

Submanifold Theory: class guide

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Prerequisites: Basics about manifolds, tensors, vector bundles, at least up to page 16 [here](#). Basics of Riemannian geometry, fundamental groups and covering maps.

Bibliography: [DT], [dC], [ON], [Pe], [Sp], [KN]....

DO ALL THE EXERCISES IN [DT] !!!!

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§1. Notations

Top. manifolds: Hausdorff + countable basis. Partitions of unity.
 n -dimensional differentiable manifolds: M^n . Everything is C^∞ .
 $\mathcal{F}(M) := C^\infty(M, \mathbb{R})$; $\mathcal{F}(M, N) := C^\infty(M, N)$.
 (x, U) chart \Rightarrow coordinate vector fields $= \partial_i := \partial/\partial x_i \in \mathfrak{X}(U)$.
Tangent bundle TM , vector fields $\mathfrak{X}(M) := \Gamma(TM) \cong \mathcal{D}(M)$.
Submersions, immersions, embeddings, local diffeomorphisms.
Vector bundles, trivializing charts, transition functions, sections.
Tensor fields $\mathfrak{X}^{r,s}(M)$, k -forms $\Omega^k(M)$, orientation, integration.
Pull-back of a vector bundle $\pi : E \rightarrow N$ over N : $f^*(E)$.
Vector fields along a map $f : M \rightarrow N \Rightarrow \mathfrak{X}_f \cong \Gamma(f^*(TN))$.
 f -related vector fields.

Distributions: Definition. Integrable and involutive distributions.

Theorem 1 (Frobenius). *A distribution $D \subset TM$ is integrable if and only if it is involutive, i.e., $[X, Y] \in \Gamma(D), \forall X, Y \in \Gamma(D)$.*

§2. Riemannian metrics

Gauss, 1827: $M^2 \subset \mathbb{R}^3 \Rightarrow \langle \cdot, \cdot \rangle|_{M^2}, K_M = K_M(\langle \cdot, \cdot \rangle)$, distances, areas, volumes... Non-Euclidean geometries.

Riemann, 1854: $\langle \cdot, \cdot \rangle \Rightarrow K_M$ (relations proved decades later).

Slow development. General Relativity pushed up!

Riemannian metric, Riemannian manifold: $(M^n, \langle \cdot, \cdot \rangle) = M^n$.

$g_{ij} := \langle \partial_i, \partial_j \rangle \in \mathcal{F}(U) \Rightarrow (g_{ij}) \in C^\infty(U, S(n, \mathbb{R}) \cap Gl(n, \mathbb{R}))$.

Isometries, local isometries, isometric immersions.

Product metric. $T_p \mathbb{V} \cong \mathbb{V}, T\mathbb{V} \cong \mathbb{V} \times \mathbb{V}$.

Examples: $(\mathbb{R}^n, \langle \cdot, \cdot \rangle_{can})$, Euclidean submanifolds. Nash.

Example: (bi-)invariant metrics on Lie groups.

Proposition 2. *Every differentiable manifold admits a Riemannian metric.*

Angles between vectors at a point. Norm.

Riemannian vector bundles: (E, \langle, \rangle) .

The natural induced metric on $f^*(E)$ is $\langle, \rangle^f := \langle, \rangle \circ f$.

It always exists local orthonormal frames: $\{e_1, \dots, e_n\}$.

Length of a piecewise differentiable curve \Rightarrow Riem. distance d .

The topology of d coincides with the original one on M .

§3. Linear connections

If $M^n = \mathbb{R}^n$, or even if $M^n \subset \mathbb{R}^N$, there is a natural way to differentiate vector fields. And this depends only on \langle, \rangle .

Def.: An *affine connection* or a *linear connection* or a *covariant derivative* on M is a map

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

with $\nabla_X Y$ being \mathbb{R} -bilinear, tensorial in X and a derivation in Y .

Tensoriality in $X \Rightarrow (\nabla_X Y)(p) = \nabla_{X(p)} Y$ makes sense.

Local oper.: $Y|_U = 0 \Rightarrow (\nabla_X Y)|_U = 0 \Rightarrow (\nabla_X Z)|_U = \nabla_{X|_U}^U (Z|_U)$

\Rightarrow The *Christoffel symbols* Γ_{ij}^k of ∇ in a coordinate system \Rightarrow Christoffel symbols completely determine the connection: all that is needed is to have local basis of sections \Rightarrow

Affine vector bundle $= (E, \nabla)$: formally exactly the same.

The local property above is a particular case of the following:

Proposition 3. (or “Everything I know about connections!”)

Let ∇ be a linear connection on a vector bundle $\pi : E \rightarrow M$. Then, for every smooth map $f : N \rightarrow M$, there exists a unique linear connection ∇^f on $f^*(E)$ such that

$$\nabla_Y^f(\xi \circ f) = \nabla_{f_*Y}\xi, \quad \forall Y \in \mathfrak{X}(N), \xi \in \Gamma(E).$$

Exercise. Give meaning and prove that $g^*(f^*(E)) = (f \circ g)^*(E)$ and $(\nabla^f)^g = \nabla^{f \circ g}$.

We will omit the superindex f in ∇^f .

In particular, Proposition 3 holds for any smooth curve $\alpha(t) = \alpha : I \subset \mathbb{R} \rightarrow M$, and if $V \in \mathfrak{X}_\alpha$ we denote $V' := \nabla_{\partial_t}V \in \mathfrak{X}_\alpha$. So, if $\alpha'(0) = v$, $\nabla_v Y = (Y \circ \alpha)'(0)$. But beware of “ $\nabla_{\alpha'}\alpha'$ ”!!

Def.: $V \in \mathfrak{X}_\alpha$ is *parallel* if $V' = 0$. We denote by \mathfrak{X}_α'' the set of parallel vector fields along α .

Proposition 4. Let $\alpha : I \subset \mathbb{R} \rightarrow M$ be a piecewise smooth curve, and $t_0 \in I$. Then, for each $v \in T_{\alpha(t_0)}M$, there exists a unique parallel vector field $V_v \in \mathfrak{X}_\alpha$ such that $V_v(t_0) = v$.

The map $v \mapsto V_v$ is an isomorphism between $T_{\alpha(t_0)}M$ and \mathfrak{X}_α'' , and the map $(v, t) \mapsto V_v(t)$ is smooth when α is smooth \Rightarrow

Def.: The *parallel transport* of $v \in T_{\alpha(t)}M$ along α between t and s is the map $P_{ts}^\alpha : T_{\alpha(t)}M \rightarrow T_{\alpha(s)}M$ given by $P_{ts}^\alpha(v) = V_v(s)$.

Notice that $\mathcal{F}(M) = \mathfrak{X}^0(M) = \mathfrak{X}^{0,0}(M)$ and $\mathfrak{X}(M) = \mathfrak{X}^{0,1}(M)$. Covariant differentiation of 1-forms and tensors: $\forall r, s \geq 0$,

$$\nabla \Rightarrow \begin{cases} \nabla : \mathfrak{X}^r(M) \rightarrow \mathfrak{X}^{r+1}(M); \\ \nabla : \mathfrak{X}^{r,s}(M) \rightarrow \mathfrak{X}^{r+1,s}(M); \\ \nabla : \mathfrak{X}^{r,s}(E, \hat{\nabla}) \rightarrow \mathfrak{X}^{r+1,s}(E, \hat{\nabla}); \end{cases}$$

for any affine vector bundle $(E, \hat{\nabla})$ (in partic., for $E = (TM, \nabla)$).

3.1 The Levi-Civita connection

Def.: A linear connection ∇ on a Riemannian manifold $(M, \langle \cdot, \cdot \rangle)$ is said to be *compatible* with $\langle \cdot, \cdot \rangle$ if, for all $X, Y, Z \in \mathfrak{X}(M)$,

$$X\langle Y, Z \rangle = \langle \nabla_X Y, Z \rangle + \langle Y, \nabla_X Z \rangle.$$

Exercise. ∇ is compatible with $\langle \cdot, \cdot \rangle \iff \forall V, W \in \mathfrak{X}_\alpha, \langle V, W \rangle' = \langle V', W \rangle + \langle V, W' \rangle \iff \forall V, W \in \mathfrak{X}_\alpha, \langle V, W \rangle$ is constant $\iff P_{ts}^\alpha$ is an isometry, $\forall \alpha, t, s \iff \nabla \langle \cdot, \cdot \rangle = 0$.

