MATH635
Riemannian Geometry

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Abstract

This is the advanced graduate-level differential geometry course focused on Riemannian geometry taught by Lydia Bieri. Topics include local and global aspects of differential geometry and the relation with the underlying topology. We'll use do Carmo's *Riemannian Geometry* [FC13] as our reference; while not required, but highly recommended have on.

This course is taken in Winter 2023, and the date on the covering page is the last updated time.

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1.1 Differentiable Manifolds

1.1.1 Topological Manifolds

Let's start with a common definition.

Definition 1.1.1 (Topological manifold)**.** A *topological manifold* $\mathcal{M}$ of dimension n is a (topological) Hausdorff space such that each point $p \in \mathcal{M}$ has a neighborhood U homeomorphic via $\varphi \colon U \to U'$ to an open subset $U' \subseteq \mathbb{R}^n$.

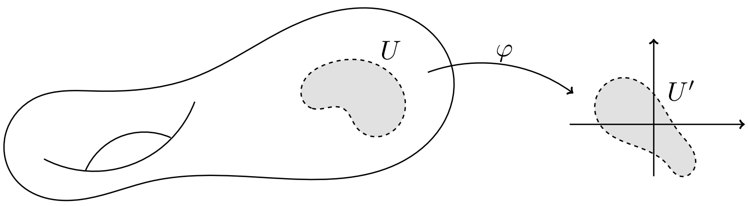
Definition 1.1.2 (Local coordinate map)**.** For every $p \in \mathcal{M}$, the corresponding homeomorphism φ is called the *local coordinate map*.

Definition 1.1.3 (Local coordinate)**.** The pull-back $(x^1, \dots, x^n)$ of the local coordinate map φ from $\mathbb{R}^n$ is called the *local coordinates* on U, given by

$$\varphi(p) = (x^1(p), \dots, x^n(p)).$$

Definition 1.1.4 (Coordinate chart)**.** The pair (U, φ) is called a *(coordinate) chart* on M.

In other words, a topological manifold can be thought of as a space such that it looks like $\mathbb{R}^n$ locally.



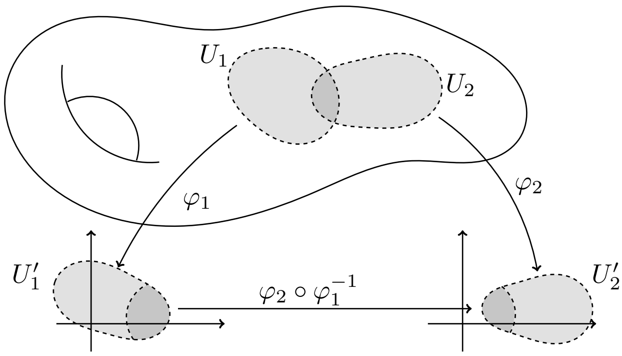
Definition 1.1.5 (Atlas)**.** An *atlas* $\mathcal{A} = \{(U_\alpha, \varphi_\alpha)\}_\alpha$ for a manifold $\mathcal{M}$ is a collection of charts such that $\{U_\alpha \subseteq \mathcal{M} \mid U_\alpha \text{ open}\}_\alpha$ are an open covering of $\mathcal{M}$, i.e., $\mathcal{M} = \bigcup_\alpha U_\alpha$.

In other words, for all $p \in \mathcal{M}$, there exists a neighborhood $U \subseteq \mathcal{M}$ and homeomorphism $h \colon U \to U' \subseteq \mathbb{R}^n$ open.

Definition 1.1.6 (Locally finite)**.** An atlas is said to be *locally finite* if each point $p \in \mathcal{M}$ is contained in only a finite collection of its open sets.

Clearly, without any help of ambient space such as $\mathbb{R}^n$, there's no clear way to make sense of differentiability of a manifold. But thankfully, we now have an explicit relation to the ambient space $\mathbb{R}^n$ via φ_α. To formalize, let $\mathcal{A}$ be an atlas for a manifold $\mathcal{M}$, and assume that $(U_1, \varphi_1), (U_2, \varphi_2)$ are 2 elements of $\mathcal{A}$. Then clearly, the map $\varphi_2 \circ \varphi_1^{-1} \colon \varphi_1(U_1 \cap U_2) \to \varphi_2(U_1 \cap U_2)$ is a homeomorphism between 2 open sets of Euclidean spaces since both φ_1 and φ_2 are homeomorphism. Due to this map's importance, it has its own name.

Definition 1.1.7 (Coordinate transition)**.** The map $\varphi_2 \circ \varphi_1^{-1}$ is called the *coordinate transition* of $\mathcal{A}$ for the pair of charts $(U_1, \varphi_1), (U_2, \varphi_2)$.



1.1.2 Differentiable Structures

Notice that the coordinate transitions are from $\mathbb{R}^n$ to $\mathbb{R}^n$; hence differentiability makes sense now, which induces the following.

Definition 1.1.8 (Differentiable atlas)**.** The atlas $\mathcal{A} = \{(U_\alpha, \varphi_\alpha)\}$ is *differentiable* if all transitions are differentiable.

Remark. Here, the differentiability depends on the content. Sometimes, we may want it to be C^∞, and sometimes may be C^k for some finite k. On the other hand, smooth always refers to C^∞. We'll use them interchangeably if it's clear which case we're referring to.

Definition 1.1.9 (Equivalence atlas)**.** Two atlases $\mathcal{U}, \mathcal{V}$ of a manifold are equivalent if for every $(U, \varphi) \in \mathcal{U}$, $(V, \psi) \in \mathcal{V}$,

$$\varphi \circ \psi^{-1} \colon \psi(U \cap V) \to \varphi(U \cap V)$$

and

$$\psi \circ \varphi^{-1} \colon \varphi(U \cap V) \to \psi(U \cap V)$$

are diffeomorphisms between subsets of Euclidean spaces.

Notably, we have the following notation.

Notation (Smoothly compatible)**.** Two charts (U, φ) and (V, ψ) are *smoothly compatible* if either $U \cap V = \varnothing$ or $\psi \circ \varphi^{-1}$ is a diffeomorphism.

This suggests the following.

Definition 1.1.10 (Smooth structure)**.** A *smooth structure* on $\mathcal{M}$ is an equivalence class $\mathcal{U}$ of coordinate atlas with the property that all transition functions are diffeomorphisms.

Remark. We can also use the *maximal* differentiable atlas to be our differentiable structure.

Definition 1.1.11 (Smooth manifold). A *smooth manifold* is a manifold $\mathcal{M}$ with a smooth structure.

In this way, we can do calculus on smooth manifolds! Furthermore, it now makes sense to say that a function $f\colon \mathcal{M} \to \mathbb{R}$ is differentiable (or C^∞) by considering differentiability of $f \circ \varphi^{-1}$ around p.

Notation. The collection of smooth functions on smooth manifold $\mathcal{M}$ is denoted by $C^\infty(\mathcal{M}, \mathbb{R})$, or $C^k(\mathcal{M}, \mathbb{R})$.

Remark. The class $C^\infty(\mathcal{M}, \mathbb{R})$ consists of functions with property is well-defined.

Proof. Let $\mathcal{A}$ be any given atlas from equivalence class that defines the smooth structure, and as we have shown, if $(U, \varphi) \in \mathcal{A}$, then $f \circ \varphi^{-1}$ is smooth on $\mathbb{R}^n$. This requirement defines the same set of smooth functions no matter the choice of representative atlas by the nature of Definition 1.1.9 requirement that defines the equivalent manifolds. ⊛

1.1.3 Orientation

Another essential property of a manifold is its orientability.

Definition. Consider an atlas $\mathcal{A}$ for a differentiable manifold $\mathcal{M}$.

Definition 1.1.12 (Oriented). $\mathcal{A}$ is *oriented* if all transitions have positive functional determinant.

Definition 1.1.13 (Orientable). $\mathcal{M}$ is *orientable* if $\mathcal{A}$ is an oriented atlas.

Motivated by the above definitions, we see that we can actually use an atlas to define an orientation.

Definition 1.1.14 (Orientation). Let $\mathcal{M}$ be an orientable manifold. Then a oriented differentiable structure is called an *orientation* of $\mathcal{M}$.

If $\mathcal{M}$ possesses an orientation, we can also say that it's *oriented*. But we don't bother to make a new definition to confuse ourselves with Definition 1.1.12.

Remark. Two differentiable structures obeying Definition 1.1.12 determine the same orientation if the union again satisfying Definition 1.1.12.

Remark. If $\mathcal{M}$ is orientable and connected, then there exists exactly 2 distinct orientations on $\mathcal{M}$.

Now, we can see some examples of smooth manifolds.

Example (Sphere). The sphere $S^n \subseteq \mathbb{R}^{n+1}$ given by

$$S^n = \left\{(x_1, \dots, x_{n+1}) \in \mathbb{R}^{n+1} \mid x_1^2 + \dots + x_{n+1}^2 = 1\right\}.$$

Consider $U_i^+ = \{x \in S^n \mid x_i > 0\}$, $U_i^- = \{x \in S^n \mid x_i < 0\}$ for $i = 1, \dots, n+1$, and $h_i^\pm\colon U_i^\pm \to \mathbb{R}^n$ such that

$$h_i^\pm(x_1, \dots, x_{n+1}) = (x_1, \dots, \hat{x}_i, .., x_{n+1}).$$

Note that the minimum charts needed to cover S^n is 2.

Example. Let $\mathcal{M} = U \subseteq \mathbb{R}^n$, then $\{(U, \varphi)\}$ is a smooth structure with $\varphi = \mathbb{1}$.

Example. Open sets of C^∞-manifolds are C^∞-manifolds.

Example (General linear group). $\mathrm{GL}(n) = \{A \in M_n(\mathbb{R}) \mid \det A \neq 0\} \subseteq M_n(\mathbb{R}) = \mathbb{R}^{n^2}$, open.

Example (Real projective space). $\mathbb{R}P^n = S^n / \sim$ where $x \sim -x$ with $\pi \colon S^n \to \mathbb{R}P^n$, $x \mapsto [x]$.

