
Preface

This is my personal script for the lecture Riemannian and Lorentzian Geometry in the winter term of 25/26 at the University of Hamburg. The script mostly follows the lecture of [Prof. Dr. Melanie Graf](#) with occasional bits adapted from the available literature. The layout is a personal adaption of [Gilles Casel's](#) layout. We will adapt most notations from [LeeSM] and [LeeRM] and use the Einstein summation convention throughout. The lecture first aims to fill some gaps often left in undergraduate differential geometry lectures, mainly the theorem of Hopf and Rinow. After that, we continue with some notions inherent to Lorentzian geometry before focussing our attention again on the (semi-)Riemannian case. Later, we will use Jacobi fields and do some comparison geometry. Unless clearly stated otherwise, we will work in a completely smooth category. For Lorentzian metrics, we choose the sign convention $(-, +, \dots, +)$.

Rasmus Raschke, December 2025

List of symbols

$M \pitchfork N$	Transverse intersection
$\Gamma(M)$	Space of smooth sections $\sigma : M \rightarrow TM$
$\Gamma_\gamma(M)$	Space of smooth sections along a curve.
$\mathfrak{X}(M)$	Space of vector fields on M .
$\mathfrak{X}(\gamma)$	Space of vector fields along a curve γ .
$\mathfrak{X}(\gamma)^\top$	Space of parallel vector fields.
$\mathfrak{X}(\gamma)^\perp$	Space of normal vector fields.
$\overline{\mathfrak{X}}(\gamma)$	Space of piecewise smooth vector fields along γ .
$\mathfrak{X}_0(\gamma)$	Space of vector fields along γ vanishing at the endpoints
$\mathfrak{J}(\gamma)$	Space of Jacobi fields along a curve γ .
$\mathfrak{J}(\gamma)^\top$	Space of parallel Jacobi fields.
$\mathfrak{J}(\gamma)^\perp$	Space of normal Jacobi fields.
R, R^l_{ijk}	$(1, 3)$ -Riemann curvature tensor.
Rm	Riemann tensor
Ric	Ricci tensor
scal	Scalar curvature
sec	Sectional curvature.

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CHAPTER ONE

Repetition

We start by listing some results that should already be known by the reader. In the following, we assume a basic understanding of smooth manifolds and Riemannian geometry.

1.1 Vector Fields and Flows

On a smooth manifold M , we consider vector fields as sections of the tangent projection $\pi : TM \rightarrow M$, i.e. a map

$$X : M \rightarrow TM$$

with $\pi \circ X = \text{id}_M$.

Notation. We write a vector field X at $p \in M$ as X_p , while $X_p(f)$ is the vector field at p applied to a function f . We denote the space of sections of the tangent projection by $\Gamma(TM)$, and the space of smooth vector fields by $\mathfrak{X}(M)$. General (k, l) -tensor fields are denoted as $\mathcal{T}_l^k = \Gamma(T^{(k,l)}TM)$.

Definition 1.1 (Integral Curve). Given a manifold M and $V \in \mathfrak{X}(M)$, an **integral curve** of V is a smooth curve

$$\gamma : I \rightarrow M$$

such that for all $t \in I$,

$$\dot{\gamma}(t) = V_{\gamma(t)}$$

holds

Example 1.2. Consider the Euclidean plane \mathbb{R}^2 with standard coordinates.

- The coordinate vector field ∂_1 has straight lines

$$\gamma(t) = (a + t, b)$$

as integral curves for some $a, b \in \mathbb{R}$.

- The curl field $x^1\partial_2 - x^2\partial_1$ has counterclockwise traversed circles

$$\gamma(t) = (a \cos t - b \sin t, a \sin t + b \cos t)$$

as integral curves.

Proposition 1.3. Let M be a manifold, $V \in \mathfrak{X}(M)$. For all $p \in M$ exists a unique maximal integral curve

$$\gamma_p : I_p \rightarrow M$$

of V with $\gamma_p(0) = p$.

Given a manifold M , we define a **flow domain** on M to be an open subset $\mathcal{D} \subseteq \mathbb{R} \times M$ such that for each $p \in M$,

$$\mathcal{D}^{(p)} = \{t \in \mathbb{R} \mid (t, p) \in \mathcal{D}\}$$

is an open interval.

Definition 1.4 (Flow). A **(local) flow** on M is a continuous local one-parameter group action

$$\theta : \mathcal{D} \rightarrow M$$

such that for all $p \in M$:

1. $\theta(0, p) := \theta_0(p) = \text{id}_M(p) = p$, and
2. if $s \in \mathcal{D}^{(p)}$, $t + s \in \mathcal{D}^{(\theta_s(p))}$: $\theta_t \circ \theta_s(p) = \theta_{t+s}(p)$ holds.

A flow gives rise to a family of curves

$$\theta^{(p)} : \mathcal{D}^{(p)} \rightarrow M$$

defined by $\theta^{(p)}(t) = \theta_t(p)$. An **infinitesimal generator** of a flow θ is then a vector field $V \in \mathfrak{X}(M)$ with

$$V_p = \left. \frac{d}{dt} \right|_{t=0} \theta^{(p)}(t)$$

for all p in the domain of θ . On the other hand, the $\theta^{(p)}$ -curves are integral curves of V . We call a flow θ **maximal** if the flow domain \mathcal{D} of θ is maximal. We call a flow **global** if $\mathcal{D} = \mathbb{R} \times M$.

Theorem 1.5 (Fundamental Theorem of Flows). Let M be a smooth manifold and $V \in \mathfrak{X}(M)$. Then there exists a unique maximal flow

$$\Theta : \mathcal{D} \rightarrow M$$

with infinitesimal generator V and the following properties:

1. For all $p \in M$, $\Theta^{(p)}$ is the unique maximal integral curve of V starting at p .
2. For $s \in \mathcal{D}^{(p)}$, we have $\mathcal{D}^{(\theta_s(p))} = \{t - s \mid t \in \mathcal{D}^{(p)}\}$.
3. For each $t \in \mathbb{R}$, the set $M_t := \{p \in M \mid (t, p) \in \mathcal{D}\}$ is open in M , and $\Theta_t : M_t \rightarrow M_{-t}$ is a diffeomorphism with inverse Θ_{-t} .

The flow of this theorem is called **flow of V** .

1.2 (Semi-)Riemannian Metrics

1.2.1 Linear Algebra

Definition 1.6 (Pseudo-Euclidean Scalar Product). Let V be a finite-dimensional real vector space. A **pseudo-Euclidean scalar product** on V is a map

$$\langle \cdot, \cdot \rangle : V \times V \rightarrow \mathbb{R}$$

which is:

1. Symmetric: $\langle u, v \rangle = \langle v, u \rangle$
2. Bilinear: $\langle \lambda u + v, w \rangle = \lambda \langle u, w \rangle + \langle v, w \rangle$
3. Non-degenerate: $v \mapsto \langle v, \cdot \rangle$ is an isomorphism $V \cong V^*$.

The **index** s of V is the number

$$s := \max\{\dim(W) \mid W \leq V : \langle \cdot, \cdot \rangle|_W \text{ negative definite}\}.$$

The pair $(V, \langle \cdot, \cdot \rangle)$ is called **pseudo-Euclidean vector space**.

We call this iso **musical isomorphism**.

The index can be easily calculated by choosing a basis (e_i) , defining a matrix $A_{ij} := \langle e_i, e_j \rangle$, and determining the negative eigenvalues of A . This will be the index of V .

Example 1.7. The standard pseudo-Euclidean vector space is the n -dimensional space $\mathbb{R}^{n-s,s}$, which consists of the vector space \mathbb{R}^n with scalar product

$$g_{ij} := \text{diag}\{\underbrace{-1, \dots, -1}_{s \text{ times}}, \underbrace{1, \dots, 1}_{n-s \text{ times}}\}.$$

We call $\mathbb{R}^{n,1}$ the $(n+1)$ -dimensional **Minkowski space**.

Remark 1.8. Sylvester's theorem of inertia tells us that the important invariants for pseudo-Euclidean vector spaces are dimension and index. Every finite-dimensional vector space of dimension n and index s is isomorphic to $\mathbb{R}^{n-s,s}$.

Proposition 1.9. Let V be a pseudo-Euclidean vector space and $W \leq V$. Then the following are equivalent:

1. $(W^\perp)^\perp = W$ and $V = W \oplus W^\perp$
2. $W \cap W^\perp = \{0\}$
3. $\langle \cdot, \cdot \rangle|_{W \times W}$ is non-degenerate.

Proof. Corollary of the dimension formula. □

Proposition 1.10 (Parallelogram Law). If $\langle \cdot, \cdot \rangle$ is a pseudo-Euclidean scalar product, the **parallelogram law**

$$\langle v, w \rangle = \frac{1}{2}(\|v + w\|^2 - \|v\|^2 - \|w\|^2)$$

holds.

Definition 1.11 (Causality in Lorentzian Geometry). If $(V, \langle \cdot, \cdot \rangle)$ is a Lorentzian vector space, we define:

1. $v \in V$ is **timelike** if $\|v\|^2 < 0$.
2. $v \in V$ is **spacelike** if $\|v\|^2 > 0$.
3. $v \in V$ is **null** or **lightlike** if $\|v\|^2 = 0$.
4. $v \in V$ is **causal** if it is time- or lightlike.
5. The zero vector is spacelike by definition.

We denote the space of timelike vectors by V^{tl} , the space of spacelike vectors by V^{sl} , the space of lightlike vectors by V^{null} , and the space of causal vectors by V^{causal} .

Proposition 1.12. Consider $\mathbb{R}^{n,1}$. Then:

1. The subspace of timelike vectors has two connected components.
2. Let v, w be lightlike. Then $\langle v, w \rangle = 0$ if and only if there is some $\lambda \in \mathbb{R}^*$ such that $v = \lambda w$.
3. If v, w are timelike with $\langle v, w \rangle < 0$, we have **reverse Cauchy-Schwarz**:

$$|\langle v, w \rangle| \geq \|v\| \|w\|$$

and **reverse triangle** identities:

$$\|v + w\| \geq \|v\| + \|w\|.$$

1.2.2 Semi-Riemannian Manifolds

Definition 1.13 (Semi-Riemannian Manifold). A **semi-Riemannian metric** on a smooth manifold M is a smooth, covariant 2-tensor field $g \in T^2(M)$ such that for each $p \in M$ and all $U, V, W \in T_p M$, $\lambda, \mu \in \mathbb{R}$, the following is satisfied:

1. g has global signature (r, s) .
2. $g_p(U, V) = g_p(V, U)$
3. $g_p(\lambda U + \mu V, W) = \lambda g_p(U, W) + \mu g_p(V, W) = g_p(W, \lambda U + \mu V)$
4. $g_p(U, U) = 0$ if and only if $U = 0$.

Hence, g_p is an inner product on each $T_p M$. The pair (M, g) is called **semi-Riemannian manifold** and s is the **index** of g . If $s = 0$, we call (M, g) **Riemannian**. If $s = 1$, we call it **Lorentzian**.

For convenience of notation, we will sometimes suppress p and write $\langle \cdot, \cdot \rangle$ for $g_p(\cdot, \cdot)$.

Notation. Given local coordinates (U, x^i) on some neighbourhood U , g can be written as

$$g = g_{ij} dx^i \otimes dx^j,$$

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where the g_{ij} are $(\dim M)^2$ smooth component functions given by $g_{ij}(p) = g_p(\partial_i|_p, \partial_j|_p)$. Interpreting these components as matrix components, one obtains a symmetric, non-singular matrix.

Example 1.14. The standard model for a semi-Riemannian manifold with index s is the space $\mathbb{R}^{r,s} = \mathbb{R}^{r+s}$. Given coordinates $(\xi^1, \dots, \xi^r, \tau^1, \dots, \tau^s)$, we define the semi-Riemannian standard metric to be

$$g^{(r,s)} = d\xi^1 \otimes d\xi^1 + \dots + d\xi^r \otimes d\xi^r + d\tau^1 \otimes d\tau^1 + \dots + d\tau^s \otimes d\tau^s.$$

For $s = 0$, we recover the **canonical Euclidean metric**

$$g_{\text{st}} = dx^1 \otimes dx^1 + \dots + dx^r \otimes dx^r = \delta_{ij} dx^i \otimes dx^j.$$

For $s = 1$, we obtain $r + 1$ -dimensional **Minkowski space** with the **Minkowski metric**

$$\eta = -dt \otimes dt + dx^1 \otimes dx^1 + \dots + dx^r \otimes dx^r.$$

Example 1.15. Given Minkowski space $\mathbb{R}^{2,1}$ and $c \neq 0$, we define the smooth submanifold

$$S_c^\eta := \{(t, x) \in \mathbb{R}^{2,1} \mid \eta((t, x), (t, x)) = c\}.$$

The restriction of η induces a semi-Riemannian metric on S_c^η , turning it into a semi-Riemannian submanifold. For $c > 0$, we call $S_c^\eta = dS_3$ (3-dimensional) **de Sitter space**, and for $c < 0$, we call $S_c^\eta = AdS_3$ **anti-de Sitter space**. Anti-de Sitter space AdS_3 has two connected components which are model hyperbolic spaces.

Every smooth manifold can be endowed with a Riemannian metric:

Proposition 1.16. Every smooth manifold M is a Riemannian manifold.

Proof. Given a smooth manifold M , we can choose an atlas (φ_i, U_i) of M and a smooth partition of unity (ϱ_i) subordinate to the covering $\cup U_i = M$. On each coordinate patch U_i , we can use the euclidean metric g_{st} and define a metric

$$g_p := \sum_{i \in I} \varrho_i(p) \varphi_i^* g_{\text{st}}.$$

This metric is clearly symmetric and bilinear. Furthermore, the sum is finite since ϱ_i is a partition of unity, and non-degenerate as g_{st} is non-degenerate. \square

This does not work in the semi-Riemannian case: Pulling back the standard semi-Riemannian metric of \mathbb{R}^n can lead to a vanishing sum because the chart-wise metrics possibly attain negative values.

Definition 1.17 (Connection). Given a smooth manifold M and a vector bundle $E \rightarrow M$, a **connection** or **covariant derivative** is a map

$$\nabla : \mathfrak{X}(M) \times \Gamma(E) \rightarrow \Gamma(E)$$

such that:

1. For all $f_1, f_2 \in \mathcal{C}^\infty$, $X_1, X_2 \in \mathfrak{X}(M)$:

$$\nabla_{f_1 X_1 + f_2 X_2} Y = f_1 \nabla_{X_1} Y + f_2 \nabla_{X_2} Y.$$

2. For all $\lambda_1, \lambda_2 \in \mathbb{R}$ and $Y_1, Y_2 \in \Gamma(E)$:

$$\nabla_X (\lambda_1 Y_1 + \lambda_2 Y_2) = \lambda_1 \nabla_X (Y_1) + \lambda_2 \nabla_X (Y_2).$$

3. For all $f \in \mathcal{C}^\infty(M)$:

$$\nabla_X (fY) = f \nabla_X Y + (Xf)Y.$$

Theorem 1.18 (Fundamental Theorem of Riemannian Geometry). Let (M, g) be a (semi)-Riemannian manifold. Then there exists a unique connection

$$\nabla : \mathfrak{X}(M) \times \Gamma(TM) \rightarrow \Gamma(TM)$$

which is:

1. metric with respect to g :

$$\nabla_X g_p(Y, Z) = g_p(\nabla_X Y, Z) + g_p(Y, \nabla_X Z)$$

2. symmetric:

$$\nabla_X Y - \nabla_Y X = [X, Y].$$

We call ∇ the **Levi-Civita-Connection**.

Note that symmetry implies that ∇ is torsion-free since the torsion tensor is given by $T(X, Y) = \nabla_X Y - \nabla_Y X - [X, Y]$

Proposition 1.19. The Levi-Civita-Connection admits the following forms:

1. **Koszul's formula:**

$$\begin{aligned} 2\langle \nabla_X Y, Z \rangle = & X\langle Y, Z \rangle + Y\langle Z, X \rangle - Z\langle X, Y \rangle \\ & - \langle Y, [X, Z] \rangle - \langle Z, [Y, X] \rangle + \langle X, [Z, Y] \rangle \end{aligned}$$

2. The coefficients in local coordinates are the **Christoffel symbols**:

$$(\nabla_{\partial_i} \partial_j)^k = \Gamma_{ij}^k = \frac{g^{kl}}{2} (\partial_i g_{jl} + \partial_j g_{il} - \partial_l g_{ij}).$$

3. Given a smooth local frame (E_i) and functions $\varepsilon_{ij}^k E_k$ given by $[E_i, E_j] = \varepsilon_{ij}^k E_k$, one has:

$$\Gamma_{ij}^k = \frac{g^{kl}}{2} (E_i g_{jl} + E_j g_{il} - E_l g_{ij} - g_{jm} \varepsilon_{il}^m - g_{lm} \varepsilon_{ji}^m + g_{im} \varepsilon_{lj}^m).$$

If (E_i) is an orthonormal frame, this reduces to:

$$\Gamma_{ij}^k = \frac{1}{2}(\varepsilon_{ij}^k - \varepsilon_{ik}^l - \varepsilon_{jk}^l).$$

1.3 Curvature and Geodesics

Given a smooth curve

$$\gamma : I \rightarrow M,$$

we call a vector field $V : I \rightarrow TM$ a **vector field along** γ if $V(t) \in T_{\gamma(t)}M$ for all $t \in I$. We denote the space of vector fields along γ by $\mathfrak{X}(\gamma)$.

Definition 1.20 (Geodesic). Let M be a smooth manifold and ∇ be a connection on TM . A smooth curve $\gamma : I \rightarrow M$ is called a **geodesic** if the acceleration $\nabla_{\frac{d}{dt}} \dot{\gamma}(t)$ vanishes for all $t \in I$. This is equivalent to the local **geodesic equation**

$$\ddot{x}^k(t) + \dot{x}^i(t)\dot{x}^j(t)\Gamma_{ij}^k(x(t)) = 0,$$

where x^i are the components of γ in some local coordinates.

Theorem 1.21 (Uniqueness and Maximality of Geodesics). Let M be a smooth manifold and ∇ be a connection on TM . For each $p \in M$ and $v \in T_pM$, there exists a unique maximal geodesic

$$\gamma_v : I_v \rightarrow M$$

with $\gamma(0) = p$ and $\dot{\gamma}(0) = v$, defined on some open interval $I \ni 0$.

Remark 1.22. Some similarities to the fundamental theorem of flows emerge: Considering the open flow domain $\mathcal{D} := \cup_{v \in TM} I_v \times \{v\}$, we obtain a one-parameter group action

$$\vartheta : I \subseteq \mathbb{R} \times TM \rightarrow TM$$

given by $\vartheta_t(v) := \gamma_v(t)$. This is called the **geodesic flow**. The geodesic flow is the maximal flow of the **geodesic spray**: Thinking of the tangent bundle TM as a manifold on its own, we can consider curves

$$\tilde{\gamma}(p, v) : I \rightarrow TM$$

given by $\tilde{\gamma}_{(p,v)} := (\gamma_v, \dot{\gamma}(v))$, where $\gamma_v : I \rightarrow M$ is a geodesic in M with initial data (p, v) . Then the geodesic spray is a vector field

$$G(t) := \nabla_{\frac{d}{dt}} \tilde{\gamma}_{(p,v)}.$$

Given a smooth manifold M and some $V \in \mathfrak{X}(\gamma)$ for some smooth curve γ , we call V **parallel along** γ if $\nabla_{\frac{d}{dt}} V \equiv 0$. In local coordinates, this reads as

$$\dot{V}^k(t) = -V^j(t)\dot{\gamma}^i(t)\Gamma_{ij}^k(\gamma(t)).$$

Theorem 1.23 (Existence and Uniqueness of Parallel Transport). Given a smooth manifold M , a connection ∇ on TM , a smooth curve $\gamma : I \rightarrow M$ with $t_0 \in I$, and a vector $v \in T_{\gamma(t_0)}M$, there exists a unique parallel vector field $V \in \mathfrak{X}(\gamma)$ with $V(t_0) = v$. We call V the parallel transport of v along γ and define for each $t_0, t_1 \in I$ the **parallel transport isomorphism**

$$P_{t_0 t_1}^\gamma : T_{\gamma(t_0)}M \rightarrow T_{\gamma(t_1)}M.$$

Definition 1.24 (Geodesic Completeness). A geodesic $\gamma : I \rightarrow \mathbb{R}$ is called **complete** if $I = \mathbb{R}$. We call M **geodesically complete** if all geodesics for the Levi-Civita-Connection are complete.

We also have that if $\gamma_v : I \rightarrow M$ is a geodesic and $h : J \rightarrow I$ is a smooth reparametrization, then $\gamma_v \circ h$ is a geodesic if and only if h is affine.

Lemma 1.25 (Rescaling Lemma). Let

$$\gamma_v : (a_v, b_v) \rightarrow M$$

be a geodesic and $C \neq 0, t_0 \in \mathbb{R}$. Then,

$$\tilde{\gamma} : \left(\frac{a_v}{C} - t_0, \frac{b_v}{C} - t_0 \right) \rightarrow M$$

given by $\tilde{\gamma}(t) := \gamma_v(Ct + t_0)$ is also a geodesic.

