Analysis of 3D Shapes (IN2238)

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Christoffel Symbols

Given a coordinate map $x\colon U \to M$ of the n-dimensional manifold $M \subset \mathbb{R}^{n+1}$, the (intrinsic) Riemannian metric is given as

$$g\colon U \to \mathbb{R}^{n \times n} \qquad g_{ij}(u) = \langle \partial_i x(u), \partial_j x(u) \rangle$$

While the first derivatives $\partial_i x(u)$ lie in the n-dimensional vector space $T_{x(u)}M$, the second derivatives might contain a normal component, *i.e.*,

$$\partial_{ij} x(u) = \sum_{k=1}^{n} \Gamma_{ij}^{k}(u) \partial_k x(u) + \alpha_{ij}(u) N(u)$$

The n^3 scalar functions $\Gamma_{ij}^k\colon U \to \mathbb{R}$ are called **Christoffel symbols**.
They are symmetric in i and j, *i.e.*, $\Gamma_{ij}^k = \Gamma_{ji}^k$. (Why?)

Christoffel Symbols and Metric

Using $\partial_i g_{j\ell}(u) = \langle \partial_{ij} x(u), \partial_\ell x(u) \rangle + \langle \partial_{i\ell} x(u), \partial_j x(u) \rangle$, we obtain

$$\begin{aligned}
\tilde{\Gamma}_{\ell ij}(u) :=& \frac{1}{2}[\partial_i g_{j\ell}(u) + \partial_j g_{\ell i}(u) - \partial_\ell g_{ij}(u)] \\
=& \frac{1}{2}[\langle \partial_{ij} x(u), \partial_\ell x(u) \rangle + \langle \partial_{\mathbf{i}\ell} \mathbf{x}(\mathbf{u}), \partial_{\mathbf{j}} \mathbf{x}(\mathbf{u}) \rangle + \langle \partial_{\mathbf{j}\ell} \mathbf{x}(\mathbf{u}), \partial_{\mathbf{i}} \mathbf{x}(\mathbf{u}) \rangle + \\
& \langle \partial_{ji} x(u), \partial_\ell x(u) \rangle - \langle \partial_{\ell\mathbf{i}} \mathbf{x}(\mathbf{u}), \partial_{\mathbf{j}} \mathbf{x}(\mathbf{u}) \rangle - \langle \partial_{\ell\mathbf{j}} \mathbf{x}(\mathbf{u}), \partial_{\mathbf{i}} \mathbf{x}(\mathbf{u}) \rangle] \\
=& \langle \partial_{ij} x(u), \partial_\ell x(u) \rangle = \sum_{k=1}^{n} \Gamma_{ij}^{k}(u) g_{k\ell}(u)
\end{aligned}$$

If we use the notation $g^{ij}(u) := (g(u)^{-1})_{ij}$, we obtain

$$\sum_{\ell=1}^{n} g^{k\ell}(u) \tilde{\Gamma}_{\ell ij}(u) = \sum_{k'=1}^{n} \sum_{\ell=1}^{n} g^{k\ell}(u) g_{\ell k'}(u) \Gamma_{ij}^{k'}(u) = \Gamma_{ij}^{k}(u)$$

Christoffel Symbols are Intrinsic

In summary, we have

$$\partial_{ij}x = \sum_{k=1}^{n} \Gamma_{ij}^{k} \partial_k x + \alpha_{ij} N$$

with the **intrinsic** Christoffel symbols

$$\Gamma_{ij}^{k} = \sum_{\ell=1}^{n} \frac{1}{2} g^{kl} [\partial_i g_{j\ell} + \partial_j g_{\ell i} - \partial_\ell g_{ij}]$$

The expression $\sum_{k=1}^{n} \Gamma_{ij}^{k} \partial_k x$ can also be seen as an intrinsic derivative of the vector field $\partial_j x$ in the direction of $\partial_i x$.

This derivative is called **covariant derivative** $\nabla_{\partial_i x} \partial_j x$.