Proof. π is a homeomorphism on each U_i^+ for $i = 1, \dots, n+1$, with

$$\left\{ \left(\pi(U_i^+), \varphi_i^+ \circ \pi^{-1} \right), i = 1, \dots, n+1 \right\}$$

is a C^∞-atlas for $\mathbb{R}P^n$. ⊛

Note. Observe that $\mathbb{R}P^n = \mathbb{R}^{n+1} \setminus \{0\} / \sim$.

Lecture 2: Maps Between Smooth Manifolds

1.1.4 Smooth Maps

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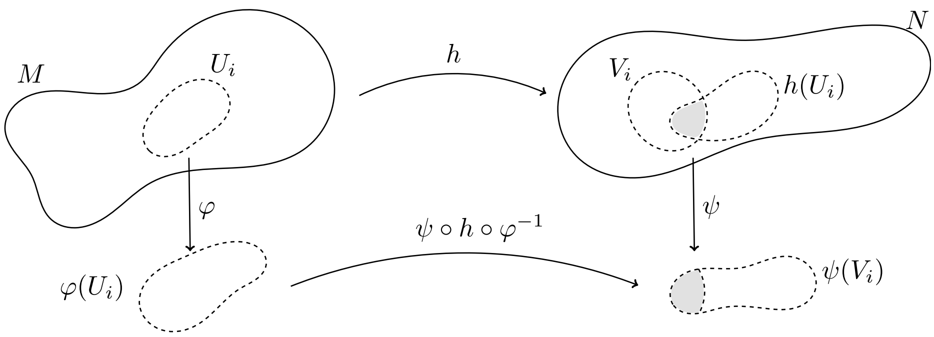
We can now consider the maps between manifolds, specifically, the smooth manifolds.

Definition 1.1.15 (Smooth function). Let M, N be two smooth manifolds, and let $\mathcal{U}$ be locally finite atlas from the equivalence class that gives the smooth structure on M, and let $\mathcal{V}$ be the corresponding for N. A map $h \colon M \to N$ is said to be *smooth* if each map in the collection

$$\left\{ \psi \circ h \circ \varphi^{-1} \colon h(U) \cap V \neq \varnothing \right\},$$

where $(U, \varphi) \in \mathcal{U}$, $(V, \psi) \in \mathcal{V}$ is C^∞-differentiable as a map from one Euclidean space to another.



Remark. Equivalence relation guarantees that Definition 1.1.15 depends only on the smooth structure of M, N, but not on the chosen representative coordinate atlas.

Definition. Consider two smooth manifolds M, N and a smooth homeomorphism $h \colon M \to N$ with smooth inverse.

Definition 1.1.16 (Diffeomorphic). The two manifolds M, N are said to be *diffeomorphic*.

Definition 1.1.17 (Diffeomorphism). The map h is said to be a *diffeomorphism*.

Let M_1, M_2 be two smooth manifolds, and let $\varphi \colon M_1 \to M_2$ be a diffeomorphism. Then the following hold. Check

(a) M_1 is orientable if and only if M_2 is orientable.

(b) If in addition, M_1 and M_2 are both connected and oriented, then φ induces an orientation on M_2 that may or may not coincide with the initial orientation of M_2.

If the induced orientation coincides, then we say φ preserves the orientation, otherwise φ reverses the orientation.

1.1.5 Grassmannian Manifold

Before proceeding, let's consider an interesting smooth manifold.

Definition 1.1.18 (Grassmannian manifold). Given $m, n \in \mathbb{N}$, the so-called *Grassmannian manifold* $G(n, m)$ is the set of all n-dimensional subspaces of $\mathbb{R}^{n+m}$.

Note. $G(1, m)$ is just $\mathbb{R}P^m$, and $G(0, m)$, $G(n, 0)$ are one-point sets.

As we will soon see, $G(n, m)$ has the smooth structure of an mn-dimensional manifold.

Intuition. We obtain the structure by exhibiting an atlas whose transitions are diffeomorphisms.

Firstly, we give $G(n, m)$ a suitable topology, i.e., the metric topology. Let $\Pi \in G(n, m)$, and let $\mathcal{L}(\Pi, \Pi^\perp)$ denote the mn-dimensional space of linear maps from Π to $\Pi^\perp$. Define the map

$$\varphi_\Pi \colon \mathcal{L}(\Pi, \Pi^\perp) \to G(n, m), \qquad \varphi_\Pi(\alpha) = (\mathbb{1}_\Pi \oplus \alpha)(\Pi)$$

where $\mathbb{1}_\Pi \oplus \alpha$ is regarded as a map $\Pi \to \Pi \oplus \Pi^\perp = \mathbb{R}^{n+m}$.[1] Clearly, φ_Π is injective, and thus, $\left(\mathcal{L}(\Pi, \Pi^\perp), \varphi_\Pi\right)$ is an mn-dimensional chart of $G(n, m)$.

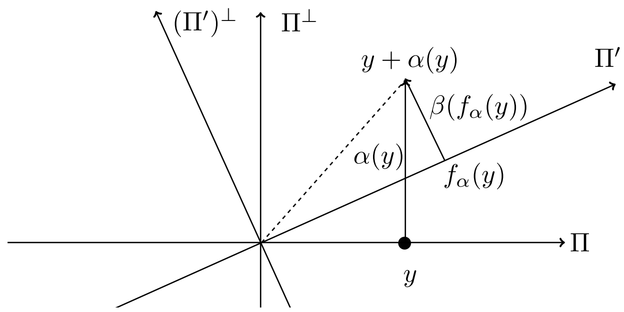
Remark. The images $\varphi_\Pi\left(\mathcal{L}(\Pi, \Pi^\perp)\right)$ cover $G(n, m)$.

Example. $\Pi = \varphi_\Pi(0) \in \varphi_\Pi\left(\mathcal{L}(\Pi, \Pi^\perp)\right)$.

We can now prove that these charts are mutually compatible. Let $\Pi, \Pi' \in G(n, m)$, and let P, P' be orthogonal projections from $\mathbb{R}^{n+m}$ onto Π, Π' respectively. Firstly,

$$F = \varphi_{\Pi'}^{-1}\varphi_\Pi \colon \varphi_\Pi^{-1}\left(\varphi_{\Pi'}(\mathcal{L}(\Pi', (\Pi')^\perp))\right) \to \varphi_{\Pi'}^{-1}\left(\varphi_\Pi(\mathcal{L}(\Pi, \Pi^\perp))\right)$$

is smooth.



Consider $\alpha \in \mathcal{L}(\Pi, \Pi^\perp)$, and $\beta \in \mathcal{L}(\Pi', (\Pi')^\perp)$, then for α, β, the equality $F(\alpha) = \beta$ means that $\varphi_\Pi(\alpha) = \varphi_{\Pi'}(\beta)$. Let $f_\alpha \colon \Pi \to \Pi'$ be defined by

$$f_\alpha = P' \circ (\mathbb{1}_\Pi \oplus \alpha).$$

We need to check

(a) f_α is invertible, and

(b) $\forall y \in \Pi$, $y + \alpha(y) = f_\alpha(y) + \beta(f_\alpha(y))$.

[1] In other words, $\varphi_\Pi(\alpha)$ is the graph of α in $\Pi \oplus \Pi^\perp = \mathbb{R}^{n+m}$.

Note. The condition that $\det f_\alpha \neq 0$ gives an exact description of the subset

$$\varphi_{\Pi^{-1}}\left(\varphi_{\Pi'}(\mathcal{L}(\Pi', (\Pi')^\perp))\right)$$

of $\mathcal{L}(\Pi, \Pi^\perp)$, which is therefore open.

For β, it is $\left(\mathbb{1}_{\Pi'} \oplus \beta\right) \circ f_\alpha = \mathbb{1}_\Pi \oplus \alpha$, and hence

$$\beta = F(\alpha) = (\mathbb{1}_\Pi \oplus \alpha) \circ f_\alpha^{-1} - \mathbb{1}_{\Pi'}.$$

It follows by the construction that the image of β is contained in $(\Pi')^\perp$.

Remark. We obtain an infinite atlas for $G(n,m)$ with charts labeled by $\Pi \in G(n,m)$. But it's suffices to consider only $\binom{n+m}{n}$ charts corresponding to subspaces Π spanned with n coordinate axes.

1.1.6 Manifolds with Boundary

We first introduce two notions.

Definition 1.1.19 (Closed manifold)**.** A manifold is *closed* if it is compact and without boundary.

Definition 1.1.20 (Open manifold)**.** A manifold is *open* if it has only non-compact components without boundary.

Lemma 1.1.1. If M can be covered by two coordinate neighborhoods V_1, V_2 such that $V_1 \cap V_2$ is connected, then M is orientable.

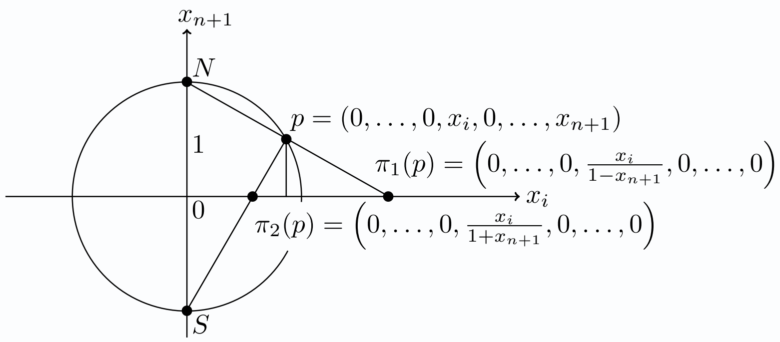
Proof. The determinant of the differential of the coordinate change $\neq 0$, so it does not change sign in $V_1 \cap V_2$. If it's negative at a single point, it's enough to change the sign of one of the coordinates to make it positive at that point, hence on $V_1 \cap V_2$. ■

Example. Let $S^n = \left\{(x_1, \dots, x_{n+1}) \in \mathbb{R}^{n+1} \mid \sum_{i=1}^{n+1} x_i^2 = 1\right\} \subseteq \mathbb{R}^{n+1}$ is orientable.

