\gamma^\nu \Gamma_{[\mu\nu]}^\lambda + \underbrace{J_\lambda^\alpha \partial_{[\beta} J_{\gamma]}^\lambda}_{=0}, \tag{6.2.4}$$

where the inhomogeneous part cancels under anti-symmetrisation because

$$\partial_\beta J_\gamma^\lambda = \frac{\partial^2 x^\lambda}{\partial y^\beta \partial y^\gamma} \tag{6.2.5}$$

is symmetric in  $\beta$  and  $\gamma$ .

This fourth property ensures that  $T = 0$  is a meaningful, coordinate-independent condition. If torsion were not tensorial, the expression  $T(X, Y) = 0$  could be true in one chart and false in another.

We are now ready to impose the condition of vanishing torsion. By the third property above, we have

$$T = 0 \Leftrightarrow T_{\mu\nu}^\lambda = \Gamma_{\mu\nu}^\lambda - \Gamma_{\nu\mu}^\lambda = 0 \Leftrightarrow \Gamma_{\mu\nu}^\lambda = \Gamma_{(\mu\nu)}^\lambda, \tag{6.2.6}$$

i.e., a connection is torsion-free if and only if the connection coefficients are symmetric in their lower indices.

**Metric Compatibility** Luckily, this second condition is simpler to motivate and introduce than that of vanishing torsion. Recall that any connection  $\nabla$  is, by definition, compatible with contractions between one co- and one contravariant index,

$$\nabla \text{tr}_j^i T = \text{tr}_j^i \nabla T. \tag{6.2.7}$$

But as we know, contractions are not restricted to mixed index types—the metric (or its inverse) also allows contractions of two covariant or two contravariant indices.

Coordinate-independently, these operations take the form

$$T \mapsto \text{tr}_{1,2}^{i,j}(g \otimes T) \quad \text{or} \quad T \mapsto \text{tr}_{1,2}^{i,j}(g^{-1} \otimes T). \quad (6.2.8)$$

depending on whether one is contracting co- or contravariant indices. Perhaps more concretely, in terms of components, this becomes

$$T_{\nu_1 \dots \nu_s}^{\mu_1 \dots \mu_r} \mapsto g_{\mu_i \mu_j} T_{\nu_1 \dots \nu_s}^{\mu_1 \dots \mu_r} \quad \text{or} \quad T_{\nu_1 \dots \nu_s}^{\mu_1 \dots \mu_r} \mapsto g^{\nu_i \nu_j} T_{\nu_1 \dots \nu_s}^{\mu_1 \dots \mu_r}. \quad (6.2.9)$$

It is thus not far-fetched to ask that the connection be compatible with such contractions as well—after all, contraction through raising and lowering indices is a natural and frequent operation.

To formalise this, we demand that contractions involving the metric commute with covariant differentiation. Explicitly, we require<sup>5</sup>

$$\nabla(\text{tr}_{1,2}^{i,j} g \otimes T) = \text{tr}_{1,2}^{i,j} g \otimes (\nabla T). \quad (6.2.10)$$

Using the axioms for  $\nabla$ , we expand the left-hand side into

$$\nabla(\text{tr}_{1,2}^{i,j} g \otimes T) = \text{tr}_{1,2}^{i,j} \nabla(g \otimes T) = \text{tr}_{1,2}^{i,j} g \otimes (\nabla T) + \text{tr}_{1,2}^{i,j} (\nabla g) \otimes T \quad (6.2.11)$$

The first term matches the desired right-hand side, whereas the remaining second term vanishes if and only if  $\nabla g = 0$ .

Hence, *metric compatibility* is the requirement that the covariant derivative of the metric vanishes,

$$\nabla g = 0. \quad (6.2.12)$$

Notice that this also covers the case involving the inverse metric, since  $\nabla g = 0 \Leftrightarrow \nabla g^{-1} = 0$ . In components, the condition  $\nabla g = 0$  reads

$$\begin{aligned} 0 &\stackrel{!}{=} \nabla g = \nabla(g_{\mu\nu} dx^\mu \otimes dx^\nu) = (\partial_\lambda g_{\mu\nu} - g_{\rho\nu} \Gamma_{\lambda\mu}^\rho - g_{\mu\rho} \Gamma_{\lambda\nu}^\rho) dx^\lambda \otimes dx^\mu \otimes dx^\nu \\ &= (\partial_\lambda g_{\mu\nu} - \Gamma_{\nu\lambda\mu} - \Gamma_{\mu\lambda\nu}) dx^\lambda \otimes dx^\mu \otimes dx^\nu, \end{aligned} \quad (6.2.13)$$

where we defined  $\Gamma_{\lambda\mu\nu} = g_{\lambda\rho} \Gamma_{\mu\nu}^\rho$ . Making use of the torsion-freeness—i.e., symmetry of the connection coefficients in the last two indices—this is equivalent to

$$g_{\mu\nu,\lambda} = \Gamma_{\mu\nu\lambda} + \Gamma_{\nu\mu\lambda}, \quad (6.2.14)$$

with  $g_{\mu\nu,\lambda} = \partial_\lambda g_{\mu\nu}$ . This is a direct relationship between the derivatives of the metric and the connection coefficients.