Def.: The tensor $T_\nabla(X, Y) := \nabla_X Y - \nabla_Y X - [X, Y]$ is called the *torsion* of ∇ . We say that ∇ is *symmetric* if $T_\nabla = 0$.

Miracle: *Every Riemannian manifold $(M, \langle \cdot, \cdot \rangle)$ has a unique linear connection that is symmetric and compatible with $\langle \cdot, \cdot \rangle$, called the *Levi-Civita connection* of $(M, \langle \cdot, \cdot \rangle)$.*

This is a consequence of the *Koszul formula*: $\forall X, Y, Z \in \mathfrak{X}(M)$,

$$2\langle \nabla_X Y, Z \rangle = X\langle Y, Z \rangle + Y\langle X, Z \rangle - Z\langle X, Y \rangle - \langle X, [Y, Z] \rangle - \langle Y, [X, Z] \rangle + \langle Z, [X, Y] \rangle.$$

Exercise. Verify that this formula defines a linear connection with the desired properties.

This is the only connection that we will work with. In coordinates, if $(g^{ij}) := (g_{ij})^{-1}$,

$$\Gamma_{ij}^k = \frac{1}{2} \sum_r \left(\frac{\partial g_{ir}}{\partial x_j} + \frac{\partial g_{jr}}{\partial x_i} - \frac{\partial g_{ij}}{\partial x_r} \right) g^{rk}.$$

Exercise. Show that, for $(\mathbb{R}^n, \langle \cdot, \cdot \rangle_{can})$, $\Gamma_{ij}^k = 0$ and ∇ is the usual vector field derivative.

Exercise. Use Koszul formula to show that the Levi-Civita connection of a bi-invariant metric of a Lie Group satisfies, and is characterized, by the property that $\nabla_X X = 0 \forall X \in \mathfrak{g}$.

Lemma 5. (*Symmetry and Compatibility Lemma*) *Let N be any manifold, and $f : N \rightarrow M$ a smooth map into a Riemannian manifold M . Then:*

- ∇^f is symmetric, that is, $\nabla_X^f f_* Y - \nabla_Y^f f_* X = f_*[X, Y]$, $\forall X, Y \in \mathfrak{X}(N)$;
- ∇^f is compatible with the natural metric $\langle \cdot, \cdot \rangle^f$ on $f^*(TM)$.

Example: For every isometric immersion $f: N \rightarrow M$ we have the natural decomposition of N -bundles

$$f^*(TM) = f_*(TN) \oplus^\perp T_f^\perp N$$

Accordingly, $\forall Z \in \mathfrak{X}_f$, we write $Z = Z^\top + Z^\perp \Rightarrow$ the relation between the Levi-Civita connections is $f_* \nabla_X^N Y = (\nabla_X^f f_* Y)^\top$.

§4. Geodesics

When do we have minimizing curves? What are those curves?
Critical points of the arc-length funct. $L: \Omega_{p,q} \rightarrow \mathbb{R}$: *geodesics*:

$$\gamma'' := \nabla_{\frac{d}{dt}} \gamma' = 0.$$

Geodesics = second order nonlinear nice ODE \Rightarrow

Proposition 6. $\forall v \in TM$, $\exists \epsilon > 0$ and a unique geodesic $\gamma_v: (-\epsilon, \epsilon) \rightarrow M$ such that $\gamma'_v(0) = v$ ($\Rightarrow \gamma_v(0) = \pi(v)$).

γ a geodesic $\Rightarrow \|\gamma'\| = \text{constant}$.

γ and $\gamma \circ r$ nonconstant geodesics $\Rightarrow r(t) = at + b$, $a, b \in \mathbb{R} \Rightarrow \gamma_v(at) = \gamma_{av}(t)$; $\gamma_v(t+s) = \gamma_{\gamma'_v(s)}(t) \Rightarrow$ geodesic field G of M :

Proposition 7. There is a unique vector field $G \in \mathfrak{X}(TM)$ such that its trajectories are γ' , where γ are geodesics of M .

The local flux of G is called the *geodesic flow* of M . In particular:

Corollary 8. For each $p \in M$, there is a neighborhood $U_p \subset M$ of p and positive real numbers $\delta, \epsilon > 0$ such that the map

$$\gamma : T_\epsilon U_p \times (-\delta, \delta) \rightarrow M, \quad \gamma(v, t) = \gamma_v(t),$$

is differentiable, where $T_\epsilon U_p := \{v \in TU_p : \|v\| < \epsilon\}$.

Since $\gamma_v(at) = \gamma_{av}(t)$, changing ϵ by $\epsilon\delta/2$ we can assume $\delta = 2 \Rightarrow$ We have the *exponential map* of M (terminology from $O(n)$):

$$\exp : T_\epsilon U_p \rightarrow M, \quad \exp(v) = \gamma_v(1).$$

$$\Rightarrow \exp(tv) = \gamma_v(t) \Rightarrow \exp_p = \exp|_{T_p M} : B_\epsilon(0_p) \subset T_p M \rightarrow M \Rightarrow$$

Proposition 9. For every $p \in M$ there is $\epsilon > 0$ such that $B_\epsilon(p) := \exp_p(B_\epsilon(0_p)) \subset M$ is open and $\exp_p : B_\epsilon(0_p) \rightarrow B_\epsilon(p)$ is a diffeomorphism.

An open set $p \in V \subset M$ onto which \exp_p is a diffeomorphism as above is called a *normal neighborhood* of p , and when $V = B_\epsilon(p)$ it is called a *normal* or *geodesic ball* centered at p .

Proposition 9 $\Rightarrow (\exp_p|_{B_\epsilon(0_p)})^{-1}$ is a chart of M in $B_\epsilon(p) \Rightarrow$ We always have (local!) *polar coordinates* for any (M, \langle, \rangle) :

$$\varphi : (0, \epsilon) \times \mathbb{S}^{n-1} \rightarrow B_\epsilon(p) \setminus \{p\}, \quad \varphi(s, v) = \gamma_v(s), \quad (1)$$

where $\mathbb{S}^{n-1} = \{v \in T_p M : \|v\| = 1\}$ is the unit sphere in $T_p M$.

Examples: (\mathbb{R}^n, can) ; (\mathbb{S}^n, can) .

Exercise. Show that for a bi-invariant metric on a Lie Group, it holds that $\exp_e = \exp^G$.

4.1 Geodesics are (local) arc-length minimizers

Lemma 10. (*Gauss' Lemma*) Let $p \in M$ and $v \in T_p M$ such that $\gamma_v(s)$ is defined up to time $s = 1$. Then,

$$\langle (\exp_p)_* v, (\exp_p)_* w \rangle = \langle v, w \rangle, \quad \forall w \in T_p M.$$

Proof. If $f(s, t) := \gamma_{v+tw}(s) = \exp_p(s(v + tw))$ then, for $t = 0$, $f_s = (\exp_p)_{*sv}(v)$, $f_t = (\exp_p)_{*sv}(sw)$ and $\langle f_s, f_t \rangle_s = \langle v, w \rangle$. ■

Gauss' Lemma $\Rightarrow \mathbb{S}_\epsilon(p) := \partial B_\epsilon(p) \subset M$ is a regular hypersurface of M orthogonal to the geodesics emanating from p , called the *geodesic sphere* of radius ϵ centered at p .

Now, $B_\epsilon(p) := \exp_p(B_\epsilon(0_p)) \subset M$ as in Proposition 9 agrees with the metric ball of (M, d) !!!!! More precisely:

Proposition 11. Let $B_\epsilon(p) \subset U$ a normal ball centered at $p \in M$. Let $\gamma : [0, a] \rightarrow B_\epsilon(p)$ be the geodesic segment with $\gamma(0) = p$, $\gamma(a) = q$. If $c : [0, b] \rightarrow M$ is another piecewise differentiable curve joining p and q , then $l(\gamma) \leq l(c)$. Moreover, if equality holds, then c is a monotone reparametrization of γ .

Proof. In polar coordinates, $c(t) = \exp_p(s(t)v(t))$ in $B_\epsilon(p) \setminus \{p\}$, and if $f(s, t) := \exp_p(sv(t)) = \gamma_{v(t)}(s)$, we have that $c' = s'f_s + f_t$. Now, use that $f_s \perp f_t$, by Gauss' Lemma. ■

Corollary 12. d is a distance on M , $d_p := d(p, \cdot)$ is differentiable in $B_\epsilon(p) \setminus \{p\}$, and d_p^2 is differentiable in $B_\epsilon(p)$.