1.4 The Exponential Map

The **domain of the exponential map** is a subset $\mathcal{E} \subseteq TM$ given by

$$\mathcal{E} := \{v \in TM \mid \gamma_v \text{ defined on interval containing } [0, 1]\}.$$

Sometimes we restrict the map to $\mathcal{E}_p := \mathcal{E} \cap T_p M$ and write \exp_p .

Definition 1.26 (Exponential Map). If M is a smooth manifold and \mathcal{E} is an exponential domain, the **exponential map** $\exp : \mathcal{E} \rightarrow M$ is given by

$$\exp(v) := \gamma_v(t).$$

Proposition 1.27. The exponential map has the following properties:

1. $\mathcal{E} \subseteq TM$ is open, contains the image of the zero section, and each \mathcal{E}_p is star-shaped at 0.
2. For each $v \in TM$, $\gamma_v(t) = \exp(tv)$ as long as one side is defined.
3. \exp is smooth.
4. For all $p \in M$, the differential

$$(\exp_p)_{0,*} : T_0(T_p M) \cong T_p M \rightarrow T_p M$$

is the identity at 0.

Proposition 1.28 (Normal Neighbourhood). Let (M, g) be a semi-Riemannian manifold. For all $p \in M$, there is an open neighbourhood U of p and a neighbourhood V of $0 \in TM$ such that $\exp_p : V \rightarrow U$ is an isomorphism. We call U a **normal coordinate neighbourhood**.

Normal neighbourhoods have very nice properties:

1. Normal charts around p are centered at p .
2. The metric coefficients at p are δ_{ij} in the Riemannian and $\pm\delta_{ij}$ in the semi-Riemannian case.
3. Given $v = v^i \partial_i \in T_p M$, the geodesic with initial data (p, v) is given by $\gamma_v(t) = (tv^1, \dots, tv^n)$.
4. All Christoffel symbols vanish at p .

Theorem 1.29 (Existence of Convex Neighbourhoods). Given a semi-Riemannian manifold M , **convex neighbourhoods**, i.e. neighbourhoods which are normal for all points contained in them, form a neighbourhood basis for all $p \in M$.

Corollary 1.30. Given a convex neighbourhood U , all $p, q \in U$ are connected by a unique geodesic $\gamma : [0, 1] \rightarrow M$ with $\gamma(0) = p$, $\gamma(1) = q$ and $\gamma = \gamma_{\exp_p^{-1}(q \exp_p^{-1}(q))}$.

Theorem 1.31 (Gauß' Lemma). Let M be a semi-Riemannian manifold. For any $p \in M$, $x \in \mathcal{E}_p$ and $v, w \in T_p M$ such that $v = \lambda w$ for $\lambda \in \mathbb{R}$, we have

$$\langle (\exp_p(v))_{x,*}, (\exp_p(w))_{x,*} \rangle = \langle v, w \rangle.$$

1.5 Curvature

Definition 1.32 (Riemann Curvature Tensor). Let M be a semi-Riemannian manifold and $X, Y, Z \in TM$. The **Curvature Tensor** is the $(1, 3)$ -tensor field

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

given by

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

Notation. There are many tensors derived from the curvature tensor:

1. The Riemann tensor itself has local form

$$R_{ijk}^l = \partial_i \Gamma_{jk}^l - \partial_j \Gamma_{ik}^l - \Gamma_{jk}^m \Gamma_{im}^l - \Gamma_{ik}^m \Gamma_{jm}^l.$$

The map $Z \mapsto R(X, Y)Z$ is the **curvature endomorphism**.

2. The **Riemann tensor** is a $(0, 4)$ -tensor field defined by $Rm := R^b = \langle R(X, Y)Z, W \rangle$.

3. The **Ricci curvature** is a $(0, 2)$ -tensor field given by

$$Ric(X, Y) = \text{tr}(Z \mapsto R(Z, X)Y)$$

with local form $R_{ij} = g^{km} R_{kijm}$.

4. The **scalar curvature** is given by

$$\text{scal} = \text{tr Ric} = g^{ij} R_{ij}.$$

CHAPTER TWO

Distances, Completeness and Causality Theory

CHAPTER THREE

Jacobi Fields

3.1 The Jacobi Equation

In this section we focus on semi-Riemannian manifolds.

Definition 3.1 (Variation through Geodesics). Let (M, g) be semi-Riemannian and $\gamma : I \rightarrow M$ be a geodesic. If K is another interval and

$$\Gamma : K \times I \rightarrow M$$

is a variation of γ such that $\gamma_s : I \rightarrow M$ is a geodesic for all $s \in K$, we call Γ a **variation through geodesics**.

Variation through geodesics give rise to several particular vector fields: The *variational field* of Γ is a vector field $J \in \mathfrak{X}(\Gamma)$ defined as

$$J(t) := \left. \frac{\partial}{\partial s} \right|_{s=0} \Gamma(s, t).$$

Furthermore, we define two accessory vector fields

$$\begin{aligned} T(s, t) &:= \frac{\partial \Gamma}{\partial t} \\ S(s, t) &:= \frac{\partial \Gamma}{\partial s} \end{aligned}$$

which will be useful.

Lemma 3.2 (Symmetry Lemma). Let $\Gamma : K \times I \rightarrow M$ be a smooth family of curves. Then we have

$$\nabla_{\frac{d}{ds}} T = \nabla_{\frac{d}{dt}} S.$$

Proof. Take local coordinates (x^i) on some coordinate neighbourhood and write $\Gamma(s, t) = (\gamma^1(s, t), \dots, \gamma^n(s, t))$. We have $S = \frac{\partial \gamma^k}{\partial s} \partial_k$ and $T = \frac{\partial \gamma^k}{\partial t} \partial_k$. Calculating the left side directly yields:

$$\begin{aligned} \nabla_{\frac{d}{ds}} T &= \nabla_{\frac{d}{ds}} \left(\frac{\partial \gamma^k}{\partial s} \partial_k \right) = \frac{\partial^2 \gamma^k}{\partial t \partial s} \partial_k + \frac{\partial \gamma^i}{\partial t} \frac{\partial \gamma^j}{\partial s} \nabla_{\partial_j} \partial_i \\ &= \left(\frac{\partial^2 \gamma^k}{\partial t \partial s} + \frac{\partial \gamma^i}{\partial t} \frac{\partial \gamma^j}{\partial s} \Gamma_{ji}^k \right) \partial_k \end{aligned}$$

Exchanging $i \leftrightarrow j$ and using the symmetry $\Gamma_{ij}^k = \Gamma_{ji}^k$ yields the desired identity. \square

Lemma 3.3 (Curvature Lemma). Let (M, g) be semi-Riemannian and $\Gamma : K \times I \rightarrow M$ be a smooth family of curves. Then for any $V \in \mathfrak{X}(\Gamma)$, we have

$$\nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} V - \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} V = R(S, T)V.$$

Proof. Take local coordinates (x^i) and write $\Gamma(s, t) = (\gamma^1(s, t), \dots, \gamma^n(s, t))$ as well as $V = V^i \partial_i$. We calculate the two left derivatives explicitly:

$$\nabla_{\frac{d}{dt}} V = \frac{\partial V^i}{\partial t} \partial_i + V^i \nabla_{\frac{d}{dt}} \partial_i$$

and

$$\nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} V = \left(\frac{\partial^2 V^i}{\partial s \partial t} + \frac{\partial V^i}{\partial t} \nabla_{\frac{d}{ds}} + \frac{\partial V^i}{\partial s} \nabla_{\frac{d}{dt}} + V^i \nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} \right) \partial_i.$$

Exchanging $s \leftrightarrow t$ yields $\nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} V$ and we see immediately that after subtraction, only the rightmost term remains:

$$\left(\nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} - \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} \right) V = V^i \left(\nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} - \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} \right) \partial_i.$$

Extending ∂_i and the covariant derivative, we can calculate:

$$\nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} \partial_i = \nabla_{\frac{d}{ds}} \left(\frac{\partial \gamma^j}{\partial t} \nabla_{\partial_j} \partial_i \right) = \frac{\partial^2 \gamma^j}{\partial s \partial t} \nabla_{\partial_j} \partial_i + \frac{\partial \gamma^j}{\partial t} \frac{\partial \gamma^k}{\partial s} \nabla_{\partial_k} \nabla_{\partial_j} \partial_i$$

and analogously

$$\nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} \partial_i = \frac{\partial^2 \gamma^j}{\partial t \partial s} \nabla_{\partial_j} \partial_i + \frac{\partial \gamma^j}{\partial s} \frac{\partial \gamma^k}{\partial t} \nabla_{\partial_k} \nabla_{\partial_j} \partial_i.$$

Exchanging $j \leftrightarrow k$ and subtracting cancels out the left term and we obtain:

$$\nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} \partial_i - \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} \partial_i = \frac{\partial \gamma^j}{\partial t} \frac{\partial \gamma^k}{\partial s} (\nabla_{\partial_k} \nabla_{\partial_j} - \nabla_{\partial_j} \nabla_{\partial_k}) \partial_i = R(S, T) \partial_i.$$

\square

We are now ready to consider the main theorem of this section:

Theorem 3.4 (Jacobi Equation). Let (M, g) be semi-Riemannian, $\gamma : I \rightarrow M$ be a geodesic and $\Gamma : K \times I \rightarrow M$ be a variation of γ through geodesics with variational field J . Then J satisfies the **Jacobi Equation**:

$$\nabla_{\frac{d}{dt}}^2 J + R(J, \dot{\gamma}) \dot{\gamma} = 0. \quad (3.1)$$

Proof. The fact that Γ is a variation through geodesics tells us that $\nabla_{\frac{d}{dt}} T \equiv 0$. Derivating once more yields $\nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} T \equiv 0$. By the curvature and the symmetry lemma, we have

$$\nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} T = \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} T + R(S, T)T = \nabla_{\frac{d}{dt}}^2 S + R(S, T)T.$$

At $s = 0$, we have $S(0, t) = \partial_s \Gamma_s(t) = J(t)$ and $T(0, t) = \partial_t \Gamma_0(t) = \dot{\gamma}(t)$ as claimed. \square

3.1. THE JACOBI EQUATION

Proposition 3.5 (Existence and Uniqueness). Let (M, g) be a SRMF, $\gamma : I \rightarrow M$ be a geodesic, $t_0 \in I$ and $p := \gamma(t_0)$. For all $v, w \in T_p M$, there is a unique Jacobi field J along γ satisfying the initial data

$$J(t_0) = v, \nabla_{\frac{d}{dt}} J(t_0) = w.$$

Proof. Take $J \in \mathfrak{X}(\gamma)$ and choose a parallel ONF (E_i) . We write $v = v^i E_i(t_0)$, $w = w^i E_i(t_0)$, $\dot{\gamma}(t) = \gamma^i(t) E_i(t)$ and $J = J^i(t) E_i(t)$. The Jacobi equation holds if and only if the following equation is satisfied:

$$\begin{aligned} 0 &= \nabla_{\frac{d}{dt}}^2 J + R(J, \dot{\gamma}) \dot{\gamma} = \nabla_{\frac{d}{dt}}^2 (J^i E_i) + R(J^j E_j, \dot{\gamma}^k E_k) \dot{\gamma}^l E_l \\ &= \ddot{J}^i E_i + J^j \dot{\gamma}^k \dot{\gamma}^l R(E_j, E_k) E_l \end{aligned}$$

This yields a second-order system of n equations

$$\frac{d^2 J^i(t)}{dt^2} = -J^j(t) \dot{\gamma}^k(t) \dot{\gamma}^l(t) R_{jkl}^i.$$

Substituting $W^i(t) := \dot{J}^i(t)$, this reduces to $2n$ first-order equations. The existence and uniqueness theorem of ODEs on manifolds thus guarantees that the claim holds. \square

Definition 3.6 (Jacobi Field). Let (M, g) be a SRMF and $\gamma : I \rightarrow M$ be a geodesic. We call a vector field $J \in \mathfrak{X}(\gamma)$ a **Jacobi field** if it satisfies the Jacobi equation. The space $\mathfrak{J}(\gamma) \subseteq \mathfrak{X}(\gamma)$ denotes the space of all Jacobi fields along γ .

Corollary 3.7. Let (M, g) be an n -dimensional SRMF and $\gamma : I \rightarrow M$ be any geodesic. Then $\mathfrak{J}(\gamma)$ is a $2n$ -dimensional linear subspace of $\mathfrak{X}(\gamma)$.

Proof. Linearity of the Jacobi equation guarantees that $\mathfrak{J}(\gamma)$ is linear. Fixing some $p = \gamma(t_0)$, we have an isomorphism $\mathfrak{J}(\gamma) \cong T_p M \oplus T_p M$ given by the previous proposition as $J \mapsto (J(t_0), \nabla_{\frac{d}{dt}} J(t_0))$. \square

Proposition 3.8. Let (M, g) be a SRMF and $\gamma : I \rightarrow M$ be a geodesic. If either

- (i) M is complete, or
- (ii) I is compact

then every Jacobi field along γ is the variation field of some variation of γ through geodesics.

Proof. Let $J \in \mathfrak{J}(\gamma)$. By translating, we can assume $0 \in I$ and set $p := \gamma(0)$, $v := \dot{\gamma}(0)$. This means we can write $\gamma(t) = \exp_p(tv)$ for all $t \in I$. By

Note that all terms of the form $\nabla_{\frac{d}{dt}} E_i$ in the left term vanish as the ONF is parallel w.r.t. ∇ .

The idea is the following: We define a small curve through a starting point on γ and use the assumptions to guarantee that (after eventually contracting the domain) \exp can be used to define a variation through geodesics. After that, we use uniqueness of Jacobi fields to show that the variational vector field of this constructed variation has to agree with J .

CHAPTER 3. JACOBI FIELDS

construction of the tangent space, there is a small open interval $(-\varepsilon, \varepsilon)$ and a smooth curve $\sigma : (-\varepsilon, \varepsilon) \rightarrow M$ satisfying

$$\sigma(0) = p, \dot{\sigma}(0) = J(0).$$

Choose a vector field $V \in \mathfrak{X}(\sigma)$ with data

$$V(0) = w \nabla_{\frac{d}{ds}} V(0) = \nabla_{\frac{d}{dt}} J(0).$$

We want to define a variation through geodesics by

$$\Gamma(s, t) := \exp_{\sigma(s)}(tV(s)). \quad (3.2)$$

If M is geodesically complete, we can always define Γ on $(-\varepsilon, \varepsilon) \times I$. If I is compact, we can use that \mathcal{E}_p is open and contains the compactum $\{(p, tv) \in TM \mid t \in I\}$. Therefore, we find some $\delta > 0$ such that Γ is definable on $(-\delta, \delta) \times M$.

Evaluating at $s = 0$ yields

$$\Gamma_0(t) = \exp_{\sigma(0)}(tV(0)) = \exp_p(tv) = \gamma(t),$$

which tells us that Γ is indeed a variation of γ : By definition of \exp , it is also a variation through geodesics with variational field $W(t) := \frac{\partial \Gamma}{\partial s}(0, t) \in \mathfrak{J}(\gamma)$. Now we match initial data:

1. $W(0) = \frac{\partial}{\partial s} \Gamma(0, 0) = \dot{\sigma}(0) = J(0)$
2. We have $\frac{\partial}{\partial t} \Gamma_s(0) = V(s) \exp(0) = V(s)$. By applying the symmetry lemma, we obtain:

$$\nabla_{\frac{d}{dt}} W(0) = \nabla_{\frac{d}{dt}} \frac{\partial}{\partial s} \Gamma(0, 0) = \nabla_{\frac{d}{ds}} \frac{\partial}{\partial t} \Gamma(0, 0) = \nabla_{\frac{d}{ds}} V(0) = \nabla_{\frac{d}{dt}} J(0).$$

Since J and W have the same initial data, we can conclude by uniqueness that $J \equiv W$.

□

3.2 Jacobi Fields vanishing at a point

We turn our attention to Jacobi fields which vanish at some point $p \in M$.

Lemma 3.9. Let (M, g) be a SRMF, $I \ni 0$ an interval, $\gamma : I \rightarrow M$ be a geodesic, and $J \in \mathfrak{J}(\gamma)$ such that $J(0) = 0$. If M is geodesically complete or I is compact, J is the variation field of the geodesic variation

$$\Gamma(s, t) := \exp_p(t(v + sw)) \quad (3.3)$$

with $p = \gamma(0)$, $v = \dot{\gamma}(0)$, and $w = \nabla_{\frac{d}{dt}} J(0)$.

Proof. This follows directly from equation 3.2 by taking $\sigma(s) \equiv p$, and $V(s) = v + sw$. □

Proposition 3.10 (Jacobi Fields Vanishing at a Point). Let (M, g) be a SRMF, $p \in M$, $\gamma : I \rightarrow M$ be a geodesic with $0 \in I$ and $\gamma(0) = p$.

1. For every $w \in T_p M$, the Jacobi field with initial data $J(0) = 0$ and $\nabla_{\frac{d}{dt}} J(0) = w$ is given by

$$J(t) = (\exp_p)_{*,tv}(tw) \quad (3.4)$$

with $v = \dot{\gamma}(0)$ and $tw \in T_{tv}(T_p M) \cong T_p M$.

2. If (x^i) are normal coordinates on a normal neighbourhood completely containing $\text{im } \gamma$ with $w = w^i \partial_i|_0$, J admits the form

$$J(t) = tw^i \partial_i|_{\gamma(t)}. \quad (3.5)$$

Proof. 1. Restricting to a compact subinterval of I , we can use equation 3.3 and calculate the pushforward:

$$\frac{\partial}{\partial s} \Gamma(0, t) = (\exp_p(t(v + sw)))_{*,s=0} = (\exp_p)_{*,tv} \circ (tw) = (\exp_p)_{*,tv}(tw).$$

As all $t \in I$ are contained in such compact subintervals, this holds for all t .

2. Given normal coordinates (U, x^i) , the exponential map is the identity in coordinates, so we get $\Gamma(s, t) = t(v^i + sw^i) \partial_i$. We can calculate directly:

$$\frac{\partial}{\partial s} \Gamma(0, t) = tw^i \partial_i|_{\gamma(t)}.$$

□

This makes it possible to reach all vectors in a normal neighbourhood with Jacobi fields:

Corollary 3.11. Let (M, g) be a SRMF, $p \in M$ and U be a normal neighbourhood centered at p . For any $q \in U \setminus \{p\}$, every vector $v \in T_q M$ is the value of a Jacobi field J vanishing at p along a radial geodesic.

Proof. Take normal coordinates (U, x^i) and $q = (q^1, \dots, q^n) \in U \setminus \{p\}$ as well as $w = w^i \partial_i|_q \in T_q M$. The radial geodesic $\gamma(t) := (tq^1, \dots, tq^n)$ has endpoints $\gamma(0) = p$ and $\gamma(1) = q$. By the previous proposition,

$$J(t) := tw^i \partial_i|_{\gamma(t)}$$

is a Jacobi field satisfying $J(0) = 0$ and $J(1) = w$.

□

3.3 Normal and Tangential Jacobi Fields

We make the following observation: Given any SRMF and geodesic $\gamma : I \rightarrow M$, there are always geodesic variations of the form

$$\Gamma_s(t) := \gamma(\alpha(t)t)$$

for $\alpha : I \rightarrow \mathbb{R}$ affine, e.g. $\Gamma_s(t) = \gamma((1+s)t)$ and $\Gamma'_s(t) = \gamma(s+t)$. They give rise to Jacobi fields if I is compact or M is complete:

$$\left. \frac{\partial}{\partial s} \right|_{s=0} \Gamma_s(t) = t\dot{\gamma}(t) =: J_0 \quad (3.6)$$

and

$$\left. \frac{\partial}{\partial s} \right|_{s=0} \Gamma'_s(t) = \dot{\gamma}(t) =: J_1. \quad (3.7)$$

Those Jacobi fields are uninteresting, so we desire a splitting

$$\mathfrak{J}(\gamma) \cong \mathfrak{J}(\gamma)^\top \oplus \mathfrak{J}(\gamma)^\perp.$$

Given a vector field $V \in \mathfrak{X}(\gamma)$ along some curve γ , we call it **tangential** if $V(t) \in T_{\gamma(t)}M^\top$ at all $t \in I$ and **normal** if $V(t) \in T_{\gamma(t)}M^\perp$ for all $t \in I$.

Definition 3.12 (Tangential and Normal Jacobi Fields). Let (M, g) be a SRMF and $\gamma : I \rightarrow M$ a geodesic. We call $J \in \mathfrak{J}(\gamma)$:

1. **tangential** if $J(t) \in T_{\gamma(t)}M^\top$ for all $t \in I$, i.e. $J(t) = f(t)\gamma(t)$ for some smooth $f : I \rightarrow \mathbb{R}$.
2. **normal** if $J(t) \in T_{\gamma(t)}M^\perp$ for all $i \in I$, i.e. $g_{\gamma(t)}(J(t), \dot{\gamma}(t)) = 0$.