Since we are attempting to single out a specific connection by imposing constraints, the next step is to solve the equation above for  $\Gamma_{\mu\nu\lambda}$ , from which the explicit form of the connection coefficients can be extracted using the inverse metric. This derivation is largely an exercise in index manipulation and combining permutations of the above equation to isolate the connection. The result is the expression for the *Christoffel symbols*,

$$\Gamma_{\mu\nu}^\lambda = \frac{1}{2} g^{\lambda\rho} [g_{\rho\mu,\nu} + g_{\rho\nu,\mu} - g_{\mu\nu,\rho}]. \quad (6.2.15)$$

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<sup>5</sup>For clarity we suppress any shifts in index positions introduced by tensor products.

The fact that this is the correct expression can also be checked by inserting equation (6.2.14) to replace the expressions  $g_{\mu\nu,\lambda}$  with the appropriate index permutations and verifying that the terms cancel correctly. This can be done in a few lines.

**Remark** The Christoffel symbols (6.2.15) above are the coefficients of the so-called *Levi-Civita connection*, which is the *unique* connection that is both torsion-free and metric-compatible.

### 6.3 Induced Connection on Foliations

The goal of this section is to define an affine connection on the submanifolds constituting a foliation  $\Sigma$  of a (pseudo-)Riemannian manifold  $\mathcal{M}$ . Just as with the ambient metric and the choice of induced metric on submanifolds, one is, in principle, free to assign any connection to these submanifolds. However, if  $\mathcal{M}$  is already equipped with an affine connection  $\nabla$ , it is natural to study a connection *induced* by this ambient structure, rather than constructing one from scratch. We begin by developing an intuitive, geometric picture of how such an induced connection should behave, before proceeding to formalise it in a precise definition.

As we have seen, an affine connection is fully characterised by its action on vector fields, encoded via the connection coefficients  $\Gamma_{\mu\nu}^\lambda$  appearing in

$$\nabla \partial_\nu = \Gamma_{\mu\nu}^\lambda dx^\mu \otimes \partial_\lambda. \quad (6.3.1)$$

Its action on functions  $\varphi \in C^\infty(\mathcal{M})$ , 1-forms, and general tensors is then determined entirely by the axioms of the connection. For example,

$$\nabla \varphi = d\varphi, \quad \nabla dx^\nu = -\Gamma_{\mu\lambda}^\nu dx^\mu \otimes dx^\lambda. \quad (6.3.2)$$

In other words, specifying how  $\nabla$  acts on vector fields suffices to determine its behaviour on all tensor fields.

Thus, the task of defining a geometrically meaningful connection on a foliation  $\Sigma = \{\Sigma_t\}$  reduces to defining how it acts on vector fields tangent to the leaves, and extending that action to arbitrary tensors via the standard axioms of an affine connection.

Therefore, given a connection  $\nabla$  on a manifold  $\mathcal{M}$  endowed with a foliation  $\Sigma = \{\Sigma_t\}$ , to define an induced connection  $\bar{\nabla}$  on each leaf  $\Sigma_t$ , we must provide a prescription for

$$\bar{\nabla}_X Y \quad \text{for any } X, Y \in \Gamma(T\Sigma), \quad (6.3.3)$$

which relates back to  $\nabla$  in a geometrically meaningful way.

Let us now build some geometric intuition. Recall that the expression  $\nabla_X Y$  describes how a vector field  $Y \in \Gamma(T\Sigma)$  changes as it is transported along the flow of  $X$ . Further, the pushforward  $\iota_*$  of the inclusion map  $\iota$  embeds  $T\Sigma$  into the ambient tangent bundle  $T\mathcal{M}$ , allowing us to view  $X$  and  $Y$  as vector fields living in  $T\mathcal{M}$  via their pushforwards  $\iota_* X$  and  $\iota_* Y$ .

Since we want the connection  $\bar{\nabla}$  on  $\Sigma$  to “mimic” the ambient connection  $\nabla$  on  $\mathcal{M}$  as closely as possible, a natural first attempt to define  $\bar{\nabla}$  would be

$$\bar{\nabla}_X Y = \nabla_{\iota_* X} (\iota_* Y). \quad (6.3.4)$$

In words, this says that  $\bar{\nabla}$  transports  $Y$  along  $X$  in precisely the same way that the ambient connection  $\nabla$  transports the embedded version of  $Y$  along that of  $X$  within  $T\mathcal{M}$ .