Example: Sphere

Given the coordinate map

$$x\colon \left]-\frac{\pi}{3},\frac{\pi}{3}\right[\times \left]-\frac{\pi}{3},\frac{\pi}{3}\right[\to \mathbb{S}^2$$
$$(\alpha_1,\alpha_2) \mapsto \begin{pmatrix}\cos(\alpha_1)\cos(\alpha_2)\\ \sin(\alpha_1)\cos(\alpha_2)\\ \sin(\alpha_2)\end{pmatrix}$$

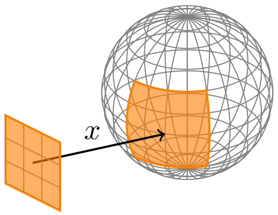
we obtain the Riemannian metric

$$g(\alpha_1,\alpha_2) = \begin{pmatrix}\cos(\alpha_2)^2 & 0\\ 0 & 1\end{pmatrix}$$

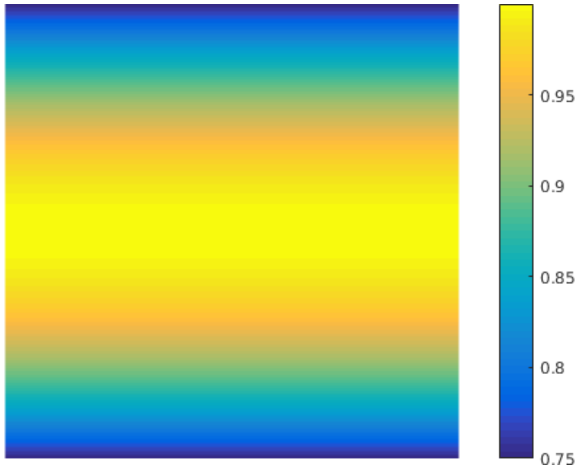
and the Christoffel symbols

$$\Gamma^1(\alpha_1,\alpha_2) = -\frac{\sin(2\alpha_2)}{2\cos(\alpha_2)^2}\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix} \qquad \Gamma^2(\alpha_1,\alpha_2) = \frac{\sin(2\alpha_2)}{2}\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}$$