We denote the space of tangential Jacobi fields by $\mathfrak{J}^\top(\gamma)$ and the space of normal Jacobi fields by $\mathfrak{J}^\perp(\gamma)$.

Lemma 3.13 (Tangential Jacobis are Uninteresting). A smooth vector field $V \in \mathfrak{X}(\gamma)^\top$ along and tangential to a geodesic γ is a Jacobi field if and only if $J(t) = (at + b)\dot{\gamma}(t)$, i.e. $f(t) = at + b$ for some $a, b \in \mathbb{R}$.

Proof. Write $V(t) = f(t)\dot{\gamma}(t)$ and calculate: geodesic

$$\nabla_{\frac{d}{dt}} V(t) = \dot{f}(t)\dot{\gamma}(t) + f(t) \nabla_{\frac{d}{dt}} \dot{\gamma}(t) = \dot{f}(t)\dot{\gamma}(t)$$

and

$$\nabla_{\frac{d}{dt}}^2 V(t) = \ddot{f}(t)\dot{\gamma}(t).$$

The Riemann tensor vanishes:

$$R(V, \dot{\gamma})\dot{\gamma} = f(t)R(\dot{\gamma}, \dot{\gamma})\dot{\gamma} = 0.$$

Hence, the Jacobi equation is satisfied if and only if

$$\ddot{f}(t) = 0,$$

so by basic ODE theory, $f(t) = at + b$ for some $a, b \in \mathbb{R}$ if and only if V is a tangential Jacobi field. \square

Proposition 3.14 (Normality Criterion). Let (M, g) be a SRMF, $\gamma : I \rightarrow M$ be a geodesic and $J \in \mathfrak{J}(\gamma)$. Then the following are equivalent:

- (a) $J \in \mathfrak{J}(\gamma)^\perp$.
- (b) J is orthogonal to $\dot{\gamma}$ at two distinct points $t_1, t_2 \in I$.

(c) J and $\nabla_{\frac{d}{dt}} J$ are orthogonal to $\dot{\gamma}$ at one point $t_0 \in I$.

Proof. Define the auxilliary function

$$f(t) := g_{\gamma(t)}(J(t), \dot{\gamma}(t))$$

expressing the tangential part of J . We have:

$$\dot{f}(t) = g_{\gamma(t)}(\nabla_{\frac{d}{dt}} J, \dot{\gamma}),$$

where the second term vanishes again as γ is a geodesic. Then, we have

$$\ddot{f}(t) = g_{\gamma(t)}(\nabla_{\frac{d}{dt}} J, \dot{\gamma}) = -g_{\gamma(t)}(R(J, \dot{\gamma})\dot{\gamma}, \dot{\gamma}) = g_{\gamma(t)}(R(\dot{\gamma}, \dot{\gamma})\dot{\gamma}, J) = 0$$

by the symmetries of R . Thus, $f(t) = at + b$ for some $a, b \in \mathbb{R}$. We see that (a) holds if and only if $f \equiv 0$. In that case, (b) and (c) hold, since $\nabla_{\frac{d}{dt}} J(t_0) \perp \gamma(t_0)$ is equivalent to $\dot{f}(t_0) = 0$. If (b) holds, we have $at_1 + b = 0$, so $b = -at_1$. We also have $at_2 + b = a(t_2 - t_1) = 0$, so $a = 0$ and hence $b = 0$, yielding $f \equiv 0$. If (c) holds, we have $\dot{f}(t_0) = a = 0$ and $f(t_0) = b = 0$, so again $f \equiv 0$. \square

Corollary 3.15 (Orthogonal Decomposition). Let (M, g) be a SRMF and $\gamma : I \rightarrow M$ be a non-null geodesic. Then:

- $\mathfrak{J}(\gamma)^\top$ is a 2-dimensional linear subspace of $\mathfrak{J}(\gamma)$.
- $\mathfrak{J}(\gamma)^\perp$ is a $(2n - 2)$ -dimensional linear subspace of $\mathfrak{J}(\gamma)$.

In addition, there is an orthogonal decomposition

$$\mathfrak{J}(\gamma) \cong \mathfrak{J}(\gamma)^\top \oplus \mathfrak{J}(\gamma)^\perp.$$

Proof. In corollary 3.7, we have already seen the isomorphism $\mathfrak{J}(\gamma) \cong T_{\gamma(t_0)}M \oplus T_{\gamma(t_0)}M$ at each $t_0 \in I$. The space $\mathfrak{J}(\gamma)^\top$ is by proposition 3.14 a preimage of the subspace

$$\left\{ v, w \in T_{\gamma(t_0)}M \mid v, w \perp \dot{\gamma}(t_0) \right\} \subseteq T_{\gamma(t_0)}M \oplus T_{\gamma(t_0)}M.$$

Since this subspace has dimension $2n - 2$, this also holds for $\mathfrak{J}(\gamma)^\top$. By lemma 3.13, we have the two Jacobi fields J_0 and J_1 from equations 3.6 and 3.7 which evidently are linearly independent for all t . Hence $\dim \mathfrak{J}(\gamma)^\perp \geq 2$. Since γ is non-null, we have $\mathfrak{J}(\gamma)^\top \cap \mathfrak{J}(\gamma)^\perp = \{0\}$ and hence $\dim \mathfrak{J}^\perp \leq 2$, so we conclude $\dim \mathfrak{J}(\gamma)^\perp = 2$. This yields the desired decomposition. \square

So even in the semi-Riemannian case, we have a splitting $J = J^\top + J^\perp$ as long as γ is not lightlike/null. In that lightlike case, the identity $\mathfrak{J}^\top \cap \mathfrak{J}^\perp = \{0\}$ does not hold.

3.4 Jacobi Fields in Constant Curvature Spaces

Our goal is to find a general formula of Jacobi fields in constant curvature spaces and use that to derive general results about the metric of such manifolds.

Lemma 3.16. A SRMF (M, g) having constant sectional curvature $c \equiv 1$ is equivalent to each of the following conditions:

1. For all $p \in M$ and $u, v \in T_p M$ such that $\text{span}\{u, v\}$ is non-degenerate:

$$c = \frac{\text{Rm}(u, v, v, u)}{\langle u, u \rangle \langle v, v \rangle - \langle u, v \rangle^2}.$$

2. For all $p \in M$ and all $u, v \in T_p M$:

$$\text{Rm}(u, v, v, u) = c(\langle u, u \rangle \langle v, v \rangle - \langle u, v \rangle^2).$$

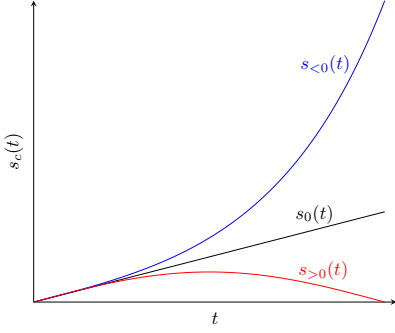
3. For all $p \in M$ and orthonormal $e_1, e_2 \in T_p M$:

$$\text{Rm}(e_1, e_2, e_2, e_1) = c\varepsilon_1\varepsilon_2$$

with $\varepsilon_i := \langle e_i, e_i \rangle$.

4. For all $p \in M$ and $u, v, w \in T_p M$:

$$\text{R}(u, v)w = c(\langle v, w \rangle u - \langle u, w \rangle v). \quad (3.8)$$



Given $c \in \mathbb{R}$, consider the following function

$$s_c : \mathbb{R} \rightarrow \mathbb{R}$$

defined as

$$s_c(t) := \begin{cases} \frac{1}{\sqrt{c}} \sin(\sqrt{c}t) & c > 0 \\ t & c = 0 \\ \frac{1}{\sqrt{-c}} \sinh(\sqrt{-c}t) & c < 0 \end{cases} \quad (3.9)$$

Example 3.17. Let us consider several model manifolds for constant sectional curvature.

1. The n -dimensional Euclidean space $(\mathbb{R}^n, g_{\text{st}})$ with the Euclidean metric and the n -dimensional Minkowski space $(\mathbb{R}^{1,n-1}, \eta)$ with the Minkowski metric have $c \equiv 0$. In polar coordinates, we have

$$g_{\text{st}} = dr^2 + r^2 \dot{g}_{n-1} = dr^2 + s_0(r)^2 \dot{g}_{n-1}$$

and

$$\eta = -d\tau^2 + \tau^2 \check{g} = -d\tau^2 + s_0(\tau)^2 \check{g}_{n-1}.$$

2. The n -sphere $(\mathbb{S}^n, \dot{g}_n)$ with the round metric has $c \equiv 1$. In polar coordinates, we have

$$\dot{g}_n = d\theta^2 + \sin^2(\theta) d\varphi^2 = d\theta^2 + s_1(\theta)^2 d\varphi^2.$$

3. The hyperbolic n -space $(\mathbb{H}^n, \check{g}_n)$ with the hyperbolic metric has $c \equiv -1$. In polar coordinates, we get

$$\check{g}_n = d\xi^2 + \sinh^2(\xi) \dot{g}_{n-1} = d\xi^2 + s_{-1}(\xi)^2 \dot{g}_{n-1}.$$

Proposition 3.18 (Jacobi Fields in Constant Curvature Spaces). Let (M, g) be a SRMF with constant sectional curvature $c \in \mathbb{R}$ and let $\gamma : I \rightarrow \mathbb{R}$ be a unit-speed geodesic with $0 \in I$. Then some $J \in \mathfrak{X}(\gamma)^\perp$ with $J(0) = 0$ and $\nabla_{\frac{d}{dt}} J(0) \neq 0$ satisfies $J \in \mathfrak{J}(\gamma)$ if and only if

$$J(t) = k \cdot s_{\varepsilon c}(t) \cdot E(t) \quad (3.10)$$

for some $k \in \mathbb{R}$, $\varepsilon := \langle \dot{\gamma}, \dot{\gamma} \rangle$ and parallel $E \in \mathfrak{X}(\gamma)^\perp$ with $\|E\|^2 = 1$.

Proof. (\Leftarrow): We do one auxilliary computation beforehand: The second derivative of $s_\alpha(t)$ for some parameter $\alpha \in \mathbb{R}$ is:

$$\ddot{s}_\alpha(t) = \begin{cases} \frac{d}{dt} \cos(\sqrt{\alpha}t) = -\sqrt{\alpha} \sin(\sqrt{\alpha}t) & \alpha > 0 \\ \frac{d}{dt} 1 = 0 & \alpha = 0 = -\alpha s_\alpha(t). \\ \frac{d}{dt} \cosh(\sqrt{-\alpha}t) = \sqrt{-\alpha} \sinh(\sqrt{-\alpha}t) & \alpha < 0 \end{cases}$$

Directly calculating the Jacobi equation yields:

$$\begin{aligned} \nabla_{\frac{d}{dt}}^2 J(t) - R(J, \dot{\gamma})\dot{\gamma} &= \nabla_{\frac{d}{dt}}^2 (k s_{\varepsilon c}(t) E(t)) + k s_{\varepsilon c}(t) R(E, \dot{\gamma})\dot{\gamma} \\ &\stackrel{\text{Lemma 3.16}}{=} k \ddot{s}_{\varepsilon c}(t) E(t) + k s_{\varepsilon c}(t) \nabla_{\frac{d}{dt}} (\nabla_{\frac{d}{dt}} E(t)) \\ &\quad + k s_{\varepsilon c}(t) (\|\dot{\gamma}\|^2 E(t) - \langle E, \dot{\gamma} \rangle \dot{\gamma}) \\ &= -k c \varepsilon s_{\varepsilon c}(t) E(t) + k c \varepsilon s_{\varepsilon c}(t) E(t) = 0, \end{aligned}$$

Note that in the $\alpha < 0$ -case, we multiply with negative α in the end, so the sign switch is intentional and correct.

where we used that E is parallel and normal and γ is unit-speed. (\Leftarrow): The goal is to find k and E such that $J(0) = J_{k,E}(0)$ and $\nabla_{\frac{d}{dt}} J(0) = \nabla_{\frac{d}{dt}} J_{k,E}(0)$. Then we can apply uniqueness of Jacobi fields to obtain the claim.

1. $J(0) = J_{k,E}$ holds by assumption.

2. We have

$$\nabla_{\frac{d}{dt}} J(0) = k \dot{s}_{\varepsilon c}(0) E(0) = k E(0).$$

This agrees with our vector field if we choose $k := \|\nabla_{\frac{d}{dt}} J(0)\|$ and $E(0) := \frac{1}{k} \nabla_{\frac{d}{dt}} J(0)$ which is well-defined since $k \neq 0$ by assumption. We extend this by using the parallel transport $P_{\gamma(t)}$ along γ to define $E(t) := P_{\gamma(t)} E(0)$. We have already seen that

$$E(t) \perp \dot{\gamma}(t) \Leftrightarrow E(0) \perp \dot{\gamma}(0) \Leftrightarrow \nabla_{\frac{d}{dt}} J(0) \perp \dot{\gamma}(0),$$

and the last statement is part of our assumption. \square

Remark 3.19. 1. If (M, g) is Riemannian (or Lorentzian and γ timelike), $J \in \mathfrak{J}(\gamma)^\perp$ already implies $\nabla_{\frac{d}{dt}} J(0) \perp \dot{\gamma}(0)$ and $\dot{\gamma}(0)^\perp \subseteq T_{\gamma(0)} M$ spacelike, so $\nabla_{\frac{d}{dt}} J(0) \neq 0$.

2. In constant curvature spaces, we have now two forms for Jacobi fields, $J(t) = t w^i \partial_i|_{\gamma(t)}$ and $J(t) = k s_{\varepsilon c}(t) E(t)$.

Given a time-oriented Lorentzian manifold, we define the radial distance function by the proper time $\tau : I^U(p) \rightarrow \mathbb{R}$ with $\tau(q) := \tau_U(p, q) > 0$. This yields a field ∂_τ .

Our goal is now to obtain the first general result with help of Jacobi fields. We will need the notion of a radial distance function and the associated vector field. Given a Riemannian manifold (M, g) and a normal chart (U, x^i) around some $p \in M$. Define the **radial distance function** $r : U \rightarrow \mathbb{R}$ by $r(q) = d(p, q) > 0$. If the coordinates are centered at p , we have the explicit form

$$r(x) = \sqrt{(x^1)^2 + \dots + (x^n)^2},$$

and on $U \setminus \{p\}$ we get the **radial vector field**

$$\partial_r = \frac{x^i}{r(x)} \partial_i.$$

This is smooth on $U \setminus \{p\}$ and independent of choice of charts.

Definition 3.20 (Polar Coordinates). In the following, \mathring{g} is the round metric and \check{g} is the hyperbolic metric.

1. **Riemannian polar coordinates** are given by the map

$$\begin{aligned} \Phi_R : (\mathbb{R}_+ \times \mathbb{S}^{n-1}, dr^2 + r^2 \mathring{g}_{n-1}) &\rightarrow (\mathbb{R}^n \setminus \{0\}, g_{\text{st}}) \\ (r, \theta) &\mapsto r \iota_{\mathbb{S}^{n-1}}(\theta), \end{aligned}$$

where $\iota : \mathbb{S}^{n-1} \hookrightarrow (\mathbb{R}^n, g_{\text{st}})$ is any isometric embedding with $\text{im } \iota_{\mathbb{S}^{n-1}} = \{x \in \mathbb{R}^n \mid \|x\| = 1\}$.

2. **Lorentian polar coordinates** are the map

$$\begin{aligned} \Phi_L : (\mathbb{R}_+ \times \mathbb{H}^{n-1}, -d\tau^2 + \tau^2 \check{g}_{n-1}) &\rightarrow (I^+(0), \eta) \\ (\tau, \xi) &\mapsto \tau \iota_{\mathbb{H}^{n-1}}(\xi), \end{aligned}$$

where $\iota : \mathbb{H}^{n-1} \hookrightarrow (\mathbb{R}^{1, n-1}, \eta)$ is any isometric embedding with $\text{im } \iota_{\mathbb{H}^{n-1}} = \{x \in \mathbb{R}^{1, n-1} \mid \eta(x, x) = -1\}$.

Theorem 3.21 (Constant-Curvature Metrics in Normal Coordinates).

Let (M, g) be a RMF or a LMF with constant curvature $c \in \mathbb{R}$. Let U be a normal neighbourhood of $p \in M$ and $\psi = (x^i)$ be normal coordinates such that $\psi_* g_p = g_{\text{st}}$. Let $r(q) = \|\exp_p^{-1}(q)\|$ resp. $\tau(q) = \|\exp_p^{-1}(q)\|$ be the radial distance function. Define angle functions $\theta(q) := \iota_{\mathbb{S}}^{-1} \left(\frac{\exp_p^{-1}(q)}{r(q)} \right)$ and $\xi(q) := \iota_{\mathbb{H}}^{-1} \left(\frac{\exp_p^{-1}(q)}{\tau(q)} \right)$. Then we have isometries

$$\begin{aligned} \varphi &:= \Psi_R^{-1} \circ \psi : U \setminus \{p\} \rightarrow \mathbb{R}_+ \times \mathbb{S}^{n-1} \\ q &\mapsto (r(q), \theta(q)) \\ \varphi_L &:= \Phi_L^{-1} \circ \psi : I_U^+(p) \rightarrow \mathbb{R}_+ \times \mathbb{H}^{n-1} \\ q &\mapsto (\tau(q), \xi(q)) \end{aligned}$$

onto their image between g and

$$g^c = dr^2 + s_c(r)^2 \mathring{g}_{n-1}$$

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or

$$g^c = -d\tau^2 + s_c(\tau)^2 \check{g}_{n-1},$$

respectively.

Proof. Our goal is to show that for all $q \in U \setminus \{p\}$ and all $w_1, w_2 \in T_{\varphi(q)}(\mathbb{R}_+ \times \mathbb{S}^{n-1})$,

$$g_q(\varphi^*(w_1), \varphi^*(w_2)) = g_{\varphi(q)}^c(w_1, w_2)$$

holds. We show this only for $w_1 = w_2 =: w$, since the general case follows by polarization. In the following, denote the Euclidean metric by $\langle \cdot, \cdot \rangle$. We split

$$T_{\varphi(q)}(\mathbb{R}_+ \times \mathbb{S}^{n-1}) \cong \text{span}\{\partial_r|_{r(q)}\} \oplus T_{\theta(q)}\mathbb{S}^{n-1}$$

and prove the claim in three parts:

$$1. \quad g_q(\varphi^*(\partial_r|_{r(q)}), \varphi^*(\partial_r|_{r(q)})) = g_{\varphi(q)}^c(\partial_r|_{r(q)}, \partial_r|_{r(q)}) = 1$$

$$2. \quad \forall w \in T_{\theta(q)}\mathbb{S}^{n-1} : g_q(\varphi^*(\partial_r|_{r(q)}), \varphi^*(w)) = 0$$

$$3. \quad \forall w \in T_{\theta(q)}\mathbb{S}^{n-1} : g_q(\varphi^*(w), \varphi^*(w)) = g_{\varphi(q)}^c(q)(w, w) = s_c(r(q))^2 \check{g}_{n-1}|_{\theta(q)}(w, w)$$

$$T_{\varphi(q)}(\mathbb{R}_+ \times \mathbb{H}^{n-1}) \cong \text{span}\{\partial_\tau|_{\tau(q)}\} \oplus T_{\xi(q)}\mathbb{H}^{n-1}$$

$$g_q(\varphi^*(\partial_\tau|_{\tau(q)}), \varphi^*(\partial_\tau|_{\tau(q)})) = -1$$

$$g_q(\varphi^*(w), \varphi^*(w)) = s_{-c}(\tau(q))^2 \check{g}_{n-1}|_{\xi(q)}(w, w)$$

For 1 and 2, note that

$$(\Phi_R)_{*,(r(q),\theta(q))}(\partial_r) = (\Phi_R^{-1})^*(\partial_r|_{\varphi(q)}) = \iota(\theta(q)) \in T_{\psi(q)}\mathbb{R}^n.$$

Since $\psi(q) = r(q)\iota(\theta(q))$, this is radial, hence the Gauß lemma applies. Defining $v := (\Phi_R^{-1})^*(w)$, we get:

$$\begin{aligned} g_q(\varphi^*(\partial_r|_{\varphi(q)}), \varphi^*(w)) &= g_q((\exp_p)_{*,\psi(q)}(\iota(\theta(q))), (\exp_p)_{*,\psi(q)}(v)) \\ &= g_p(\iota(\theta(q)), v) = \langle \iota(\theta(q)), v \rangle \\ &= \begin{cases} 1 & v = \iota(\theta(q)) \Leftrightarrow w = \partial_r|_{\varphi(q)} \\ 0 & v \perp \iota(\theta(q)) \Leftrightarrow w \in T_{\theta(q)}\mathbb{S}^{n-1} \end{cases}. \end{aligned}$$

This proves 1 and 2 simultaneously.

