Riemannian and Lorentzian Geometry

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Chapter 1

Introduction

1.0 Review of important topics

1.0.1 Lecture 14.10.25

Definition 1.1 (Integral Curve). Let $X \in \Gamma(TM)$ and $\gamma : I \to M$ be a smooth curve. We call γ **integral curve** of X if

$$\dot{\gamma}(t) = X_{\gamma(t)}.$$

Furthermore, γ is maximal if for all other integral curves $\omega : J \to M$ with $I \cap J \neq \emptyset$ and $\omega|_{I \cap J} = \gamma|_{I \cap J}$ we have $J \subseteq I$.

Theorem 1.2 (Existence of Integral Curves). Let $X \in \Gamma(TM)$. For all $p \in M$ exists a unique maximal integral curve $\gamma_p : I_p \to M$ of X with $\gamma_p(0) = p$.

Definition 1.3 (Local Flow). Let $X \in \Gamma(TM)$. A **local flow** of X is a smooth map

$$\Theta : I \times U \to M$$

where $I \subseteq \mathbb{R}$ is an open interval, $0 \in I$ and $U \subseteq M$ is open such that

$$\Theta(t, p) = \gamma_p(t),$$

where γ_p is the maximal integral curve of X with $\gamma_p(0) = p$ for all $(t, p) \in I \times U$.

Note. Similarly, a maximal flow for $X \in \Gamma(TM)$ is a smooth map $\Theta : \mathcal{D} \to M$ with

$$\mathcal{D} := \bigcup_{p \in M} I_p \times \{p\} \subseteq \mathbb{R} \times M$$

being open. We call $\mathcal{D}$ the **maximal domain**. It always containes $\{0\} \times M$. A **global flow** is then a unique maximal flow with $\mathcal{D} = \mathbb{R} \times M$.

Notation. To emphasize that Θ depends on X, we write Θ_X and $\mathcal{D}^X$. Fixing $t \in \mathcal{D}$, we write

$$\theta_t : \mathcal{D} \cap (\{t\} \times M) \to M$$

with $\theta_t(p) := \Theta(t,p)$.

Definition 1.4 (Riemannian and Lorentzian Metrics)**.** Let $\nu \in \mathbb{N}$ with $0 \leq \nu \leq n$. A **semi-Riemannian metric** of **index** ν is a $(0,2)$-tensor field such that

$$g_p : T_pM \times T_pM \to \mathbb{R}$$

is a symmetric non-degenerate bilinear form on T_pM with index ν. We say:

- $\nu = 0$: g is **Riemannian**.
- $\nu = 1$: g is **Lorentzian**.

In the Lorentzian case, we take the convention $(-,+,+,\dots)$.

Theorem 1.5 (Levi-Civita Connection)**.** Given a semi-Riemannian manifold (M,g), there exists exactly one connection

$$\nabla : \mathfrak{X}(M) \times \mathfrak{X}(M) \to \mathfrak{X}(M)$$

, called the **Levi-Civita connection**, such that:

- ∇^g is torsion-free: $\nabla_X Y - \nabla_Y X = [X,Y]$
- ∇^g is compatible with g: $Zg(X,Y) = g(\nabla_Z X, Y) + g(X, \nabla_Z Y)$
- The Koszul identity is satisfied:

$$\begin{aligned} 2g(\nabla_X Y, Z) =& X(g(Y,Z)) + Y(g(X,Z)) - Z(g(X,Y)) \\ & - g(X,[Y,Z]) - g(Y,[X,Z]) + g(Z,[X,Y]) \end{aligned}$$

.

Definition 1.6 (Riemann Curvature Tensor)**.** The **Riemann Curvature Tensor** is the $(1,3)$-tensor field

$$R : \mathfrak{X}(M)^3 \to \mathfrak{X}(M)$$

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

Remark. In local coordinates (x^i), we have

$$R^l_{ijk} := (R(\partial_i, \partial_j)\partial_k)^l = \partial_i \Gamma^l_{jk} - \partial_j \Gamma^l_{ik} + \Gamma^l_{is}\Gamma^s_{jk} - \Gamma^l_{js}\Gamma^s_{ik}.$$

Definition 1.7 (Geodesic). A $\mathcal{C}^\infty$-curve $\gamma : (a,b) \to M$ is called a **geodesic** if $\dot\gamma$ is ∇^g*−parallel* along γ, i.e.

$$\ddot\gamma(t) = \nabla^g_{\frac{d}{dt}}\dot\gamma = 0.$$

In local coordinates, one finds the *geodesic equation*

$$0 = \frac{d^2}{dt^2}(x^i \circ \gamma) + (\Gamma^i_{kl} \circ \gamma)\frac{d}{dt}(x^k \circ \gamma)\frac{d}{dt}(x^l \circ \gamma).$$

Theorem 1.8 (Maximal Geodesic). For all $v \in TM$, there is exactly one geodesic

$$\gamma_v : I_v \to M$$

such that $\gamma_v(0) = \pi\|v\|$ and $\dot\gamma_v(0) = v$ and I_v is maximal.