Exercise. Compute $\|\nabla d_p\|$ and the integral curves of ∇d_p inside $B_\epsilon(p) \setminus \{p\}$.

Remark 13. Proposition 11 is LOCAL ONLY, and $\epsilon = \epsilon(p)$: \mathbb{R}^n ; \mathbb{S}^n ; $\mathbb{R}^n \setminus \{0\}$.

§5. Curvature

Gauss: $K(M^2 \subset \mathbb{R}^3) = K(\langle, \rangle)$. Riemann: $K(\sigma) = K_p(\exp_p(\sigma))$.

Def.: The *curvature tensor* or *Riemann tensor* of M is (sign!)

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

We also call R the (4,0) tensor given by

$$R(X, Y, Z, W) = \langle R(X, Y)Z, W \rangle.$$

Curvature tensor $R_{\hat{\nabla}}$ of a vector bundle E with a connection $\hat{\nabla}$: exactly the same.

Proposition 14. *For all $X, Y, Z, W \in \mathfrak{X}(M)$, it holds that:*

- R is a tensor;
- $R(X, Y, Z, W)$ is skew-symmetric in X, Y and in Z, W ;
- $R(X, Y, Z, W) = R(Z, W, X, Y)$;
- $R(X, Y)Z + R(Y, Z)X + R(Z, X)Y = 0$ (first Bianchi id.);
- $R_{ijk}^s = \sum_l \Gamma_{ik}^l \Gamma_{jl}^s - \sum_l \Gamma_{jk}^l \Gamma_{il}^s + \partial_j \Gamma_{ik}^s - \partial_i \Gamma_{jk}^s$ ($\Rightarrow R \cong \partial^2 \langle, \rangle$).

Proof. Exercise. ■

$\langle, \rangle \Rightarrow \mathfrak{X}(M) \cong \Omega^1(M)$ and \langle, \rangle extends to the tensor algebra \Rightarrow the *curvature operator* $R : \Omega^2(M) \rightarrow \Omega^2(M)$ is self-adjoint.

Def.: If $\sigma \subset T_p M$ is a plane, then the *sectional curvature* of M at σ is given by

$$K(\sigma) := \frac{R(u, v, v, u)}{\|u\|^2 \|v\|^2 - \langle u, v \rangle^2}, \quad \sigma = \text{span}\{u, v\}.$$

Proposition 15. *If R and R' are tensors with the symmetries of the curvature tensor and Bianchi such that $R(u, v, v, u) = R'(u, v, v, u)$ for all u, v , then $R = R'$ (i.e., K determines R).*

Corollary 16. *If M has constant sectional curvature $c \in \mathbb{R}$, then $R(X, Y, Z, W) = c(\langle X, W \rangle \langle Y, Z \rangle - \langle X, Z \rangle \langle Y, W \rangle)$.*

Def.: The *Ricci tensor* is the symmetric $(2,0)$ tensor given by

$$\text{Ric}(X, Y) := \frac{1}{n-1} \text{trace } R(X, \cdot, \cdot, Y),$$

and the *Ricci curvature* is $\text{Ric}(X) = \text{Ric}(X, X)$ for $\|X\| = 1$.

Example: $\mathbb{C}\mathbb{P}^n$ as $\mathbb{S}^{2n+1}/\mathbb{S}^1$ has $K(X, Y) = 1 + 3\langle JX, Y \rangle^2$ and $\text{Ric} \equiv (n+2)/(n-1)$.

Def.: The *scalar curvature* of M is $\text{scal} = \frac{1}{n} \text{trace } \text{Ric}$.

Lemma 17. *(Compare with Lemma 5) Let $f : U \subset \mathbb{R}^2 \rightarrow M$ be a map into a Riemannian manifold and $V \in \mathfrak{X}_f$. Then,*

$$\nabla_{\partial_t} \nabla_{\partial_s} V - \nabla_{\partial_s} \nabla_{\partial_t} V = R(f_* \partial_t, f_* \partial_s) V.$$

More generally, $R_{\hat{\nabla}f} = f^(R_{\hat{\nabla}})$ for any affine vector bundle $(E, \hat{\nabla}) \rightarrow M$ and every smooth map $f : N \rightarrow M$.*

Proof. Since $R_{\hat{\nabla}f}$ is a tensor, it is enough to check the lemma for coordinate vector fields on N and for $\xi = \bar{\xi} \circ f$, $\bar{\xi} \in \Gamma(E)$. ■

Exercise. Let $\pi : E \rightarrow M$ be a vector bundle of rank k with a linear connection ∇ . Then ∇ is flat if and only if each $\xi \in E$ has a (unique!) local parallel extension. If M is simply connected, such an extension exists globally and therefore $E \cong M \times \mathbb{R}^k$ is trivial.

§6. Isometric immersions (finally!)

As we have seen in the Example in page 6, if $f : M \rightarrow N$ is an isometric immersion $\Rightarrow f^*(TN) = f_*(TM) \oplus^\perp T_f^\perp M$, and $\nabla_X^M Y = (\nabla_X^f f_* Y)^\top, \forall X, Y \in TM$. Moreover, we have that

$$\alpha(X, Y) := \left(\nabla_X^f f_* Y \right)^\perp$$

is a symmetric tensor, called the *second fundamental form* of f . In addition, the map $\nabla^\perp : TM \times \Gamma(T_f^\perp M) \rightarrow \Gamma(T_f^\perp M)$ given by

$$\nabla_X^\perp \eta := \left(\nabla_X^f \eta \right)^\perp$$

is a connection in $T_f^\perp M$, called the *normal connection* of f .
 Identifications.

Exercise. Show that ∇^\perp is a compatible connection with the induced metric on $T_f^\perp M$.

$\alpha(p)$ is the quadratic approximation of $f(M) \subset N$ at $p \in M$.

$\alpha(v, v) = \gamma'_v(0)$: Picture!

$\eta \in T_{f(p)}^\perp M \Rightarrow$ (self-adjoint!) *shape operator* $A_\eta : T_p M \rightarrow T_p M$.

The Fundamental Equations. Particular case: $K = \text{constant} \Rightarrow$ the *Fundamental Theorem of Submanifolds*.

Gauss equation $\Leftrightarrow K(\sigma) = \bar{K}(\sigma) + \langle \alpha(u, u), \alpha(v, v) \rangle - \|\alpha(u, v)\|^2$
 \Rightarrow Riemann notion of sectional curvature agrees with ours.

Example: $\mathbb{S}^{n-1}(r) \subset \mathbb{R}^n \Rightarrow K \equiv 1/r^2$ (it had to be constant!).

Model of the hyperbolic space \mathbb{H}^n as a submanifold of \mathbb{L}^{n+1} .

The second fundamental form of a composition of is. immersions.

Example: Second fund. form of a graph of a real function.

Example: The catenoid without a meridian and a periodic piece of the helicoid are isometric, but not congruent. Yet, the helicoid second fundamental form is periodic, hence it serves as a ‘candidate’ second fundamental form of the full catenoid. Yet, it is not realized by an isometric immersion of the catenoid! Reason: the catenoid is not simply connected.

Lemma 18. *Given $f : M^n \rightarrow \mathbb{R}^m$ and $v \in \mathbb{R}^m$, the set of critical points of the *height function* $h^v := \langle f, v \rangle$ is the set $\{x \in M : v \in T_x^\perp M\}$. Moreover, $\text{Hess}_{h^v} = A_{v^\perp}$.*

§7. Hypersurfaces

Principal curvatures and directions; mean curvature;

Gauss-Kronecker curvature; Gauss map.

The fundamental equations for hypersurfaces.

Convex, locally convex and strictly locally convex hypersurfaces.

Lemma 19. *Given a compact $M^n \subset \mathbb{R}^{n+p}$, for every $0 \neq v \in \mathbb{R}^{n+p}$ there exists $x \in M^n$ such that v is normal to M^n at x and $A_v \geq 0$. Moreover, \exists such a v with $A_v > 0$.*

Theorem 20. *For a compact Euclidean hypersurface M^n :
 The Gauss-Kronecker curvature never vanishes \iff
 M is orientable and the Gauss map is a diffeomorphism \iff
 The second fundamental form is definite everywhere \implies
 M is a convex hypersurface ($M = \partial B$ for a convex body B).*

§8. Totally geodesic and umbilical submanifolds

$f : M \rightarrow N$ totally geodesic $\iff f_*(TM)$ is parallel in $f^*(TN)$.