Now we turn our attention to 3.: Let $w \in T_{\theta(q)}\mathbb{S}^{n-1}$ and set $v := (\Phi_R^{-1})^*(w) \in T_{\psi(q)}\mathbb{R}^n$. We have by definition

$$g_{\varphi(q)}^c(w, w) = s_c(r(q))^2 \check{g}_{n-1}|_{\theta(q)}(w, w) = \frac{s_c(r(q))^2}{r(q)^2} \langle v, v \rangle.$$

Let J be the unique Jacobi field along the unit-speed radial geodesic $\gamma : [0, b] \rightarrow U$ from p to q ($b = r(q)$) with $J(0) = 0$ and $J(b) = \varphi^*(w) \in T_q M$. We have $\dot{\gamma}(b) \propto \varphi_{r(q),\theta(q)}^*(\partial_r) \perp \varphi^*(w)$, so $J \in \mathfrak{J}(\gamma)^\perp$. This means we can write

$$J(t) = k s_c(t) E(t)$$

with $E(b) \propto \varphi^*(w)$. We calculate explicitly:

$$k^2 = g_p(\nabla_{\frac{d}{dt}} J(0), \nabla_{\frac{d}{dt}} J(0))$$

and obtain

$$\|\varphi^*(w)\|_{g_q}^2 = \|J(b)\|_{g_q}^2 = k^2 s_c(b)^2 = s_c(r(q))^2 \|\nabla_{\frac{d}{dt}} J\|_{g_p}^2.$$

Note that we have not used our constant curvature assumption so far. This will become important in chapter 4.

This largely goes through for the Lorentzian case, just switch Φ_R for Φ_L and use $s_{-c}(t)$. Note that J is normal to a timelike geodesic, so the sign is still positive.

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Now rescale γ to $[0, 1] \rightarrow M$ and use $\varphi^*(w) = \psi^*(v) = v^i \partial_i|_q \in T_q M$ to get $J(t) = \frac{t}{b} v^i \partial_i|_{\gamma(t)}$. With this, we calculate

$$\|\nabla_{\frac{d}{dt}} J(0)\|_{g_p}^2 = \left\| \frac{1}{b} v^i \partial_i|_{\gamma(0)} \right\|_{g_p}^2 = \frac{1}{b^2} \langle v, v \rangle$$

With this, claim 3 follows. \square

The Lorentzian case is a bit harder to phrase, but the idea still holds. The problem is that families of Riemannian metrics on \mathbb{H}^{n-1} are generally not globally definable on \mathbb{H}^{n-1} as $\psi(I_U^+(p))$ does not contain an entire \mathbb{H}_r^{n-1} , no matter how small τ is.

Corollary 3.22. Let (M, g) be a RMF, $p \in M$ and U a normal neighbourhood with normal coordinates ψ such that $\psi_* g_p = g_{\text{st}}$. Let $\varepsilon > 0$ such that $B_\varepsilon(0) \subseteq \psi(U)$. Then we find a family $\{h(r) \mid r \in (0, \varepsilon)\}$ of Riemannian metrics on \mathbb{S}^{n-1} such that

$$\varphi : \Phi_R^{-1} \circ \psi : B_\varepsilon^{d_g}(p) \setminus \{p\} \rightarrow (0, \varepsilon) \times \mathbb{S}^{n-1}$$

given again by $\varphi(q) := (r(q), \theta(q))$ is a bijective isometry between g and $dr^2 + h(r)$.

Proof. We know that $B_\varepsilon^{d_g}(p) = \psi^{-1}(B_\varepsilon(0))$ by theorem ???. Let $r \in (0, \varepsilon)$, $\theta \in \mathbb{S}^{n-1}$ and $w_1, w_2 \in T_\theta \mathbb{S}^{n-1}$. We define

$$h(r)(w_1, w_2) := g_{\varphi^{-1}(r, \theta)}(\varphi_{*,(r, \theta)}^{-1}(0\partial_r + w_1), \varphi_{*,(r, \theta)}^{-1}(0\partial_r + w_2)).$$

This is a smooth, symmetric, non-degenerate $(0, 2)$ -tensor field on \mathbb{S}^{n-1} . φ being an isometry follows from the definition of $h(r)$, 1, and 2 of the previous proof. \square

Corollary 3.23 (Constant Curvature implies local Isometry). All Riemannian and Lorentzian manifolds of constant curvature are locally isometric.

The Riemannian case is easier and can be found in [LeeRM]. The theorem also holds for the semi-Riemannian case in general with a different proof, found in [ONeill10].

Proof. We do the Lorentzian case. Given LMFs (M_1, g_1) and (M_2, g_2) with $p_i \in M_i$, we want to show that there are open neighbourhoods $U_i \subseteq M_i$ and a local isometry $\varphi : (U_1, g_1) \xrightarrow{\cong} (U_2, g_2)$. So let \tilde{U}_i be convex neighbourhoods of p_i , $p_i^- \ll_{\tilde{U}_i} p_i$ and $\tau_{\tilde{U}_1}(p_1^-, p_1) = \tau_{\tilde{U}_2}(p_2^-, p_2) = \varepsilon$. Choose normal coordinates at p_i^- such that $\psi_i(p_i) = (\varepsilon, 0, \dots, 0)$. Consider polar-normal coordinates

$$\varphi_i : \tilde{U}_i \rightarrow V_i \subseteq (0, \infty) \times \mathbb{H}^{n-1}.$$

They satisfy

$$\varphi_1(p_1) = \varphi_2(p_2) = (\varepsilon, \xi_0) \in V_1 \cap V_2,$$

so $V_1 \cap V_2$ is an open neighbourhood of (ε, ξ_0) . Setting $U_i := \varphi_i^{-1}(V_1 \cap V_2)$, we obtain the desired isometry

$$\varphi := \varphi_2^{-1} \circ \varphi_1 : U_1 \xrightarrow{\cong} U_2.$$

\square

3.5 Conjugate Points

Definition 3.24 (Regular and Critical Points). Let M, N be smooth manifolds and $F : M \rightarrow N$ be a smooth map. We call $p \in M$ a **regular point** of F if $F_{*,p} : T_p M \rightarrow T_{F(p)} N$ is surjective. Otherwise, we call p a **critical point**. We denote the critical points by $\text{crit } F$.

Consider the exponential map

$$\exp_p : T_p M \rightarrow M$$

. The inverse function theorem guarantees that locally around all regular points, \exp_p is a diffeomorphism. What happens at critical points?

Exercise. Consider \mathbb{S}^2 . Given the unit circle $S_0 := \{v \in T_p \mathbb{S}^2 \mid \|v\| = \pi\} \subseteq T_p \mathbb{S}^2$, the image, which is the antipodal point to p , consists only of critical points of \exp_p . At that point, several things happen:

1. Jacobi fields admit zeros: Given $J(t) = k s_1(t) E(t) = k \sin(t) E(t)$, we have $J(0) = J(\pi) = 0$.
2. All unit-speed geodesics originating at p meet at the antipodal point at $t = \pi$.
3. All these geodesics stop being minimizing after $t = \pi$.

The question is, which of these hold generally?

Definition 3.25 (Conjugate Points). Let (M, g) be a SRMF, $\gamma : I \rightarrow M$ be a geodesic, $a, b \in I$, and $\gamma(a) := p$, $\gamma(b) := q$. We call p **conjugate** to q along γ if there exists a non-zero Jacobi field $J \in \mathfrak{J}(\gamma)$ with $J(a) = J(b) = 0$. We call the dimension of the subspace of Jacobi fields vanishing at a and b the **order** or **multiplicity** of conjugacy.

Remark 3.26. Let γ be a timelike or spacelike geodesic. If there is a Jacobi field witnessing conjugacy, we can always choose a normal one satisfying the same condition since

$$J^\top = (kt + d)\dot{\gamma}(t),$$

which vanishes at most at one point. Hence the order of conjugacy is always $\leq \dim M - 1$.

Proposition 3.27 (Conjugacy and Critical Points). Let (M, g) be a SRMF, $p \in M$, $v \in \mathcal{E}_p$, and let $\gamma = \gamma_v : [0, 1] \rightarrow M$ be the unique geodesic with $\gamma(0) = p$ and $\dot{\gamma}(0) = v$. Set $q := \gamma_v(1) = \exp_p(v)$. Then p is conjugate to q along γ if and only if $v \in \text{crit}(\exp_p)$.

Proof. (\Leftarrow): Let $v \in \text{crit}(\exp_p)$. We find $w \in T_p M$ such that $(\exp_p)_{*,v}(w) = 0$ but $w \neq 0$. Take a Jacobi field with initial data $J(0) = 0$ and $\nabla_{\frac{d}{dt}} J(0) = w$. By lemma 3.9, we can write J as variation field of the

geodesic variation

$$\Gamma(s, t) := \exp_p(t(v + sw)).$$

We have

$$J(1) = \frac{\partial}{\partial s} \Big|_{s=0} \Gamma(s, 1) = \frac{\partial}{\partial s} \Big|_{s=0} \exp_p(v + sw) = (\exp_p)_{*,v}(w) = 0.$$

(\Rightarrow) : Let J be a non-zero Jacobi field along γ with $J(0) = J(1) = 0$. Writing $w := \nabla_{\frac{d}{dt}} J(0) \neq 0$ and again J as variation field of

$$\Gamma(s, t) = \exp_p(t(v + uw))$$

yields $J(1) = 0 = (\exp_p)_{*,v}(w)$, so $(\exp_p)_{*,v}$ fails to be injective. \square

If (M, g) is a SRMF and $\gamma : I \rightarrow M$ is a geodesic, the **two-point boundary value problem** asks whether it is always possible to find a Jacobi field along γ with two prescribed boundary values $J(0) = v \in T_{\gamma(0)}M$ and $J(1) = w \in T_{\gamma(1)}M$.

Proposition 3.28 (The two-point Boundary Value Problem). Let (M, g) be a SRMF and $\gamma : [a, b] \rightarrow M$ be a geodesic segment. The two-point boundary value problem is solvable if and only if $\gamma(a)$ is not conjugate to $\gamma(b)$.

Exercise. Prove the preceding proposition.

Proposition 3.29 (Conjugacy and Sectional Curvature). Let (M, g) be a RMF with non-positive sectional curvature. For any $p \in M$ and any geodesic $\gamma : [0, b] \rightarrow M$ originating at p , there are no points conjugate to p along γ .

Exercise. Prove the preceding proposition.

3.6 The Second Variation Formula for Arc-Length

Theorem 3.30 (Second Variation Formula for Arc-Length). Let $(M, \langle \cdot, \cdot \rangle)$ be a SRMF, $\gamma : [a, b] \rightarrow M$ be a unit-speed geodesic segment, and let

$$\Gamma : (-\delta, \delta) \times [a, b] \rightarrow M$$

be a continuous, fixed-endpoint variation of γ such that all curves $t \mapsto \Gamma_s(t)$ have the same causal character. Additionally, let there be a partition $\{t_i\}_{1 \leq i \leq n}$ of $[a, b]$ such that $\Gamma|_{[t_i, t_{i+1}]}$ is smooth with $t_1 = a$

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and $t_n = b$. Then the **second variation of arc-length** is given by

$$\left. \frac{d^2}{ds^2} \right|_{s=0} L[\Gamma_s] = \varepsilon \int_a^b \left(\text{Rm}(V^\perp, \dot{\gamma}, V^\perp, \dot{\gamma}) + \langle \nabla_{\frac{d}{dt}} V^\perp, \nabla_{\frac{d}{dt}} V^\perp \rangle \right) dt \quad (3.11)$$

where $\varepsilon = \langle \dot{\gamma}, \dot{\gamma} \rangle$, $V = \left. \frac{\partial}{\partial s} \right|_{s=0} \Gamma$, and $V^\perp = V - \varepsilon \langle \dot{\gamma}, \dot{\gamma} \rangle \dot{\gamma}$.

Note that the sign change in **[LeeRM]** originates from switching the second and third entry of the Riemann tensor.

Proof. The proof is done by direct calculation. We set $\left. \frac{\partial}{\partial s} \right|_{s=0} \Gamma =: S(s, t)$ and $\left. \frac{\partial}{\partial t} \right|_{t=0} \Gamma =: T(s, t)$. We have

$$\begin{aligned} \frac{d^2}{ds^2} L[\Gamma_s] &= \frac{d}{ds} \int_{t_i}^{t_{i+1}} \frac{\partial}{\partial s} \langle \dot{\Gamma}_s, \dot{\Gamma}_s \rangle dt = \frac{d}{ds} \int_{t_i}^{t_{i+1}} \frac{\varepsilon \langle \nabla_{\frac{d}{ds}} T, T \rangle}{\sqrt{\varepsilon \langle T, T \rangle}} dt \\ &= \varepsilon \int_{t_i}^{t_{i+1}} \frac{\partial}{\partial s} \frac{\langle \nabla_{\frac{d}{ds}} S, T \rangle}{\sqrt{\varepsilon \langle T, T \rangle}} dt \\ &= \varepsilon \int_{t_i}^{t_{i+1}} \left[\frac{\langle \nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} S, T \rangle + \langle \nabla_{\frac{d}{dt}} S, \nabla_{\frac{d}{ds}} T \rangle}{\sqrt{\varepsilon \langle T, T \rangle}} - \frac{\langle \nabla_{\frac{d}{dt}} S, T \rangle \langle \nabla_{\frac{d}{ds}} T, T \rangle}{(\varepsilon \langle T, T \rangle)^{\frac{3}{2}}} \right] dt \\ &= \varepsilon \int_{t_i}^{t_{i+1}} \left[\frac{\langle \nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} S, T \rangle + \langle \nabla_{\frac{d}{dt}} S, \nabla_{\frac{d}{ds}} S \rangle}{\sqrt{\varepsilon \langle T, T \rangle}} - \frac{\langle \nabla_{\frac{d}{dt}} S, T \rangle \langle \nabla_{\frac{d}{dt}} S, T \rangle}{(\varepsilon \langle T, T \rangle)^{\frac{3}{2}}} \right] dt \end{aligned}$$

Evaluating at $s = 0$ yields $\left. \frac{\partial}{\partial t} \right|_{t=0} \Gamma(0, t) = \dot{\gamma}(t)$ and hence $\langle T, T \rangle = \varepsilon$. Also, we obtain $\nabla_{\frac{d}{ds}} S(0, t) = \nabla_{\frac{d}{dt}} V$. This yields

$$\left. \frac{d^2}{ds^2} \right|_{s=0} L[\Gamma_s] = \varepsilon \int_{t_i}^{t_{i+1}} \left[\underbrace{\langle \nabla_{\frac{d}{ds}} \nabla_{\frac{d}{dt}} S, \dot{\gamma} \rangle}_{=:A} + \underbrace{\langle \nabla_{\frac{d}{dt}} V, \nabla_{\frac{d}{dt}} V \rangle}_{=:B} - \underbrace{\varepsilon \langle \nabla_{\frac{d}{dt}} V, \dot{\gamma} \rangle^2}_{=:C} \right] dt.$$

Term A can be simplified by lemma 3.3 to:

$$\begin{aligned} A|_{s=0} &= \langle \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} S(0, t), \dot{\gamma} \rangle + \langle \text{R}(S(0, t), T(0, t)) S(0, t), \dot{\gamma} \rangle \\ &= \langle \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} S(0, t), \dot{\gamma} \rangle + \langle R(V, \dot{\gamma}) V, \dot{\gamma} \rangle \\ &= \text{Rm}(V^\perp, \dot{\gamma}, V^\perp, \dot{\gamma}) + \langle \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} S(0, t), \dot{\gamma} \rangle \end{aligned}$$

That the only contribution is from the normal part follows either by direct calculation or by using the symmetry $\text{Rm}(\cdot, \cdot, v, v) = \text{Rm}(v, v, \cdot, \cdot) = 0$.

Term B can be written as

$$\langle \nabla_{\frac{d}{dt}} V, \nabla_{\frac{d}{dt}} V \rangle = \langle (\nabla_{\frac{d}{dt}} V)^\perp, (\nabla_{\frac{d}{dt}} V)^\perp \rangle + \langle \nabla_{\frac{d}{dt}} V, \dot{\gamma} \rangle^2 \varepsilon.$$

A direct calculation shows that taking the normal part commutes with the covariant derivative:

$$\nabla_{\frac{d}{dt}} V^\perp = \nabla_{\frac{d}{dt}} V - \varepsilon \nabla_{\frac{d}{dt}} \langle V, \dot{\gamma} \rangle \dot{\gamma} = \nabla_{\frac{d}{dt}} V - \varepsilon \langle \nabla_{\frac{d}{dt}} V, \dot{\gamma} \rangle \dot{\gamma} = (\nabla_{\frac{d}{dt}} V)^\perp.$$

All other Leibniz rule terms vanish since γ is a geodesic segment.

This yields

$$\langle \nabla_{\frac{d}{dt}} V, \nabla_{\frac{d}{dt}} V \rangle = \langle \nabla_{\frac{d}{dt}} V^\perp, \nabla_{\frac{d}{dt}} V^\perp \rangle + \langle \nabla_{\frac{d}{dt}} V, \dot{\gamma} \rangle^2.$$

However, the rightmost term cancels with C . It remains to show that

$$\varepsilon \int_{t_i}^{t_{i+1}} \langle \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} S(0, t), \dot{\gamma} \rangle dt$$

vanishes when summing over i . We have:

$$\begin{aligned} \sum_{i=1}^n \int_{t_i}^{t_{i+1}} \langle \nabla_{\frac{d}{dt}} \nabla_{\frac{d}{ds}} S(0, t), \dot{\gamma} \rangle dt &= \sum_{i=1}^n \int_{t_i}^{t_{i+1}} \frac{d}{dt} \langle \nabla_{\frac{d}{ds}} S(0, t), \dot{\gamma} \rangle dt \\ &= \sum_{i=1}^n \left(\langle \nabla_{\frac{d}{ds}} S(0, t_{i+1}), \dot{\gamma}(t_{i+1}) \rangle - \langle \nabla_{\frac{d}{ds}} S(0, t_i), \dot{\gamma}(t_i) \rangle \right) \\ &= \langle \nabla_{\frac{d}{ds}} S(0, b), \dot{\gamma}(b) \rangle - \langle \nabla_{\frac{d}{ds}} S(0, s), \dot{\gamma}(a) \rangle = 0, \end{aligned}$$

where we used that Γ is a variation with fixed endpoints in the last step. \square

There is also a slightly different version:

Proposition 3.31 (Second Variation for Submanifolds). Let (M, g) be a RMF or LMF and Σ_1, Σ_2 be two **spacelike** submanifolds. Let $\gamma : [a, b] \rightarrow M$ be a **timelike** unit-speed geodesic segment meeting Σ_1 orthogonally at $t = a$ and Σ_2 orthogonally at $t = b$. Let Γ be a continuous variation of γ which is smooth on some partition of $[a, b]$, and with $\Gamma(s, a) \in \Sigma_1$ and $\Gamma(s, b) \in \Sigma_2$ for all s . Let \mathbb{I}_i be the second fundamental form of Σ_i , and let $\varepsilon = \langle \dot{\gamma}, \dot{\gamma} \rangle$. Then the second variation of arc-length is given by

$$\begin{aligned} \varepsilon \frac{d^2}{ds^2} \Big|_{s=0} L[\Gamma_s] &= \int_a^b \left[\langle \nabla_{\frac{d}{dt}} V^\perp, \nabla_{\frac{d}{dt}} V^\perp \rangle + \text{Rm}(V^\perp, \dot{\gamma}, V^\perp, \dot{\gamma}) \right] dt \\ &\quad + \langle \mathbb{I}_2(V(b), V(b)), \dot{\gamma}(b) \rangle - \langle \mathbb{I}_1(V(a), V(a)), \dot{\gamma}(a) \rangle \end{aligned}$$

Exercise. Prove the preceeding proposition.

The second variation behaves a bit like the Hessian in real analysis on \mathbb{R}^n : It tells us something about the maxima and minima of the length functional. We use this to define something akin to a Hessian for vector fields.

Notation. We denote the space of piecewise smooth vector fields along a curve γ by $\overline{\mathfrak{X}}$. If $\gamma : [a, b] \rightarrow M$, we denote the space of vector fields with $X(a) = X(b) = 0$ by \mathfrak{X}_0 .

Definition 3.32 (Index Form). Let $(M, \langle \cdot, \cdot \rangle)$ be a SRMF and $\gamma : [a, b] \rightarrow M$ be a unit-speed geodesic segment. We define the **index form** to be a map

$$I : \overline{\mathfrak{X}}(\gamma)^\perp \times \overline{\mathfrak{X}}(\gamma)^\perp \rightarrow \mathbb{R}$$

given by

$$I(X, Y) := \varepsilon \int_a^b (\langle \nabla_{\frac{d}{dt}} X, \nabla_{\frac{d}{dt}} Y \rangle + \text{Rm}(X, \dot{\gamma}, Y, \dot{\gamma})) dt.$$

Corollary 3.33 (Index Form and Extremizing Behaviour). Let (M, g) be a RMF and $\gamma : [a, b] \rightarrow M$ be a unit-speed geodesic segment. If there exists $V \in \mathfrak{X}_0(\gamma)^\perp$ such that

$$I(V, V) < 0,$$

then γ cannot minimize the distance from $\gamma(a)$ to $\gamma(b)$.