Exponential Map

Definition 1.9 (Exponential Map). Define the (Riemannian) **exponential map**

$$\exp_p : \mathcal{D}_p \subseteq T_pM \to M$$

by

$$(p,v) \mapsto \exp_p(v) := \gamma_v(1)$$

where γ_v is the unique maximal geodesic.

We always have

$$\mathcal{D}_p \supseteq \{tv \in T_pM \mid t \in [0,1]\}.$$

We can consider $s \mapsto \gamma_v(st)$ for fixed $t \in \mathbb{R}$. Then, we have

$$\dot\gamma_v(st) = t\dot\gamma_v(0) = tv = \dot\gamma_{tv}(s)$$

for all s, and therefore $\gamma_{tv}(s) = \gamma_v(ts)$. This yields the useful formula

$$\exp_p(tv) = \gamma_{tv}(1) = \gamma_v(t).$$

Lemma 1.10. For all $p \in M$,

$$d(\exp_p)_0 : T_0(T_pM) \cong T_pM \to T_pM$$

is the identity $d(\exp_p)_0 = \mathrm{id}$ under the identification $\mathrm{id}(v^i\partial_{u_i}|_0) = v^i\partial_{x_i}|_p$.

Definition 1.11 (Normal Neighbourhood). An open set $U \ni p$ is a **normal neighbourhood** of p if there exists an open set $\tilde{U} \ni o_p \subseteq \mathcal{D}_p$ which is star-shaped such that

$$\exp_p|_{\tilde{U}} : \tilde{U} \to U$$

is a diffeomorphism.

Theorem 1.12 (Existence of Normal Neighbourhoods). For any $p \in M$, there is a normal neighbourhood around p.

Proof. Inverse function theorem. □

Definition 1.13 (Convex Neighbourhood). U is a **convex neighbourhood** if it is a normal neighbourhood for all $q \in U$.

Remark. If U is a normal neighbourhood of p, then for all $q \in U$ there is exactly one geodesic γ_{pq} in U from p to q, called **radial geodesic**.

Theorem 1.14 (Normal Coordinate Lines). For all $p \in M$ and a basis $\{v_1, \ldots, v_n\}$ of T_pM exists a chart $(U, (x^1, \ldots, x^n))$ such that:

1. U is a normal neighbourhood of p.
2. $\partial_i|_p = v$
3. $\Gamma^k_{ij} = 0$ for all i, j, k.

If the basis $\{v_1, \ldots, v_n\}$ is orthonormal, we also have

$$g_{ij}(p) = \epsilon_i \delta_{ij}$$

and

$$\partial_k g_{ij}(p) = 0.$$

The chart $(U, (x^1, \ldots, x^n))$ is called **normal coordinate chart**.

Chapter 2

Riemannian Geometry

In this chapter, we are concerned with Riemannian manifolds as metric spaces. The main goal is to prove the theorem of Hopf-Rinow.

Definition 2.1 (Regular Curve)**.** A piecewise $\mathcal{C}^1$-curve

$$\gamma : [a, b] \to M$$

is called **regular** if

$$\forall s \in [a, b] : \dot{\gamma}(s) \neq 0$$

and

$$\dot{\gamma}_\pm(t_i) \neq 0$$

at all $\mathcal{C}^1$-break-points.

Definition 2.2 (Arc-length)**.** Let (M, g) be a semi-Riemannian manifold and $\gamma : [a, b] \to M$ a (piecewise) $\mathcal{C}^1$-curve. The **arc-length** is defined to be the functional

$$L[\gamma] = \int_a^b \sqrt{|g(\dot{\gamma}(t), \dot{\gamma}(t))|}\, dt.$$

Remark.