This is a good starting point—essentially all of the geometric structure of  $\nabla$  is being transferred to  $\bar{\nabla}$ . However, this definition has a fundamental flaw. It is subtle but crucial: an induced

connection on the foliation  $\Sigma$  must restrict to a connection on each individual leaf  $\Sigma_t$ , which is a map

$$\bar{\nabla} : \Gamma(T^{(r,s)}\Sigma_t) \rightarrow \Gamma(T^{(r,s+1)}\Sigma_t), \quad T \mapsto \bar{\nabla}T, \quad (6.3.5)$$

and, when acting on (and along) vector fields, is given more concretely by a map

$$\bar{\nabla} : \Gamma(T\Sigma_t) \times \Gamma(T\Sigma_t) \rightarrow \Gamma(T\Sigma_t), \quad (X, Y) \mapsto \bar{\nabla}_X Y. \quad (6.3.6)$$

In short, the connection must send vector fields tangent to the leaves to other vector fields tangent to the leaves. But  $\nabla_{\iota_* X}(\iota_* Y)$ , although well-defined in  $\Gamma(T\mathcal{M})$ , need not lie in the subbundle  $T\Sigma$ . The ambient connection  $\nabla$  is under no obligation to preserve tangency to the leaves—it can easily produce components orthogonal to them when transporting vectors through the submanifolds.

We are therefore forced to modify our first attempt so as to eliminate any normal components that may arise. For this purpose, recall the left-inverse  $(\iota_*)^{-1} : T\mathcal{M} \rightarrow T\Sigma$  introduced earlier. While there exist infinitely many such left-inverses, we singled out a unique one by requiring that the projection  $P = \iota_* \circ (\iota_*)^{-1}$  be orthogonal with respect to the ambient metric. This construction gives us precisely the tool we need:  $(\iota_*)^{-1}$  acts as the identity on  $T\Sigma$ , while annihilating vectors in the normal bundle  $N\Sigma$ ; that is,

$$\ker((\iota_*)^{-1}) = N\Sigma. \quad (6.3.7)$$

Thus, applying  $(\iota_*)^{-1}$  to our first attempt yields a vector field in  $\Gamma(T\Sigma)$ , with all normal components stripped away. This motivates the corrected definition

$$\bar{\nabla}_X Y = (\iota_*)^{-1} \nabla_{\iota_* X} (\iota_* Y). \quad (6.3.8)$$

This expression is admittedly cumbersome to read, but its geometric interpretation is clear. To compute  $\bar{\nabla}_X Y$  for  $X, Y \in \Gamma(T\Sigma)$ , we push both vector fields forward (i.e., embed) into the ambient tangent bundle, transport one along the other with the ambient connection, and then project the result back onto  $T\Sigma$  using the orthogonal “projection”  $(\iota_*)^{-1}$ . This removes any component normal to the foliation that may have been introduced by  $\nabla$ , while remaining true to the tangent contributions.

Let us now formalise this geometric construction as a rigorous definition.

**Definition** (Induced Connection on a Foliation) Let  $\mathcal{M}$  be a smooth manifold,  $\Sigma = \{\Sigma_t\}$  a foliation of  $\mathcal{M}$ , and

$$\nabla : \Gamma(T^{(r,s)}\mathcal{M}) \rightarrow \Gamma(T^{(r,s+1)}\mathcal{M}) \quad (6.3.9)$$

a connection on  $\mathcal{M}$ . We call the linear map

$$\bar{\nabla} : \Gamma(T^{(r,s)}\Sigma) \rightarrow \Gamma(T^{(r,s+1)}\Sigma) \quad (6.3.10)$$

the *induced connection on  $\Sigma$*  (associated to  $\nabla$ ) if

1. it reduces to the exterior derivative on functions  $\varphi \in C^\infty(\mathcal{M})$ ,

$$\bar{\nabla}\varphi = d\varphi, \quad (6.3.11)$$

2. acts on vector fields  $X, Y \in \Gamma(T\Sigma)$  as

$$\bar{\nabla}_X Y = (\iota_*)^{-1} (\nabla_{\iota_* X} (\iota_* Y)) \quad (6.3.12)$$

where  $(\iota_*)^{-1} : T\mathcal{M} \rightarrow T\Sigma$  is the left-inverse of  $\iota_*$  such that

$$\ker((\iota_*)^{-1}) = N\Sigma, \quad (6.3.13)$$

or equivalently,  $P = \iota_* \circ (\iota_*)^{-1}$  is the orthogonal projection  $P : T\mathcal{M} \rightarrow T\Sigma$ ;

3. satisfies a tensorial Leibniz rule,

$$\bar{\nabla}(T \otimes S) = (\bar{\nabla}T) \otimes S + T \otimes (\bar{\nabla}S), \quad (6.3.14)$$

on arbitrary tensors  $T, S$ ;

4. and is compatible with contractions,

$$\bar{\nabla}(\text{tr}_j^i T) = \text{tr}_j^i(\bar{\nabla}T), \quad (6.3.15)$$

for any tensor  $T$ .