Let (\mathcal{L}, g) be a time-oriented LMF and $\gamma : [a, b] \rightarrow \mathcal{L}$ be a unit-speed future-directed timelike geodesic segment. If there exists a non-zero $V \in \mathfrak{X}_0(\gamma)^\perp$ such that

$$I(V, V) > 0,$$

then γ cannot maximize the distance from $\gamma(a)$ to $\gamma(b)$.

In the Lorentzian case, maximizing γ implies negative semi-definiteness.

Remark 3.34. We can also phrase this as if γ is minimizing from $\gamma(a)$ to $\gamma(b)$, then $I|_{\mathfrak{X}_0(\gamma)^\perp \times \mathfrak{X}_0(\gamma)^\perp}$ is positive semi-definite.

Corollary 3.35 (Sectional Curvature and Submanifolds). Let (M, g) be a connected, complete RMF with positive sectional curvature. If Σ_1, Σ_2 are compact, totally geodesic submanifolds such that

$$\dim \Sigma_1 + \dim \Sigma_2 \geq \dim M,$$

then $\Sigma_1 \cap \Sigma_2 \neq \emptyset$.

Exercise. Prove the preceding corollary.

3.7 The Theorems of Bonnet-Myers and Hawking

Our goal in this section is to control the diameter of certain Riemannian and Lorentzian manifolds. Given a Riemannian manifold (M, g) , we define its **diameter** by

$$\text{diam}_g(M) = \sup_{p, q \in M} d_g(p, q).$$

Note that in the Lorentzian case, $d_g = \tau$.

3.7.1 The Theorem of Bonnet-Myers

We first try to control the diameter by controlling the Ricci curvature of a given manifold.

Theorem 3.36 (Bonnet-Myers). Let (M, g) be a complete Riemannian n -manifold such that there exists a constant $c \in \mathbb{R}$ with $\text{Ric}_g \geq c > 0$ on all of M . Then

$$\text{diam}_g(M) \leq \pi \sqrt{\frac{n-1}{c}}.$$

Proof. Let $p, q \in M$ be arbitrary. Since M is complete, there is a unit-speed minimizing geodesic $\gamma : [0, b] \rightarrow M$ such that $b = L[\gamma] = d_g(p, q)$. Let $f : [0, b] \rightarrow M$ be a smooth function with $f(0) = f(b) = 0$. Let $(E_i)_{1 \leq i \leq n-1}$ be a parallel ONF for $\dot{\gamma}^\perp$. Define vector fields $V_i(t) := f(t)E_i(t)$ along γ , so $V_i \in \mathfrak{X}_0(\gamma)^\perp$ for all i . Since γ is minimizing, Corollary 3.33 tells us that

the index form has to be positive on V_i , yielding:

$$\begin{aligned}
 0 \leq I(V_i, V_i) &= \int_0^b \left[\|\nabla_{\frac{d}{dt}} V_i\|^2 - \text{Rm}(\dot{\gamma}, V_i, V_i, \dot{\gamma}) \right] dt \\
 &= \int_0^b \left[\|\nabla_{\frac{d}{dt}} (f E_i)\|^2 - \text{Rm}(\dot{\gamma}, f E_i, f E_i, \dot{\gamma}) \right] dt \\
 &\stackrel{\text{E}_i \text{ parallel}}{\downarrow} = \int_0^b \left[\dot{f}^2 - f^2 \text{Rm}(\dot{\gamma}, E_i, E_i, \dot{\gamma}) \right] dt.
 \end{aligned}$$

Now we sum over $1 \leq i \leq n-1$:

$$\begin{aligned}
 0 \leq \sum_{i=1}^{n-1} I(V_i, V_i) &= \int_0^b \left[(n-1) \dot{f}^2 - f^2 \sum_{i=1}^{n-1} \text{Rm}(E_i, \dot{\gamma}, \dot{\gamma}, E_i) \right] dt \\
 &= (n-1) \int_0^b \dot{f}^2 dt - \int_0^b f^2 \text{Ric}(\dot{\gamma}, \dot{\gamma}) dt \\
 &\leq (n-1) \int_0^b \dot{f}^2 dt - c \int_0^b f^2 dt
 \end{aligned}$$

This calculation uses the explicit form of the Ricci tensor: Given an ONB $(e_i)_{1 \leq i \leq n}$ and a vector v , the trace of the Riemann tensor is given by

$$\text{Ric}(v, v) = \sum_{i=1}^n \langle R(v, e_i) e_i, v \rangle.$$

In our case, the tangent space is spanned by $(E_i) \cup \dot{\gamma}$, so the n -th term of the sum in the Ricci tensor evaluated at $\dot{\gamma}$ is $\langle R(\dot{\gamma}, \dot{\gamma}) \dot{\gamma}, \dot{\gamma} \rangle$, which vanishes anyway. Hence, discarding the n -th term of the Ricci tensor changes nothing.

At this point, the choice $f(t) = \sin(\pi \frac{t}{b})$ is most useful. We have $f^2 = \sin^2(\pi \frac{t}{b})$ and $\dot{f}^2 = \frac{\pi^2}{b^2} \cos^2(\pi \frac{t}{b})$. Note that

$$\int_0^b \cos^2\left(\pi \frac{t}{b}\right) dt = \frac{b}{2} = \int_0^b \sin^2\left(\pi \frac{t}{b}\right) dt.$$

We obtain:

$$0 \leq \left(\frac{\pi^2(n-1)}{b^2} - c \right) \frac{1}{b}.$$

Since $b > 0$, we need $b \leq \pi \sqrt{\frac{n-1}{c}}$, and the claim follows with $b = d_g(p, q)$. \square

Remark 3.37. 1. The n -sphere \mathbb{S}_R^n for $R = \frac{1}{\sqrt{c}}$ shows that the bound is sharp: We have $\text{Ric} = \frac{n-1}{R^2} g = (n-1)cg =: \tilde{c}g$ and hence

$$\text{diam}(\mathbb{S}_R^n) = \frac{\pi}{R} = \pi \sqrt{\frac{n-1}{\tilde{c}}}.$$

2. The condition cannot be relaxed: For $\text{Ric} \geq 0$, \mathbb{R}^n is an immediate counterexample. Also for $\text{Ric} > 0$ without global lower bound the theorem fails as one can take the paraboloid in \mathbb{R}^3 with infinite diameter.
3. It is also not sufficient to control the scalar curvature: For $\text{scal} \geq c > 0$, one can take $\mathbb{S}^n \times \mathbb{H}^n$, which is a counterexample for appropriate choices of radii.
4. It is, however, possible to obtain the statement by controlling sectional curvature, cf. sheet 12.

Lemma 3.38. Let M be a smooth manifold with universal covering $p : \tilde{M} \rightarrow M$. Then each fiber $p^{-1}(x)$ has the same cardinality as $\pi_1 M$.

Proof. See [LeeTM]. \square

Corollary 3.39. If (M, g) is a complete RMF with $\text{Ric} \geq c > 0$ for some $c \in \mathbb{R}$, M is compact and $\pi_1 M$ is finite.

Proof. M being compact follows directly by the diameter bound and completeness with Hopf-Rinow. If $p : \widetilde{M} \rightarrow M$ is the universal covering of M , the Ricci curvature bound applies also to \widetilde{M} since g and π^*g are locally isometric. Geodesic completeness of \widetilde{M} follows since every geodesic in \widetilde{M} arises as lift of a geodesic in M . Hence \widetilde{M} is compact, and discrete by definition. Using Lemma 3.38, the claim follows since each fiber is finite. \square

One can actually show (but we will not do that):

Theorem 3.40 (Cheng's Maximal Diameter Rigidity). Let (M, g) be a complete Riemannian n -manifold such that there is a constant $c \in \mathbb{R}$ with $\text{Ric} \geq c > 0$ and $\text{diam}(M) = \pi \sqrt{\frac{n-1}{c}}$. Then (M, g) is isometric to $(\mathbb{S}_R^n, \mathring{g}_n)$.

3.7.2 Hawking's Singularity Theorem

We now turn our attention towards the Lorentzian case, which is a bit different in terms of conditions. Also, it is (especially physically) hardly as useful as it seems. However, Hawking's Theorem provides a more useful alternative with one trade-off.

Theorem 3.41 (Variant of Hawking's Theorem). Let (\mathcal{L}, g) be a time-oriented globally hyperbolic Lorentzian manifold. If there exists a constant $c \in \mathbb{R}$ such that at all $p \in \mathcal{L}$ we have $\text{Ric}(v, v) \geq c > 0$ for all $v \in T_p \mathcal{L}^{\text{t.l.}}$, then

$$\text{diam}_g(p, q) = \sup_{p, q \in \mathcal{L}} \tau(p, q).$$

Proof. The proof is essentially the same as in Theorem 3.36, but we consider $p \ll q$. Theorem ?? yields a unit-speed causal future-directed geodesic connecting p and q which is now maximizing instead of minimizing. Furthermore, the ONF (E_i) is now completely spacelike. Since γ maximizes, the index form will be negative semi-definite, reversing all inequalities. Furthermore, we have to introduce $\varepsilon = g(\dot{\gamma}, \dot{\gamma}) = -1$ in the index form, reversing all signs. Therefore, we obtain the same inequality in the end. \square

Remark 3.42. Given a timelike observer $\gamma : I \rightarrow \mathcal{L}$ parametrized by proper time, i.e. $\tau(\gamma(0), \gamma(t)) \leq \pi \sqrt{\frac{n-1}{c}}$, we see that the proper time spent by such an observer is strictly bound. This implies a very bad future for the

observer, e.g. a big bang or a big crunch.

Note that this need not be so bad from a mathematical point of view: Take $(\mathcal{L}, g) := (I^+(0) \cap I^-(1, 0, \dots, 0), \eta) \subseteq (\mathbb{R}^{1, n-1}, \eta)$. This space does not satisfy our assumptions, but nevertheless $\tau(p, q) \leq 1$, so the proper time experienced by any timelike observer is bound above. But for $\gamma : (a, b) \rightarrow \mathcal{L}$, nothing bad happens as $t \rightarrow a$ and $t \rightarrow b$. The theorem simply predicts geodesic incompleteness, which leads us to define a singularity as existence of incomplete causal geodesics. Moreover, the theorem is physically rather useless because $\text{Ric} \geq c > 0$ excludes open subsets with $\text{Ric} = 0$, i.e. vacuum regions in our space-time for $\Lambda = 0$. The **Einstein Equation**

$$\text{Ric}_g - \frac{1}{2} \text{scal}_g g = T$$

tells us that $\text{Ric} = T + \frac{1}{2} \text{scal}_g g$ in any GR space-time. If there is $c > 0$ with $(T + \frac{1}{2} \text{scal}_g g)(X, X) \geq c|g(X, X)|$ for all timelike X , no observer can exist in the universe for an infinite amount of time.

We can do better in terms of physical usefulness:

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Theorem 3.43 (Hawking's Singularity Theorem). Let $(\mathcal{L}, \langle \cdot, \cdot \rangle)$ be a globally hyperbolic Lorentzian n -manifold with $\text{Ric}(X, X) \geq 0$ for all $X \in T_p M^{\text{t.l.}}$ and $p \in M$. If there exists a spacelike hypersurface Σ such that:

- (a) $J_-(\Sigma) \cap J_+(q)$ is compact for all $q \in J_-(\Sigma)$.
- (b) There exists $\beta > 0$ such that $\langle H_p, N_p \rangle \geq \beta > 0$ for all $p \in \Sigma$, where N is the past-pointing timelike unit normal vector field to Σ and H_p is the mean curvature vector, i.e.

$$H_p := \frac{1}{n-1} \text{tr}_\Sigma \mathbb{I}_p = \frac{1}{n-1} \sum_{i=1}^{n-1} \mathbb{I}_p(E_i, E_i)$$

for any orthonormal frame E_i of $T_p \mathcal{L}|_\Sigma$.

Then

$$\tau_\Sigma(q) = \sup \{ \tau(q, x) \mid x \in \Sigma \} \leq \frac{1}{\beta}.$$

Proof. Let $q \in J^-(\Sigma)$. By assumption (a) and strong causality, which follows from global hyperbolicity by a previous exercise, there exists a future-directed timelike unit-speed geodesic $\gamma : [0, b] \rightarrow \mathcal{L}$ from q to Σ with $\dot{\gamma}(b) \perp T_{\gamma(b)} \Sigma$ and $b = L[\gamma] = \tau_\Sigma(q)$. Let $(E_i)_{1 \leq i \leq n-1}$ be a parallel ONF for $\dot{\gamma}^\perp$ along γ . Consider vector fields $V_i := f E_i$ for some f with $f(0) = 0$ and $f(b) = 1$. Let Γ_i be a variation of γ with variational vector field V_i , and such that $\Gamma_i(s, 0) = q$ as well as $\Gamma_i(s, b) \in \Sigma$ for all s . This is possible since $V_i(0) = 0$ and $V_i(b) \in T_{\gamma(b)} \Sigma$. Since $L[\gamma] = \tau_\Sigma(q)$, proposition 3.31 yields

$$0 \geq \frac{d^2}{ds^2} \Big|_{s=0} L[\Gamma_{i,s}]$$

for all i . We sum over i to obtain:

$$\begin{aligned}
 0 &\geq \sum_{i=1}^{n-1} \frac{d^2}{ds^2} \Big|_{s=0} L[\Gamma_{i,s}] \\
 &= \varepsilon \left[\int_0^b f^2(n-1) - \sum_{i=1}^{n-1} \text{Rm}(fE_i, \dot{\gamma}, \dot{\gamma}, fE_i) \right] dt + \sum_{i=1}^{n-1} \langle \mathbb{I}(E_i, E_i), \dot{\gamma}(b) \rangle \\
 &= -(n-1) \int_0^b f^2 dt + \int_0^b f^2 \cdot \underbrace{\text{Ric}(\dot{\gamma}, \dot{\gamma})}_{\geq 0} dt + \underbrace{\left\langle \sum_{i=1}^{n-1} \mathbb{I}(E_i, E_i), \dot{\gamma}(b) \right\rangle}_{=(n-1)H} = -N_{\gamma(b)} \\
 &\geq -(n-1) \int_0^b f^2 dt + (n-1)\beta = (n-1) \left(-\frac{1}{b} + \beta \right)
 \end{aligned}$$

Here we see that $f(t) = \frac{t}{b}$ is a good choice.

Therefore, we get $0 \geq -\frac{1}{b} + \beta$, so

$$\frac{1}{\beta} \geq b = \tau_{\Sigma}(q).$$

□

Example 3.44. An interesting example is $\mathcal{L} = (I^+(0), \eta)$ in Minkowski space where Σ is a hyperboloid.

The Riemannian version is a bit more difficult to phrase.

Proposition 3.45 (Hawking's Riemannian Theorem). If (M, g) is a RMF with boundary ∂M , this implies the existence of an inward-pointing smooth unit-normal vector field N along ∂M . Assume:

1. M is (metrically) complete.
2. $\text{Ric} \geq 0$
3. $\langle H, N \rangle < \beta \leq 0$ on ∂M .

Then

$$d_{\partial M}(p) \leq \frac{1}{\beta}$$

for all $p \in M$.

Proof. We can prove this as follows:

1. Show there exists a geodesic $\gamma : [0, b] \rightarrow M$ orthogonal to ∂M such that $\gamma(0) = p$ and $\gamma(b) \in \partial M$, so $L[\gamma] = d_{\partial M}(p)$.
2. For any $q \in \partial M$, there exists γ_q with $L[\gamma_q] = d(p, q)$. Hopf-Rinow tells us that if ∂M is compact, then

$$d_{\partial M}(p) = \inf \{d(p, q) \mid q \in \partial M\} = d(p, q_0)$$

for some $q_0 \in \partial M$. Take $\gamma = \gamma_{q_0}$. If ∂M is non-compact, consider $B_R(p)$. Then for all $q' \in \partial M \setminus B_R(p)$ we have $d(p, q') > R$. This yields

$$d_{\partial M}(p) = \left\{ d(p, \bar{q}) \mid q \in \partial M \cap \overline{B_R(p)} \right\}.$$

However, $\partial M \cap \overline{B_R(0)}$ is compact by completeness and Hopf-Rinow.

□

3.8 The Min/Max-Behaviour of Geodesics

3.9 The Riemannian Cut Locus

 20.01.25

Definition 3.46 (Injectivity Radius). Let (M, g) be a RMF. For $p \in M$, we define the **injectivity radius** at p as

$$\text{inj}(p) := \sup \left\{ r > 0 \mid \exp_p : B_r^{g_{\text{st}}}(0) \rightarrow M \text{ diffeomorphic on its image} \right\}.$$

CHAPTER FOUR

Comparison Geometry

4.1 Hessian Operators and the Riccati Equation

Definition 4.1 (Hessian). Let (M, g) be a SRMF and $u : M \rightarrow \mathbb{R}$ smooth. The **covariant Hessian** is the $(0, 2)$ -tensor

$$\text{Hess}_u(X, Y) := (\nabla^2 u)(X, Y) = \nabla_X(\nabla_Y u) - \nabla_{\nabla_X Y} u.$$

The **Hessian operator** is the $(1, 1)$ -tensor

$$\mathcal{H}_u := \text{Hess}_u^\sharp.$$

In local coordinates (x^i) , the Hessian has the (familiar) form

$$\text{Hess}_u = (\partial_j \partial_i u - \Gamma_{ij}^k \partial_k u) dx^i \otimes dx^j.$$

Remark 4.2. The Hessian is symmetric if ∇ is the Levi-Civita-Connection (or, more generally, if and only if ∇ is torsion-free):

$$\begin{aligned} \text{Hess}_u(X, Y) &= Y(X(u)) - du(\nabla_Y X) = (XY - [X, Y])u - du(\nabla_Y X) \\ &= X(Y(u)) - du(\nabla_Y X + [X, Y]) \\ &= X(Y(u)) - du(\nabla_X Y - T(X, Y)) \\ &= \text{Hess}_u(Y, X) + T(X, Y)(u) \end{aligned}$$

Unraveling the definition of \mathcal{H}_u , we get

$$g(\mathcal{H}_u(X), Y) = \text{Hess}_u(X, Y) = \text{Hess}_u(Y, X) = g(X, \mathcal{H}_u(Y)),$$

and hence \mathcal{H}_u is self-adjoint.

With the radial distance function defined above, we obtain the Hessian operator \mathcal{H}_r associated to that function.

Notation. Given a normal neighbourhood U , we denote the geodesic spheres of radius r_0 and proper time τ_0 , respectively, by

$$S_{r_0} := \{x \in U \mid r(x) = r_0\}$$

and

$$H_{\tau_0} := \{x \in I_U^+(p) \mid \tau(x) = \tau_0\}.$$

The Gauß' Lemma immediately tells us that $T_q \mathbb{S}_{r(q)} = \partial_r|_q^\perp \subseteq T_q M$

and similarly for τ . Denote the projection on the radial tangent by

$$\pi_q^r : T_q M \rightarrow T_q S_{r(q)}.$$

Lemma 4.3. Let (M, g) be a Riemannian or time-oriented Lorentzian manifold, (U, x^i) be a normal chart around $p \in M$ and let r be the radial distance function. Then we have for all $q \in U \setminus \{p\}$:

1. $\mathcal{H}_r(\partial_r|_q) = 0$ and $\mathcal{H}_\tau(\partial_\tau|_q) = 0$
2. For all $X \in T_q M$ with $X \perp \partial_r|_q$:

$$\mathcal{H}_r(X) = \pi_q(\nabla_X(\text{grad } r)),$$

and similarly for $X \perp \partial_\tau|_q$:

$$\mathcal{H}_\tau(X) = \pi_q(\nabla_X(\text{grad } \tau)) = \pi_q^{\mathbb{H}}(\nabla_X \text{grad}(\tau)),$$

where $\pi_q^{\mathbb{H}} : T_q M \rightarrow \partial_\tau|_q^\perp \cong T\mathbb{H}^{n-1}$ denotes the orthogonal projection

$$\pi_q^{\mathbb{H}}(Y) = Y + g(Y, \partial_\tau) \partial_\tau.$$

Proof. We proof the Lorentzian case:

1. Let $Y \in T_q M$ be arbitrary. We have:

$$\begin{aligned} g(\mathcal{H}_\tau(\partial_\tau|_q), Y) &= g(\partial_\tau|_q, \mathcal{H}_\tau(Y)) = g(\partial_\tau|_q, -\nabla_Y \text{grad}(\tau)) \\ &= g(\nabla_Y \partial_\tau, \partial_\tau|_q) = \frac{1}{2} Y_q(g(\partial_\tau, \partial_\tau)) = 0, \end{aligned}$$

where we used symmetry of g and the fact that $-\text{grad}(\tau) = \partial_\tau$ since the metric is $-d\tau^2 + \tilde{g}$.

2. This follows since the previous remark showed $\mathcal{H}_\tau(X) = \nabla_X \text{grad}(\tau)$ and $\mathcal{H}_\tau(X) \perp \partial_\tau$ follows from the upper equation.