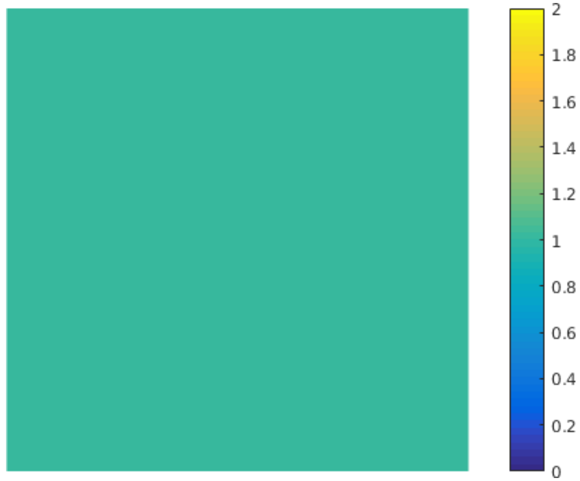
Example: Christoffel Symbols



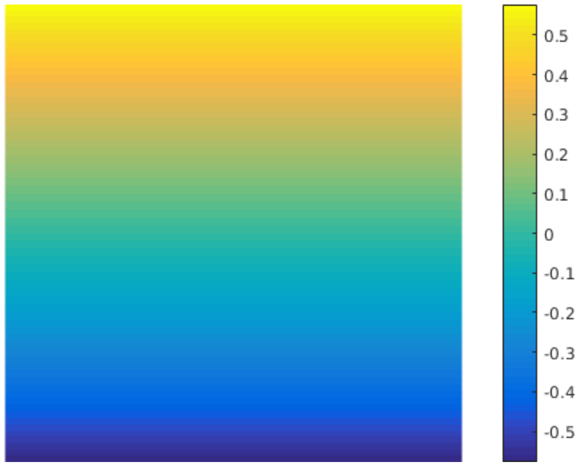
Parametrization



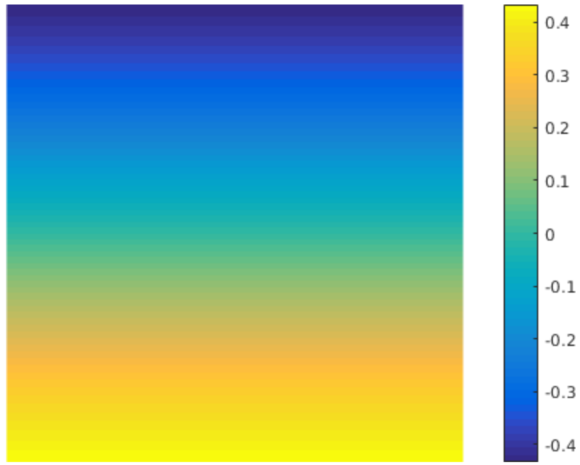
g_{11}



g_{22}

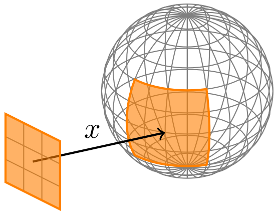


$\Gamma^1_{12} = \Gamma^1_{21}$

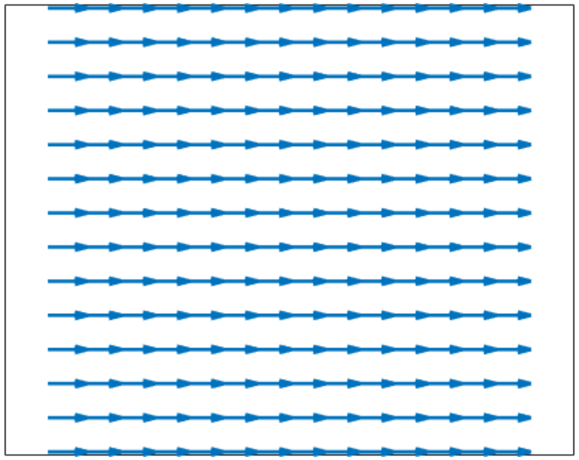


Γ^2_{11}

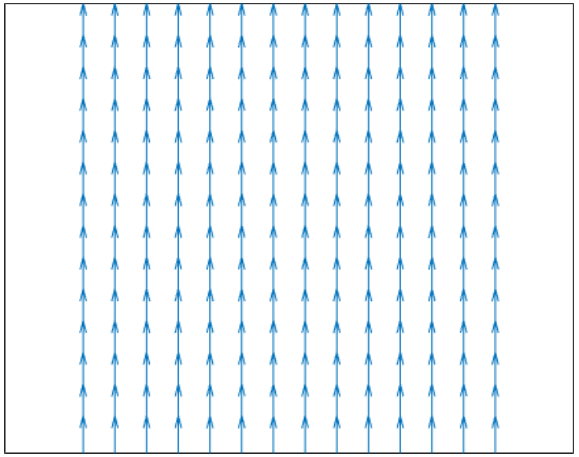
Example: Covariant Derivative



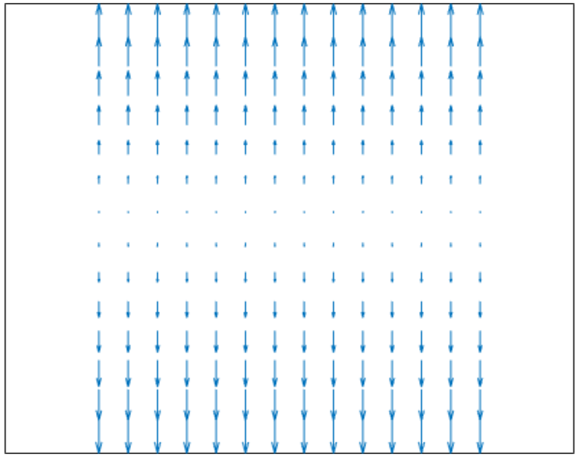
Parametrization



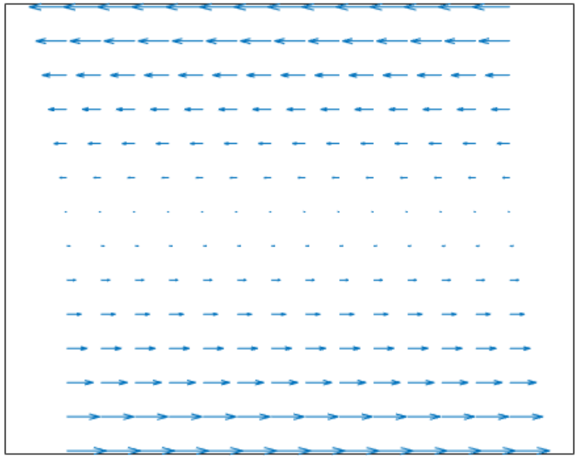
"$\partial_1 x$"