**Remarks:**

- The axioms 1., 3. and 4. guarantee that  $\bar{\nabla}$  is itself an affine connection.
- Since the connection coefficients  $\bar{\Gamma}_{ij}^k$  in coordinates  $(t, y^i)$  adapted to  $\Sigma$  are defined by the action of the connection on basis vectors, axiom 2. allows for their explicit computation in terms of the coefficients  $\Gamma_{\mu\nu}^\lambda$  of the ambient connection  $\nabla$ , the pushforward matrix  $E_i^\mu$  and its orthogonal left-inverse  $E_\mu^i$ . Concretely, we may derive

$$\begin{aligned} \bar{\Gamma}_{ij}^k \partial_k &= \bar{\nabla}_i \partial_j = (\iota_*)^{-1}(\nabla_{\iota_* \partial_i}(\iota_* \partial_j)) \\ &= (\iota_*)^{-1}(\nabla_{E_i^\mu \partial_\mu}(E_j^\nu \partial_\nu)) \\ &= E_i^\mu (\iota_*)^{-1}(\nabla_\mu(E_j^\nu \partial_\nu)) \\ &= E_i^\mu (\iota_*)^{-1}((\partial_\mu E_j^\nu) \partial_\nu + E_j^\nu \underbrace{\nabla_\mu \partial_\nu}_{=\Gamma_{\mu\nu}^\lambda \partial_\lambda}) \\ &= E_i^\mu ((\partial_\mu E_j^\lambda) + E_j^\nu \Gamma_{\mu\nu}^\lambda) \underbrace{(\iota_*)^{-1}(\partial_\lambda)}_{=E_\lambda^k \partial_k} \\ &= (E_\lambda^k E_i^\mu E_j^\nu \Gamma_{\mu\nu}^\lambda + E_\lambda^k \partial_i E_j^\lambda) \partial_k \end{aligned} \quad (6.3.16)$$

from which we conclude

$$\bar{\Gamma}_{ij}^k = E_\lambda^k E_i^\mu E_j^\nu \Gamma_{\mu\nu}^\lambda + E_\lambda^k \partial_i E_j^\lambda. \quad (6.3.17)$$

This matches the structure of the coordinate transformation behaviour (6.1.24) of the connection.

- Since  $\bar{\nabla}$  is an affine connection, the above relationship that

$$\bar{\nabla}_i \partial_j = \bar{\Gamma}_{ij}^k \partial_k \quad (6.3.18)$$

on vectors extends to 1-forms by

$$\bar{\nabla}_i dy^j = -\bar{\Gamma}_{ik}^j dy^k \quad (6.3.19)$$

by the general result (6.1.34). Further, the linearity and Leibniz rule that hold for  $\bar{\nabla}$  allow for the extension onto any tensor  $T$ .



## 6.4 Proof: Induced Connection from Levi-Civita Connections

The previous section introduced the notion of a connection on the submanifolds of a foliation, induced from a connection on the ambient manifold. This construction defines a specific connection on each submanifold, but it is not immediately clear which properties of the ambient connection are preserved, or whether the induced connection might acquire new properties absent from the ambient. Such questions typically require case-by-case analysis.

There is, however, an important special case, which we explore in this section. Recall that the Levi-Civita is uniquely characterised by two conditions: vanishing torsion and compatibility with the metric. We will show that if the ambient connection satisfies these conditions, then the induced connection does as well—in this sense, they are inherited. It follows that the connection induced by a Levi-Civita connection is itself Levi-Civita. In particular, this yields an alternative to the projection of connection coefficients (6.3.17), as the coefficients of the induced connection can now be computed directly from linear combinations of partial derivatives of the induced metric.

In the following, let  $\mathcal{M}$  denote a (pseudo-)Riemannian manifold with metric tensor  $g \in \Gamma(T^{(0,2)}\mathcal{M})$ ,  $\Sigma = \{\Sigma_t\}$  a hypersurface foliation of  $\mathcal{M}$ , and  $\gamma = \iota^*g$  the induced metric on  $\Sigma_t$ . Further, let  $\nabla$  be a connection on  $\mathcal{M}$  and  $\bar{\nabla}$  the connection on  $\Sigma$  induced by  $\nabla$ .