1. In the Riemannian case, the $|\cdot|$ is redundant.
2. In semi-Riemannian geometry, there are curves with $L[\gamma] = 0$.
3. The arc-length functional is invariant under length parametrization.
4. If γ is regular, there exists a strictly monotonous reparametrization

   $$\varphi : [\tilde{a}, \tilde{b}] \to [a, b]$$

   such that $\tau := \gamma \circ \varphi$ satisfies $g(\dot{\tau}, \dot{\tau}) = 1$. This is a reparametrization by arc-length:

   $$L[\tau_{[\tilde{a}, s]}] = s - \tilde{a}$$

   for all $s \in [\tilde{a}, \tilde{b}]$.

Theorem 2.3 (Gauß' Lemma)**.** The exponential map is a radial isometry: For any $p \in M$, $x \in \mathcal{D}_p$ and $v, w \in T_x(T_pM) \cong T_pM$ with $v = \alpha x$ for some $\alpha \in \mathbb{R}$, the equations

$$g_{\exp_p(x)}(d(\exp_p(v))_x, d(\exp_p(w))_x) = g_p(v, w)$$

and

$$\dot{\gamma}(t) = \frac{d}{dt}\exp_p(tv)$$

hold.

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Theorem 2.4 (Minimizing Geodesic)**.** Let (M, g) be a Riemannian manifold and U be a normal neighbourhood of $p \in M$. Then, γ_{pq} is the shortest curve from p tp q unique up to monotonically increasing, piecewise $\mathcal{C}^1$ reparametrization.

Proof. Let $\omega : [a, b] \to M$ be a piecewise $\mathcal{C}^1$ curve in U from p to q. W.l.o.g., $a = 0$, $b = 1$ and $\omega([0, 1]) \subseteq U \setminus \{p\}$. We can write

$$\omega(t) = \exp_p(R(t)v(t))$$

with $R(t) := |\exp_p^{-1}(\omega(t))|_{g_p}$ and $v(t) := \frac{\exp_p^{-1}(\omega(t))}{|\exp_p^{-1}(\omega(t))|_{g_p}}$ such that $v \in \mathbb{S}^{m-1}_{g_p} \subseteq T_pM$. Both R and v are piecewise $\mathcal{C}^1$ and $R(t) \in (0, \infty)$ for $t > 0$, since $\omega(t)$ does not meet p again. Away from the breakpoints, we have

$$\dot{\omega}(t) = d_{R(t)v(t)}\exp_p([R(t)v(t)]) = R(t)\underbrace{d_{R(t)v(t)}\exp_p(\dot{v}(t))}_{:=A} + \dot{R}(t)\underbrace{d_{R(t)v(t)}\exp_p(v(t))}_{:=B}.$$

With this, we can calculate

$$g(\dot{\omega}(t), \dot{\omega}(t)) = R^2(t)g(A, A) + R(t)\dot{R}(t)g(A, B) + \dot{R}(t)g(B, B)$$

and

$$g(B, B) = g(d_{R(t)v(t)}\exp_p(v(t)), d_{R(t)v(t)}\exp_p(v(t))) = g_p(v(t), v(t)) = 1,$$

where we used Gauß' Lemma.
Turning our attention to the second term, we obtain

$$\begin{aligned} g(A, B) &= g(d_{R(t)v(t)}\exp(v(t)), d_{R(t)v(t)}\exp_p(\dot{v}(t))) \\ &= g_p(v(t), \dot{v}(t)) = \frac{1}{2}\frac{d}{dt}g_p(v(t), v(t)) = 0. \end{aligned}$$

For the arc-length, this yields

$$
\begin{aligned}
L[\omega] &= \int_0^1 \sqrt{g(\dot\omega(t),\dot\omega(t))}\,dt && (2.1)\\
&\geq \int_0^1 \sqrt{\dot R^2(t)}\,dt \geq \int_0^1 \dot R(t)\,dt && (2.2)\\
&= R(1) - R(0) = |\exp_p^{-1}(q)|_{g_p} = L[\gamma_{pq}] && (2.3)
\end{aligned}
$$

where the last equation is left as an exercise. □

Remark. We actually have equality if:

1. If $d_{R(t)v(t)}\exp_p(\dot v(t)) = 0$, we have $\dot v(t) = 0$ and $v = \frac{\exp_p^{-1}(q)}{|\exp_p^{-1}(q)|_{g_p}}$, hence $\omega(t) = \exp_p\left(\frac{R(t)}{|\exp_p^{-1}(q)|_{g_p}}\exp_p^{-1}(q)\right)$.
2. If $\dot R(t) \geq 0$

With this result and the convex neighbourhood theorem, one obtains that any piecewise $\mathcal{C}^1$-curve minimizing L from p to q must be a broken geodesic.