Proof. Let $N = (0, \dots, 0, 1)$ and $S = (0, \dots, 0, -1)$, consider given $p = (0, \dots, 0, x_i, 0, \dots, x_{n+1})$, then $\pi_1 \colon S^n \setminus \{N\} \to \mathbb{R}^n$ given by

$$\pi_1(p) = \left(0, \dots, 0, \frac{x_i}{1 - x_{n+1}}, 0, \dots, 0\right)$$

to be the stereographic projection from the north pole N.



More generally, it takes $p(x_1, \dots, x_{n+1}) \in S^n - \{N\}$ into the intersection at the hyperplane

$x_{n+1} = 0$ with the line passing through p ad N. In this way, we have

$$\pi_1(x_1, \ldots, x_n) = \left(\frac{x_1}{1 - x_{n+1}}, \frac{x_2}{1 - x_{n+1}}, \ldots, \frac{x_n}{1 - x_{n+1}} \right),$$

hence $\pi_1 \colon S^n \setminus \{N\} \to \mathbb{R}^n$ is differentiable, and is injective. Similarly, $\pi_2 \colon S^n \setminus \{S\} \to \mathbb{R}^n$ for S can also be defined and everything holds similarly. We see that these two parametrizations $(\mathbb{R}^n, \pi_1^{-1}), (\mathbb{R}^n, \pi_2^{-1})$ cover S^n. The change of coordinate is given by

$$y_j = \frac{x_j}{1 - x_{n+1}} \leftrightarrow y_j' = \frac{x_j}{1 + x_{n+1}}, \ (y_1, \ldots, y_n) \in \mathbb{R}^n, \ j = 1, \ldots, n,$$

where

$$y_j' = \frac{y_j}{\sum_{i=1}^n y_i^2}.$$

This implies that $\left\{ (\mathbb{R}^n, \pi_1^{-1}), (\mathbb{R}^n, \pi_2^{-1}) \right\}$ is a differentiable structure for S^n. Now, consider $\pi_1^{-1}(\mathbb{R}^n) \cap \pi_2^{-1}(\mathbb{R}^n) = S^n \setminus \{N \cup S\}$, which is connected, and hence S^n is orientable, and the above structure gives an orientation of S^n. ⊛

Lecture 3: Complex Manifolds, Tangent Spaces and Bundles

Let's look at two more examples about orientation. 12 Jan. 14:30

Example. Let $A \colon S^n \to S^n$ be the antipodal map given by $A(p) = -p$ for $p \in \mathbb{R}^{n+1}$. It's easy to see that A is differentiable with $A^2 = \mathbb{1}$. Furthermore, A is diffeomorphism of $S^n \subseteq \mathbb{R}^{n+1}$. We see that

- if n is even, A reverses the orientation;
- if n is odd, A preserves the orientation.

Example. $G(k, n)$ is orientable if and only if n is even or $n = 1$.

1.1.7 Complex Manifolds

Here we introduce the notion of complex manifold.

Definition 1.1.21 (Complex manifold). A *complex manifold* $\mathcal{M}$ of complex dimension d ($\dim_{\mathbb{C}} \mathcal{M} = d$) is a differentiable manifold of (real) dimension $2d$ ($\dim_{\mathbb{R}} \mathcal{M} = 2d$) whose charts take values in open subsets of $\mathbb{C}^d$ with holomorphic chart transitions.

As previously seen. The chart transitions $z_\beta \circ z_\alpha^{-1} \colon z_\alpha(U_\alpha \cap U_\beta) \to z_\beta(U_\alpha \cap U_\beta)$ is holomorphic if $\partial z_\beta^j / \partial \overline{z_\alpha^k} = 0$ for all j, k where

$$\frac{\partial}{\partial \overline{z^k}} = \frac{1}{2} \left(\frac{\partial}{\partial \overline{x^k}} + i \frac{\partial}{\partial \overline{y^k}} \right).$$

Remark. Complex Grassmannians $G_{\mathbb{C}}(k, n)$ are all orientable. More generally, complex manifolds are always orientable because holomorphic maps always have positive functional determinant.

1.1.8 Partition of Unity

We state, without proof, of an important lemma about the partition of unity.

Definition 1.1.22 (Partition of unity). Let $\mathcal{M}$ be a differentiable manifold, and let $(U_\alpha)_{\alpha \in \mathcal{A}}$ be an open covering of $\mathcal{M}$. Then a *partition of unity* is a locally finite refinement $(V_\beta)_{\beta \in \mathcal{B}}$ of (U_α) and

C^∞-functions $\varphi_\beta \colon \mathcal{M} \to \mathbb{R}$ with

(a) $\operatorname{supp}(\varphi_\beta) \subseteq V_\beta$ for all $\beta \in \mathcal{B}$;

(b) $0 \leq \varphi_\beta(x) \leq 1$ for all $x \in \mathcal{M}$, $\beta \in \mathcal{B}$;

(c) $\sum_{\beta \in \mathcal{B}} \varphi_\beta = 1$ for all $x \in \mathcal{M}$.[a]

[a] There are only finitely many non-vanishing summands of each point, since only finitely many φ_β are non-zero of any given point as the covering (V_β) is locally finite.

Lemma 1.1.2 (Partition of unity)**.** Let $\mathcal{M}$ be a differentiable manifold, and let $(U_\alpha)_{\alpha \in \mathcal{A}}$ be an open covering of $\mathcal{M}$. Then there exists a partition of unity subordinate to (U_α),

1.2 Tangent Vectors

1.2.1 Tangent Vectors in Euclidean Spaces

To discuss the concept of calculus between manifolds formally, we start with our discussion in Euclidean spaces, where we naturally have the coordinates for every point.

Definition. Let $\mathcal{M}$ be a Euclidean manifold of dimension d, $x = (x^1, \ldots, x^d)$ be Euclidean coordinates of $\mathbb{R}^d$, and $x_0 \in \Omega \subseteq \mathbb{R}^d$ where Ω is open.

Definition 1.2.1 (Tangent space of Euclidean space)**.** The *tangent space $T_{x_0}\Omega$ of Ω at x_0* is the vector space $\{x_0\} \times E$[a] spanned by the basis $(\partial/\partial x^1, \ldots, \partial/\partial x^d)$.

[a] E is a d-dimensional Euclidean space.

Definition 1.2.2 (Tangent vector of Euclidean space)**.** The elements in the tangent space of Euclidean spaces is called *tangent vectors*.

Before proceeding, we introduce a shorthand notation.

Notation (Einstein notation)**.** The *Einstein notation* abbreviates the summation $\sum_i v^i x_i$ as $v^i x_i$, where we implicitly sum over the upper and lower index.

Definition 1.2.3 (Differential of Euclidean space)**.** If $\Omega \subseteq \mathbb{R}^d$, $\Omega' \subseteq \mathbb{R}^d$ are open, and $f \colon \Omega \to \Omega'$ is differentiable, then the *differential* $\mathrm{d}f(x_0)$ for $x_0 \in \Omega$ is the induced linear map between tangent spaces

$$\mathrm{d}f(x_0) \colon T_{x_0}\Omega \to T_{f(x_0)}\Omega', \quad v = v^i \frac{\partial}{\partial x^i} \mapsto v^i \frac{\partial f^j}{\partial x^i}(x_0) \frac{\partial}{\partial f^j}.$$

Definition 1.2.4 (Tangent bundle of Euclidean space)**.** The *tangent bundle* is defined as $T\Omega := \coprod_{x \in \Omega} T_x\Omega \cong \Omega \times E \cong \Omega \times \mathbb{R}^d$, which is an open subset of $\mathbb{R}^d \times \mathbb{R}^d$.

Note (Total space)**.** $T\Omega$ is also called the *total space*.

Remark. Given a tangent bundle $T\Omega$, we define π to be the projection $\pi \colon T\Omega \to \Omega$ given by $\pi(x, v) = x$. This makes $T\Omega$ naturally a differentiable manifold.

With the notion of tangent bundle, given $f \colon \Omega \to \Omega'$, we can also define $\mathrm{d}f \colon T\Omega \to T\Omega'$ as

$$\left(x, v^i \frac{\partial}{\partial x^i}\right) \mapsto \left(f(x), v^i \frac{\partial f^j}{\partial x^i}(x_0) \frac{\partial}{\partial f^j}\right).$$

> **Notation.** We often write $\mathrm{d}f(x)(v)$ instead of $\mathrm{d}f(x,v)$ to coincide with the notation of differential.

In particular, for $v = v^i \partial/\partial x^i$, we have

$$\mathrm{d}f(x)(v) = v^i \frac{\partial f}{\partial x^i}(x) \in T_{f(x)}\mathbb{R} \cong \mathbb{R},$$

and we write $v(f)(x)$ for $\mathrm{d}f(x)(v)$.

1.2.2 Tangent Vectors in Manifolds

We now try to formally define the tangent space on a smooth manifold. A natural idea is the following.

> **Intuition.** Let $\mathcal{M}^d$ be a differentiable manifold with a chart $x\colon U \to \Omega \subseteq \mathbb{R}^d$ and $p \in U \subseteq \mathcal{M}$ where U is open. The *tangent space* $T_p\mathcal{M}$ of $\mathcal{M}$ at p *should be* represented in the chart x by $T_{x(p)}x(U)$.

To see that the above are well-defined, i.e., $T_p\mathcal{M}$ are independent of the choice of charts, let $x' \colon U' \to \mathbb{R}^d$ to be another chart with $p \in U' \subseteq \mathcal{M}$ where U' is also open. Denote $\Omega := x(U)$, and $\Omega' := x'(U')$, then the transition map

$$x' \circ x^{-1} \colon x(U \cap U') \to x'(U \cap U')$$

induces a vector space isomorphism

$$L := \mathrm{d}(x' \circ x^{-1})(x(p)) \colon T_{x(p)}\Omega \to T_{x'(p)}\Omega',$$

such that $v \in T_{x(p)}\Omega$ and $L(v) \in T_{x'(p)}\Omega'$ represent the same tangent vector in $T_p\mathcal{M}$.

> **Remark.** A tangent vector in $T_p\mathcal{M}$ is given by the family of the coordinate representations.

Now, we want to define the similar notion of differential of Euclidean spaces. Let consider a simple case first, where we let $f\colon \mathcal{M} \to \mathbb{R}$ to be a differentiable function, and assume that the tangent vector $w \in T_p\mathcal{M}$ is represented by $v \in T_{x(p)}x(U)$.