**Vanishing Torsion** Suppose  $\nabla$  has vanishing torsion. Concretely, this means that

$$T(X, Y) = \nabla_X Y - \nabla_Y X - [X, Y] = 0 \quad \forall X, Y \in \Gamma(T\mathcal{M}), \quad (6.4.1)$$

or equivalently,

$$\nabla_X Y - \nabla_Y X = [X, Y] \quad (6.4.2)$$

The torsion of the induced connection, evaluated on vector fields  $X, Y \in \Gamma(T\Sigma)$  is given by

$$\begin{aligned} \bar{T}(X, Y) &= \bar{\nabla}_X Y - \bar{\nabla}_Y X - [X, Y] \\ &= (\iota_*)^{-1} [\nabla_{\iota_* X} (\iota_* Y) - \nabla_{\iota_* Y} (\iota_* X)] - [X, Y] \\ &= \underbrace{(\iota_*)^{-1} [\iota_* X, \iota_* Y]}_{=[X, Y] \quad (*)} - [X, Y] = 0. \end{aligned} \quad (6.4.3)$$

Thus, as a consequence of the vanishing torsion of  $\nabla$ , the induced connection  $\bar{\nabla}$  is torsion-free as well. The identity  $(*)$  originates from

$$[\iota_* X, \iota_* Y] = \iota_* [X, Y], \quad (6.4.4)$$

which can be shown coordinate-independently using the definition of the commutator,

$$[X, Y][f] = X[Y[f]] - Y[X[f]], \quad f \in C^\infty(\mathcal{M}), \quad (6.4.5)$$

and the fact that  $(\iota_* X)[f] = X[f \circ \iota]$ .

Alternatively, one can show this on the level of components as well. The ambient connection being torsion free implies that its connection coefficients  $\Gamma_{\mu\nu}^\lambda$  are symmetric in the lower indices. The induced connection coefficients, given by

$$\bar{\Gamma}_{ij}^k = E_\lambda^k E_i^\mu E_j^\nu \Gamma_{\mu\nu}^\lambda + E_\lambda^k \partial_i E_j^\lambda \quad (6.4.6)$$

(cf. eq. (6.1.24)), are then symmetric in the lower indices  $i, j$  as well—the first term is symmetric due to the symmetry of  $\Gamma_{\mu\nu}^\lambda$ , and the second because of

$$\partial_i E_j^\lambda = \frac{\partial^2 x^\lambda}{\partial y^i \partial y^j}, \quad (6.4.7)$$

which is symmetric as well.

We have now given a coordinate-free and a component-based proof of the fact that an induced connection inherits torsion-freeness from the ambient connection. It remains to show that metric compatibility is preserved as well, allowing us to conclude that an ambient Levi-Civita connection induces a Levi-Civita connection on the submanifolds of a foliation.

**Metric Compatibility** To show that metric compatibility of  $\nabla$  is inherited to  $\bar{\nabla}$ , let us first derive a useful identity—a product rule for the inner product induced by the metric  $g$ . Observe that for  $X, Y, Z \in \Gamma(TM)$ , we have

$$\begin{aligned}\nabla_X g(Y, Z) &= \nabla_X \text{tr}_{1,2}^{3,4}(g \otimes Y \otimes Z) \\ &= \text{tr}_{1,2}^{3,4}[(\nabla_X g) \otimes Y \otimes Z + g \otimes (\nabla_X Y) \otimes Z + g \otimes Y \otimes (\nabla_X Z)] \\ &= (\nabla_X g)(Y, Z) + g(\nabla_X Y, Z) + g(Y, \nabla_X Z),\end{aligned}\tag{6.4.8}$$

which is equivalent to

$$\nabla_X g(Y, Z) - (\nabla_X g)(Y, Z) = g(\nabla_X Y, Z) + g(Y, \nabla_X Z).\tag{6.4.9}$$

In particular, a connection  $\nabla$  is compatible with a metric  $g$  if and only if the first term vanishes, i.e. if

$$\nabla_X g(Y, Z) = g(\nabla_X Y, Z) + g(Y, \nabla_X Z) \quad \forall X, Y, Z \in \Gamma(TM).\tag{6.4.10}$$