□

Note that $g|_{TH_{\tau_0} \times TH_{\tau_0}}$ is Riemannian, so the restriction is self-adjoint for a positive-definite inner product even in the Lorentzian case.

Remark 4.4. For any τ_0 such that $H_{\tau_0} \neq \emptyset$, \mathcal{H}_τ restricts to a self-adjoint linear operator

$$\mathcal{H}_\tau : TH_{\tau_0} \rightarrow TH_{\tau_0}$$

and is given by the Weingarten map $\mathcal{H}_\tau(X) = -\nabla_X N$ where $N = \partial_\tau$ is the future-pointing unit normal to H_{τ_0} .

Proposition 4.5 (The Hessian and Jacobi Fields). Let (\mathcal{L}, g) be a LMF, $p \in \mathcal{L}$ and $U \subseteq \mathcal{L}$ be a normal neighbourhood around p . Set $\tau := \tau_U(p, \cdot)$. Let $\gamma : [0, b] \rightarrow U$ be a future-directed timelike unit-speed geodesic starting at p and let $J \in \mathfrak{J}^\perp(\gamma)$ such that $J(0) = 0$. Then

$$\nabla_{\frac{d}{dt}} J(t) = -\mathcal{H}_\tau(J(t))$$

for all $\tau_0 \in (0, b]$.

In the Riemannian case, we have

$$\nabla_{\frac{d}{dt}} J(t) = \mathcal{H}_r(J(t)).$$

4.1. HESSIAN OPERATORS AND THE RICCATI EQUATION

Proof. Let $v := \dot{\gamma}(0)$ and $w := \nabla_{\frac{d}{dt}} J(0)$. By equation 3.3, we have a variation through geodesics

$$\Gamma_s(t) = \exp_{\sigma(s)}(tU(s))$$

where $\sigma(s)$ is any curve with $\sigma(0) = p$ and $\dot{\sigma}(0) = J(0)$. The vector field U satisfies $U(0) = 0$ and $\nabla_{\frac{d}{ds}} U(0) = w$ and the variational field of Γ is $\frac{\partial}{\partial s} \Big|_{s=0} = J$. Since $J(0) = 0$, choose $\sigma(s) \equiv p$. Since $w \perp v$ (J is normal), we have

$$v \in H := \{X \in T_p \mathcal{L} \mid g_p(X, X) = -1\}.$$

Hence, $w \in T_v H$. Since $U : I \rightarrow T_p M = T_{\sigma(s)} M$ with $\nabla_{\frac{d}{ds}} U(0) \in T_v H$ and $U(0) = v \in H$, we can choose U such that $U(s) \in H$ for all s . Therefore, each curve $t \mapsto \Gamma_s(t)$ is a future-directed timelike unit-speed geodesic starting at p , implying

$$\partial_t \Gamma_{s_0}(t_0) = \partial_\tau \Big|_{\Gamma(s_0, t_0)} \quad (4.1)$$

Now we compute:

$$\nabla_{\frac{d}{dt}} J = \nabla_{\frac{d}{dt}} \frac{\partial}{\partial s} \Big|_{s=0} \Gamma = \nabla_{\frac{d}{ds}} \left(\frac{\partial}{\partial t} \Gamma \right) (0, t) = \nabla_{\frac{d}{ds}} (\partial_\tau \circ \Gamma) (0, t),$$

where we used equation 4.1. Since ∂_τ is a smooth vector field on $I_U^+(p)$ (which is an open neighbourhood of $\Gamma_0(\tau_0)$ for any $\tau_0 \in (0, b]$). This implies

$$\nabla_{\frac{d}{ds}} (\partial_\tau \circ \Gamma) (0, t) = \nabla_{\partial_s \Gamma|_{s=0}} \partial_\tau = \nabla_J \partial_\tau = -\nabla_J \text{grad}(\tau) = \mathcal{H}_\tau(J)$$

using $J \perp \dot{\gamma} = \partial_\tau$. \square

Recall the previously defined function 3.9.

Proposition 4.6 (Sectional Curvature and Hessian). Let (\mathcal{L}, g) be a LMF, $p \in \mathcal{L}$ and U be a normal neighbourhood of p . Then (\mathcal{L}, g) has constant sectional curvature c on $I_U^+(p)$ if and only if

$$\mathcal{H}_\tau = -\frac{s'_{-c} \circ \tau}{s_{-c} \circ \tau} \cdot \pi^H$$

on $I_U^+(p)$.

Proof. (\Rightarrow): Let $q \in I_U^+(p)$, $\gamma : [0, b] \rightarrow M$ be the future-directed timelike unit-speed geodesic from p to q , and let $\{E_1 = \dot{\gamma}, E_2, \dots, E_n\}$ be an ONF along γ . Proposition 3.18 tells us that

$$J_i := s_{-c} E_i, i \geq 2$$

are normal Jacobi fields along γ with $J_i(0) = 0$. Compute

$$s'_{-c} E_i = \nabla_{\frac{d}{dt}} J_i = -\mathcal{H}_\tau(J_i) = -s_{-c} \mathcal{H}_\tau(E_i),$$

where we used proposition 4.5 evaluating at $t = b$ and $s_{-c}(b)^{-1}$ noting $s_{-c}(b) \neq 0$ because $\gamma(b) = q \in U$, which is normal. Hence q is not conjugate to p , implying $J_i(b) \neq 0$. This yields

$$\mathcal{H}_\tau(E_i(b)) = -\frac{s'_{-c}(b)}{s_{-c}(b)} E_i(b),$$

Note that $g_p \cong \eta_p$.

but $E_i(b) = \pi^H(E_i(b))$ because it is already orthogonal to $\dot{\gamma}(b)$. For $i = 1$, we have

$$0 = \mathcal{H}_\tau(E_1(b)) = \pi^H(E_1(b))$$

because $E_1(b) = \dot{\gamma}(b)$.

(\Leftarrow) : Let $q \in I_U^+(p)$ and $\gamma : [0, b] \rightarrow U$ be the corresponding geodesic. From theorem 3.21, we know that

$$\varphi : I_U^+(p) \rightarrow \mathbb{R}_+ \times \mathbb{H}^{n-1}$$

given by $\varphi(q) = (\tau(q), \xi(q))$ is a diffeomorphism onto its image. If we can show that it is an isometry between g and $g_c := -d\tau^2 + s_{-c}(\tau)^2 g_{\mathbb{H}^{n-1}}$, then g has constant sectional curvature. Following the proof of theorem 3.21, we immediately get 1 and 2. In 3, the constant curvature assumption only entered via Jacobi fields, more precisely via proposition 3.18 yielding: Any $J \in \mathfrak{J}^\perp(\gamma)$ with $J(0) = 0$ is given by

$$J(t) = k s_{-c}(t) E(t)$$

for some $k \in \mathbb{R}$ and $E \perp \dot{\gamma}$ as well as parallel. It only remains to show this in our setting. Let $J \in \mathfrak{J}^\perp(\gamma)$. We have

$$\nabla_{\frac{d}{dt}} J = \frac{s'_{-c}}{s_{-c}} J$$

on $(0, b]$. By the product rule, $\frac{1}{s_{-c}} J$ is parallel along γ on $(0, b]$. Define $\tilde{E}(t) := \frac{1}{s_{-c}} J$ and let $E = \frac{\tilde{E}}{\|\tilde{E}\|}$. Then E is a parallel unit VF orthogonal $\dot{\gamma}$ and $J = \|\tilde{E}\| s_{-c} E$. Set $k := \|\tilde{E}\|$, which is constant since \tilde{E} was parallel. It suffices to have this for $t \in (0, b]$ since this still gives $k = \|\nabla_{\frac{d}{dt}} J(0)\|$ by k constant. \square

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Consider a LMF (\mathcal{L}, g) with a normal neighbourhood U . The radial distance function $\tau := \tau_U(p, \cdot)$ is smooth on $I_U^+(p)$. Let $\gamma : [0, b] \rightarrow U$ be a timelike future-directed unit-speed geodesic starting at p . In this case, the Hessian operator restricts to

$$\mathcal{H}_\tau : \mathfrak{X}(\gamma) \rightarrow \mathfrak{X}(\gamma),$$

which is a $(1, 1)$ -tensor field along γ and $\mathcal{C}^\infty(I)$ -linear. Therefore, we also get another $\mathcal{C}^\infty(I)$ -linear $(1, 1)$ -tensor field

$$\nabla_{\frac{d}{dt}} \mathcal{H}_\tau(X) := \nabla_{\frac{d}{dt}} (\mathcal{H}_\tau(X)) - \mathcal{H}_\tau \left(\nabla_{\frac{d}{dt}} X \right). \quad (4.2)$$

One sees that this is indeed $\mathcal{C}^\infty(I)$ -linear, self-adjoint and $\text{tr } R_\gamma = -\text{Ric}(\dot{\gamma}, \dot{\gamma})$. Comparing with the Jacobi equation also shows that

$$R_\gamma(J) = \nabla_{\frac{d}{dt}}^2 J.$$

Definition 4.7 (Tidal Force Operator). Let (M, g) be a RMF or a LMF and let $\gamma : [0, b] \rightarrow M$ be a (timelike) geodesic. The **tidal force operator** is defined by

$$\begin{aligned} R_\gamma : \mathfrak{X}(\gamma) &\rightarrow \mathfrak{X}(\gamma) \\ X &\mapsto R_\gamma(X) := -R(X, \dot{\gamma})\dot{\gamma}. \end{aligned}$$

Remark 4.8. The tidal force operator restricts to a well-defined $\mathcal{C}^\infty(I)$ -linear operator $\mathfrak{X}(\gamma)^\perp \rightarrow \mathfrak{X}(\gamma)^\perp$ and the trace of that restriction still yields $-\text{Ric}(\dot{\gamma}, \dot{\gamma})$ since $R_{\dot{\gamma}}(\dot{\gamma}) = 0$. This restriction is still self-adjoint with respect to $g|_{\mathfrak{X}(\gamma)^\perp \times \mathfrak{X}(\gamma)^\perp}$. This metric restriction is Riemannian even if the original g is Lorentzian.

Theorem 4.9 (Riccati Equation). Let (M, g) be a RMF or a LMF, U be a normal neighbourhood of some $p \in M$ and $\gamma : [0, b] \rightarrow U$ be a timelike future-directed radial unit-speed geodesic starting at p . Let $r(\tau)$ be the radial distance function on $U(I_U^+(p))$. Then, the Hessian operator satisfies the **Riccati equation** (REQ):

$$\nabla_{\frac{d}{dt}} \mathcal{H}_r + \mathcal{H}_r^2 - R_{\dot{\gamma}} = 0 \quad (4.3)$$

$$\nabla_{\frac{d}{dt}} \hat{\mathcal{H}} + \hat{\mathcal{H}}^2 - R_{\dot{\gamma}} = 0, \quad (4.4)$$

with $\hat{\mathcal{H}} := -\mathcal{H}_\tau$ in the Lorentzian case, on $\gamma|_{(0, b]}$.

One can compare this with the classical scalar Riccati equation: Let $f : I \rightarrow \mathbb{R}$ and $\sigma : I \rightarrow \mathbb{R}$. Then the classical RQN is given by

$$f' + f^2 + \sigma = 0.$$

Note that this can only apply on the half-open interval $(0, b]$ since r and τ are undefined at 0.

Proof. We prove the Lorentzian case, the Riemannian case can be found in [LeeRM]. Fix $\tau_0 \in (0, b]$. It suffices to check the (REQ) for $\partial_\tau|_{\tau_0}$ and $X \in T_{\gamma(\tau_0)}H_{\tau_0}$, i.e. $X \perp \partial_\tau|_{\tau_0}$. For ∂_τ , we already know $\mathcal{H}_\tau(\partial_\tau) = 0$, so $\mathcal{H}_\tau^2(\partial_\tau) = 0$. Furthermore, $\partial_\tau|_{\tau_0} = \dot{\gamma}(\tau_0)$, and hence $R_{\dot{\gamma}}(\partial_\tau) = 0$. Lastly, we have

$$\nabla_{\frac{d}{dt}} \mathcal{H}_\tau(\partial_\tau) = \nabla_{\frac{d}{dt}} \left(\overset{\text{vanishes on } (0, b]}{\mathcal{H}_\tau(\partial_\tau)} \right) - \mathcal{H}_\tau \left(\overset{\text{geodesic}}{\nabla_{\frac{d}{dt}} \gamma} \right) = 0,$$

and thus the REQ holds in this case. Now, let $X \perp \dot{\gamma}(\tau_0)$. By 3.11, we find $J \in \mathfrak{J}(\gamma)^\perp$ with $J(\tau_0) = X$ and $J(0) = 0$. This yields:

$$\begin{aligned} \nabla_{\frac{d}{dt}} \mathcal{H}_\tau(X) &= \left(\nabla_{\frac{d}{dt}} (\mathcal{H}_\tau(J)) - \mathcal{H}_\tau(\nabla_{\frac{d}{dt}} J) \right) \Big|_{t=\tau_0} \\ &\stackrel{\text{Proposition 4.5}}{=} \left(\nabla_{\frac{d}{dt}} \left(-\nabla_{\frac{d}{dt}} J \right) - \mathcal{H}_\tau(-\mathcal{H}_\tau(J)) \right) \Big|_{t=\tau_0} \\ &= -\nabla_{\frac{d}{dt}}^2 J(\tau_0) + \mathcal{H}_\tau^2(X) = -R_{\dot{\gamma}}(J(\tau_0)) + \mathcal{H}_\tau^2(X). \end{aligned}$$

□

Theorem 4.10 (Matrix Riccati Comparison). Let $\text{Sym}_{\mathbb{R}}(n) \subseteq \text{Mat}_{\mathbb{R}}(n)$ be the space of symmetric real $n \times n$ -matrices identified with self-adjoint endomorphisms of Euclidean \mathbb{R}^n . Let $H, \tilde{H} : (a, b] \rightarrow \text{Sym}_{\mathbb{R}}(n)$ be smooth such that the **matrix Riccati equations**

$$H' + H^2 + S = 0$$

and

$$\tilde{H}' + \tilde{H}^2 + \tilde{S} = 0$$

are satisfied for some continuous $S, \tilde{S} : [a, b] \rightarrow \text{Sym}_{\mathbb{R}}(n)$ which are smooth on $(a, b]$. If

$$\tilde{S} \geq S$$

We use the notion

$$A \geq B := A - B \geq 0 \Leftrightarrow \langle (A - B)x, x \rangle$$

for all $x \in \mathbb{R}^n$. This means all eigenvalues of $A - B$ are non-negative.

on $[a, b]$ and

$$\lim_{t \searrow 0} \tilde{H}(t) - H(t) \leq 0$$

(meaning the limit also exists in the first place), then

$$\tilde{H} \leq H$$

on $(a, b]$.

Proof. See [LeeRM]. □

Theorem 4.11 (Riccati Manifold Comparison). Let (M, g) be a RMF or a LMF and $\gamma : [a, b] \rightarrow M$ be a timelike unit-speed geodesic segment. Suppose

$$\eta, \tilde{\eta} : \mathfrak{X}(\gamma|_{(a,b]})^\perp \rightarrow \mathfrak{X}(\gamma|_{(a,b]})$$

are $\mathcal{C}^\infty(I)$ -linear, self-adjoint with respect to the restricted metric and satisfy the REQs

$$\nabla_{\frac{d}{dt}} \eta + \eta^2 + \sigma = 0$$

and

$$\nabla_{\frac{d}{dt}} \tilde{\eta} + \tilde{\eta}^2 + \tilde{\sigma} = 0$$

for some self-adjoint, $\mathcal{C}^\infty(I)$ -linear $\sigma, \tilde{\sigma} : \mathfrak{X}(\gamma)^\perp \rightarrow \mathfrak{X}(\gamma)^\perp$. If

$$\forall t \in [a, b] : \tilde{\sigma}(t) \geq \sigma(t)$$

and

$$\lim_{t \searrow a} \tilde{\eta}(t) - \eta(t) \leq 0$$

holds, then

$$\forall t \in [a, b] : \tilde{\eta}(t) \leq \eta(t).$$

This roughly means that a comparison of RQNs and initial values leads to a comparison of solutions.

Proof. The goal is to utilize theorem 4.10. To this end, take a parallel ONF $(E_i) \cup \{\dot{\gamma}\}$ with $1 \leq i \leq n-1$ along γ . In this frame, we represent $\eta, \tilde{\eta}, \sigma, \tilde{\sigma}$ by symmetric, matrix valued maps

$$H, \tilde{H} : [a, b] \rightarrow \text{Sym}_{\mathbb{R}}(n-1)$$

and

$$S, \tilde{S} : [a, b] \rightarrow \text{Sym}_{\mathbb{R}}(n-1)$$

with components $\eta(t)(E_i) = H_i^j(t)E_j$ and analogously for the other operators. We have:

$$\begin{aligned} \nabla_{\frac{d}{dt}} (\eta(E_i)) &= \nabla_{\frac{d}{dt}} \eta(E_i) + \eta \left(\nabla_{\frac{d}{dt}} E_i \right) = -\eta^2(E_i) - \sigma(E_i) \\ &= -\eta(H_i^j E_j) - S_i^k E_k = -H_i^j \eta(E_j) - S_i^k E_k \\ &= -H_i^j H_j^k E_k - S_i^k E_k \end{aligned}$$

Without expanding, we obtain:

$$\begin{aligned} \nabla_{\frac{d}{dt}} (\eta(E_i)) &= \nabla_{\frac{d}{dt}} (H_i^k E_k) \\ &= (H_i^k)' E_k + H_i^k \nabla_{\frac{d}{dt}} E_k = (H_i^k)' E_k. \end{aligned}$$

4.2. HESSIAN COMPARISON

Therefore,

$$H' + H^2 + S = 0$$

holds, with similar calculations establishing the same for \tilde{H} and \tilde{S} . Clearly, $\tilde{\sigma} \geq \sigma$ is equivalent to $\tilde{S} \geq S$ and similar for the other condition. Theorem 4.10 is thus applicable and we conclude

$$\tilde{H} \leq H \Leftrightarrow \tilde{\eta} \leq \eta.$$

□

Remark 4.12. In the Riemannian case, we can do the same for

$$\eta, \tilde{\eta} : \mathfrak{X}(\gamma) \rightarrow \mathfrak{X}(\gamma).$$

However, we mainly consider $\eta = \mathcal{H}_r$ and $\tilde{\eta} \propto \pi^S$. Splitting $\mathfrak{X}(\gamma) \cong \text{span}\{\dot{\gamma}\} \oplus \mathfrak{X}(\gamma)^\perp$, then we obtain the following matrix forms of \mathcal{H}_r and π^S :

$$\begin{pmatrix} 0 & 0 \\ 0 & \mathcal{H}_r|_{\mathfrak{X}(\gamma)^\perp} \end{pmatrix}$$

and

$$\begin{pmatrix} 0 & 0 \\ 0 & \text{id} \end{pmatrix}.$$

Therefore, the restriction to $\mathfrak{X}(\gamma)^\perp$ does not discard any information.

4.2 Hessian Comparison

In this section, we attempt to compare \mathcal{H}_r with $\frac{s'_c \circ r}{s_c \circ r} \pi^S$ and \mathcal{H}_τ with $-\frac{s'_{-c} \circ \tau}{s_{-c} \circ \tau} \pi^H$. In the following, any inequalities for \mathcal{H}_τ in the Lorentzian case are to be understood for the restriction

$$\mathcal{H}_\tau|_{\mathfrak{X}(\gamma)^\perp} : \mathfrak{X}(\gamma)^\perp \rightarrow \mathfrak{X}(\gamma)^\perp.$$

Theorem 4.13 (Hessian Comparison). Let (M, g) be a RMF or a **LMF**, $p \in M$, U be a normal neighbourhood of p and $r : U \rightarrow [0, \infty)$ ($\tau = \tau|_U(p, \cdot)$) be the radial distance function at p . Let $c \in \mathbb{R}$.

(a) If all **timelike** sectional curvatures of M are less or equal c , then

$$\mathcal{H}_r(q) \geq \frac{\dot{s}_c(r(q))}{s_c(r(q))} \pi_q^S$$

for

$$\begin{cases} \forall q \in U \setminus \{p\} & c \leq 0 \\ \forall q \in U \setminus \{p\} : r(q) < \pi R & c > 0 \end{cases}$$

with $R := \frac{1}{\sqrt{c}}$.

(b) If all sectional curvatures of M are greater or equal c , then

$$\mathcal{H}_r|_q \leq \frac{\dot{s}'_c(r(q))}{s_c(r(q))} \pi_q^S$$

$\mathcal{H}_\tau|_q \geq -\frac{\dot{s}_{-c}(\tau(q))}{s_{-c}(\tau(q))} \pi_q^H$
Note this is equal to $\varphi^*(\mathcal{H}_\tau^c|_{\tilde{q}})$ for $\tilde{q} = \varphi(q) \in \mathbb{R} \times \mathbb{H}^{n-1}$ with metric g^c .

for all $q \in I_U^+(p)$

$$\mathcal{H}_\tau|_q \leq -\frac{\dot{s}_{-c}(\tau(q))}{s_{-c}(\tau(q))} \pi_q^H$$

for

$$\begin{cases} \forall q \in I_U^+(p) & c \geq 0 \\ \forall q \in I_U^+(p) : \tau(q) \leq \pi R & c < 0 \end{cases}.$$

for all $q \in U \setminus \{p\}$.