Umbilical distributions, submanifolds and extrinsic spheres.

Lemma 21. *A distribution (or submanifold) D is umbilical $\Leftrightarrow \nabla_X Y \in D$ for every $X, Y \in D$ with $X \perp Y$.*

Umbilic $\mathbb{Q}_{\tilde{c}}^m \subset \mathbb{Q}_c^{m+p}$ for $\tilde{c} \geq c$. Same if $\tilde{c} < c$ for the Lorentzian \mathbb{Q}_c^{m+p} .

Lemma 22. *For a curvature-like tensor R on \mathbb{V}^n with $n \geq 3$ the following assertions are equivalent:*

1. *There exists $2 \leq r \leq n - 1$ such that R preserves every r -dimensional subspace, i.e., $R(V, V)V \subset V$;*
2. *$\langle R(X, Y)Z, X \rangle = 0$ for every o.n. X, Y, Z ;*
3. *All sectional curvatures of R are constant;*
4. *R preserves every subspace of \mathbb{V}^n .*

Axiom of r -planes. Axiom of r -spheres.

§9. Nullity distributions

The (relative) nullity distribution $(\Delta) \Gamma_c$ and the index of (relative) nullity ($\nu = \dim \Delta$) $\mu_c = \dim \Gamma_c$. $\Gamma := \text{Ker}(R - f^*(\tilde{R})) = \{X : R(X, \dots) = \tilde{R}(X, \dots)\}$ and $\mu := \dim \Gamma$ are extrinsic.

Remark 23. Γ_c is always an intrinsic totally geodesic distribution where μ_c is constant (why?). Moreover, $\Delta \subset \Gamma$.

Proposition 24. *For an isometric immersion $f : M \rightarrow \tilde{M}$, the following assertions hold:*

- i) ν , μ and μ_c are upper semicontinuous. Hence, the subsets where ν , μ and μ_c attain their minimum values are open,

and there is an open and dense subset of M^n where ν , μ and μ_c are locally constant;

ii) Δ (resp. Γ and Γ_c) is smooth on any open subset of M^n where ν (resp. μ and μ_c) is constant;

iii) If \tilde{M} has constant sectional curvature, then Δ is a totally geodesic (hence integrable) distribution on any open subset where ν is constant, and the restriction of f to each leaf of Δ is totally geodesic.

Exercise. Every umbilical distribution in a Riemannian manifold is integrable, and its leaves are umbilical submanifolds.

§10. Principal Normals and flat normal bundle

Principal and Dupin principal normals. Eigendistributions.

Proposition 25. *If η is a principal normal of $f : M^n \rightarrow \mathbb{Q}_c^m$:*

1. $E_\eta := \text{Ker}(\alpha_f - \langle \cdot, \cdot \rangle_\eta)$ is smooth and umbilical;
2. If $\text{rank } E_\eta \geq 2$, then η is Dupin;
3. η is Dupin $\Leftrightarrow E_\eta$ is spherical, and the leaves of f are mapped to extrinsic spheres;
4. $\eta \neq 0$ Dupin and $c = 0 \Rightarrow f + \frac{\eta}{\|\eta\|^2}$ is constant along E_η .

Proof. The only tricky part is to show that E_η is spherical in (3). If $\text{rank } E_\eta \geq 2$ take $X, Y \in E_\eta$ with $X \perp Y$ and $\|X\| = 1$. Then, $0 = \overline{R}(Y, X)X)_{E_\eta^\perp} = (\overline{\nabla}_Y(\overline{\nabla}_X X)_{E_\eta^\perp})_{E_\eta^\perp}$ and so E_η is spherical. We leave the case $\text{rank } E_\eta = 1$ as an exercise. ■

Theorem 26. *If M^n is compact and $f : M^n \rightarrow \mathbb{R}^m$ has a principal curvature of multiplicity $k \geq n/2$, then M^n has the homotopy type of a CW-complex with no cells of dimension $n - k < r < k$. In particular, $H_r(M, G) = 0$, for all $n - k < r < k$ and any coefficient group G .*

Proof. Let $v \in \mathbb{R}^m$ such that h_v is a Morse function. By Lemma 18, $\text{Hess}_{h_v}|_{E_\eta} = \lambda I_{E_\eta}$, with $\lambda(p) = \langle \eta(p), v \rangle$. In particular, at a critical point x , $\lambda(x) \neq 0$, and the index of x is at least k if $\lambda(x) < 0$ and at most $n - k$ if $\lambda(x) > 0$. Morse Theory implies the result. ■

- Submanifolds with flat normal bundle.

§11. Reduction of codimension

First normal spaces $N_1(x) := \text{span}\{\alpha(X, Y) : X, Y \in T_x M\}$.

Proposition 27. *Let $f : M^n \rightarrow \mathbb{Q}_c^{n+p}$ be an isometric immersion. Suppose that there exists a parallel normal subbundle $L^q \subset T^\perp M$ of rank $q < p$ such that $N_1(x) \subset L^q(x)$ for all $x \in M^n$. Then the codimension of f reduces to q .*

s -nullities: ν_s and ν_s^* .

1-regular and substantial isometric immersions.

Example: Draw a globally substantial curve in \mathbb{R}^3 that is nowhere locally substantial (better than Example 2.3 in [DT]).

Proposition 28. *Let $f : M^n \rightarrow \mathbb{Q}_c^m$ be a 1-regular (necessary!) isometric immersion such that $\text{rank } N_1 = q \leq n - 1$. If $\nu_s^*(x) < n - s$ for all $1 \leq s \leq q$ at any point $x \in M^n$, then N_1 is parallel and thus f reduces codimension to q .*

§12. Minimal submanifolds

Let $f_t : M^n \rightarrow \bar{M}$ be an isotopy of $f = f_0$. Write $f'_0 = f_*Z + \eta \in \mathfrak{X}_f$, with $Z \in TM$ and $\eta \in T_f^\perp M$ (i.e., $\mathfrak{X}_f = T_f\mathcal{F}(M, \bar{M})$). We will denote by $H = \text{trace } \alpha/n \in \Gamma(T_f^\perp M)$ the *mean curvature vector* of f . Then,

$$(d\text{vol}_t)'(0) = (-n\langle H, \eta \rangle + \text{div } Z) d\text{vol}.$$

Proposition 29. *M^n compact orientable with boundary and $Z|_{\partial M} = 0 \Rightarrow \text{Vol}(f_t(M))'(0) = -n \int_M \langle H, \eta \rangle d\text{vol}$. In particular, minimal submanifolds are precisely the critical points of the volume functional for *compactly supported variations*.*

$f : M^n \rightarrow \mathbb{R}^m \Rightarrow \Delta f = nH$. Hence, minimal \Rightarrow harmonic \Rightarrow There are no compact minimal Euclidean submanifolds. Also:

Proposition 30. *A compact minimal Euclidean submanifold with boundary is contained in the convex hull of its boundary. When substantial, it is contained in the interior of this hull.*

If $f : M^n \rightarrow \mathbb{Q}_c^{n+p}$ is minimal, then $\text{Ric}_M \leq c$ since

$$\text{Ric}_M(X) = c + \frac{n}{n-1} \langle A_H X, X \rangle - \frac{1}{n-1} \sum_{i=1}^p \langle A_{\xi_i}^2 X, X \rangle. \quad (2)$$

In particular, $\text{scal}_M = c + \frac{n}{n-1} \|H\|^2 - \frac{1}{n(n-1)} \|\alpha\|^2$.