We will now assume that this holds for  $\nabla$  and  $g$ , and show that as a consequence, it is also true for the induced connection  $\bar{\nabla}$  and metric  $\gamma$ . This proceeds as follows, for  $X, Y, Z \in \Gamma(T\Sigma)$ :

$$\begin{aligned}\bar{\nabla}_X \gamma(Y, Z) - (\bar{\nabla}_X \gamma)(Y, Z) &\stackrel{1.}{=} \gamma(\bar{\nabla}_X Y, Z) + (Y \leftrightarrow Z) \\ &\stackrel{2.}{=} (\iota^* g)((\iota_*)^{-1} \nabla_{\iota_* X} (\iota_* Y), Z) + (Y \leftrightarrow Z) \\ &\stackrel{3.}{=} g(\underbrace{\iota_* \circ (\iota_*)^{-1}}_{=P} \nabla_{\iota_* X} (\iota_* Y), \iota_* Z) + (Y \leftrightarrow Z) \\ &\stackrel{4.}{=} g(\nabla_{\iota_* X} (\iota_* Y), \underbrace{P \iota_* Z}_{=\iota_* Z}) + (Y \leftrightarrow Z) \\ &\stackrel{5.}{=} \nabla_{\iota_* X} g(\iota_* Y, \iota_* Z) \\ &\stackrel{6.}{=} \bar{\nabla}_X \gamma(Y, Z)\end{aligned}\tag{6.4.11}$$

which shows that

$$(\bar{\nabla}_X \gamma)(Y, Z) = 0,\tag{6.4.12}$$

i.e. that  $\bar{\nabla} \gamma = 0$  and hence the induced connection is compatible with the induced metric. Since the algebra is quite dense here, let us outline the individual steps in the derivation (6.4.11):

1. Make use of identity (6.4.9);
2. Insert definitions,  $\gamma = \iota^* g$  and  $\bar{\nabla}_X Y = (\iota_*)^{-1} \nabla_{\iota_* X} (\iota_* Y)$ ;
3. Employ  $(\iota^* g)(X, Y) = g(\iota_* X, \iota_* Y)$
4. Apply orthogonality of  $P$ , i.e.  $g(PX, Y) = g(X, PY)$ ;
5. Use identity (6.4.10)—here, the assumption that  $\nabla$  is metric-compatible enters;
6. Employ  $(\iota^* g)(X, Y) = g(\iota_* X, \iota_* Y)$  as well as  $\nabla_{\iota_* X} \varphi = (\iota_* X)[\varphi] = X[\varphi] = \bar{\nabla}_X \varphi$  on functions  $\varphi \in C^\infty(\mathcal{M})$ .

Though somewhat algebra-heavy and light on geometric intuition, the above derivations yield a powerful result: The induced connection  $\bar{\nabla}$  on the foliation  $\Sigma$ —induced by the Levi-Civita

connection  $\nabla$  on  $\mathcal{M}$ —is of Levi-Civita type as well. In particular, it follows that the induced connection components are given by the Christoffel symbol expression for  $\gamma$ , i.e.,

$$\bar{\Gamma}_{ij}^k = \frac{1}{2} \gamma^{k\ell} (\gamma_{\ell i,j} + \gamma_{\ell j,i} - \gamma_{ij,\ell}). \quad (6.4.13)$$

This is a direct construction of the connection coefficients that makes no reference to the ambient connection.

## 6.5 Example: Induced Connection on the Foliation of $\mathbb{R}^3 \setminus \{0\}$ into Spheres

To see the machinery of induced connections as well as the inheritance of the Levi-Civita property in action, in this section, we reconsider the example of  $\mathcal{M} = \mathbb{R}^3 \setminus \{0\}$ , foliated into concentric origin-centered spheres from Section 5.5. Let us briefly reestablish the setting.

On  $\mathbb{R}^3 \setminus \{0\}$ , in cartesian coordinates  $x^\mu = (x, y, z)$ , the Euclidean metric reads

$$g = g_{\mu\nu} dx^\mu \otimes dx^\nu = dx \otimes dx + dy \otimes dy + dz \otimes dz. \quad (6.5.1)$$

We foliate  $\mathbb{R}^3 \setminus \{0\}$  by introducing the function

$$r : \mathcal{M} \rightarrow \mathbb{R}, \quad r(p) = \sqrt{x^2 + y^2 + z^2}, \quad p = (x, y, z) \quad (6.5.2)$$

and define the leaves of the foliation  $\Sigma = \{\Sigma_r\}$  to be its level sets,

$$\Sigma_{r_0} \equiv \{p \in \mathcal{M} \mid r(p) = r_0\} = r_0 S^2. \quad (6.5.3)$$

In spherical coordinates  $(r, y^i) = (r, \theta, \varphi)$  on  $\mathbb{R}^3 \setminus \{0\}$ , the induced metric on a leaf  $\Sigma_r$  was derived to be

$$\gamma = \gamma_{ij} dq^i \otimes dq^j = r^2 d\theta \otimes d\theta + r^2 \sin^2 \theta d\varphi \otimes d\varphi, \quad (6.5.4)$$

with nonzero components  $\gamma_{\theta\theta} = r^2$ ,  $\gamma_{\varphi\varphi} = r^2 \sin^2 \theta$ .