> **Intuition.** We want to define $\mathrm{d}f(p)$ as a linear map from $T_p\mathcal{M} \to \mathbb{R}$. In chart x, let $w \in T_p\mathcal{M}$ be given as $v = v^i \partial/\partial x^i \in T_{x(p)}x(U)$. Say that $\mathrm{d}f(p)(w)$ in this chart represented by
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> $$\mathrm{d}(f \circ x^{-1})(x(p))(v).$$
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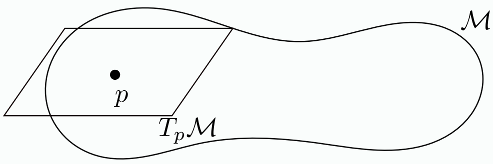
> 
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> **Remark.** $T_p\mathcal{M}$ is a vector space of dimension d isomorphic to $\mathbb{R}^d$, where the isomorphism depends on choice of chart.

> **Intuition.** Pull functions on $\mathcal{M}$ back by a chart to an open subset of $\mathbb{R}^d$, differentiate there.

In order to obtain a tangent space which does not depend on charts, we need to have transformation behavior under change of charts. Let $F\colon \mathcal{M}^d \to \mathcal{N}^c$ be a differentiable map where $\mathcal{M}, \mathcal{N}$ are smooth manifolds. Then we want to represent $\mathrm{d}F$ in local charts $x\colon U \subseteq \mathcal{M} \to \mathbb{R}^d, y\colon V \subseteq \mathcal{N} \to \mathbb{R}^c$ by $\mathrm{d}(y \circ F \circ x^{-1})$. The local coordinates on U is given by $(x^1, \ldots, x^d)$, and on V is $(F^1, \ldots, F^c)$ such that

$$F(x) = \left(F^1(x^1, \ldots, x^d), \ldots, F^c(x^1, \ldots, x^d)\right).$$

Then, $\mathrm{d}F$ induces a linear map $\mathrm{d}F\colon T_p\mathcal{M} \to T_{F(x)}\mathcal{N}$ which in our coordinate representation is given by the matrix

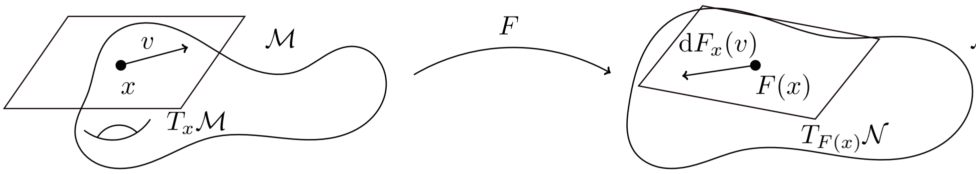
$$\left(\frac{\partial F^\alpha}{\partial x^i}\right)_{\substack{\alpha=1,\ldots,c\\ i=1,\ldots,d}},$$

and a change of charts is then just the base change at tangent spaces: if

$$(x^1, \dots, x^d) \mapsto (\xi^1, \dots, \xi^d)$$
$$(F^1, \dots, F^c) \mapsto (\phi^1, \dots, \phi^c)$$

are coordinate changes, then $\mathrm{d}F$ represented in the new coordinates is given by

$$\left(\frac{\partial \phi^\beta}{\partial \xi^j}\right) = \left(\frac{\partial \phi^\beta}{\partial F^\alpha}\frac{\partial F^\alpha}{\partial x^i}\frac{\partial x^i}{\partial \xi^j}\right).$$



Lecture 4: Submanifolds, Vector Bundles, and Riemannian metrics

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Definition. Let $\mathcal{M}^d$ be a differentiable manifold with a chart $x\colon U \to \Omega \subseteq \mathbb{R}^d$ and $p \in U \subseteq \mathcal{M}$ where U is open. On $\left\{(x, v) \mid v \in T_{x(p)}\Omega\right\}$, we define an equivalence relation by $(x, v) \sim (y, w)$ if and only if $w = \mathrm{d}(y \circ x^{-1})v$.

Definition 1.2.5 (Tangent space)**.** The space of equivalence classes is called the *tangent space* $T_p\mathcal{M}$ at point p to $\mathcal{M}$.

Definition 1.2.6 (Tangent vector)**.** The elements in the tangent space is called *tangent vectors*.

Remark. $T_p\mathcal{M}$ naturally caries the structure of a vector space.

Now, $T\mathcal{M}$ is defined as

$$T\mathcal{M} \coloneqq \coprod_{p\in\mathcal{M}} T_p\mathcal{M}.$$

Recall the projection $\pi\colon T\mathcal{M} \to \mathcal{M}$ with $\pi(w) = p$ for $w \in T_p\mathcal{M}$. Then we can define the following.

Definition 1.2.7 (Derivation)**.** If $x\colon U \to \mathbb{R}^d$ be a chart for $\mathcal{M}$, and let $TU = \coprod_{p\in U} T_pU$. Then we define the *derivation* $\mathrm{d}x\colon TU \to Tx(U) \coloneqq \coprod_{p\in x(U)} T_p\mathcal{M}$ by $w \mapsto \mathrm{d}x(\pi(w))(w) \in T_{x(\pi(w))}x(U)$.

The transition maps

$$\mathrm{d}x' \circ (\mathrm{d}x)^{-1} = \mathrm{d}(x' \circ x^{-1})$$

are differentiable. π is local represented by $x \circ \pi \circ \mathrm{d}x^{-1}$ maps $(x_0, v) \in Tx(U)$ to x_0.

Definition 1.2.8 (Tangent bundle)**.** The triple $(T\mathcal{M}, \pi, \mathcal{M})$ is called the *tangent bundle* of $\mathcal{M}$ of $\mathcal{M}$.

Consider the product of

Definition 1.2.9 (Total space)**.** $T\mathcal{M}$ is called the *total space* of the tangent bundle.

Finally, we introduce the notion of vector field.

Definition 1.2.10 (Vector field)**.** A *vector field* X on a differentiable manifold $\mathcal{M}$ is a correspondence associating to each point $p \in \mathcal{M}$ a vector $X(p) \in T_p\mathcal{M}$, i.e., $X\colon \mathcal{M} \to T\mathcal{M}$.

Remark. Naturally, we say that the field X is differentiable if the map X is differentiable.

1.3 Submanifolds, Immersions, Embeddings

We now study the relation between manifolds.

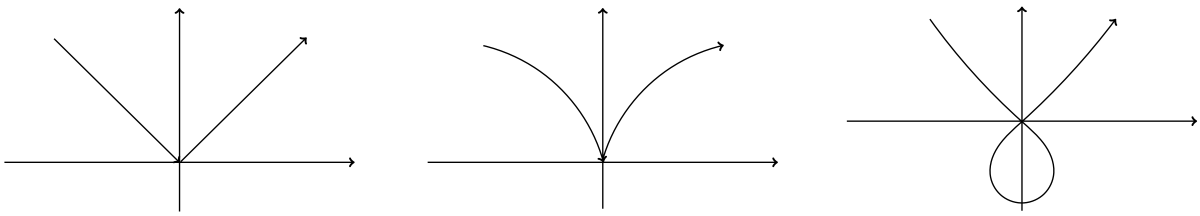
Definition 1.3.1 (Immersion). Let $\mathcal{M}^m, \mathcal{N}^n$ be smooth manifolds. A differentiable mapping $\varphi\colon \mathcal{M} \to \mathcal{N}$ is an *immersion* if

$$\mathrm{d}\varphi_p\colon T_p\mathcal{M} \to T_{\varphi(p)}\mathcal{N}$$

is injective for every $p \in \mathcal{M}$.

Definition 1.3.2 (Embedding). An immersion $\varphi\colon \mathcal{M} \to \mathcal{N}$ is an *embedding* if it is also a homeomorphism onto $\varphi(\mathcal{M}) \subseteq \mathcal{N}$, with $\varphi(\mathcal{M})$ having the subspace topology induced from $\mathcal{N}$.

Definition 1.3.3 (Submanifold). If the inclusion $\iota\colon \mathcal{M} \hookrightarrow \mathcal{N}$ between two manifolds is an embedding, then $\mathcal{M}$ is a *submanifold* of $\mathcal{N}$.



(a) Non-differentiable curve. (b) Non-immersion curve. (c) Non-embedding curve.

Figure 1.1: Three simple examples

Lemma 1.3.1. Let $f\colon \mathcal{M}^m \to \mathcal{N}^n$ to be an immersion and $x \in \mathcal{M}$.[a] Then there exists a neighborhood U of x and a chart (V, y) on $\mathcal{N}$ with $f(x) \in V$ such that $f|_U$ is a differentiable embedding and $y^{m+1}(p) = \ldots = y^n(p) = 0$ for all $p \in f(U \cap V)$.

[a] Hence, $n \geq m$.

Proof. In the local coordinates $(z^1, \ldots, z^n)$ on $\mathcal{N}$, and $(x^1, \ldots, x^m)$ on $\mathcal{M}$, without loss of generality,[a] let

$$\left(\frac{\partial z^\alpha(f(x))}{\partial x^i}\right)_{i,\alpha=1,\ldots,m}$$

be non-singular. Consider

$$F(z, x) \coloneqq \left(z^1 - f^1(x), \ldots, z^n - f^n(x)\right),$$

which has maximal rank in $x^1, \ldots, x^m, z^{m+1}, \ldots, z^n$. By the implicit function theorem, locally, there exists a map $\varphi\colon U \to \mathbb{R}^n$ such that

$$(z^1, \ldots, z^m) \mapsto (\varphi^1(z^1, \ldots, z^m), \ldots, \varphi^n(z^1, \ldots, z^m)) = x$$

such that $F(z, x) = 0$, i.e.,

$$\varphi^i(z^1, \ldots, z^m) = \begin{cases} x^i, & \text{if } i = 1, \ldots, m; \\ z^i, & \text{if } i = m+1, \ldots, n. \end{cases}$$

for which

$$\left(\frac{\partial \varphi^i}{\partial z^\alpha}\right)_{\alpha, i=1,\dots,m}$$

has maximal rank. Now, we choose a new coordinate

$$(y^1, \dots, y^n) = \big(\varphi^1(z^1, \dots, z^m), \dots, \varphi^m(z^1, \dots, z^m),\\ z^{m+1} - \varphi^{m+1}(z^1, \dots, z^m), \dots, z^n - \varphi^n(z^1, \dots, z^m)\big).$$

Then, we have $z = f(x) \Leftrightarrow F(z, x) = 0$, i.e., $(y^1, \dots, y^n) = (x^1, \dots, x^n, 0, \dots, 0)$, proving the result. ■

[a] Since $\mathrm{d}f(x)$ is injective.