Lemma 31. *Given $F : M^n \rightarrow \mathbb{R}^{m+1}$, there exists a minimal $f : M^n \rightarrow \mathbb{S}_c^m$ such that $F = \text{inc} \circ f \iff \Delta F = -ncF$.*

§13. Veronese embeddings

Let $\mathcal{H}(m, d)$ be the real vector space of homogeneous harmonic polynomials of degree d in $(m + 1)$ real (similarly for \mathbb{C}, \mathbb{H}) variables. Then, $\dim \mathcal{H}(m, d) = n + 1$, where $n = n(m, d) = \frac{(2d+m-1)(d+m-2)!}{d!(m-1)!} - 1$. Then, $W = W(m, d) = \{f|_{\mathbb{S}^m} : f \in \mathcal{H}(m, d)\}$ is contained in (actually, it is equally to) the eigenspace of $\Delta_{\mathbb{S}^m}$ with eigenvalue $\lambda = \lambda(m, d) = -d(m + d - 1)$. Fix $\langle \cdot, \cdot \rangle$ the L^2 -inner product on W , and $\{f_0, \dots, f_n\}$ an orthonormal basis of W . Set $G := O(m + 1)$,

$$F := (f_0, \dots, f_n) : \mathbb{S}^m \rightarrow \mathbb{R}^{n+1}.$$

Since $\langle \cdot, \cdot \rangle$ is invariant under the G -action $A \cdot f = f \circ A$, the basis $\{A \cdot f_0, \dots, A \cdot f_n\}$ is also orthonormal. So, identifying W with \mathbb{R}^{n+1} via $f_i \mapsto e_i$, we conclude that there is $\tilde{A} \in O(W) \cong O(n + 1)$ such that $F \circ A = \tilde{A} \circ F$, and the map $A \mapsto \tilde{A}$ is a group homomorphism (such an F is said to be *G -equivariant*). In particular, G acts isometrically and transitively with the metric induced by F , and the isotropy groups $O(m)$ act irreducibly on each tangent space and transitively on its Grassmannians. Thus, there exists $\tilde{c} > 0$ such that $F^* \langle \cdot, \cdot \rangle = \tilde{c} \langle \cdot, \cdot \rangle$, and hence F induces an isometric immersion of $\mathbb{S}_{1/\tilde{c}}^m$ into \mathbb{R}^{n+1} with $\Delta F = -(1/\tilde{c})\lambda F$. We conclude by Lemma 31 that there is a minimal equivariant isometric immersion $g : \mathbb{S}_{1/\tilde{c}}^m \rightarrow \mathbb{S}_c^n$, $c = \lambda/m\tilde{c}$, $F = inc \circ g$. We just constructed the (essentially *unique!*) *minimal, equivariant, and substantial Veronese embeddings*,

$$g : \mathbb{S}_k^m \rightarrow \mathbb{S}^n, \quad k = k(m, d) := \frac{m}{d(m + d - 1)}$$

(g is an embedding if d is odd, embedding of the projective space if d is even, and always induces an embedding $\mathbb{R}P_k^m \rightarrow \mathbb{R}P^n$).

For $d = 1$ we get the identity, while for $d = 2$ we have, setting $\Pi = \{x_4 + x_5 + x_6 = 0\} \subset \mathbb{R}^6$, that $g = g(x, y, z)$ can be given by

$$\left(\frac{xy}{\sqrt{3}}, \frac{yz}{\sqrt{3}}, \frac{zx}{\sqrt{3}}, \frac{x^2 - y^2}{3\sqrt{2}}, \frac{y^2 - z^2}{3\sqrt{2}}, \frac{z^2 - x^2}{3\sqrt{2}} \right) \subset \mathbb{S}^5 \cap \Pi = \mathbb{S}^4. \quad (3)$$

§14. Minimal rigidity of hypersurfaces

Kahler structure of orientable Riemannian surfaces.

The associated family of a minimal $M^2 \subset \mathbb{Q}_c^3$.

Exercise. Any minimal submanifold $M^n \subset \mathbb{Q}_c^m$ with $\mu_c \equiv n - 2$ has an associated family.

Deformability and rigidity.

Theorem 32. *Let $f : M^n \rightarrow \mathbb{Q}_c^{n+1}$ be a minimal immersion of a Riemannian manifold with $\mu_c \not\equiv n - 2$. Then, f is rigid among minimal immersions $g : M^n \rightarrow \mathbb{Q}_c^{n+p}$, i.e., $g = inc \circ f$.*

Proof. By Gauss equation, $\lambda_i^2 = \sum_k \|\alpha_{ik}\|^2$, where λ_i are the principal curvatures of f and $\alpha_{ij} := \alpha_g(e_i, e_j)$, $1 \leq i, j \leq n$. So,

$$\begin{aligned} (\langle \alpha_{ii}, \alpha_{jj} \rangle - \|\alpha_{ij}\|^2)^2 &= \lambda_i^2 \lambda_j^2 = \sum_k \|\alpha_{ik}\|^2 \sum_k \|\alpha_{jk}\|^2 \\ &\geq (\|\alpha_{ii}\|^2 + \|\alpha_{ij}\|^2)(\|\alpha_{jj}\|^2 + \|\alpha_{ij}\|^2) \geq (\langle \alpha_{ii}, \alpha_{jj} \rangle + \|\alpha_{ij}\|^2)^2. \end{aligned}$$

Hence, $\alpha_{ij} \neq 0 \Rightarrow \langle \alpha_{ii}, \alpha_{jj} \rangle \leq 0 \Rightarrow \lambda_i \lambda_j \leq -\|\alpha_{ij}\|^2 < 0$. Thus, at the open subset U with minimum $\nu = \mu_c \leq n - 3$, there should be a pair with $\alpha_{ij} = 0$. The above equation implies that α_{ii} and α_{jj} are linearly dependent, and $\alpha_{is} = 0$ for $i \neq s \neq j$. Changing the roles of s and j we get $\alpha_{ij} = 0$. We conclude by the first

equation that $(\alpha_g)_{N_g^1} = \pm\alpha_f$. Done, since N_g^1 is parallel in U by Proposition 28 and g is analytic. ■

§15. Local rigidity and flat bilinear forms

In local coordinates, an isometric immersion is a solution of a nonlinear PDE, so if the codimension is small it should be overdetermined. Hence rigidity should hold under *generic conditions*.

Analyze the proof of Theorem 32: It's just Gauss equation!

But: f rigid \Rightarrow Find $\tau : T_f^\perp M \rightarrow T_g^\perp M$ satisfying

$$\tau \circ \alpha_f = \alpha_g.$$

Such τ is unique if f is full (or unique in N_1^f), and its parallelism is not hard to check (see Proposition 39 below). Now, a necessary condition for the existence of such a bundle [isometry](#) τ is that

$$\|\alpha_f(X, Y)\| = \|\alpha_g(X, Y)\|, \quad \forall X, Y \in TM. \quad (4)$$

which is equivalent by polarization to that, $\forall X, Y, X', Y' \in TM$,

$$\langle \alpha_f(X, Y), \alpha_f(X', Y') \rangle = \langle \alpha_g(X, Y), \alpha_g(X', Y') \rangle.$$

But this is also sufficient(!): just define τ as $\tau \circ \alpha_f = \alpha_g$ and extend linearly. In other words, we need to understand when the [flat bilinear form](#) (FBF) $\beta = (\alpha_f, \alpha_g)$ is [null](#), where

$$\beta = (\alpha_f, \alpha_g) : TM \times TM \rightarrow (T_f^\perp M \times T_g^\perp M, \langle \cdot, \cdot \rangle_f - \langle \cdot, \cdot \rangle_g).$$

15.1 Flat bilinear forms

Let $\beta : \mathbb{V} \times \mathbb{V}' \rightarrow \mathbb{W}^{p,q}$ a FBF.

Def.: $RE(\beta)$. $S(\beta)$. β_X for $X \in \mathbb{V}$. Isotropic (null) subspaces. $\nu_\beta := \dim N(\beta)$. For $X \in RE(\beta)$ set $\mathcal{U}(X) := \text{Im } \beta_X \cap \text{Im } \beta_X^\perp$.

Proposition 33. *The subset $RE(\beta)$ is open and dense in V .*

Observe that, by flatness: *if $\beta_X(\mathbb{V}') \subset \mathbb{W}$ is isotropic for all X in a dense subset, then β is null.*

Proposition 34. *For any bilinear form β and $X \in RE(\beta)$, $\beta(\mathbb{V}, \text{Ker } \beta_X) \subset \text{Im } \beta_X$. If β is also flat, then $\beta|_{\mathbb{V} \times \text{Ker } \beta_X}$ is null (since $\beta(\mathbb{V}, \text{Ker } \beta_X) \subset \mathcal{U}(X)$).*

Proof. For any $Y \in \mathbb{V}$ and t small, $L_t = \text{Im } \beta_{X+tY} \subset \mathbb{W}$ is a continuous family of subspaces that contain $\beta_{X+tY}(\text{Ker } \beta_X) = \beta_Y(\text{Ker } \beta_X)$, which does not depend on t . ■

Corollary 35. $\beta: \mathbb{V} \times \mathbb{V}' \rightarrow \mathbb{W}^{p,0}$ FBF $\Rightarrow \nu_\beta \geq \dim \mathbb{V}' - \dim \mathbb{W}$.

