



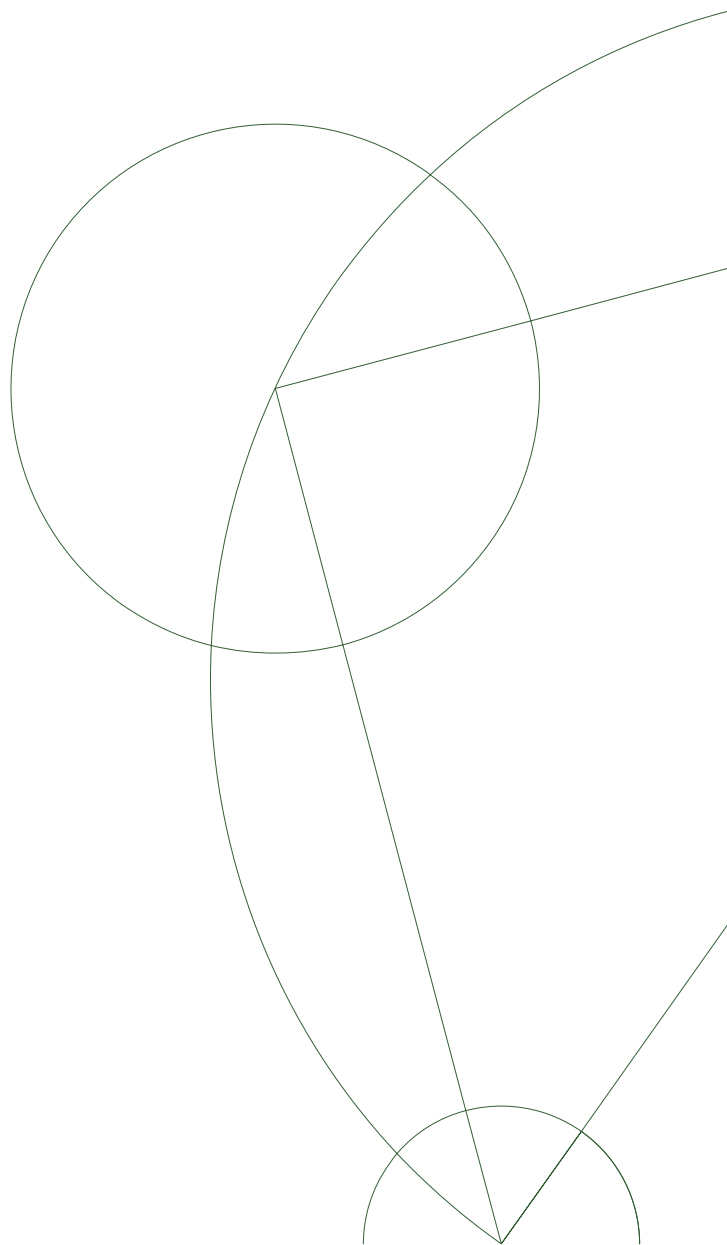
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ANALYSIS OF SHAPE SPACES

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## Abstract

Abstract about analysis of shapes.



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# Introduction

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Intro





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# 1. Preliminaries

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## 1.1 Notation

In the following  $M$  denotes a smooth manifold and  $TM$  is the tangent bundle of  $M$  and  $\mathcal{T}(M)$  denotes the space of all vector fields on  $M$ . For  $I \subset \mathbb{R}$ ,  $\gamma : I \rightarrow M$  is a curve in  $M$ , i.a. a smooth map.

## 1.2 Connections

To consider the geodesic distance between two points in a manifold, geodesics need to be defined in a coordinate-invariant way such that the distance is independent of the coordinate charts. One property of geodesics in a Euclidean space, straight lines, is that they have acceleration 0. In order to make sense of acceleration of a curve in a manifold, we need to be able to compute "differences" between tangent spaces along the curve. *Connections* are exactly a way of making computations between tangent spaces possible - they allow us to differentiate vector fields along curves.

Since our use of connections is to define geodesics, we define connections in the tangent bundle of a manifold (instead of defining them generally on smooth sections of vector bundles) following chapter 4 of Lee (1997).

**Definition 1.2.1.** *A connection in  $TM$  is a map*

$$\nabla : \mathcal{T}(M) \times \mathcal{T}(M) \rightarrow \mathcal{T}(M),$$

*written  $(X, Y) \mapsto \nabla_X Y$  satisfying (for  $f, g \in C^\infty(M)$  and  $a, b \in \mathbb{R}$ );*

$$a) \nabla_{fX_1 + gX_2} Y = f\nabla_{X_1} Y + g\nabla_{X_2} Y \quad (\text{linearity over } C^\infty(M) \text{ in } X)$$

$$b) \nabla_X (aY_1 + bY_2) = a\nabla_X Y_1 + b\nabla_X Y_2 \quad (\text{linearity over } \mathbb{R} \text{ in } Y)$$

$$c) \nabla_X (fY) = f\nabla_X Y + (Xf)Y \quad \text{product rule}$$

In accordance with connections allowing "differences" between tangent spaces,  $\nabla_X Y$  is called the *covariant derivative of  $Y$  in the direction of  $X$* . Note that the product rule for connections is identical to the product rule of derivations. To use connections to derivate along curves, we need the definition of a *vector field along a curve*, which is a smooth map  $V : I \rightarrow TM$  such that  $V(t) \in T_{\gamma(t)}M$  for all  $t \in I$ . The prime example of a vector field along a curve is its velocity,  $\dot{\gamma}(t) \in T_{\gamma(t)}M$ , which acts on functions,  $f \in C^\infty(M)$ ,

by

$$\dot{\gamma}(t)f = \frac{d}{dt}(f \circ \gamma)(t).$$

We denote by  $\mathcal{T}(\gamma)$  all vector fields along  $\gamma$ . To define geodesics all we now need is to define what it means to take the covariant derivative of  $V \in \mathcal{T}(\gamma)$  along  $\gamma$ . This covariant derivative is noted  $D_t V$  and has the following properties.