We equip the ambient manifold  $\mathbb{R}^3 \setminus \{0\}$  with the Levi-Civita connection, which in cartesian coordinates has vanishing coefficients, i.e.

$$\Gamma_{\mu\nu}^\lambda = \frac{1}{2} g^{\lambda\rho} (g_{\rho\mu,\nu} + g_{\rho\nu,\mu} - g_{\mu\nu,\rho}) = 0, \quad (6.5.5)$$

since the metric components  $g_{xx} = g_{yy} = g_{zz} = 1$  are constant.

We now have two formulae to compute the components  $\bar{\Gamma}_{ij}^k$  of the connection  $\bar{\nabla}$  induced by  $\nabla$  at our disposal; we can either use the projection formula (6.3.17), or calculate them directly using the Christoffel expression (6.4.13). We now proceed to evaluate both.

The evaluation of the projection formula (6.3.17) requires us to compute the components of the pushforward matrix

$$E_i^\mu = \frac{\partial x^\mu}{\partial q^i} \quad (6.5.6)$$

as well as its left-inverse  $E_\mu^i$  subject to the condition that  $P^\mu_\nu = E_\mu^i E_\nu^i$  is orthogonal. The components of the pushforward matrix read

$$\begin{aligned}
E_\theta^x &= r \cos \theta \cos \varphi, & E_\varphi^x &= -r \sin \theta \sin \varphi, \\
E_\theta^y &= r \cos \theta \sin \varphi, & E_\varphi^y &= r \sin \theta \cos \varphi, \\
E_\theta^z &= -r \sin \theta, & E_\varphi^z &= 0.
\end{aligned} \tag{6.5.7}$$

The orthogonal left-inverse can be computed using

$$E_\mu^i = \gamma^{ij} g_{\mu\nu} E_j^\nu, \tag{6.5.8}$$

as then

$$E_\mu^i E_k^\mu = \gamma^{ij} \underbrace{g_{\mu\nu} E_j^\nu E_k^\mu}_{=\gamma_{jk}} = \gamma^{ij} \gamma_{jk} = \delta_k^i, \tag{6.5.9}$$

ensures the left-inverse property and

$$P_{\mu\nu} = g_{\mu\lambda} P^\lambda_\nu = g_{\mu\lambda} E_i^\lambda E_\nu^i = g_{\mu\lambda} E_i^\lambda \gamma^{ij} g_{\nu\rho} E_j^\rho \tag{6.5.10}$$

symmetry of  $P_{\mu\nu}$  which is equivalent to orthogonality.

The components of the orthogonal left-inverse read

$$\begin{aligned}
E_x^\theta &= \frac{1}{r} \cos \theta \cos \varphi, & E_x^\varphi &= -\frac{1}{r \sin \theta} \sin \varphi, \\
E_y^\theta &= \frac{1}{r} \cos \theta \sin \varphi, & E_y^\varphi &= \frac{1}{r \sin \theta} \cos \varphi, \\
E_z^\theta &= -\frac{1}{r} \sin \theta, & E_z^\varphi &= 0.
\end{aligned} \tag{6.5.11}$$

Since the ambient connection coefficients vanish in cartesian coordinates, the induced components reduce to the inhomogeneous term in (6.3.17), that is,

$$\bar{\Gamma}_{ij}^k = E_\lambda^k \partial_i E_j^\lambda. \tag{6.5.12}$$

While entirely mechanical, the computation of all components is somewhat laborious. We'll carry out one as an illustration and state the remaining results without derivation. As our example, we choose to calculate

$$\begin{aligned}
\bar{\Gamma}_{\varphi\varphi}^\theta &= E_\lambda^\theta \partial_\varphi E_\varphi^\lambda = E_x^\theta \partial_\varphi E_\varphi^x + E_y^\theta \partial_\varphi E_\varphi^y \\
&= \left( \frac{1}{r} \cos \theta \cos \varphi \right) \partial_\varphi (-r \sin \theta \sin \varphi) + \left( \frac{1}{r} \cos \theta \sin \varphi \right) \partial_\varphi (r \sin \theta \cos \varphi) \\
&= -\cos \theta \sin \theta \cos^2 \varphi - \cos \theta \sin \theta \sin^2 \varphi = -\cos \theta \sin \theta \\
&= -\frac{1}{2} \sin(2\theta)
\end{aligned} \tag{6.5.13}$$

The remaining non-vanishing connection coefficients are given by

$$\bar{\Gamma}_{\theta\varphi}^\varphi = \bar{\Gamma}_{\varphi\theta}^\varphi = \cot \theta, \tag{6.5.14}$$

where  $\cot \theta = \frac{\cos \theta}{\sin \theta}$ .