"$\partial_2 x$"



"$\nabla_{\partial_1 x} \partial_1 x$"



"$\nabla_{\partial_1 x} \partial_2 x$" = "$\nabla_{\partial_2 x} \partial_1 x$"

"$\nabla_{\partial_2 x} \partial_2 x$"

Covariant Derivative

Given a coordinate map $x\colon U \to M$ of the n-dimensional manifold $M \subset \mathbb{R}^{n+1}$, and two vector fields Y and Z represented as ($p = x(u)$)

$$Y(p) = \sum_{i=1}^{n} y_i(u)\partial_i x(u) \qquad\qquad Z(p) = \sum_{j=1}^{n} z_j(u)\partial_j x(u),$$

the **covariant derivative** $\nabla_Z Y$ is a vector field that can be represented as

$$\left[\nabla_{\partial_j x}\partial_i x\right](p) = \sum_{k=1}^{n} \Gamma_{ij}^{k}(u)\partial_k x(u)$$

$$\left[\nabla_{\partial_j x} Y\right](p) = \sum_{i=1}^{n} y_i(u)\nabla_{\partial_j x}\partial_i x(p) + \partial_j y_i(u)\partial_i x(u) \qquad \text{(product rule in } Y\text{)}$$

$$\left[\nabla_Z Y\right](p) = \sum_{j=1}^{n} z_j(u)\cdot\nabla_{\partial_j x} Y(p) \qquad \text{(linearity in } Z\text{)}$$

Extrinsic Formulation

$\nabla_Z Y$ can be formulated in a simpler manner if Y and Z can be extended to the ambient space $\mathbb{R}^{n+1}$ of M. To this end let

$$\tilde{Y}, \tilde{Z} \colon \mathbb{R}^{n+1} \to \mathbb{R}^{n+1}$$

with $\tilde{Y}|M = Y$ and $\tilde{Z}|M = Z$.

Then, we have for every $p \in M$

$$\nabla_Z Y(p) = \pi_{T_pM} \left(D\tilde{Y}(p) \cdot \tilde{Z}(p) \right),$$

where

$$\pi_{T_pM} \colon \mathbb{R}^{n+1} \to T_pM$$

is the orthogonal projection of the ambient space $\mathbb{R}^{n+1}$ onto T_pM.

Shortest Path in Local Coordinates

Given a coordinate map $x\colon U \to M$ of the n-dimensional manifold M, we like to find the shortest path $\gamma\colon [0,1] \to U$ that connects two points $u_0, u_1 \in U$.

The length of γ is induced by the Riemannian metric $g\colon U \to \mathbb{R}^{n\times n}$ via

$$\mathrm{length}(\gamma) = \int_0^1 \langle \dot\gamma(t), g(\gamma(t)) \cdot \dot\gamma(t)\rangle^{\frac{1}{2}}\,\mathrm{dt}$$

It is often easier to consider the following energy function instead

$$E(\gamma) = \left[\int_0^1 \langle \dot\gamma(t), g(\gamma(t)) \cdot \dot\gamma(t)\rangle\,\mathrm{dt}\right]^{\frac{1}{2}}$$

Using the Cauchy-Schwarz inequality, we obtain

$$\mathrm{length}(\gamma) \leqslant E(\gamma)$$

with equality iff $\|\dot\gamma\|_g \equiv \mathrm{const}$, *i.e.*, γ is uniformly parametrized.