Lemma 1.3.2. Let $f\colon \mathcal{M}^m \to \mathcal{N}^n$ be a differentiable map such that $m \geq n$ with $p \in \mathcal{N}$. Let $\mathrm{d}f(x)$ has rank n for all $x \in \mathcal{M}$ with $f(x) = p$. Then $f^{-1}(p)$ is the union of differentiable submanifolds of $\mathcal{M}$ of dimension $m - n$.

Remark. Let $\mathcal{N}^n$ be a smooth manifold, and let $1 \leq m \leq n$. Then an arbitrary subset $\mathcal{M} \subseteq \mathcal{N}$ has the structure of differentiable submanifold of $\mathcal{N}$ of dimension m if and only if for all $p \in \mathcal{M}$, there exists a smooth chart (U, φ) of $\mathcal{N}$ such that $p \in U$, $\varphi(p) = 0$, $\varphi(U)$ is open, and

$$\varphi(U \cap \mathcal{M}) = (-\epsilon, +\epsilon)^n \times \{0\}^{n-m},$$

where $(-\epsilon, +\epsilon)^n$ is the cube. Noticeably, the C^∞-manifold structure of $\mathcal{M}$ is uniquely determined.

Remark. Let $\mathcal{M} \subseteq \mathcal{N}$ be a differentiable submanifold of $\mathcal{N}$, and let $\iota\colon \mathcal{M} \hookrightarrow \mathcal{N}$ be the inclusion. Then, for $p \in \mathcal{M}$, $T_p\mathcal{M}$ can be considered as subspace of $T_p\mathcal{N}$, namely as the image of $\mathrm{d}\iota(T_p\mathcal{M})$.

Lemma 1.3.3. Let $f\colon \mathcal{M}^m \to \mathcal{N}^n$ be a differentiable map such that $m \geq n$ with $p \in \mathcal{N}$. Let $\mathrm{d}f(x)$ has rank n for all $x \in \mathcal{M}$ with $f(x) = p$. For the submanifold $X = f^{-1}(p)$ and for $q \in X$, it is true that

$$T_q X = \ker \mathrm{d}f(q) \subseteq T_q\mathcal{M}.$$

Chapter 2

Riemannian Manifolds

Lecture 5: Riemannian Manifolds

In this chapter, we start our discussion on Riemannian manifolds. 19 Jan. 14:30

2.1 Riemannian Metrics

We start by defining the Riemannian metric.

Definition 2.1.1 (Riemannian metric). A *Riemannian metric* g on a differentiable manifold $\mathcal{M}$ is given by a scalar product I on each $T_p\mathcal{M}$ which depends smoothly on the base point p.

Definition 2.1.2 (Riemannian manifold). A *Riemannian manifold* $(\mathcal{M}, g)$ is a smooth manifold $\mathcal{M}$ equipped with a Riemannian metric g.

Let $x = (x^1, \dots, x^d)$ be the local coordinates. In these, a metric is represented by a positive definite symmetric matrix

$$\left(g_{ij}(x)\right)_{i,j=1,\dots,d},$$

i.e., $g_{ij} = g_{ji}$, and $g_{ij}\xi^i\xi^j > 0$ for all $\xi = (\xi^1, \dots, \xi^d) \neq 0$ with coefficients smoothly depending on x.

2.1.1 Transformation Behavior

We now see that the smoothness does not depend on coordinates, i.e., the smooth dependence on the base point (as required in Definition 2.1.1) can be represented in the local coordinates. Given 2 tangent vectors $v, w \in T_p\mathcal{M}$ with coordinate representations $(v^1, \dots, v^d), (w^1, \dots, w^d)$ given by x such that $v = v^i \frac{\partial}{\partial x^i}$ and $w = w^i \frac{\partial}{\partial x^i}$, their product is

$$\langle v, w\rangle \coloneqq g_{ij}(x(p))v^i w^j.$$

In particular,

$$\left\langle \frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j} \right\rangle = g_{ij}.$$

Remark. The length of v is given as $\lVert v\rVert \coloneqq \langle v, v\rangle^{1/2}$.

Let $y = f(x)$ define different local coordinates. In these, v, w are given as

$$(\widetilde{v}^1, \dots, \widetilde{v}^d), (\widetilde{w}^1, \dots, \widetilde{w}^d)$$

with $\widetilde{v}^j = v^i \frac{\partial f^j}{\partial x^i}$ and $\widetilde{w}^j = w^i \frac{\partial f^j}{\partial x^i}$. Denote the metric in new coordinates y by $h_{k\ell}(y)$, then we have

$$h_{k\ell}(f(x))\widetilde{v}^k \widetilde{w}^\ell = \langle v, w\rangle = g_{ij}(x)v^i w^j.$$

Plug everything in, we have

$$h_{k\ell}(f(x))\frac{\partial f^k}{\partial x^i}\frac{\partial f^\ell}{\partial x^j}v^i w^j = g_{ij}(x)v^i w^j.$$

We see that this holds for any tangent vectors v, w, therefore,

$$h_{k\ell}(f(x))\frac{\partial f^k}{\partial x^i}\frac{\partial f^\ell}{\partial x^j} = g_{ij}(x),$$

which is the transformation behavior under coordinates changes.

Remark. This shows that the smoothness does not depend on the choice of coordinates!

Example. Consider the Euclidean space Ω, then given $v, w \in T_p\Omega$, we have

$$\langle v, w\rangle = \delta_{ij}v^i w^j = v^i w_i.$$

Theorem 2.1.1. Every differentiable manifold can be equipped with a Riemannian metric.

Shown in HW

2.2 Geodesics

2.2.1 Length and Energy

We're interested in the following two quantities.

Definition. Let $\gamma\colon [a, b] \to \mathcal{M}$ be a smooth curve on a Riemannian manifold $(\mathcal{M}, g)$.

Definition 2.2.1 (Length)**.** The *length* of γ is defined as

$$L(\gamma) := \int_a^b \left\lVert \frac{\mathrm{d}\gamma}{\mathrm{d}t}(t)\right\rVert \,\mathrm{d}t.$$

Definition 2.2.2 (Energy)**.** The *energy* of γ is defined as

$$E(\gamma) := \frac{1}{2}\int_a^b \left\lVert \frac{\mathrm{d}\gamma}{\mathrm{d}t}(t)\right\rVert^2 \,\mathrm{d}t.$$

We now want to compute $L(\gamma)$, $E(\gamma)$ in local coordinates. Let the local coordinates be

$$(x^1(\gamma(t)), \dots, x^d(\gamma(t))),$$

we write

$$\dot{x}^i(t) = \frac{\mathrm{d}}{\mathrm{d}t}(x^i(\gamma(t))).$$

Then, we have

$$L(\gamma) = \int_a^b \sqrt{g_{ij}(x(\gamma(t)))\dot{x}^i(t)\dot{x}^j(t)}\,\mathrm{d}t, \quad E(\gamma) = \frac{1}{2}\int_a^b g_{ij}(x(\gamma(t)))\dot{x}^i(t)\dot{x}^j(t)\,\mathrm{d}t.$$

Definition 2.2.3 (Distance)**.** Given a Riemannian manifold $(\mathcal{M}, g)$, the *distance* between 2 points $p, q \in \mathcal{M}$ is defined as

$$d(p, q) := \inf\left\{L(\gamma) \mid \gamma\colon [a, b] \to \mathcal{M} \text{ piecewise smooth curve with } \gamma(a) = p, \gamma(b) = q\right\}.$$

Note. Any 2 points $p, q \in \mathcal{M}$ can be connected by a piecewise smooth curve, hence $d(p, q)$ always exists.

Corollary 2.2.1. The topology of $\mathcal{M}$ induced by the distance function d coincides with the original manifold topology of $\mathcal{M}$.

Lemma 2.2.1. If $\gamma\colon [a, b] \to \mathcal{M}$ is a smooth curve, and $\psi\colon [\alpha, \beta] \to [a, b]$ is a change of parameter, then $L(\gamma \circ \psi) = L(\gamma)$.

Proof. This can be proved by computation, and the take-away is that the length functional is invariant under parameter changes. ■

Notation. $\left(g^{ij}\right)_{i,j=1,\ldots,d} = (g_{ij})^{-1}_{i,j=1,\ldots,d}$, i.e., $g^{i\ell} g_{\ell j} = \delta^i_j$.

Notation. $g_{j\ell,k} \coloneqq \frac{\partial}{\partial x^k} g_{j\ell}$.

Definition 2.2.4 (Christoffel symbol)**.** The *Christoffel symbol* is defined as

$$\Gamma^i_{jk} \coloneqq \frac{1}{2} g^{i\ell} \left(g_{j\ell,k} + g_{k\ell,j} - g_{jk,\ell}\right).$$

for all i.x

Proposition 2.2.1. The Euler-Lagrange equations for the energy E are

$$\ddot{x}^i(t) + \Gamma^i_{jk}(x(t))\dot{x}^j(t)\dot{x}^k(t) = 0$$

for $i = 1, \ldots, d$.