Theorem 36 (Chern-Kuiper). $M^n \subset \tilde{M}^{n+p} \Rightarrow \nu \leq \mu \leq \nu + p$.

Corollary 37. $M^n \subset \mathbb{R}^{n+p}$ compact $\Rightarrow \mu (= \mu_0) \not\geq p$.

Corollary 38. $M^n \subset \mathbb{R}^{n+p}$ compact and flat $\Rightarrow p \geq n$.

15.2 Uniqueness of the normal connection

Proposition 39. *Let $f, f' : M^n \rightarrow \mathbb{Q}_c^{n+p}$ be isometric immersions and let $\tau : T_f^\perp M \rightarrow T_{f'}^\perp M$ be a vector bundle isometry that preserves the second fundamental forms. Then it also preserves the normal connections on the first normal bundles. In particular, it is parallel if either immersion is full.*

Def.: Type number τ of f .

Obs.: $\tau(x) \geq 1 \Rightarrow f$ is full at x , $\nu_s(x) \leq n - s\tau(x)$, and $p \geq \lceil n/\tau(x) \rceil$.

Remark 40. Allendoerfer: if $\tau \geq 4$, then $G \Rightarrow C+R$.

§16. Local algebraic rigidity

Lemma 41 (Lorentzian version of Corollary 35). *If β is a FBF with $S(\beta) = \mathbb{W}^{p,1}$ Lorentzian $\Rightarrow \nu_\beta \geq \dim \mathbb{V}' - \dim \mathbb{W}$.*

Exercise. Replace the Lorentzian hypothesis in the above by $\dim \mathcal{U}(X) = 1$ for $X \in RE(\beta)$. Actually, by $\dim \mathcal{U}(X) \leq 3$, so it holds even if \mathbb{W} has index ≤ 3 (see Lemma 45).

Theorem 42 (Beez-Killing). *$M \subset \mathbb{Q}_c^{n+1}$ with $\tau \geq 3$ is rigid.*

Corollary 43. *Let $f, f' : M^n \rightarrow \mathbb{Q}_c^{n+1}$ be nowhere congruent isometric immersions of a Riemannian manifold with no points of constant sectional curvature c . Then f and f' carry a common relative nullity distribution of rank $n - 2$.*

Theorem 44 (Allendoerfer). *Any $f : M^n \rightarrow \mathbb{Q}_c^{n+p}$ with $\tau \geq 3$ everywhere is rigid.*

Proof. By Proposition 39, we only need to show that $\beta = \alpha \oplus \alpha'$ is null, since $\tau \geq 3$ implies that f is null.

Let $k := \min\{\dim \mathcal{U}(X) : X \in RE(\beta)\}$. Similarly to $RE(\beta)$, $RE^o(\beta) := \{X \in \mathbb{V} : \dim \mathcal{U}(X) = k\}$ is also open and dense in \mathbb{V} . So, we only need to show that $k = p$.

$\tau \geq 3 \Rightarrow \exists L^{n-3p} := (\text{span}\{A_{\xi_j} X_i : 1 \leq j \leq p, 1 \leq i \leq 3\})^\perp = \bigcap_{i=1}^3 \text{Ker } \alpha_{X_i}$. But $\dim \text{Ker } \beta_{X_1} = n - \text{rank } \beta_{X_1} \geq n - 2p + k$. Proposition 34 $\Rightarrow \dim \text{Ker } \beta_{X_1} \cap \text{Ker } \beta_{X_2} \geq \dim \text{Ker } \beta_{X_1} - \dim \mathcal{U}(X_1) \geq n - 2p$ and similarly $\dim \bigcap_{i=1}^3 \text{Ker } \beta_{X_i} \geq n - 2p - k$. Done, since $\bigcap_{i=1}^3 \text{Ker } \beta_{X_i} \subset L^{n-3p}$. ■

§17. The Main Lemma

Def.: Nondegenerate FBFs.

Given a FBF $\beta : \mathbb{V}^n \times \mathbb{V}^n \rightarrow \mathbb{W}^{p,q}$, set $U := S(\beta) \cap S(\beta)^\perp$, $W = U \oplus \hat{U} \oplus^\perp L$ nondegenerate with \hat{U} null, $S(\beta) = U \oplus L$, and $\beta = \beta_U + \beta_L$, with β_U null and β_L nondegenerate.

Lemma 45 (The Main Lemma). β symmetric nondegenerate with $\min\{p, q\} \leq 5 \Rightarrow \nu_\beta \geq n - p - q$.

Remark 46. The above is **false** for $\min\{p, q\} \geq 6$. In fact, there are not even linear estimates: $\forall r \in \mathbb{N}, \exists$ a SFBF $\beta : \mathbb{V}^n \times \mathbb{V}^n \rightarrow \mathbb{W}^{p,p}$, $p = r(r+1)/2$, with $S(\beta) = \mathbb{W}$ and $\nu_\beta = n - 2p - \binom{r}{3}$.

Theorem 47. $f : M^n \rightarrow \mathbb{Q}_c^{n+p}$ with $p \leq 5$ and $\nu_j \leq n - 2j - 1$ for all $1 \leq j \leq p \Rightarrow f$ is rigid.

Proof. Just show that U above has dimension p . Since $\nu_1 \leq n-3$, f is full. ■

§18. Submanifolds with constant curvature

FBF were introduced by Cartan to study $f : M_c^n \rightarrow \mathbb{Q}_c^{n+p}$. Moore.

Examples: Product immersion $T^n = \mathbb{S}^1 \times \dots \times \mathbb{S}^1 \rightarrow \mathbb{S}_{1/n}^{2n-1}$, and local immersions $U^n \subset \mathbb{H}^n \rightarrow \mathbb{R}^{2n-1}$. Hilbert: $\mathbb{A}\mathbb{H}^n \rightarrow \mathbb{R}^{2n-1}$??

Lemma 48. $f : M_c^n \rightarrow \mathbb{Q}_{\tilde{c}}^{n+p}$. $c < \tilde{c} \Rightarrow p \geq n - 1$. $c > \tilde{c}$ and $p \leq n - 2 \Rightarrow \alpha_f = \gamma + \sqrt{c - \tilde{c}} \langle \cdot, \cdot \rangle \xi$ with γ flat and ξ unit.

Proof. Define

$$\beta = \alpha \oplus \sqrt{|c - \tilde{c}|} \langle \cdot, \cdot \rangle : TM \times TM \rightarrow \mathbb{W} := T_f^\perp M \oplus \mathbb{R} \quad (5)$$

with the natural Lorentzian (resp. Riemannian) inner product in \mathbb{W} if $c > \tilde{c}$ (resp. $c < \tilde{c}$) and apply the Main Lemma 45. ■

A point $x \in M$ where $\alpha_f(x) = \gamma(x) + \sqrt{c - \tilde{c}} \langle \cdot, \cdot \rangle \xi(x)$ is called a *weak umbilic* of f . Weak umbilic everywhere \Rightarrow composition???

What happens if $c > \tilde{c}$, f free of weak umbilics, and $p = n - 1$?

Proposition 49 (Moore). $\beta : \mathbb{V}^n \times \mathbb{V}^n \rightarrow \mathbb{W}^{p,q}$ symmetric FBF, with $q = 0, 1$ and $\nu_\beta = n - p - q$. If $q = 1$, assume further that β is nondegenerate and that there exist a vector $e \in \mathbb{W}$ such that $\langle \beta, e \rangle > 0$. Then, β decomposes uniquely as the direct sum of $p + q$ rank one flat forms.

Proof. Let's do the case $q=0$ only. We may assume $p=n$, $\nu_\beta=0$. Fix $X_0 \in RE(\beta) \Rightarrow \beta_{X_0}$ is an isomorphism $\Rightarrow C(Y) := \beta_Y \circ \beta_{X_0}^{-1} \in \text{End}(\mathbb{W})$ are all self-adjoint and commuting by flatness $\Rightarrow \exists$ an O.N.B. of \mathbb{W} such that $C(Y)\xi_i = \mu_i(Y)\xi_i$. Set $\beta_i = \langle \beta, \xi_i \rangle$, $\beta_{X_0} X_i = \xi_i \Rightarrow \beta(Y, X_i) = \mu_i(Y)\xi_i \Rightarrow \beta(X_i, X_j) = 0$ if $i \neq j \Rightarrow \beta = \sum_i a_i \rho_i \otimes \rho_i \xi_i$, where $\{\rho_i\} = \{X_i\}^*$ and $a_i = \mu_i(X_i)$. Uniqueness follows easily from this. ■

Corollary 50. Let $f: M_c^n \rightarrow \mathbb{Q}_c^{2n}$ with $\nu = 0 \Rightarrow \exists$ unique basis $\{X_i\}$ of unit vectors and o.n.b. $\{\eta_i\}$ such that $\alpha(X_i, X_j) = \delta_{ij}\eta_j$. The basis $\{X_i\}$ is orthogonal if and only if $R^\perp = 0$, in which case the $\{\eta_i\}$ are the principal normals of f .