Geodesics

Let us select the two minimizers $\gamma^* \in \operatorname{argmin} \operatorname{length}(\cdot)$ and $\hat{\gamma} \in \operatorname{argmin} E(\cdot)$. Further we assume that $\bar{\gamma}^*$ is a uniform re-parametrization of γ^*.

Then we have

$$\operatorname{length}(\gamma^*) = \operatorname{length}(\bar{\gamma}^*) = E(\bar{\gamma}^*) \geqslant E(\hat{\gamma}) \geqslant \operatorname{length}(\hat{\gamma}) \geqslant \operatorname{length}(\gamma^*).$$

Therefore, we know

Every minimizer of E minimizes length	$[\operatorname{length}(\hat{\gamma}) = \operatorname{length}(\gamma^*)]$
The minimum of E is the minimal length	$[\operatorname{length}(\hat{\gamma}) = E(\hat{\gamma})]$
The minimizer of E is uniformly parametrized	$[\operatorname{length}(\hat{\gamma}) = E(\hat{\gamma})]$

Minimizing E provides us with a uniformly parametrized shortest path between two points. Every local minimum of E is called **geodesic**.

Geodesic Equation

Given two points $u_0, u_1 \in U$, a geodesic $\gamma = (\gamma_1, \dots, \gamma_n)\colon [0,1] \to U$ that connects these points minimizes

$$E(\gamma_1, \dots, \gamma_n) := \int_0^1 \sum_{i,j=1}^{n} g_{ij}(\gamma(t)) \cdot \dot{\gamma}^i(t)\dot{\gamma}^j(t)\mathrm{dt}$$

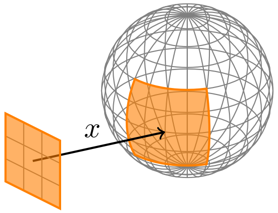
The **Euler-Lagrange equation** is

$$0 = \frac{\partial E}{\partial \gamma_k} = \sum_{i,j=1}^{n} \partial_k g_{ij}(\gamma(t))\dot{\gamma}^i(t)\dot{\gamma}^j(t) - \frac{\mathrm{d}}{\mathrm{dt}}\left[2\sum_{i=1}^{n} g_{ik}(\gamma(t))\dot{\gamma}^i(t)\right]$$

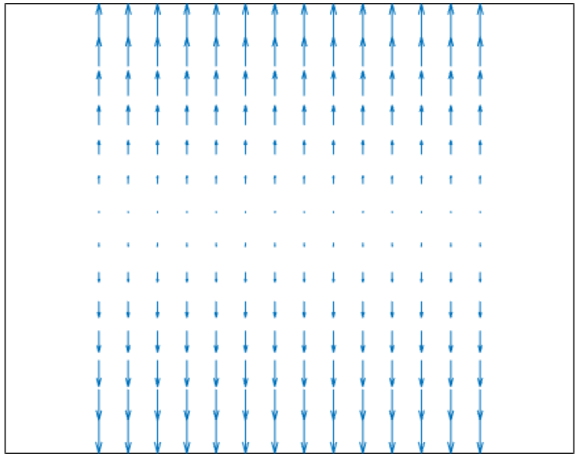
$$\ddot{\gamma}^k = -\left\langle \dot{\gamma}, \Gamma^k \dot{\gamma} \right\rangle$$

and can therefore be presented with respect to the Christoffel symbols.

Example: Geodesics

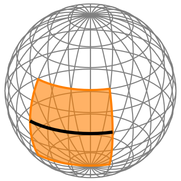


Parametrization

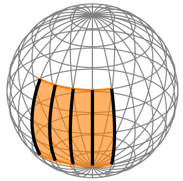


“$\nabla_{\partial_1 x}\partial_1 x$”

“$\nabla_{\partial_2 x}\partial_2 x$”