Proof. The Euler-Lagrange equations of a functional

$$I(x) = \int_a^b f(t, x(t), \dot{x}(t)) \,\mathrm{d}t$$

are

$$\frac{\mathrm{d}}{\mathrm{d}t} \frac{\partial f}{\partial \dot{x}^i} - \frac{\partial f}{\partial x^i} = 0$$

for $i = 1, \ldots, d$. Just by plugging in, we obtain for E, we have

$$\frac{\mathrm{d}}{\mathrm{d}t} \left(g_{ik}(x(t))\dot{x}^k(t) + g_{ji}(x(t))\dot{x}^j(t)\right) - g_{jk,i}(x(t))\dot{x}^j(t)\dot{x}^k(t) = 0$$

for $i = 1, \ldots, d$. Hence,

$$g_{ik}\ddot{x}^k + g_{ji}\ddot{x}^j + g_{ik,\ell}\dot{x}^\ell\dot{x}^k + g_{ji,\ell}\dot{x}^\ell\dot{x}^j - g_{jk,i}\dot{x}^\ell\dot{x}^j = 0$$

Rename some indices and use $g_{ij} = g_{ji}$, we have that

$$2g_{\ell m}\ddot{x}^m + \left(g_{k\ell,j} + g_{j\ell,k} - g_{jk,\ell}\right)\dot{x}^j\dot{x}^k = 0$$

for $\ell = 1, \ldots, d$. Hence, we have

$$g^{i\ell} g_{\ell m}\ddot{x}^m + \frac{1}{2} g^{i\ell} \left(g_{\ell k,j} + g_{j\ell,k} - g_{jk,\ell}\right)\dot{x}^j\dot{x}^k = 0$$

for $i = 1, \ldots, d$. Finally, observe that

$$g^{i\ell} g_{\ell m} = \delta_{im} \Rightarrow g^{i\ell} g_{\ell m} \ddot{x}^m = \ddot{x}^i,$$

hence the claim follows. ∎

Definition 2.2.5 (Geodesic). A smooth curve $\gamma\colon [a, b] \to \mathcal{M}$ that obeys

$$\ddot{x}^i(t) + \Gamma^i_{jk}(x(t)) \dot{x}^j(t) \dot{x}^k(t) = 0 \tag{2.1}$$

for $i = 1, \ldots, d$ is called a *geodesic*.

2.2.2 The Action Functional

Definition 2.2.6 (Action). Let $\mathcal{L}$ be the Lagrangian, then let

$$I[w(\cdot)] \coloneqq \int_0^t \mathcal{L}(\dot{w}(s), w(s)) \, \mathrm{d}s$$

defined for functions $w(\cdot) = (w^1(\cdot), \ldots w^n(\cdot))$ of the admissible class

$$\mathcal{A} = \left\{ w(\cdot) \in C^2([0, t]; \mathbb{R}^n) \mid w(0) = y, w(t) = x \right\}.$$

From the calculus of variation, we can find a curve $x(\cdot) \in \mathcal{A}$ such that

$$I[x(\cdot)] = \min_{w(\cdot) \in \mathcal{A}} I[w(\cdot)].$$

Theorem 2.2.1 (Euler-Lagrangian equations). $x(\cdot)$ from $I[x(\cdot)] = \min_{w(\cdot)\in\mathcal{A}} I[w(\cdot)]$ solves the system of Euler-Lagrangian equations

$$\frac{\mathrm{d}}{\mathrm{d}s} \left(D_{\dot{x}} \mathcal{L}(\dot{x}(s), x(s)) + D_x \mathcal{L}(\dot{x}(s), x(s)) \right) = 0$$

for $0 \leq s \leq t$.

Lecture 6: Geodesic and the Exponential Map

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Proposition 2.2.2. For all smooth curve $\gamma\colon [a, b] \to \mathcal{M}$,

$$\mathcal{L}(\gamma)^2 \leq 2(b - a) E(\gamma)$$

with equality if and only if $\lVert \mathrm{d}\gamma / \mathrm{d}t \rVert$ is a constant.

Proof. From Hölder's inequality,

$$\int_a^b \left\lVert \frac{\mathrm{d}\gamma}{\mathrm{d}t} \right\rVert \mathrm{d}t \leq (b - a)^{1/2} \left(\int_a^b \left\lVert \frac{\mathrm{d}\gamma}{\mathrm{d}t} \right\rVert^2 \mathrm{d}t \right)^{1/2}$$

with equality if and only if $\lVert \mathrm{d}\gamma / \mathrm{d}t \rVert$ is a constant. ∎

Example. Let

$$\mathcal{L}(q, x) = \frac{1}{2} m |q|^2 - V(x)$$

with $m > 0, q = \dot{x}$, the Euler-Lagrangian equations is given by

$$m \ddot{x}(s) = F(x(s))$$

for $F := -DV$.

As previously seen. Regular curves can be parametrized by arc length with unit speed $\|\mathrm{d}\gamma/\mathrm{d}t\| = \|\dot{\gamma}\| \equiv 1$.

Lemma 2.2.2. Each geodesic is parametrized proportionally to the arc length.[a]

[a] This means that we have constant speed, i.e., $\|\dot{\gamma}\|$ is a constant.

Proof. For a solution of $\ddot{x}^i(t) + \Gamma^i_{jk}(x(t))\dot{x}^j(t)\dot{x}^k(t) = 0$,

Do the computation!

$$\frac{\mathrm{d}}{\mathrm{d}t}\langle \dot{x}, \dot{x}\rangle = \frac{\mathrm{d}}{\mathrm{d}t}\left(g_{ij}(x(t))\dot{x}^i(t)\dot{x}^j(t)\right) = 0.$$

∎

Our goal now is to minimize the length within class of regular smooth curves.

As previously seen. The length and the energy functionals are invariants under parameter changes.

This means that it's enough to look at curves parametrized by arc length.

Theorem 2.2.2. Let $\mathcal{M}$ be a Riemannian manifold, $p \in \mathcal{M}$ and $v \in T_p\mathcal{M}$. Then there exists an $\epsilon > 0$ and a unique geodesic such that $c\colon [0, \epsilon] \to \mathcal{M}$ with $c(0) = p$ and $\dot{c}(0) = v$. In addition, c smoothly depend on p, v.

Proof. Since Equation 2.1 is a system of second order ODE, by Picard-Lindelöf theorem, we have local existence and uniqueness of the solution with prescribed initial values and derivative such that the solution depends smoothly on p, v. ∎

Remark. If $x(t)$ is the solution of Equation 2.1, then $x(\lambda t)$ is also a solution for any constant $\lambda \in \mathbb{R}$. Denote geodesic from Theorem 2.2.2 by c_v, then

$$c_v(t) = c_{\lambda v}(t/\lambda)$$

for $\lambda > 0$, $t \in [0, \epsilon]$, and hence $c_{\lambda v}$ defined on $[0, \epsilon/\lambda]$. Since c_v depends smoothly on v, the set $\{v \in T_p\mathcal{M} \mid \|v\| = 1\}$ is compact, hence there exists $\epsilon_0 > 0$ such that for $\|v\| = 1$, c_v defined at least on $[0, \epsilon_0]$, implying that for all $w \in T_p\mathcal{M}$ with $\|w\| \leq \epsilon_0$, c_w is defined at least on $[0, 1]$.

2.2.3 Exponential Maps

Definition 2.2.7 (Exponential map). Let $(\mathcal{M}, g)$ be a Riemannian manifold, $p \in \mathcal{M}$, and $V_p := \{v \in T_p\mathcal{M} \mid c_v \text{ defined on } [0, 1]\}$. Then *exponential map of $\mathcal{M}$ at p*, $\exp_p\colon V_p \to \mathcal{M}$, is defined as $v \mapsto c_v(1)$.

Theorem 2.2.3. The exponential map $\exp_p$ maps a neighborhood of $0 \in T_p\mathcal{M}$ diffeomorphically onto a neighborhood of $p \in \mathcal{M}$.

Consider $\exp_p\colon B(0, \epsilon) \subseteq T_p\mathcal{M} \to \mathcal{M}$ diffeomorphically onto its image, we now introduce the coordinates around m. Let $(e_1, \ldots, e_n)$ be the orthonormal basis of $T_m\mathcal{M}$, and $(x_1, \ldots, x_n)$ be the associated local coordinates. Given $p \in \mathcal{M}^n$, $0 \in \mathbb{R}^n$, we have

$$g_{ij}(p) = \delta_{ij}, \quad \Gamma^k_{ij}(p) = 0, \quad g_{ij,k} = 0$$

for all i, j, k.

Definition 2.2.8 (Normal coordinate).

Note. The first derivative vanishes, so locally, the manifold looks Euclidean.

Theorem 2.2.4. For all $p \in \mathcal{M}$, there exists $\rho > 0$ such that the Riemannian polar coordinates may be introduced on $B(p,\rho) = \{q \in \mathcal{M} \mid d(p,q) \leq \rho\}$. For any such ρ and $q \in \partial B(p,\rho)$, there exists a unique geodesic of shortest length ($= \rho$) from p to q And in the polar coordinates, this geodesic is given by the straight line $x(t) = (t, \varphi_0)$, $0 \leq t \leq \rho$, with q represented by coordinates (ρ, φ_0), $\varphi_0 \in S^{d-1}$.

Proof. Take an arbitrary curve from p to q, namely $c(t) = \big(r(t), \varphi(t)\big)$, $0 \leq t \leq T$, which does not have to be entirely be contained in $B(p,\rho)$. Let t_0 be defined as

$$t_0 \coloneqq \inf\left\{t \leq T \mid d(x(t), p) \geq \rho\right\}.$$

Then $t_0 \leq T$ such that $c|_{[0,t_0]}$ lies entirely in $B(p,\rho)$. We want to show that

(a) $L\left(c|_{[0,t_0]}\right) \geq \rho$, and

(b) $L\left(c|_{[0,t_0]}\right) = \rho$ only for a straight line in the polar coordinates,

where

$$L\left(c|_{[0,t_0]}\right) \coloneqq \int_0^{t_0} \sqrt{g_{ij}(c(t))\dot{c}^i\dot{c}^j}\,\mathrm{d}t.$$

Observe that $g_{r\varphi} = 0$, with $g_{\varphi\varphi}$ being positive definite, hence

$$L\left(c|_{[0,t_0]}\right) \geq \int_0^{t_0} \sqrt{g_{rr}(c(t))\dot{r}\dot{r}}\,\mathrm{d}t = \int_0^{t_0} |\dot{r}|\,\mathrm{d}t \geq \int_0^{t_0} \dot{r}\,\mathrm{d}t = r(t_0) = \rho,$$

where we know that $g_{rr} \equiv 1$. ∎

Remark (Compact manifold). For compact manifold, from Theorem 2.2.4, we can prove that Riemannian polar coordinates can be introduced. Also, there exists $\rho_0 > 0$ such that for any 2 points $p, q \in \mathcal{M}$ with $d(p,q) \leq \rho_0$ can be connected by minimizing geodesic.