Proof. **We prove the Lorentzian version.** Let $q \in I_U^+(p)$ (with $\tau(q) < \pi R$ in case (b) if $c < 0$) and $\gamma : [0, b] \rightarrow U$ be the unit-speed timelike geodesic from p to q . Set $\xi(q) := \dot{\gamma}(0) \in \mathbb{H}^{n-1} \subseteq T_p M$. We want to apply Theorem 4.11 along γ to $\hat{\mathcal{H}} := -\mathcal{H}_\tau \circ \gamma$, comparing it with $\hat{\mathcal{H}}^c(t) := \frac{s-c(t)}{s-c(t)} \pi_q^H = -\mathcal{H}_\tau^c((t, \xi(q)))$. Case (a) turns into $\hat{\mathcal{H}}^c \geq \hat{\mathcal{H}}$ while case (b) becomes $\hat{\mathcal{H}}^c \leq \hat{\mathcal{H}}$. We divide the proof in four steps:

1. Step: We show that, wherever defined, $\hat{\mathcal{H}}^c$ satisfies the Riccati equation

$$\nabla_{\frac{d}{dt}} \hat{\mathcal{H}}^c + (\hat{\mathcal{H}}^c)^2 - R^c = 0$$

on $(0, b]$ for $R^c(t) := c\pi_{\gamma(t)}^H$. This follows directly by computation or by using the fact that $\hat{\mathcal{H}}^c$ and R^c are pullbacks of the Hessian and the tidal force operator, respectively, in constant curvature spaces along a radial geodesic. This in turn follows from Proposition 4.6.

2. Step: We have $-R^c \leq -R_\gamma$ on $(0, b]$ in case (a) and $-R^c \geq -R_\gamma$ in case (b). To see this, let $t \in (0, b]$ and $w \in T_{\gamma(t)} H_t$. Then w is spacelike, so $\{\dot{\gamma}, w\}$ spans a timelike plane, implying

$$g(-R_\gamma(w), w) = \sec(\dot{\gamma}(t), w)g(w, w)(-1) = -\sec(\dot{\gamma}, w)g(w, w).$$

Therefore, we have

$$g(-R_\gamma(w), w) = \begin{cases} \geq -cg(w, w) = g(-R^c(w), w) & \text{(a)} \\ \leq -cg(w, w) = g(-R^c(w), w) & \text{(b)} \end{cases}.$$

3. Step: We continue by showing that $\lim_{t \rightarrow 0} \hat{\mathcal{H}}^c(t) - \hat{\mathcal{H}}(t)$ exists and is either non-negative in case (a) or non-positive in case (b). Direct computation shows $\hat{\mathcal{H}}^c(t) = \frac{1}{t}\pi_{\gamma(t)}^H + \mathcal{O}$. Therefore, it suffices to show that also $\hat{\mathcal{H}}(t) = \frac{1}{t}\pi_{\gamma(t)}^H + \mathcal{O}(t)$. Choose normal coordinates around p such that $\gamma(t) = (t, 0, \dots, 0)$. In these coordinates, we have

Note that

$$\pi_{\gamma(t)}^H = 0 \oplus \text{id} : \text{span}\{\dot{\gamma}(t)\} \oplus \dot{\gamma}(t)^\perp \rightarrow \text{span}\{\dot{\gamma}(t)\} \oplus \dot{\gamma}(t)^\perp$$

extends continuously at $t = 0$ to

$$0 \oplus \text{id} : \text{span}\{\dot{\gamma}(0)\} \oplus \dot{\gamma}(0)^\perp \rightarrow \text{span}\{\dot{\gamma}(0)\} \oplus \dot{\gamma}(0)^\perp.$$

$$\tau(x) = \sqrt{-\eta(x, x)} = \sqrt{x_0^2 - \sum_{i=1}^{n-1} x_i^2},$$

$$g_{ij}(\gamma(t)) = \eta_{ij} + \mathcal{O}(t^2),$$

and

$$\Gamma_{jk}^m(\gamma(t)) = 0 + \mathcal{O}(t).$$

Calculating

$$\partial_m \tau = \frac{-\varepsilon_m x_m}{\tau} = \begin{cases} \frac{x_0}{\tau} & m = 0 \\ -\frac{x_m}{\tau} & 1 \leq m \leq n-1 \end{cases},$$

we see that ∂_m remains bounded as $t \rightarrow 0$ along γ since $\partial_m \tau_{\gamma(t)} = -1$ for $m = 0$ and otherwise, it vanishes. Furthermore, we get

$$\partial_j \partial_k \tau = -\varepsilon_j \varepsilon_k \frac{x_j x_k}{\tau^3} - \frac{\eta_{jk}}{\tau},$$

yielding

$$\partial_j \partial_k \tau|_{\gamma(t)} = -\frac{\delta_{j0} \delta_{k0} + \eta_{jk}}{t} = \mathcal{O}\left(\frac{1}{t}\right).$$

Putting everything together, we obtain

$$\begin{aligned} -(\mathcal{H}_\tau|_{\gamma(t)})_k^i &= -g^{ij}(\partial_j \partial_k \tau - \Gamma_{jk}^m \partial_m \tau) \\ &= -\eta^{ij}(\partial_j \partial_k \tau|_\gamma - \mathcal{O}(t)) + \mathcal{O}(t^2) \mathcal{O}\left(\frac{1}{t}\right) \\ &= \begin{cases} 0 & i = 0 \text{ or } k = 0 \\ \frac{\delta_k^i}{t} + \mathcal{O}(t) & \text{else} \end{cases} \end{aligned}$$

So on $\dot{\gamma}(t)^\perp$, we have $\widehat{\mathcal{H}}(t) = \frac{1}{t} \text{id} + \mathcal{O}(t)$. Now, Theorem 4.11 guarantees $\widehat{\mathcal{H}}^c \geq \widehat{\mathcal{H}}$ in case (a) and $\widehat{\mathcal{H}}^c \leq \widehat{\mathcal{H}}$ in case (b) for all $t \in (0, b]$, eventually with the restriction $t < \pi R$.

4. Step: In case (a), we still have to show that $-c > 0$ already forces $\tau(q) < \pi R$ for any $q \in I_U^+(p)$ to guarantee that $\widehat{\mathcal{H}}^c$ is well-defined along γ . We show that $b < \pi R$ automatically holds in this case. Since $\widehat{\mathcal{H}}$ is well-defined on $(0, b]$, the eigenvalues are bounded on this interval. But the inequality

$$\widehat{\mathcal{H}}(t) \leq \widehat{\mathcal{H}}^c(t) = \frac{\dot{s}_{-c}(t)}{s_{-c}(t)} \pi_{\gamma(t)}^H = \frac{1}{R} \frac{\cos(\frac{t}{R})}{\sin(\frac{t}{R})} \pi_{\gamma(t)}^H \xrightarrow{t \rightarrow \pi R} -\infty$$

forces the eigenvalues to diverge as $t \rightarrow \pi R$, so $b < \pi R$.

□

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Theorem 4.14 (Lorentzian Jacobi Field Comparison). Let (M, g) be a LMF, $\gamma : [0, b] \rightarrow M$ be a unit-speed timelike geodesic, and $J \in \mathfrak{J}(\gamma)^\perp$ with $J(0) = 0$.

1. If all timelike sectional curvatures are non-positive, then

$$\|J(t)\|_g \leq s_{-c}(t) \cdot \|\nabla_{\frac{d}{dt}} J(0)\|_g$$

for all $t \in [0, b_1]$ where

$$b_1 := \sup\{t \in [0, b] \mid \gamma(t) \text{ is not conjugate to } \gamma(0) \text{ along } \gamma\}.$$

2. If all timelike sectional curvatures are non-negative, then

$$\|J(t)\| \geq s_{-c}(t) \|\nabla_{\frac{d}{dt}} J(0)\|$$

for all $t \in [0, b_2]$ where

$$b_2 := \begin{cases} b & c \leq 0 \\ \min\{b, R\pi\} & c > 0 \end{cases}.$$

Proof. Let J be such a Jacobi field which is not the zero field.

1. Step: We show monotonicity. Let $b_0 := \min\{b_0, b_1\}$ and define

$$f : (0, b_0) \rightarrow \mathbb{R}$$

by

$$f(t) := \log(s_{-c}(t)^{-1}\|J(t)\|) = \log(\|J(t)\|) - \log(s_{-c}(t)).$$

Define $\tilde{f}(t) := s_{-c}(t)^{-1}\|J(t)\|$, which is strictly positive on $(0, b_0)$ since $s_{-c}(t)$ and $J(t)$ are not zero by choice of b_0 and spacelike character of $J(t)$ (which is normal). Note that f is non-increasing resp. non-decreasing if and only if \tilde{f} is by monotonicity of \log . Now compute

$$\dot{f}(t) = \frac{1}{\|J\|^2} g(\nabla_{\frac{d}{dt}} J, J) - \frac{\dot{s}_{-c}}{s_{-c}}.$$

Assume for now that $\gamma : [0, b_0] \rightarrow M$ is contained in a normal neighbourhood of $p := \gamma(0)$. Using $\widehat{\mathcal{H}}(J) = \nabla_{\frac{d}{dt}} J$ (prop. 3.5) and Hessian comparison, we get

$$\dot{f}(t) = \frac{1}{\|J\|^2} (g(\widehat{\mathcal{H}}(J), J) - \underbrace{g(\frac{\dot{s}_{-c}}{s_{-c}} J, J)}_{=\widehat{\mathcal{H}}^c(J)}) = \begin{cases} \leq 0 & \text{Case 1} \\ \geq 0 & \text{Case 2} \end{cases}.$$

2. Step: Now we treat the initial condition. We want to show that

$$\lim_{t \searrow 0} \frac{\|J(t)\|}{s_{-c}(t)} = \|\nabla_{\frac{d}{dt}} J(0)\|,$$

which is equivalent to

$$\lim_{t \searrow 0} \frac{\|J\|}{s_{-c}(t)} = \|\nabla_{\frac{d}{dt}} J(0)\| > 0.$$

The last inequality holds as J is normal. Applying l'Hospital's rule twice yields

$$\begin{aligned} \lim_{t \searrow 0} \frac{1}{s_{-c}^2} \|J\| &= \lim_{t \searrow 0} \frac{2g(\nabla_{\frac{d}{dt}} J, J)}{2s_{-c}\dot{s}_{-c}} \\ &= \lim_{t \searrow 0} \frac{\|\nabla_{\frac{d}{dt}} J\| +}{\dot{s}}. \end{aligned}$$

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3. Step: It remains to show that the image of γ does not need to be contained in a normal neighbourhood. Let $t \in [0, b_0)$. We know that $\gamma(t)$ is not conjugated to $\gamma(0)$. This means we find a neighbourhood $W_+ \subseteq T_p M$ of $t\dot{\gamma}(0)$ such that

$$\exp_p : W_+ \rightarrow \exp_p(W_+) =: V_+$$

is a diffeomorphism. Eventually by shrinking, we find a convex neighbourhood $W \subseteq T_p M$ of the ray $\{t\dot{\gamma}(0) \mid t \in [0, b_0)\}$ such that

$$\varphi := \exp_p : W \rightarrow M$$

4.3. GEODESIC CONSEQUENCES OF JACOBI FIELD COMPARISON

is a local diffeomorphism. Pulling back, we get a metric $\tilde{g} := \varphi^*(g)$ on W . Hence φ is a local isometry. By Gauß' Lemma, radial lines in W are exactly the radial \tilde{g} -geodesics. Therefore, $\tilde{\gamma}(t) := t\dot{\gamma}(0)$ is a \tilde{g} -geodesic with $\varphi \circ \tilde{\gamma} = \gamma$, and W is a normal neighbourhood for $\tilde{\gamma}$. Define

$$\tilde{J}(t) := (\varphi)_{*, t\dot{\gamma}(0)}^{-1} J(t).$$

This is a vector field along $\tilde{\gamma}$ which is \tilde{g} -normal to $\dot{\tilde{\gamma}}$ with $\tilde{J}(0) = 0$. By exercise 1 of sheet 7, \tilde{J} is a \tilde{g} -Jacobi field along $\tilde{\gamma}$. As \tilde{g} has the same curvature bounds as g , we can apply the first two steps to arrive at

$$\|J(t)\|_g = \|\tilde{J}(t)\|_{\tilde{g}} = \begin{cases} \leq s_{-c}(t) \|\tilde{\nabla}_{\frac{d}{dt}} \tilde{J}(0)\|_{\tilde{g}} = s_{-c}(t) \|\nabla_{\frac{d}{dt}} J(0)\|_g & \text{Case 1} \\ \geq s_{-c}(t) \|\tilde{\nabla}_{\frac{d}{dt}} \tilde{J}(0)\|_{\tilde{g}} = s_{-c}(t) \|\nabla_{\frac{d}{dt}} J(0)\|_g & \text{Case 2} \end{cases}.$$

4. Step: It suffices to show that $b_2 \geq b_1$ in case 1 and $b_1 \geq b_2$ in case 2. We show 1. By the inequality for $t < b_0$, we get

$$s_{-c}(t) \|\nabla_{\frac{d}{dt}} J(0)\| \geq \|J(t)\| > 0$$

for $t < b_1$. Hence for all $t < \min(b_1, b_0)$, we have $s_{-c}(t) > 0$, and thus $b_2 \geq \min(b_1, b_0) = \min(b_1, b_2)$. Now case 2: By the inequality, we obtain

$$\|J(t)\| \geq s_{-c}(t) \|\nabla_{\frac{d}{dt}} J(0)\| > 0$$

on $(0, \min(b_0, b_2))$. Therefore, $\gamma(t)$ cannot be conjugated to $\gamma(0)$ for $t < \min(b_0, b_2) = \min(b_1, b_2)$, so $b_1 \geq \min(b_1, b_2)$.

□

4.3 Geodesic Consequences of Jacobi Field Comparison

Metric Comparison

Theorem 4.15 (Metric Comparison). Let (M, g) be a RMF (LMF), U be a normal neighbourhood of M with normal coordinates (x^i) , and let

$$\varphi : U \setminus \{p\} \rightarrow (0, \infty) \times \mathbb{S}^{n-1}$$

be Riemannian (Lorentzian) polar coordinates. Let

$$g^c = dr^2 + s_c(r)^2 \dot{g}_{n-1}$$

denote the constant curvature metric on

$$\widetilde{M} := \begin{cases} (0, \infty) \times \mathbb{S}^{n-1} & c \leq 0 \\ (0, \pi R) \times \mathbb{S}^{n-1} & c > 0 \end{cases}.$$

Then:

$$\varphi_L : I_U^+(p) \rightarrow (0, \infty) \times \mathbb{H}^{n-1}$$

$$g^c = -d\tau^2 + s_{-c}(\tau)^2 \check{g}_{n-1}$$

$$\widetilde{M} := \begin{cases} (0, \infty) \times \mathbb{H}^{n-1} & c \leq 0 \\ (0, \pi R) \times \mathbb{H}^{n-1} & c > 0 \end{cases}$$

$$((\varphi_L)_*g)|_{\varphi(q)}(w, w) \leq g^c|_{\varphi(q)}(w, w)$$

- (a) If the **timelike** sectional curvature of (M, g) is non-positive, then

$$(\varphi_*g)|_{\varphi(q)}(w, w) \geq g^c|_{\varphi(q)}(w, w)$$

for all $w \in T_q\widetilde{M}$ and all $q \in U \setminus \{p\}$ ($q \in I_U^+(p)$) with $d_g(p, q) \leq \pi R$ if $c > 0$.

- (b) If the sectional curvature is non-negative, then

$$((\varphi_L)_*g)|_{\varphi(q)}(w, w) \geq g^c|_{\varphi(q)}(w, w)$$

$$(\varphi_*g)|_{\varphi(q)}(w, w) \leq g^c|_{\varphi(q)}(w, w)$$

for all $w \in T_q\widetilde{M}$ and all $q \in U \setminus \{p\}$ (implying $d(p, q) < \pi R$ for $c > 0$) (all $q \in I_U^+(p)$ with $\tau_U(p, q) < \pi R$ for $c < 0$).

Proof. **We prove the Lorentzian case.** By corollary 2.24/theorem 2.23: Set $\widetilde{q} := \varphi(p)$. In cases (a) and (1b), we have

$$((\varphi_L)_*g)_{\widetilde{q}} = -d\tau^2 + h_{\widetilde{q}}$$

for a family h_τ of *Riemannian* metrics with $h_{\widetilde{q}}(\partial_\tau, \cdot) = 0$. Therefore it suffices to consider $w \in T_{\widetilde{q}}\widetilde{M}$ with w tangent to \mathbb{H}^{n-1} , i.e. $w \perp \partial_\tau$. Let $q \in I_U^+(p)$ and $\gamma : [0, b] \rightarrow M$ be the radial geodesic from p to q on U . Let J be the unique normal Jacobi field along γ with $J(0) = 0$ and $J(b) = \varphi^*(w)$. By Jacobi field comparison,

$$g(\varphi_L^*(w), \varphi_L^*(w)) = \|J(b)\|_g^2 \begin{cases} \leq s_{-c}(b)^2 \|\nabla_{\frac{d}{dt}} J(0)\|_g^2 & \text{Case 1} \\ \geq s_{-c}(b)^2 \|\nabla_{\frac{d}{dt}} J(0)\|_g^2 & \text{Case 2} \end{cases}$$

since $b_1 = b$ for normal neighbourhoods. Set $\varphi_L^*(w) = v^i \partial_i|_{\gamma(t)}$, so $J(t) = \frac{t}{b} v^i \partial_i|_{\gamma(t)}$. Hence

$$\nabla_{\frac{d}{dt}} J(0) = \frac{v^i}{b} \partial_i|_p.$$

We obtain $\|\nabla_{\frac{d}{dt}} J(0)\|_g^2 = \frac{1}{b^2} \|(v^1, \dots, v^n)\|_\eta^2$. This yields

The last equality demands a kind of longish calculation.

$$(\varphi_L)_*g(w, w) \begin{cases} \leq \frac{s_{-c}(b)^2}{b^2} \|(v^1, \dots, v^n)\|_\eta^2 = g_q^c(w, w) & \text{Case (a)} \\ \geq \frac{s_{-c}(b)^2}{b^2} \|(v^1, \dots, v^n)\|_\eta^2 = g_q^c(w, w) & \text{Case (b)} \end{cases}.$$

□

Corollary 4.16 (Area Comparison). In the Riemannian case, we get for any t such that $S_t(p)$ is completely contained in a normal neighbourhood:

- (a) If the sectional curvature is non-positive:

$$\text{area}_g(S_t) \geq \text{area}_{g^c}(S_t^c)$$

as long as $t < \pi R$ if $c > 0$.

- (b) If the sectional curvature is non-negative:

$$\text{area}_g(S_t) \leq \text{area}_{g^c}(S_t^c).$$

In the Lorentzian case, we get similar inequalities for the area/volume elements.

Laplace-d'Alembertian Comparison

Definition 4.17 (Laplacian (d'Alembertian) Operators). Let $u : M \rightarrow \mathbb{R}$ be a smooth function on a smooth Riemannian (Lorentzian) manifold M . The **Laplacian** is given by

$$\Delta u = \text{tr}_g \text{Hess}_u = \text{tr}(\mathcal{H}_u).$$

The **d'Alembertian** is given by

$$\square u = \text{tr}_g \text{Hess}_u = \text{tr}(\mathcal{H}_u).$$

Theorem 4.18 (Laplacian (d'Alembertian) Comparison). Let (M, g) be a RMF (LMF) and U be a normal neighbourhood of M . Then:

- (a) If the (timelike) sectional curvature is non-positive, we get

$$\Delta r \geq (n-1) \frac{\dot{s}_c(r)}{s_c(r)}$$

on $U \setminus \{p\}$.

- (b) If the (timelike) sectional curvature is non-negative, we get

$$\Delta r \leq (n-1) \frac{\dot{s}_c(r)}{s_c(r)}$$

on $U \setminus \{p\}$.

$$\square \tau \leq (n-1) \frac{\dot{s}_{-c}(\tau)}{s_{-c}(\tau)}$$

$$\square \tau \geq (n-1) \frac{\dot{s}_{-c}(\tau)}{s_{-c}(\tau)}$$

Proof. Take the trace in the Hessian comparison. \square

Remark 4.19. The conclusions of case (b) also hold under the weaker assumption of $\text{Ric} \geq (n-1)cg$ in the Riemannian case and $\text{Ric}(X, X) \geq (n-1)c|g(X, X)|$ for timelike X in the Lorentzian case. The idea to prove this is to take the trace of the Riccati equation since $\text{tr} \nabla_{\frac{d}{dt}} \mathcal{H} = \nabla_{\frac{d}{dt}} \text{tr} \mathcal{H}$ and $\text{tr} R_{\dot{\gamma}} = -\text{Ric}(\dot{\gamma}, \dot{\gamma})$.