Corollary 51. Let $f: M_c^n \rightarrow \mathbb{Q}_{\tilde{c}}^{2n-1}$ with $c \neq \tilde{c}$. If $c > \tilde{c}$ assume that f has no weak umbilics. Then $R^\perp = 0$.

Proof. β in (5) is nondegenerate and has $\nu_\beta = 0$. By the Main Lemma $S(\beta) = \mathbb{W}$. The proof follows from Proposition 49. ■

Exercise. If $\mu = \nu + p$ in Theorem 36 $\Rightarrow R = f^*(\tilde{R})$ and so $\mu = n$. (Sug: use Proposition 49).

§19. Nonpositive extrinsic curvature

Asymptotic vectors of α : $A(\alpha) := \{X \in \mathbb{V} : \alpha(X, X) = 0\}$.

As we saw in the proof of Lemma 48, we have:

Lemma 52 (Otsuki). *Let $\alpha : \mathbb{V}^n \times \mathbb{V}^n \rightarrow \mathbb{W}^{p,0}$ symmetric and $\lambda > 0$ such that $K_\alpha \leq \lambda$ and $\alpha(X, X) > \sqrt{\lambda}\|X\|^2 \Rightarrow p \geq n$.*

Corollary 53 (Otsuki). *Let $\alpha : \mathbb{V}^n \times \mathbb{V}^n \rightarrow \mathbb{W}^{p,0}$ symmetric such that $K_\alpha \leq 0$ and $A(\alpha) = 0 \Rightarrow p \geq n$.*

Corollary 54. *$f : M^n \rightarrow \mathbb{Q}_c^{n+p}$ with $K_M(x_0) < c \Rightarrow p \geq n-1$.*

Corollary 55. *$f : M^n \rightarrow \mathbb{Q}_c^{n+p}$ such that $\exists x \in M$ and $V_x^m \subset T_x M$ with $K(\sigma) < c \forall \sigma \in V_x^m \Rightarrow p \geq m-1$.*

Corollary 56. *$f : M^n \rightarrow \mathbb{R}^{n+p}$ compact such that, $\forall x \in M$ there is $V_x^m \subset T_x M$ with $K(\sigma) \leq 0 \forall \sigma \in V_x^m \Rightarrow p \geq m$.*

19.1 The relative nullity in nonpositive extrinsic curvature

The following is a deep generalization of Otsuki Corollary 53, whose first step is a deeper understanding of the structure of the set of asymptotic vectors $A(\alpha)$. Picture with $R^\perp \equiv 0$:

Theorem 57. *$\alpha : \mathbb{V}^n \times \mathbb{V}^n \rightarrow \mathbb{W}^{p,0}$ symmetric with $K_\alpha \leq 0$. Then, $\nu_\alpha \leq n - 2p$ (and this estimate is sharp!).*

This follows from a sequence of three propositions:

- $X_0 \in A(\alpha)$, $\hat{V} = \text{Ker } \alpha_{X_0} \Rightarrow S(\alpha|_{\hat{V} \times \hat{V}}) \subset (\text{Im } \alpha_{X_0})^\perp$.
Proof. $K_\alpha(X_0 + tY, Z) \leq 0$ for $Z \in \hat{V}$. ■
- $\exists T^m \subset A(\alpha)$ subspace with $m \geq n-p$ (\Rightarrow Otsuki Lemma 52!).
Proof. Induction in p using $X \in A(\alpha)$ with max rank α_X . ■
- $\nu_\alpha \geq \dim T - p$.

Proof. Let $T \oplus T' = \mathbb{V}$, $\beta := \alpha|_{T' \times T}$, $Y_0 \in RE(\beta)$. Use that $K_\alpha(Y_0 + tZ, Y + sZ') \leq 0$ for $Z' \in \text{Ker } \beta_{Y_0} \subset T$, $Z \in T$, $Y \in T'$ is affine in $s \Rightarrow \beta(Y, \text{Ker } \beta_{Y_0}) \subseteq \beta_{Y_0}(T')^\perp \Rightarrow \text{Ker } \beta_{Y_0} \subset \Delta_\alpha$. ■

Many corollaries (no proofs):

Corollary 58. M^n complete and finite volume, $K \leq c < 0$. $f: M^n \rightarrow N_c^{n+p}$ for $2p < n \Rightarrow f$ totally geodesic.

Corollary 59. $f: M^{2n} \rightarrow \mathbb{Q}_c^{2n+p}$ Kahler. If $\exists x_0 \in M$ with $K(x_0) \leq c \neq 0 \Rightarrow p \geq n$.

Corollary 60. $M^n \subset \mathbb{R}^{n+p}$, $p \leq n/2$, $K \leq 0$ and $Ric < 0 \Rightarrow 2p = n$, local and global product of p surfaces $K < 0$ in \mathbb{R}^3 .

Special cases of Thm. 57: $R^\perp = 0$, $\nu_f = n - 2p$ and $\nu_f = n - 2p + 1$.

Remark 61. $\nu_f = n - 2p$ for $M^n \subset \mathbb{Q}_c^{n+p}$ when $c \neq 0$.

19.2 The Omori-Yau maximum principle

Compactness in Corollary 56 can be relaxed. In order to do this, we first need a slight generalization of Lemma 52:

Lemma 62. Let $\alpha: \mathbb{V}^n \times \mathbb{V}^n \rightarrow \mathbb{W}^p$ symmetric. If $p < n$ and $A(\alpha) = 0$, there are $X, Y \in \mathbb{V}$ L.I. such that $\alpha(X, X) = \alpha(Y, Y)$ and $\alpha(X, Y) = 0$.

Proof. Complexifying, it is equivalent to p quadratic equations $\alpha(Z, Z) = 0$ in $n > p$ variables, which is well-known to always have a nontrivial solution that cannot be real by assumption. ■

Def.: The *Omori-Yau maximum principle for the Hessian* (OYMP for short) is said to hold on a given Riemannian manifold M if for any function $g \in C^2(M)$ with $g^* := \sup g < +\infty$ there

exists a sequence of points $\{x_k\}$ in M satisfying the following:
 $g(x_k) > g^* - 1/k$, $\|\nabla g(x_k)\| < 1/k$, $\text{Hess}_g(x_k) < 1/k$.

The following result by Pigola-Rigoli-Setti gives conditions for the OYMP to hold in a complete manifold (no proof):

Theorem 63. *Let M be a complete noncompact R.M, $\rho(x) := d(x, x_0)$. If $K_M \geq -\phi^2 \circ \rho$, where $\phi \in C^1([0, +\infty))$ satisfies $\phi(0) > 0$, $\phi' > 0$, $1/\phi \notin L^1$, then M satisfies the OYMP.*

Theorem 64. *Let $f : M^n \rightarrow P^m \times \mathbb{R}^\ell$, $2 \leq m \leq 2(n - \ell) - 1$, i.i. between complete R.M. such that $f(M) \subset B_R(o) \times \mathbb{R}^\ell$ with $K_P|_{B_R(o)} \leq b$ and $R < \min\{\text{inj}_P(o), \pi/2b\}$ ($\pi/2b = +\infty$ if $b \leq 0$). If $\text{scal}_M \geq -C\rho^2(\Pi_{j=1}^N \log^{(j)} \circ \rho)^2$ outside of a compact set for certain $C > 0$ and $N \in \mathbb{N}$, then $\sup K_f \geq c_b^2(R)(= \cot\dots)$.*

Proof. May assume $\sup K < +\infty$. Then, $K \geq -C'\rho^2(\dots)$ also \Rightarrow OYMP by Theorem 63. Find a contradiction like Otsuki. ■

Corollary 65. *$f : M^n \rightarrow N^{n+p}$, $p \leq n - 1$, M complete, N Hadamard. Assume that the scalar curvature of M is bounded from below. If $K_f \leq 0$, then $f(M)$ is unbounded.*

§20. The relative nullity

Splitting tensor $C : D \times D^\perp \rightarrow D^\perp$ of a distribution D .