**Lemma 1.2.2.** *Let  $\nabla$  be a linear connection on  $M$ . For each  $\gamma : I \rightarrow M$ ,  $\nabla$  determines a unique operator*

$$D_t : \mathcal{T}(\gamma) \rightarrow \mathcal{T}(\gamma),$$

*satisfying (for  $f, g \in C^\infty(I)$  and  $a, b \in \mathbb{R}$ );*

- a)  $D_t(aV + bW) = aD_tV + bD_tW$  *(linearity over  $\mathbb{R}$ )*
- b)  $D_t(fV) = \dot{f}V + fD_tV$  *(product rule)*
- c) *If  $V$  is extendible, then for any extension  $\tilde{V}$  of  $V$ ,  $D_tV(t) = \nabla_{\dot{\gamma}(t)}\tilde{V}$ .*

*Proof.*

Proof of Lemma 4.9 in Lee (1997) □

$V$  is said to be extendible if it can be constructed by any vector field on  $M$ ,  $\tilde{V}$  by letting  $V(t) := \tilde{V}_{\gamma(t)}$ . This is not always the case; if  $V$  is the velocity of an intersecting curve  $\gamma$  with different covariant derivative at the intersection times. The covariant derivative of the velocity of a curve is now used to define a geodesic.

**Definition 1.2.3.** *Let  $\nabla$  be a linear connection on  $M$  and  $\gamma$  a curve in  $M$ . The acceleration of  $\gamma$  is  $D_t\dot{\gamma}(t)$ . If this vector field is zero,  $D_t\dot{\gamma}(t) \equiv 0$ , then  $\gamma(t)$  is a geodesic with respect to  $\nabla$*

It follows from Theorem 4.10 in Lee (1997) that for any manifold,  $M$ , with a linear connection, for any  $p \in M$  and  $V \in T_pM$  and  $t_0 \in \mathbb{R}$  there exists an un-extendable geodesic,  $\gamma_V : I \rightarrow M$ , with  $\gamma(0) = p$  and  $\dot{\gamma}(0) = V$ . The geodesic is called the (maximal) geodesic with initial value  $p$  and initial velocity  $V$ .

In this construction of geodesics the only necessary structure of  $M$  is that it should be a smooth manifold. When  $M$  is also equipped with a Riemannian metric, making  $M$  a Riemannian manifold, the choice of connection (determining the geodesics) should in some way respect the metric. Geodesics resulting from this specific choice of connection are called *Riemannian geodesics*.

### 1.3 Riemannian Geodesics

Let  $M$  be Riemannian manifold with metric  $g$ . To define Riemannian geodesics, we must first choose a specific connection on  $M$  with two properties - *compatibility w.r.t.  $g$*  and *symmetric* (these properties arise when trying to generalize the tangential connection of a manifold submersed in  $\mathbb{R}^n$ ).

**Definition 1.3.1.** *A connection on  $M$  is compatible with  $g$  if the product rule*

$$\nabla_X(Y, Z) = \langle \nabla_X Y, Z \rangle + \langle Y, \nabla_X Z \rangle$$

*holds for all vector fields,  $X, Y$  and  $Z$ .*

By Lemma 5.2 in Lee (1997) this condition is equivalent with

$$\frac{d}{dt} \langle V, W \rangle = \langle D_t V, W \rangle + \langle V, D_t W \rangle,$$

for  $V, W$  being vector fields along any curve  $\gamma$ .

The definition of a symmetric connection involves the Lie bracket of two vector fields. If we think of vector fields on  $M$ ,  $X, Y$ , as derivations acting on  $C^\infty(M)$ , then the Lie bracket of  $X$  and  $Y$ ,  $[X, Y]$ , is the vector field (derivation) which acts on  $f \in C^\infty(M)$  by

$$[X, Y](f) := X(Y(f)) - Y(X(f)),$$

where  $X(f) \in C^\infty(M)$  is the function which evaluated at  $p$  is the derivative of  $f$  at  $p$  in the direction of  $X(p)$ .

**Definition 1.3.2.** *A connection on  $M$  is symmetric if*

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

(Note that interchanging  $X$  and  $Y$  makes sense, since  $[X, Y] = -[Y, X]$ .) A symmetric connection is also called *torsion free*, which corresponds to the vector fields along any curve not being "twisted" when they are parallel transported along the curve. By the Fundamental Theorem of Riemannian Geometry, given any Riemannian manifold  $(M, g)$ , there exists a unique connection,  $\nabla$ , on  $M$  that is symmetric and compatible with  $M$ . This connection is called the Riemannian connection or the Levi-Civita connection, and geodesics with respect to this connection are called Riemannian geodesics. Since this choice of connection is unique, geodesics in a Riemannian manifold will always mean Riemannian geodesics.



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# Bibliography

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Lee, John M (1997). *Riemannian Manifolds*. Vol. 1. Springer.