Lecture 7: Hopf-Rinow Theorem

We have shown the following in the homework. 26 Jan. 14:30

Theorem 2.2.5. Let $(\mathcal{M}, g)$ be a compact Riemannian manifold.

(a) Any 2 points $p, q \in \mathcal{M}$ can be connected by a minimizing geodesic.

(b) For all $p \in \mathcal{M}$, the exponential map $\exp_p$ is defined on all of $T_p\mathcal{M}$ and any geodesic may be extended indefinitely in each direction.

We now want to generalize it. However, this is not true in the most general setting, and we need one more requirement.

Definition 2.2.9 (Geodesically complete). A Riemannian manifold $(\mathcal{M}, g)$ is *geodesically complete* if for all $p \in \mathcal{M}$, $\exp_p$ is defined on all of $T_p\mathcal{M}$, if any geodesic $c(t)$ with $c(0) = p$ can be extended for all $t \in \mathbb{R}$.

Theorem 2.2.6 (Hopf-Rinow theorem). Let $(\mathcal{M}, g)$ be a compact Riemannian manifold, then the following statements are equivalent.

(a) $\mathcal{M}$ is complete as a metric space.[a]

(b) The closed and bounded subsets of $\mathcal{M}$ are compact.

(c) There exists $p \in \mathcal{M}$ such that $\exp_p$ is defined on all $T_p\mathcal{M}$.

(d) $\mathcal{M}$ is geodesically complete.

Furthermore, (d) (and hence (a), (b), and (c)) implies

(e) for two points $p, q \in \mathcal{M}$ can be joined by a minimizing geodesic, i.e., geodesic of the shortest distance $d(p, q)$.

[a]Hence, equivalently, complete as a topological space w.r.t. the underlying topology.

Proof. We start by proving (d) implies (e). Let $\mathcal{M}$ be geodesically complete, and let $r := d(p, q)$, and let ρ be as in the corollary from handout for HW1. Let $p_0 \in \partial B(p, \rho)$ be a point where the continuous functional $d(q, \cdot)$ attains its minimum on the compact set $\partial B(p, \rho)$. Then, for some $V \in T_p\mathcal{M}$,

$$p_0 = \exp_p \rho V.$$

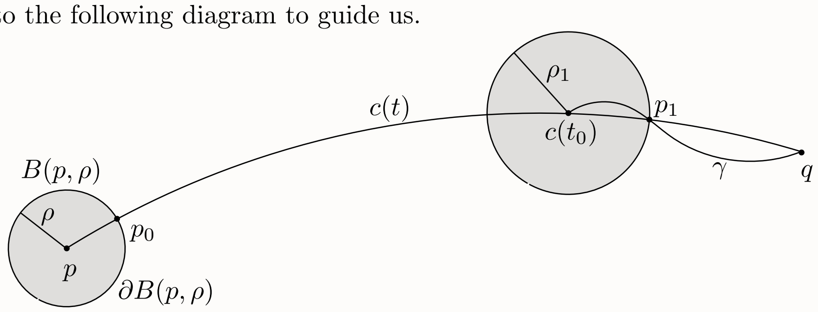
Consider the geodesic $c(t) = \exp_p tV$, by showing

$$c(r) = q,$$

$c|_{[0,r]}$ will be the shortest geodesic from p to q. We start by defining

$$I := \{t \in [0, r] \mid d(c(t), q) = r - t\},$$

and referring to the following diagram to guide us.



Now, we want to show that $I = [0, r]$, which will follow from showing that I is open.

Note. I is not empty since by definition it contains 0 and r. Further, I is closed by continuity.

Let $t_0 \in I$, and let $\rho_1 > 0$ be the radius as in the corollary, without loss of generality, $\rho_1 < r - t_0$. Let $p_1 \in \partial B(c(t_0), \rho_1)$ be the point where the continuous functional $d(q, \cdot)$ attains its minimum on the compact set $\partial B(c(t_0), \rho_1)$. By the triangle inequality,

$$d(p, q) \leq d(p, p_1) + d(p_1, q).$$

For every curve γ from $c(t_0)$ to q, there exists $\gamma(t) \in \partial B(c(t_0), \rho_1)$, hence

$$L(\gamma) \geq \underbrace{d(c(t_0), \gamma(t))}_{\rho_1} + d(\gamma(t), q) = \rho_1 + d(p_1, q),$$

implying $d(q, c(t_0)) \geq \rho_1 + d(p_1, q)$. But from the triangle inequality, we actually have

$$d(q, c(t_0)) = \rho_1 + d(p_1, q) \Leftrightarrow d(p_1, q) = \underbrace{d(q, c(t_0))}_{r - t_0} - \rho_1,$$

hence $d(p_1, p) \geq r - (r - t_0 - \rho_1) = t_0 + \rho_1$, i.e., this is a minimizing curve!

On the other hand, there exists a curve from p to p_1 of length $t_1 + \rho_1$ since it's composed by the portion from p to $c(t_0)$ along $c(t)$ and the portion being the geodesic from $c(t_0)$ to p_1 of length ρ_1.

Then, by the theorem we have proved in the HW1#5, this curve is a geodesic curve. Finally, from the uniqueness of geodesic with the given extra data, this geodesic coincides with c. Hence,

$$p_1 = c(t_0 + \rho_1),$$

with $d(p_1, q) = r - t_0 - \rho_1$,

$$d(c(t_0 + \rho_1), q) = d(p_1, q) = r - t_0 - \rho = r - (t_0 + \rho_1),$$

thus $t_0 + \rho_1 \in I$, hence I is open, i.e., $I = [0, r]$, so $c(r) = q$ follows. ■

Lecture 8

In the proof we did last time, the last step can be shown via [FC13, Corollary 3.9]. 31 Jan. 14:30

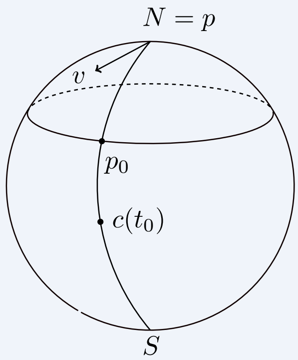


Figure 2.1: title

Example.

Proof.
- (d) $\Rightarrow$ (c) is trivial
- (c) $\Rightarrow$ (b): Let $K \subseteq \mathcal{M}$ be closed and bounded. As K bounded, $K \subseteq B(p, r)$ for some $r > 0$. Then any point in $B(p, r)$ can be joined with p by geodesic of length $\leq r$, and $B(p, r)$ is the image of the compact ball in $T_p\mathcal{M}$ of radius r under continuous map $\exp_p$, hence $B(p, r)$ is compact. As K closed and $K \subseteq B(p, r)$, K is compact.
- (b) $\Rightarrow$ (a): Let $(p_n)_{n\in\mathbb{N}} \subseteq \mathcal{M}$ be a Cauchy sequence, so it's bounded, and by (b), its closure is compact. It contains a convergent subsequence, so it converges, i.e., $\mathcal{M}$ is complete.
- (a) $\Rightarrow$ (d): Let c be a geodesic in $\mathcal{M}$, parametrized by arc length defined on *a* maximal interval I. Since I s non-empty, and we can show that I is both open and closed. Exercise

■

Definition 2.2.10 (Isometry). A diffeomorphism $h\colon \mathcal{M} \to \mathcal{N}$ is an *isometry* between two Riemannian manifolds if it preserves the Riemannian metric, i.e., for $p \in \mathcal{M}$, $v, w \in T_p\mathcal{M}$,

$$\langle v, w\rangle_{\mathcal{M}} = \langle \mathrm{d}h(v), \mathrm{d}h(w)\rangle_{\mathcal{N}}.$$

Definition 2.2.11 (Local isometry). A diffeomorphism $h\colon \mathcal{M} \to \mathcal{N}$ is a *local isometry* between two Riemannian manifolds if for every $p \in \mathcal{M}$, there exists a neighborhood U such that $h|_U : U \to h(U)\colon \mathcal{M} \to \mathcal{N}$ is an isometry and $h(U) \subseteq \mathcal{N}$ is open.

Definition 2.2.12 (Injectivity radius). Let $\mathcal{M}$ be a Riemannian manifold, and $p \in \mathcal{M}$. The *injectivity radius* $i(p)$ of p is

$$i(p) := \sup \left\{ \rho > 0 \mid \exp_p \text{ defined on } B(0, \rho) \subseteq T_p\mathcal{M} \text{ and injective} \right\}.$$

Similarly, the *injectivity radius* $i(\mathcal{M})$ of $\mathcal{M}$ is defined as $i(\mathcal{M}) := \inf_{p \in \mathcal{M}} i(p)$.

Example (Sphere). $i(S^n) = \pi$.

Example (Torus). $i(T^n) = 1/2$.

Definition 2.2.13 (Vector bundle). A (differentiable) *vector bundle* of rank n consists of a total space E, a base $\mathcal{M}$, a projection $\pi \colon E \to \mathcal{M}$ with $E, \mathcal{M}$ differentiable manifolds, π differentiable. Each fiber $E_x := \pi^{-1}(x)$ for $x \in \mathcal{M}$, carries structure of n-dimensional (real) vector space, and local triviality condition holds, i.e., for all $x \in \mathcal{M}$, there exists a neighborhood U and diffeomorphism $\varphi \colon \pi^{-1}(U) \to U \times \mathbb{R}^n$ with property such that for all $x \in U$,

$$\varphi_y := \varphi|_{E_y} : E_y \to \{y\} \times \mathbb{R}^n$$

is a vector space isomorphism.

Definition 2.2.14 (Bundle chart). (φ, U) is the so-called *bundle chart*.