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Theorem 4.20 (Günther's Volume Comparison). Let (M, g) be a RMF with $\text{sec} \leq c$ for some $c \in \mathbb{R}$ and let $p \in M$. Set

$$\delta_0 := \begin{cases} \text{inj}(p) & c \leq 0 \\ \min \{\text{inj}(p), \pi R\} & c > 0 \end{cases}$$

where $\pi R = \text{inj}^c(\tilde{p})$. For $0 \leq \delta \leq \delta_0$, let

$$v_g(\delta) := \text{vol}_g(B_\delta^{d_g}(p))$$

and

$$v_c(\delta) := \text{vol}_{g^c}(B_\delta^{d_{g^c}}(\tilde{p}))$$

The Lorentzian case is considerably more difficult: There are versions of the theorem, but one has to be very careful with the regions one chooses. Taking Minkowski space, one can only compare certain "wedges" before the volume diverges.

Depending on the sign of c , M^c is one of the model spaces \mathbb{S}_R^n , \mathbb{R}^n , or \mathbb{H}_R^n .

for arbitrary $\tilde{p} \in (M^c, g^c)$. Then:

- (1) $v_g(\delta) \geq v_c(\delta)$ for all $\delta \in [0, \delta_0]$.
- (2) $\delta \mapsto \frac{v_g(\delta)}{v_c(\delta)}$ is non-decreasing on $(0, \delta_0]$ and converges to 1 as $\delta \rightarrow 0$.
- (3) If $v_g(\delta) = v_c(\delta)$ for some $\delta \in (0, \delta_0]$, then g has constant sectional curvature c on $B_\delta^{d_g}(p)$.

Remark 4.21. • Statement (1) would already follow from metric comparison.

- Analogous results are available for $\text{sec} \geq c$, but a stronger result only exists for $\text{Ric} \geq (n-1)c$.

Lemma 4.22. The Laplacian has the following form in normal coordinates:

$$\Delta r = \partial_r \log \left(r^{n-1} \sqrt{\det g_{ij}} \right). \quad (4.5)$$

Proof. See [LeeRM]. □

Proof. Let (x^i) be normal coordinates on $B_{\delta_0}(p)$. Laplacian comparison yields

$$\partial_r \left(\log(r^{n-1} \sqrt{\det g}) \right) = \Delta r \geq (n-1) \frac{\dot{s}_c(r)}{s_c(r)} = \Delta^c r^c = \partial_r (\log(s_c(r)^{n-1})).$$

Define

$$f : (0, \delta) \times \mathbb{S}^{n-1} \rightarrow \mathbb{R}$$

by

$$f(r, \theta) := \frac{r^{n-1} \sqrt{\det g(x^1(r, \theta), \dots, x^n(r, \theta))}}{s_c(r)^{n-1}}.$$

Why did we choose this f ? Writing g^c in polar coordinates, we get $g^c = dr^2 + s_c(r)^2 \dot{g}_{n-1}$.

Therefore

$$d \text{vol}_{g^c} = s_c(r)^{n-1} dr \wedge d \text{vol}_{\dot{g}_{n-1}}.$$

For g , we have

$$d \text{vol}_g = \sqrt{\det g_{ij}} \underbrace{dx^1 \wedge \dots \wedge dx^n}_{= r^{n-1} dr \wedge d \text{vol}_{\mathbb{S}^{n-1}}}.$$

Therefore, $f(r, \theta)$ is the quotient of the coefficient functions of the volume elements. But note that $\int \frac{\alpha}{\beta} \neq \frac{\int \alpha}{\int \beta}$ in general.

For any fixed θ , this is non-decreasing in r since $\partial_r \log f \geq 0$ and $\lim_{r \rightarrow 0} f(r, \theta) = 1$ since $g_{ij} = \delta_{ij} + \mathcal{O}(r^2)$ and $s_c(r) = r + \mathcal{O}(r^3)$. Now look at

$$\begin{aligned} \frac{v_g(\delta)}{v_c(\delta)} &= \frac{\int_0^\delta \int_{\mathbb{S}^{n-1}} r^{n-1} \sqrt{\det g(x(r, \theta))} d \text{vol}_{\mathbb{S}^{n-1}} dr}{\int_0^\delta \int_{\mathbb{S}^{n-1}} s_c(r)^{n-1} d \text{vol}_{\mathbb{S}^{n-1}} dr} \\ &= \frac{1}{\text{vol}(\mathbb{S}^{n-1})} \int_{\mathbb{S}^{n-1}} \underbrace{\frac{\int_0^\delta \sqrt{\det g(x(r, \theta))} r^{n-1} dr}{\int_0^\delta s_c(r)^{n-1} dr}}_{=: Q(\delta, \theta)} d \text{vol}_{\mathbb{S}^{n-1}} \end{aligned}$$

We know:

- (a) $Q(\delta, \theta) \rightarrow 1$ as $\delta \rightarrow 0$, and this convergence is uniform in θ : We see this by integration. Hence $Q(\delta, \theta) \sim \frac{\delta^n}{\delta^n}$.
- (b) $Q(\delta, \theta)$ is non-decreasing in δ : Let $0 < \delta_1 < \delta_2 \leq \delta_0$. We estimate:

$$\begin{aligned} \int_0^{\delta_1} f(r, \theta) s_c(r)^{n-1} dr \cdot \int_{\delta_1}^{\delta_2} s_c(r)^{n-1} dr &\leq f(\delta_1, \theta) \int_0^{\delta_1} s_c(r)^{n-1} dr \int_{\delta_1}^{\delta_2} \dots dr \\ &\leq \int_0^{\delta_1} \dots dr \int_{\delta_1}^{\delta_2} f(r, \theta) s_c(r)^{n-1} dr \end{aligned}$$

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This works since f is non-decreasing. We estimate further:

$$\begin{aligned}
\int_0^{\delta_1} f s_c^{n-1} dr \int_0^{\delta_2} s_c^{n-1} dr &\leq \int_0^{\delta_1} f s_c^{n-1} dr + \int_{\delta_1}^{\delta_2} s_c^{n-1} dr \\
&\leq \int_0^{\delta_1} f s_c^{n-1} dr \int_0^{\delta_1} s_c^{n-1} dr + \int_0^{\delta_1} s_c^{n-1} dr \int_{\delta_1}^{\delta_2} f s_c^{n-1} dr \\
&= \int_0^{\delta} s_c(r)^{n-1} dr \int_0^{\delta_2} f s_c^{n-1} dr.
\end{aligned}$$

This is fully equivalent to $Q(\delta_1, \theta) \leq Q(\delta_2, \theta)$. This proves claim (2).

Since (2) implies (1), only (3) remains.

(c) If $v_g(\bar{\delta}) = v_c(\bar{\delta})$, we have $Q(\delta, \theta) = 1$ for all δ and θ . This implies

$$\Delta r = (n-1) \frac{\dot{s}_c(r)}{s_c(r)}$$

on $B_{\bar{\delta}}(p)$. In turn, this implies

$$\text{tr} \left(\underbrace{\mathcal{H}_r - \frac{\dot{s}_c(r)}{s_c(r)} \pi^S}_{\text{pos. semi-def. by Hessian comparison}} \right) = 0.$$

Therefore, vanishing trace implies that the operator vanishes as a whole. We obtain

$$\mathcal{H}_r = \frac{\dot{s}_c(r)}{s_c(r)} \pi^S$$

on $B_{\bar{\delta}}(p)$. The "only if"-part of Theorem (Hessian in Constant Curvature) now implies that $(B_{\bar{\delta}}(p), g)$ has constant curvature c .

□

CHAPTER FIVE

Global Results for Riemannian Manifolds

5.1 The Theorem of Killing-Hopf

For some constant c , one considers the **model spaces** of constant curvature c .

$$M^c = \begin{cases} \mathbb{S}_R^n & c > 0, R = \frac{1}{\sqrt{c}} \\ \mathbb{R}^n & c = 0 \\ \mathbb{H}_R^n & c < 0, R = \frac{1}{\sqrt{-c}} \end{cases}.$$

Theorem 5.1 (Killing-Hopf). Let (M, g) be a complete, simply connected RMF of $\dim M \geq 2$ with constant sectional curvature c . Then (M, g) is globally isometric to the model space of constant curvature c .

The tools we need to prove this theorem are twofold:

- (a) Local isometries are uniquely determined by the volume and tangent map at a single point.
- (b) Some results about isometries of model spaces.

Proposition 5.2. (a) Any isometry

(i) $\varphi : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is given by $\varphi(x) = Ax + y$ for some orthogonal matrix A and $a \in \mathbb{R}^n$.

(ii) $\varphi : \mathbb{S}^n \rightarrow \mathbb{S}^n$ is given by $\varphi = \Phi|_{\mathbb{S}^n}$ where $\Phi : \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{n+1}$ is given by $Ax = \Phi(x)$ for some orthogonal $(n+1)$ -matrix A .

(iii) $\varphi : \mathbb{H}^n \rightarrow \mathbb{H}^n$ is given by $\Psi|_{\mathbb{H}^n}$ where Ψ is an isometry of $(\mathbb{R}^{1,n}, \eta)$ leaving \mathbb{H}^n invariant.

(b) Any local isometry of a model space is also of this form (in particular automatically global).

Theorem 5.3 (Covering Map). Let (M, g) and $(\widetilde{M}, \widetilde{g})$ be RMF, and let \widetilde{M} be complete. If $\varphi : \widetilde{M} \rightarrow M$ is a local isometry, then (M, g) is also complete and φ is a covering map.

Proof. We need to show that for all $p \in M$ there is some neighbourhood U of p such that $\varphi^{-1}(U)$ is a disjoint union of connected open \widetilde{U}_α with $\varphi|_{\widetilde{U}_\alpha} : \widetilde{U}_\alpha \rightarrow U$ being a diffeomorphism for all α . We start with the path lifting property: Let $p \in \varphi(\widetilde{M}) \subseteq M$ and $\gamma : I \rightarrow M$ be a geodesic with $\gamma(0) = p$. Fix $\tilde{p} \in \varphi^{-1}(p)$. If $\tilde{\gamma} : I \rightarrow \widetilde{M}$ is any geodesic with $\tilde{\gamma}(0) = \tilde{p}$ and $\varphi \circ \tilde{\gamma} = \gamma$, then we know that

$$\dot{\tilde{\gamma}}(0) = (\varphi)_{*, \tilde{p}}^{-1}(\dot{\gamma}(0)) =: v \in T_{\tilde{p}}\widetilde{M}.$$

Since $(\widetilde{M}, \widetilde{g})$ is complete, there exists precisely one geodesic $\tilde{\gamma}_v : \mathbb{R} \rightarrow \widetilde{M}$ with $\tilde{\gamma}_v(0) = \tilde{p}$ and $\dot{\tilde{\gamma}}_v(0) = v$. Hence $\tilde{\gamma} := \tilde{\gamma}_v|_I : I \rightarrow \widetilde{M}$ is a geodesic in \widetilde{M} . Since φ is a local isometry, $\varphi \circ \tilde{\gamma} : I \rightarrow M$ is a geodesic in M with initial data $(\varphi \circ \tilde{\gamma})(0) = p$ and $\partial_t(\varphi \circ \tilde{\gamma})(0) = \dot{\gamma}(0)$. Therefore, $\varphi \circ \tilde{\gamma} = \gamma$ as desired. Since $\varphi \circ \tilde{\gamma}_v : \mathbb{R} \rightarrow M$ is an extension of $\gamma : I \rightarrow M$, this also shows completeness.

Next we show surjectivity of φ . Let $q \in M$ be arbitrary and $p \in \varphi(\widetilde{M})$. Since M is complete, there exists a geodesic $\gamma_{pq} : [0, 1] \rightarrow M$ connecting p and q . Let $\tilde{\gamma}$ be a geodesic lift of γ , then $(\varphi \circ \tilde{\gamma})(1) = \gamma(1) = q$, so $q = \varphi(\tilde{\gamma}(1)) \in \text{im } \varphi$.

Now it remains to show that φ covers M . Let $p \in M$ be arbitrary, and set $U = B_\varepsilon^{d_g}(p)$ with ε small enough for U to be a normal neighbourhood of p . Write $\varphi^{-1}(p) = \{p_\alpha\}_{\alpha \in A}$. For each $\alpha \in A$, let $\tilde{U}_\alpha := B_\varepsilon^{d_{\tilde{g}}}(\tilde{p}_\alpha)$. Let $\alpha, \beta \in A$ with $\alpha \neq \beta$. Then $\tilde{p}_\alpha \neq \tilde{p}_\beta$, and we can find a minimizing geodesic $\tilde{\gamma}$ connecting the points. As φ is a local isometry, $\gamma := \varphi \circ \tilde{\gamma}$ is a geodesic from p to p with $L_g[\gamma] = L_{\tilde{g}}[\tilde{\gamma}] > 0$. Therefore, γ must leave U eventually and return to p , implying $L_g[\gamma] \geq 2\varepsilon$. Henceforth,

$$d(\tilde{p}_\alpha, \tilde{p}_\beta) = L_{\tilde{g}}[\tilde{\gamma}] \geq 2\varepsilon,$$

so $\tilde{U}_\alpha \cap \tilde{U}_\beta = \emptyset$.

We also have to show that $\varphi^{-1}(U) = \bigcup_{\alpha \in A} \tilde{U}_\alpha$. Let $\tilde{q} \in \bigcup_{\alpha \in A} \tilde{U}_\alpha$, so $\tilde{q} \in \tilde{U}_{\alpha_0}$ for some $\alpha_0 \in A$. Let $\tilde{\gamma}$ be the minimizing geodesic from \tilde{p}_{α_0} to \tilde{q} . Then

$$\varepsilon > d_{\tilde{g}}(\tilde{p}_{\alpha_0}, \tilde{q}) = L_{\tilde{g}}[\tilde{\gamma}] = L_g[\varphi \circ \tilde{\gamma}].$$

This implies $d_g(\varphi(\tilde{p}_{\alpha_0}), \varphi(\tilde{q})) < \varepsilon$, so $\varphi(\tilde{q}) \in U$, as desired. Now let $\tilde{q} \in \varphi^{-1}(U)$. Then $q := \varphi(\tilde{q}) \in U$. Let γ be the minimizing geodesic connecting p and q in M . By the unique path lifting property, there exists precisely one geodesic $\tilde{\gamma}$ in \widetilde{M} with $\tilde{\gamma}(1) = \tilde{q}$ and $\varphi \circ \tilde{\gamma} = \gamma$. Therefore,

$$d_{\tilde{g}}(\tilde{\gamma}(0), \tilde{q}) < L_{\tilde{g}}[\tilde{\gamma}] = L_g[\gamma] = d_g(p, q) < \varepsilon.$$

Hence $\tilde{q} \in B_\varepsilon^{d_{\tilde{g}}}(\tilde{\gamma}(0)) = \tilde{U}_\alpha$ for some $\alpha \in A$.

The only remaining property to show is that $\varphi|_{\tilde{U}_\alpha} : \tilde{U}_\alpha \rightarrow U$ is a diffeomorphism for all $\alpha \in A$, so we need bijectivity since it is already a local isometry. Let $q \in U$ and let γ be the unique geodesic connection p to q in

5.1. THE THEOREM OF KILLING-HOPF

U . By the path lifting, there exists precisely one $\tilde{\gamma}$ from \tilde{p}_α to $\tilde{\gamma}(1) \in \tilde{U}_\alpha$ and $\tilde{\gamma}(1) = (\varphi|_{\tilde{U}_\alpha})^{-1}(q)$. This means we can even explicitly construct $(\varphi|_{\tilde{U}_\alpha})^{-1}$. \square

Back to Killing-Hopf: We know that for all $p \in M$ exists some U_p and φ_p with $\varphi_p : U_p \rightarrow M_c$ being a local isometry. The question is whether we are able to patch those φ_p together to obtain a local isometry $\Phi : M \rightarrow M_c$. Before that, we have to know if we can extend a given φ_p to a local isometry $\varphi : U \rightarrow M_c$ along a given curve starting at p .

Definition 5.4 (Isometric Continuation). Let (M, g) and (\tilde{M}, \tilde{g}) be RMF, and let, for $U \subseteq M$, $\varphi : U \rightarrow \tilde{M}$ be a local isometry. Let $\gamma : [0, 1] \rightarrow M$ be a continuous curve with $\gamma(0) \in U$. Then an **isometric (analytic) continuation** of φ along γ is a family of pairs

$$\{(U_t, \varphi_t) \mid t \in [0, 1]\}$$

of connected, open neighbourhoods U_t of $\gamma(t)$ and local isometries $\varphi_t : U_t \rightarrow \tilde{M}$ such that $\varphi_0 = \varphi$ on $U_0 \cap U$, and for any $t \in [0, 1]$ exists $\delta_t > 0$ such that:

$$\forall s \in [0, 1] \text{ with } |t - s| < \delta_t : \gamma(s) \in U_t \text{ and } \varphi_t = \varphi_s \text{ on } U_t \cap U_s.$$

Lemma 5.5 (Uniqueness of Isometric Continuation). In the setting of Definition 5.4: If $\{(U_t, \varphi_t)\}$ and $\{(U'_t, \varphi'_t)\}$ are two isometric continuations of φ along the same curve γ , then $\varphi_1 = \varphi'_1$ on a neighbourhood of $\gamma(1)$.

For large T we do not require $\varphi_T = \varphi_0$ on $U_0 \cap U_T$ even though $U_0 \cap U_T \neq \emptyset$ is possible.

Proof. Let

$$\mathcal{I} := \{t \in [0, 1] \mid \varphi_t = \varphi'_t \text{ on a nbhd. of } \gamma(t)\}.$$

We have $0 \in \mathcal{I}$ since $\varphi_0 = \varphi = \varphi'_0$ on $U \cap U_0 \cap U'_0$. Now we show \mathcal{I} is clopen.

Let $t \in \mathcal{I}$. There exists δ_t, δ'_t as in the definition such that for all

$$s \in [t - \min(\delta_t, \delta'_t), t + \min(\delta_t, \delta'_t)] \cap \mathcal{I}$$

we have $\varphi_s = \varphi_t = \varphi'_t = \varphi'_s$ on $U_s \cap U_t \cap \tilde{U} \cap U'_s \cap U'_t$, so there exists an open neighbourhood of $t \in \mathcal{I}$. Therefore, \mathcal{I} is open in $[0, 1]$.

Let $t_i \rightarrow t \in [0, 1]$ be a sequence with $t_i \in \mathcal{I}$ for all i . For i large enough, $\varphi_t = \varphi_{t_i} = \varphi'_{t_i} = \varphi'_t$ on a neighbourhood of $\gamma(t_i)$ in $U_t \cap U'_t$. This implies $(\varphi_t)_{*, \gamma(t_i)} = (\varphi'_{t_i})_{*, \gamma(t_i)}$ and $\varphi_t(\gamma(t_i)) = \varphi'_{t_i}(\gamma(t_i))$ for all i . Taking the limit $i \rightarrow \infty$ then leads to $(\varphi_t)_{*, \gamma(t)} = (\varphi'_t)_{*, \gamma(t)}$ and $\varphi_t(\gamma(t)) = \varphi'_t(\gamma(t))$. By exercise 5 on sheet 10, $\varphi_t = \varphi'_t$ on a neighbourhood of $\gamma(t)$. Hence \mathcal{I} is also closed, therefore clopen. The only non-empty clopen subset of $[0, 1]$ is $[0, 1]$, so $\mathcal{I} = [0, 1]$. \square

Theorem 5.6 (Homotopic Uniqueness). With the same setup as in Definition 5.4: Assung φ has an isometric continuation along any continuous curve starting at p . If $\omega_1, \omega_2 : [0, 1] \rightarrow M$ are continuous curves starting at p which are also fixed-endpoint homotopic, then any isometric continuations (U_t^0, φ_t^0) and (U_t^1, φ_t^1) along ω_0 resp. ω_1 satisfy

$$\varphi_1^0 = \varphi_1^1$$

on a neighbourhood of q .

Proof. Let $H : [0, 1]^2 \rightarrow M$ be a fixed-endpoint homotopy from $\omega_1 = H_1$ to $\omega_0 = H_0$. For any $s \in [0, 1]$, there exist isometric continuations (U_t^s, φ_t^s) of φ along H_s . Since H is continuous and $[0, 1]$ compact, any $\bar{s} \in [0, 1]$ has a neighbourhood $(\bar{s} - \delta_{\bar{s}}, \bar{s} + \delta_{\bar{s}})$ such that $H_s(t) \in U_{\bar{t}}^{\bar{s}}$ for all $t \in [0, 1]$ and all $s \in (\bar{s} - \delta_{\bar{s}}, \bar{s} + \delta_{\bar{s}})$. Hence (U_t^s, φ_t^s) is an isometric continuation along H_s for all $s \in (\bar{s} - \delta_{\bar{s}}, \bar{s} + \delta_{\bar{s}})$. \square