Equator



Meridians

Covariant Derivative along Curves

Given a curve $\gamma\colon (0,L) \to U$ and a vector field X along the curve $c = x \circ \gamma$, we would like to define

$$\frac{\nabla}{\mathrm{dt}} X := \nabla_{\dot{c}} X$$

To this end let $Y = \sum_{i=1}^{n} y^i \partial_i x$ be a vector field on M that coincides along c with X. Further let $Z = \sum_{i=1}^{n} z^i \partial_i x$ be a vector field that coincides along c with $\dot{c}$. Then we have $(p = x(u) = c(\tau))$

$$\nabla_Z Y(p) = \sum_{k=1}^{n} \left[\frac{\mathrm{d}}{\mathrm{dt}} \left(y^k \circ \gamma(t) \right)\Big|_{t=\tau} + \sum_{i,j=1}^{n} y^i(u) \Gamma_{ij}^k(u) z^j(u) \right] \partial_k x(u)$$

If we restrict this vector field to a vector field along the curve, it only depends on X and c, but not on the extension of Y and Z. Thus, $\frac{\nabla}{\mathrm{dt}}$ is well defined.

Geodesic Equation in Terms of the Covariant Derivative

Given a geodesic $c\colon (0,1) \to M$, we have for $\dot{c} = \sum_{i=1}^{n} \dot{\gamma}^i \partial_i x$

$$
\begin{aligned}
\frac{\nabla}{\mathrm{dt}}\dot{c} &= \sum_{k=1}^{n} \left[\ddot{\gamma}^k + \sum_{i,j=1}^{n} \dot{\gamma}^i \Gamma_{ij}^k \dot{\gamma}^j \right] \partial_k x \\
&= \sum_{k=1}^{n} \left[\ddot{\gamma}^k + \left\langle \dot{\gamma}, \Gamma^k \dot{\gamma} \right\rangle \right] \partial_k x = 0
\end{aligned}
$$

The geodesic equation can therefore be written as

$$\frac{\nabla}{\mathrm{dt}}\dot{c} = 0$$

Since $\frac{\nabla}{\mathrm{dt}}\dot{c}$ measures how different a curve c is from a geodesic we can use it to define the **geodesic curvature** of a curve.

Geodesic curvature

Given a curve $c\colon (0, L) \to \mathbb{R}^2$ parametrized by arc-length ($\|\dot{c}\| \equiv 1$), the curvature $\kappa(t)$ at $c(t)$ can be computed via

$$\kappa(t) = \frac{\det(\dot{c}(t), \ddot{c}(t))}{\|\dot{c}(t)\|^3} = \det(\dot{c}(t), \ddot{c}(t))$$

Given a curve $c\colon (0, L) \to M$ in the 2D manifold M that is parametrized by arc-length, we can compute the **geodesic curvature** $\kappa_g(t)$ by replacing $\ddot{c}$ with $\frac{\nabla}{\mathrm{dt}}\dot{c}$ and obtain

$$\kappa_g(t) = \det\left(\dot{c}(t), \frac{\nabla}{\mathrm{dt}}\dot{c}(t)\right)$$

The geodesic curvature is 0 for geodesics and can therefore be understood as an intrinsic reformulation of the classical curvature of curves.

Gauss Map

Given a 2D manifold $M \subset \mathbb{R}^3$, we call a smooth mapping

$$N \colon M \to \mathbb{S}^2 \qquad \forall p \in M \colon N(p) \perp T_p M$$

its **Gauss map**. For every 3D shape there exists such a mapping. (Why?)

If $x \colon U \to M$ is a coordinate mapping, we can always define a local Gauss map via

$$\begin{aligned} N \colon M &\to \mathbb{S}^2 \\ p &\mapsto \frac{\partial_1 x(u) \times \partial_2 x(u)}{\|\partial_1 x(u) \times \partial_2 x(u)\|} \end{aligned} \qquad \text{for } u = x^{-1}(p)$$

If $M = f^{-1}(c)$ is given implicitly via a function $f \colon \mathbb{R}^3 \to \mathbb{R}$, the Gauss map is given via $N(p) = \frac{\nabla f(p)}{\|\nabla f(p)\|}$.

Shape Operator

Given a 2D manifold $M \subset \mathbb{R}^3$ together with its Gauss map $N: M \to \mathbb{S}^2$, we call its differential the **shape operator** or **Weingarten mapping** S

$$\begin{aligned} S_p: T_pM &\to T_{N(p)}\mathbb{S}^2 \\ v &\mapsto DN(p)[v] \end{aligned}$$

Since $T_{N(p)}\mathbb{S}^2 = N(p)^\perp = T_pM$, $S_p: T_pM \to T_pM$ is an endomorphism.