We now proceed to recompute these coefficients using the standard Christoffel formula. To do so, it is usually advantageous to first compute the components

$$\bar{\Gamma}_{kij} = \frac{1}{2} (g_{ki,j} + g_{kj,i} - g_{ij,k}) \tag{6.5.15}$$

and to then raise the first index with the inverse metric. Before wildly starting to evaluate all possible index combinations, we should first examine the nature of the components  $\gamma_{ij}$  of the induced metric. There is only one component,  $\gamma_{\varphi\varphi} = r^2 \sin^2 \theta$ , which is non-constant<sup>6</sup> and hence has a chance of contributing to  $\bar{\Gamma}_{kij}$ . It only depends on  $\theta$ , and hence the only non-zero component of the partial gradient of  $\gamma_{ij}$  is

$$\partial_\theta \gamma_{\varphi\varphi} = 2r^2 \sin \theta \cos \theta. \quad (6.5.16)$$

Consequently, a coefficient  $\bar{\Gamma}_{kij}$  can only be non-zero if one of the indices is  $\theta$  and the other two are  $\varphi$ . Due to symmetry in the last two indices, this leaves us with two options,

$$\begin{aligned} \bar{\Gamma}_{\theta\varphi\varphi} &= \frac{1}{2} \left( \underbrace{\gamma_{\theta\varphi,\varphi}}_{=0} + \underbrace{\gamma_{\varphi\theta,\varphi}}_{=0} - \gamma_{\varphi\varphi,\theta} \right) = -r^2 \sin \theta \cos \theta, \\ \bar{\Gamma}_{\varphi\theta\varphi} = \bar{\Gamma}_{\varphi\varphi\theta} &= \frac{1}{2} \left( \gamma_{\varphi\varphi,\theta} + \underbrace{\gamma_{\varphi\theta,\varphi}}_{=0} - \underbrace{\gamma_{\varphi\varphi,\varphi}}_{=0} \right) = r^2 \sin \theta \cos \theta. \end{aligned} \quad (6.5.17)$$

Given the components of the inverse metric,

$$\gamma^{\theta\theta} = \frac{1}{r^2}, \quad \gamma^{\varphi\varphi} = \frac{1}{r^2 \sin^2 \theta}, \quad (6.5.18)$$

we can compute the connection coefficients as

$$\begin{aligned} \bar{\Gamma}_{\varphi\varphi}^\theta &= g^{\theta\theta} \bar{\Gamma}_{\theta\varphi\varphi} = -\sin \theta \cos \theta = -\frac{1}{2} \sin(2\theta), \\ \bar{\Gamma}_{\theta\varphi}^\varphi = \bar{\Gamma}_{\varphi\theta}^\varphi &= g^{\varphi\varphi} \bar{\Gamma}_{\varphi\varphi\theta} = \frac{\cos \theta}{\sin \theta} = \cot \theta. \end{aligned} \quad (6.5.19)$$

This reproduces exactly the same result as the projection formula, as we would expect from our derivations made for general manifolds—it is nevertheless satisfying to see that the abstract machinery does indeed work when applied to concrete examples.

## 7 Curvature

serves as a transitional section introducing ambient vs intrinsic curvature, before isolating the extrinsic part.

### 7.1 Intrinsic Curvature

- Recap the ambient Riemann tensor  $R^\mu_{\nu\rho\sigma}$  on  $\mathcal{M}$ .
- Define the intrinsic Riemann tensor on  $\Sigma$  via the induced connection  $\bar{\nabla}$ .
- Begin separating the *difference* between  $\nabla$  and  $\bar{\nabla}$  to motivate extrinsic curvature.

### 7.2 Extrinsic Curvature

- Define the *second fundamental form* or *extrinsic curvature* tensor:

$$K(X, Y) := g(\nabla_X n^\sharp, Y), \quad X, Y \in T\Sigma, \quad (7.2.1)$$

or equivalently as the normal part of  $\nabla_X Y$ .

- Show symmetry:  $K(X, Y) = K(Y, X)$ .
- Express  $K$  in coordinates (adapted to foliation) and link to the Lie derivative of the induced metric:

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<sup>6</sup>Recall that on a leaf,  $r$  is constant.

$$K_{ij} = \frac{1}{2\alpha} \mathcal{L}_n \gamma_{ij}. \quad (7.2.2)$$

### 7.3 Gauss-Codazzi Equations

- **Gauss equation:** relates intrinsic curvature of  $\Sigma$  to ambient curvature and  $K$ :

$$R_{ijk\ell}^\Sigma = R_{ijk\ell} + \varepsilon(K_{ik}K_{j\ell} - K_{i\ell}K_{jk}). \quad (7.3.1)$$

- **Codazzi equation:** relates derivatives of  $K$  to ambient curvature:

$$D_i K_{jk} - D_j K_{ik} = R_{\ell ijk} n^\ell. \quad (7.3.2)$$

- Optionally: show how these identities constrain initial data in general relativity.