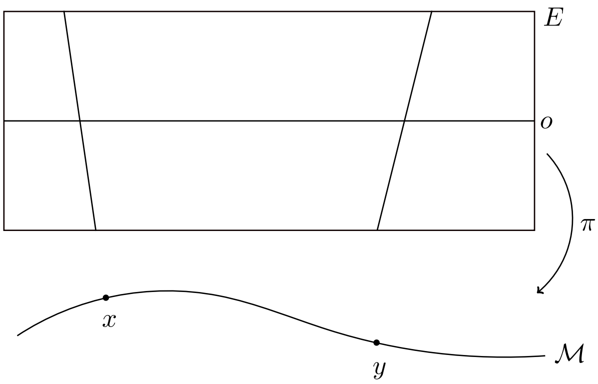


Figure 2.2: title

Definition 2.2.15. A *p-times contravariant* and *q-times covariant tensor field* on a differentiable manifold $\mathcal{M}$ is a section of

$$\underbrace{T\mathcal{M} \otimes \ldots \otimes T\mathcal{M}}_{p\text{-times}} \otimes \underbrace{T^*\mathcal{M} \otimes \ldots \otimes T^*\mathcal{M}}_{q\text{-times}}.$$

Lecture 9: Connections and Curvatures

Any manifold carries a complete Riemannian metric. 31 Jan. 14:30

If $(\mathcal{M}, g_1)$ is not complete, we can find g_2 such that $(\mathcal{M}, g_2)$ is complete.

Example (Hyperbolic half-plane). The half-plane $P = \left\{(x, y) \in \mathbb{R}^2 \mid y > 0\right\}$ equipped with metric induced by the Euclidean metric on $\mathbb{R}^2$, which is not complete.

However, it becomes complete when equipped with the following metric

$$\frac{1}{y^2}(\mathrm{d}x^2 + \mathrm{d}y^2).$$

In fact, P with the above metric is called the *hyperbolic half-plane* H^2, and we can extend it to H^n.

Another question we may ask is the following.

Problem. Is the converse of Hopf-Rinow theorem true? I.e., can we show that (e) implies (d)?

Answer. No! Any 2 points in the open half-sphere can be joint by a unique minimal geodesic, but this manifold is not geodesically complete. ⊛

Example. The injectivity radius of H^n is ∞.

Remark. Given a compact $\mathcal{M}$, the injectivity radius is always > 0 by continuity argument.

Now, given a complete but not compact $\mathcal{M}$, the injectivity radius can be 0.

Example. Take the quotient of the Poincaré half-plane by the translations

$$(x, y) \mapsto (x + n, y), \quad n \in \mathbb{Z}.$$

We then obtain a complete Riemannian manifold $\mathcal{M}$ with $i(\mathcal{M}) = 0$.

Note. Finding lower bounds for $i(\mathcal{M})$ introduces curvature estimates.

Definition 2.2.16 (Tensor)**.** Let V be a vector space of dimension $m < \infty$, and the dual space V^*. Then the vector space of *r-times contravariant and s-times covariant tensors* $T^r_s(V)$ over V is defined by

$$T^r_s(V) = \{A \colon \underbrace{V^* \times \ldots \times V^*}_{r} \times \underbrace{V \times \ldots \times V}_{s} \to \mathbb{R}\} = \underbrace{V \otimes \ldots \otimes V}_{r} \otimes \underbrace{V^* \otimes \ldots \otimes V^*}_{s}.$$

Definition 2.2.17 (Section)**.** A *section* of E is a differentiable map $s \colon \mathcal{M} \to E$ such that $\pi \circ s = \mathrm{id}_{\mathcal{M}}$.

Definition 2.2.18. Let $\Lambda^s(V^*) := \left\{A \in T^0_s(V) \mid A \text{ skew-symmetric}\right\}$, where $x \in \mathbb{N}$. Let $\mathcal{M}^n$ be a manifold, and $\pi \colon E \to \mathcal{M}$. The C^∞ *vector bundle* is the tuple $(E, \pi, \mathcal{M})$.

Definition 2.2.19 (Contravariant tensor field)**.** Denote $\Gamma(E) := \{s \in C^\infty(\mathcal{M}, E) \mid \pi \circ s = \mathrm{id}_{\mathcal{M}}\}$, then the *contravariant tensor field* $\Gamma(T\mathcal{M})$ is defined as

$$\Gamma(T\mathcal{M}) := \{\text{vector fields on } \mathcal{M}\}$$

with $T\mathcal{M} = \bigcup_{p \in \mathcal{M}} T_p\mathcal{M}$.

Definition 2.2.20 (Covariant tensor field)**.** The *covariant tensor field* $\Gamma(\Lambda_s\mathcal{M})$ is defined as

$$\Gamma(\Lambda_s\mathcal{M}) := \{s\text{-forms on } \mathcal{M}\}$$

with $\Lambda_s\mathcal{M} = \Lambda^s\left(\bigcup_{p \in \mathcal{M}} T^*_p\mathcal{M}\right)$.

Definition 2.2.21 (Covariant tensor field). The *covariant tensor field* $\Gamma(T^r_s\mathcal{M})$ is defined as

$$\Gamma(T^r_s\mathcal{M}) := \{(r,s)\text{-tensor fields on } \mathcal{M}\}$$

with $T^r_s\mathcal{M}$ is the section of $T\mathcal{M}\otimes\ldots\otimes T\mathcal{M}\otimes T^*\mathcal{M}\otimes\ldots\otimes T^*\mathcal{M}$.

As previously seen. A Riemannian metric g on $\mathcal{M}$ is a $(0,2)$-tensor field, i.e.,

$$g\in\Gamma(T^0_2(\mathcal{M}))$$

for all $p\in\mathcal{M}$.[a]

[a] Recall that $g_p\colon T_p\mathcal{M}\times T_p\mathcal{M}\to\mathbb{R}$ is just the scalar product.

Definition 2.2.22 (Pseudo-Riemannian metric). A *pseudo-Riemannian metric* on a differentiable manifold $\mathcal{M}$ is a tensor field $g\in T^0_2\mathcal{M}$ with

(a) $g(X,Y)=g(Y,X)$ for all $X,Y\in T\mathcal{M}$.

(b) For all $p\in\mathcal{M}$, g_p is non-degenerate bilinear form on $T_p\mathcal{M}$, i.e., $g_p(X,Y)=0$ for all $X,Y\in T_p\mathcal{M}$ if $Y=0$.

Definition 2.2.23 (Lorentzian metric). A *Lorentzian metric* g is a continuous assignment of a non-degenerate quadratic form g_p of index 1 in $T_p\mathcal{M}$ for all $p\in\mathcal{M}$, where index 1 means that the maximal dimension of a subspace of $T_p\mathcal{M}$ on which g_p is negative definite is 1.

An equivalent definition is the following.

Definition 2.2.24 (Lorentzian). A quadratic form g_p in $T_p\mathcal{M}$ is *Lorentzian* if there exists a vector $V\in T_p\mathcal{M}$ such that $g_p(V,V)<0$ while setting the g_p-orthogonal complement of V, i.e., $g_p|_{\Sigma_V}$ where

$$\Sigma_V=\{X\mid g_p(X,V)=0\}$$

is positive definite.

Definition 2.2.25 (Linear connection). A *linear connection* (*covariant derivative*) ∇ (or D) on $T\mathcal{M}$ is a bilinear map

$$\nabla\colon\Gamma(T\mathcal{M})\times\Gamma(T\mathcal{M})\to\Gamma(T\mathcal{M}),$$

and we write $\nabla(X,Y)=\nabla_XY$ with

(a) $\nabla_{fX}Y=f\nabla_XY$;

(b) $\nabla_XfY=X(f)Y+f;\nu_XY$ for all vector fields $X,Y\in\Gamma(T\mathcal{M})$, $f\in C^\infty(\mathcal{M})$.

Definition 2.2.26 (Torsion tensor). Given ∇, the map $T\colon\Gamma(T\mathcal{M})\times\Gamma(T\mathcal{M})\to\Gamma(T\mathcal{M})$ such that $T(X,Y):=\nabla_XY-\nabla_YX-[X,Y]$ is the *torsion tensor* of ∇.

Definition 2.2.27 (Torsion-free). Given ∇, if the torsion tensor $T=0$, then we say ∇ is *torsion-free*.

Definition 2.2.28 (Metric connection). Given ∇, if g is a Riemannian metric $\mathcal{M}$, then ∇ is called *metric* (or *Riemannian*) if

$$Z_g((X,Y))=(\nabla_ZX,Y)+g(X,\nabla_ZY)$$

for all $X,Y,Z\in\Gamma(T\mathcal{M})$.

Proposition 2.2.3 (Koszul formula)**.** On each Riemannian manifold $(\mathcal{M}, g)$, there exists a unique metric, torsion-free connection ∇ on $T\mathcal{M}$ determined by the *Koszul formula*

$$\langle \nabla_X Y, Z\rangle = \frac{1}{2}\left(X\langle Y, Z\rangle - Z\langle X, Y\rangle + Y\langle Z, X\rangle - \langle X, [Y, Z]\rangle + \langle Z, [X, Y]\rangle + \langle Y, [Z, X]\rangle\right). \quad (2.2)$$

Proof. Firstly, we prove that for each metric and torsion-free connection satisfies Equation 2.2. Then it will imply uniqueness. As for existence, we verify that the unique $\mathbb{R}$-bilinear map

$$\nabla\colon \Gamma(T\mathcal{M}) \times \Gamma(T\mathcal{M}) \to \Gamma(T\mathcal{M})$$

given by Equation 2.2 has the desired properties, i.e., 2 product rules from connection, torsion-free, and being metric. ■

Remark. This is called the Levi-Civita connection.

Definition 2.2.29 (Riemannian curvature tensor)**.** Let ∇ be the Levi-Civita connection on $T\mathcal{M}$. Then the *Riemannian curvature tensor* $R\colon \Gamma(T\mathcal{M}) \times \Gamma(T\mathcal{M}) \times \Gamma(T\mathcal{M}) \to \Gamma(\mathcal{M})$ is defined by

$$R(X, Y)Z \coloneqq \nabla_X \nabla_Y Z - \nabla_Y \nabla_X Z - \nabla_{[X,Y]} Z.$$

Appendix

Appendix A

Additional Handouts

Theorem A.0.1.

Bibliography

[FC13] F. Flaherty and M.P. do Carmo. *Riemannian Geometry*. Mathematics: Theory & Applications. Birkhäuser Boston, 2013. ISBN: 9780817634902. URL: https://books.google.com/books?id=ct91XCWkWEUC.