If we choose a base of T_pM, we would obtain a 2×2 matrix, but this matrix would depend on the chosen base. Nonetheless, the eigenvalues of these matrices would remain the same.

The goal is to show that S_p can be put in diagonal form and that both eigenvalues are real.

Self-Adjointness of the Shape Operator

We know (Linear Algebra) that self-adjoint endomorphisms are diagonalizable with real eigenvalues. Therefore, we have to prove that

$$\langle v_1, S_p(v_2)\rangle = \langle S_p(v_1), v_2\rangle \qquad \text{for all } v_1, v_2 \in T_pM$$

If v_1 and v_2 are co-linear this is obvious. If they are not co-linear, one can find a local coordinate map $x: U \to M$ with $x(0) = p$ and $v_i = \partial_i x(0)$.

Using $\langle N \circ x(u), \partial_i x(u)\rangle \equiv 0$ leads to

$$\begin{aligned} 0 &= \partial_1 \langle N \circ x(u), \partial_2 x(u)\rangle|_{u=0} = \langle S_p(v_1), v_2\rangle + \langle N(p), \partial_{12} x(0)\rangle \\ 0 &= \partial_2 \langle N \circ x(u), \partial_1 x(u)\rangle|_{u=0} = \langle S_p(v_2), v_1\rangle + \langle N(p), \partial_{21} x(0)\rangle \end{aligned}$$

which proves the self-adjointness of the shape operator.

Principal Curvatures

The two eigenvalues $\kappa_1(p)$ and $\kappa_2(p)$ of S_p are called **principal curvatures** and corresponding eigenvectors $v_1(p)$ and $v_2(p)$ are called **principal curvature directions**.

Note that $\kappa_g(p)$ along the geodesic c_i corresponding to $v_i(p)$ is 0 and the curvature of this curve coincides with $\kappa_i(p)$. In that sense, we can think of the principal curvatures as natural generalizations of the planar curvature.

We can derive two other curvatures from the principal curvatures:

$$H(p) := \frac{\kappa_1(p) + \kappa_2(p)}{2} = \frac{1}{2}\operatorname{tr}(\mathcal{M}) \quad \text{(mean curvature)}$$
$$K(p) := \kappa_1(p) \cdot \kappa_2(p) = \det(\mathcal{M}) \quad \text{(Gauss curvature)}$$

given any representing matrix $\mathcal{M}$ of S_p.

Second Fundamental Form

Given the shape operator $S_p\colon T_pM \to T_pM$, we can define the **Second Fundamental Form**

$$\mathbb{I}\colon T_pM \times T_pM \to \mathbb{R} \qquad (v_1, v_2) \mapsto \langle S_p v_1, v_2 \rangle$$

This means, we have

$$\partial_{ij} x = \sum_{k=1}^{n} \Gamma_{ij}^k \partial_k x - \mathbb{I}(\partial_i x, \partial_j x) \cdot N$$

and the second fundamental form can be computed via

$$\mathbb{I}(\partial_i x, \partial_j x) = -\langle \partial_{ij} x, N \rangle .$$

Shape Operator in Local Coordinates

Any coordinate map $x\colon U \to M$ provides for a base $\{\partial_1 x(u), \dots, \partial_n x(u)\}$ of T_pM for $p = x(u)$. In this base, the shape operator S_p can be written as

$$S_p(\partial_j x(u)) = \sum_{i=1}^{n} \nu_j^i \partial_i x(u)$$

This means, we have

$$\mathbb{I}(\partial_j x, \partial_k x) = \langle S_p(\partial_j x), \partial_k x\rangle = \sum_{i=1}^{n} \left\langle \nu_j^i \partial_i x, \partial_k x \right\rangle = \sum_{i=1}^{n} g_{ki} \nu_j^i$$

In other words the representating matrix ν of S_p satisfies the **Weingarten equations**

$$\nu = \mathcal{M}_{Dx}^{Dx}(S_p) = g^{-1} \cdot \mathbb{I}$$