Theorem 2.5 (Normal Basis)**.** Let (M,g) be a Riemannian manifold. Then, every point $p \in M$ has a basis of normal neighbourhoods $\{U_\epsilon\}$ of the form $U_\epsilon = \exp_p^{-1}(B_\epsilon(0))$ and such that for all $q \in U_\epsilon$, γ_{pq} is the shortest curve from p to q in M.

Proof. Idea: Show that any piecewise $\mathcal{C}^1$ shortest curve starting from o and leaving U_ϵ has $L \geq \epsilon$ ($\implies L < \epsilon$). □

Definition 2.6 (Induced Metric)**.** Let (M,g) be a Riemannian manifold. The **induced distance function** by g is given by

$$d_g(p,q) := \inf\{L_g[\gamma] \mid \gamma : [a,b] \to M \text{ pw. cont.}, \gamma(a) = p, \gamma(b) = q\}$$

for all $p,q \in M$. A piecewise $\mathcal{C}^1$-curve is **minimizing** if

$$d_g(p,q) = L[\gamma]..$$

Theorem 2.7 (Hopf-Rinow)**.** Let (M,g) be a Riemannian manifold. The induced distance function

$$d_g : M \times M \to \mathbb{R}$$

is a distance function and the topology induced by d_g conincides with the topology of M.

Proof. 1. For finiteness, let γ be a $\mathcal{C}^1$ geodesic connecting p and q. We can cover the image of γ by a finite amount of sets and connect between the intersection points with geodesics.

2. For $d(p,q) \geq 0$, we start by showing that $d(p,q) = 0 \implies p = q$. If $p \neq q$, we can find a normal neighbourhood $U_\epsilon \ni p$ such that $q \notin U_\epsilon$ by the Hausdorff condition. Hence, $d(p,q) \geq \epsilon \neq 0$.

3. Next, we show symmetry. This is clear from the reparametrization invariance of L, using $t \mapsto \gamma(-t)$.

4. For the triangle equality, let $p, q, x \in M$. For any $\epsilon > 0$, choose γ_1, γ_2 such that

$$L[\gamma_1] \leq d(p,x) + \frac{\epsilon}{2}$$
$$L[\gamma_2] \leq d(x,q) + \frac{\epsilon}{2}.$$

Joining γ_1 and γ_2, we have $\gamma = \gamma_1 * \gamma_2$ with

$$d(p,q) \leq L[\gamma] = L[\gamma_1] + L[\gamma_2] \leq d(p,x) + d(x,q) + \epsilon$$

and $\epsilon > 0$ is arbitrary.

5. Lastly, we have to prove that the topologies agree. This means showing that
$$U_\epsilon = B_\epsilon^d(p) := \{q \in M \mid d(p,q) < \epsilon\}$$
for U_ϵ from theorem **??**. By the same theorem, U_ϵ is a basis, and by definition, so is $B_\epsilon^d(p)$. Now, we have:

   - $$\forall q \in U_\epsilon \implies d(p,q) = L[\gamma_{pq}] < \epsilon \implies U_\epsilon \subseteq B_\epsilon^d(p)$$
   - $\forall q \in B_\epsilon^d(p)$ there is a curve such that $\gamma(a) = p$, $\gamma(b) = q$ and $L[\gamma] < \epsilon$. But any curve leaving U_ϵ has length $L \geq \epsilon$, so $B_\epsilon^d(p) \subseteq U_\epsilon$.

□

Remark. Any Riemannian manifold is metrizable.

We will now consider another kind of length.

Definition 2.8 (Piecewise Arc-length). Let $\gamma : [a,b] \to M$ be a $\mathcal{C}^0$ curve. The piecewise length is given by

$$L_d[\gamma] := \sup_{N \in \mathbb{N}} \sup \left\{ \sum_{i=1}^{N} d(\gamma(t_i), \gamma(t_{i+1})) \mid a = t < \cdots < t_i < t_i + 1 < \cdots < t_N = b \right\}..$$

Theorem 2.9 (Piecewise Length)**.** If γ is piecewise $\mathcal{C}^1$, then

$$L_d[\gamma] = L[\gamma].$$

Proof.

$$\sum_{i=1}^{N} d(\gamma(t_i), \gamma(t_{i+1})) \leq L[\gamma|_{[t_i,t_{i+1}]}] \leq L[\gamma].$$

Taking the supremum, we have $L_d[\gamma] \leq L[\gamma]$. $\square$