C_T is self-adjoint $\forall T \iff D^\perp$ is integrable.

C_T is a multiple of the identity $\forall T \iff D^\perp$ is umbilic.

$C \equiv 0 \iff D^\perp$ is totally geodesic \iff locally a product.

Proposition 66. *Let $f : M^n \rightarrow \mathbb{Q}_c^{n+p}$ and $D \subset \Delta$ a totally geodesic distribution. Then, $\forall \xi \in T^\perp M$, $S, T \in D$, $X, Y \in D^\perp$, and $\gamma' \subset D$ geodesic with parallel transport P_γ , we have:*

1. $\nabla_T C_S = C_S C_T + C_{\nabla_T S} + c\langle T, S \rangle I$;
2. $C'_{\gamma'} = C_{\gamma'}^2 + cI$ (*Riccati !!*);
3. $P_\gamma^{-1} \circ C_{\gamma'} \circ P_\gamma^{-1} = (\sin(t)I + \cos(t)B)(\cos(t)I - \sin(t)B)^{-1}$
for e.g. $c = 1$, where $B = C_{\gamma'}(\gamma(0))$;
4. $(\nabla_X C_T)Y - (\nabla_Y C_T)X = C_{(\nabla_X T)_D} Y - C_{(\nabla_Y T)_D} X$;
5. $\nabla_T A_\xi = A_\xi C_T + A_{\nabla_T^\perp \xi}$ (A_\bullet restricted to D^\perp);
6. $A'_\xi = A_\xi C_{\gamma'}$, if ξ is parallel along geodesic $\gamma \subset D$;
7. $A_\xi C_T = C_T^t A_\xi$;
8. Both $\text{Ker } A_\xi$ and $\text{Im } A_\xi$ are parallel along γ if ξ also is.

Corollary 67. *By Proposition 66.3, B and $C_{\gamma'}$ cannot have a real eigenvalue if γ is defined in $[a, +\infty)$.*

Definitions 68. 1. Given $g : M \rightarrow \mathbb{R}^m$, the k -cylinder over g is the product immersion $f = g \times \text{Id} : N \times \mathbb{R}^k \rightarrow \mathbb{R}^{m+k}$.

2. Given $g : M \rightarrow \mathbb{Q}_c^m$ and $i : \mathbb{Q}_c^m \rightarrow \mathbb{Q}_c^{m+k}$ umbilic, the *generalized cone over g* is (the local regular image of) the map $f : g^*(T_i^\perp \mathbb{Q}_c^m) \rightarrow \mathbb{Q}_c^{m+k}$ defined by $f(x, \xi) = \exp_{i \circ g(x)}(\xi)$, where \exp is the exponential map of \mathbb{Q}_c^{m+k} (e.g., for $\tilde{c} = 1, c = 0$, it is just $f(x, s, t) = (sg(x), t)$, with $s \in \mathbb{R}, t \in \mathbb{R}^r$.)

Proposition 69. *a) If $D^{k\perp}$ as in Proposition 66 is totally geodesic, then $c = 0$ and f is (locally) a k -cylinder. b) If $D^{k\perp}$ is umbilic and $k \leq n-2$, then f is (locally) a generalized cone.*

Proof. I'll do (a) and leave (b) as an exercise. ■

§21. Completeness of the relative nullity

Proposition 70. *Let $f: M^n \rightarrow \mathbb{Q}_c^{n+p}$, and $U \subset M$ an open subset where $\nu_f = s > 0$. If $\gamma: [0, b] \rightarrow M$ is a geodesic such that $\gamma([0, b))$ is contained in a leaf of Δ in U , then $\Delta(\gamma(b)) = P_\gamma(\Delta(\gamma(0)))$ and $\nu_f(\gamma(b)) = s$. Moreover, $C_{\gamma'}$ extends smoothly to $\gamma(b)$ and Proposition 66 items 2, 6, 7 and 8 hold on $[0, b]$.*

Proof. Let $V_t = \Delta(\gamma(t))^\perp = P_{0,t}^\gamma(V_0)$, and consider the solution in $\text{End}(V_t)$ of $J' + CJ = 0$, $J(0) = I$, for $C := C_{\gamma'} \Rightarrow J'' + cJ = 0$ (Jacobi!) $\Rightarrow J$ smoothly extends to b in $\text{End}(P_{0,b}^\gamma(V_0))$. If $Z, Y \in \mathfrak{X}_\gamma''$ with $Y \in \Delta^\perp \Rightarrow \alpha(JY, Z)' = 0 \Rightarrow J$ invertible in $[0, b]$, $P_{0,b}^\gamma(V_0) = V_b$ and C smoothly extends to b since $C = -J'J^{-1}$. ■

Corollary 71 (!!!!). *The minimum relative nullity distribution is complete if M is complete.*

Remark 72. Propositions 66,70 and Corollary 71 hold for the intersection of the relative nullities of a finite number of immersions (since $(\alpha_1, \alpha_2, \dots)$ is Codazzi).

Let $\kappa(m) = (\# \text{ L.I. vector fields in } \mathbb{S}^{m-1} + 1)$ be the [Radon-Hurwitz number](#), which is given by $\kappa((\text{odd})2^{4d+b}) = 8d + 2^b$, with $d \in \mathbb{N} \cup \{0\}$ and $b = 0, 1, 2, 3$ (F. Adams, 1962). Set

$$\rho_n := \max\{k : \kappa(n - k) \geq k + 1\}.$$

Some values of ρ_n are: $\rho_n = n - (\text{highest power of } 2 \leq n)$ for $n \leq 24$, $\rho_n \leq 8d - 1$ for $n < 16d$, and $\rho_{2d} = 0$.

Corollary 73. *M^n complete and $f: M^n \rightarrow \mathbb{S}^{n+p}$ with $\nu > \rho_n \Rightarrow f$ totally geodesic.*

Proof. Pick x in the open set with min relative nullity $r < n$, $\{X_1, \dots, X_r\}$ a basis of $\Delta(x) \cong \mathbb{R}^r$ and $0 \neq Z \in \Delta(x)^\perp \cong \mathbb{R}^{n-r}$. Then, $\{Z, C_{X_1}Z, \dots, C_{X_r}Z\}$ are L.I. by Corollary 67. So we have a cross-section between the Stiefel manifolds $V_{n-r, r+1} \rightarrow V_{n-r, 1}$ (\iff we have r L.I. vector fields in \mathbb{S}^{n-r-1}) $\Rightarrow r \leq \rho_n$. ■

Corollary 74. M^n complete with $K \leq 1$ and $f : M^n \rightarrow \mathbb{S}^{n+p}$ with $2p < n - \rho_n \Rightarrow f$ is totally geodesic (by Theorem 57).

Remark 75. At least for some dimensions, the hypothesis on p in the above cannot be improved to $2p < n$. For example, the simplest of Cartan's isoparametric hypersurfaces, i.e., the unit normal bundle of the Veronese surface (3) in \mathbb{S}^4 , is a compact non-totally geodesic hypersurface of \mathbb{S}^4 with curvature ≤ 1 .

21.1 Zero extrinsic curvature: The spherical case

Two leaves of minimum relative nullity $\nu_0 < n$ of a non-totally geodesic $f : \mathbb{S}^n \rightarrow \mathbb{S}^{n+p}$ have dimension $\nu_0 \geq n - p$ by Chern-Kuiper, are complete, and cannot intersect in \mathbb{S}^n . Then $\nu_0 + 1 \leq 2(n + 1)$, and hence $p > n/2$. In fact, Corollary 73 and Chern-Kuiper imply that $p \geq n - \rho_n$. But we can do better:

Theorem 76. [DG] M^n complete, $f : M^n \rightarrow \mathbb{S}^{n+p}$ with $\nu > 0$. Then, at any point in $U = \{\nu = \nu_0 > 0\}$ where ν is minimal, and for any normal direction at that point, the numbers of positive and negative principal curvatures are equal.

Proof. Let $\gamma : \mathbb{R} \rightarrow U$ a geodesic in a leaf of Δ , ξ normal parallel along γ . By Proposition 66.6, $\text{Ker } A_\xi$ is parallel along $\gamma \Rightarrow \text{rank } A_\xi(\gamma(t))$ is constant \Rightarrow so are the number of positive and negative eigenvalues. But the antipodal map I of \mathbb{S}^{n+p} leaves U invariant $\Rightarrow \exists \tau \in \text{Iso}(U)$ such that $f \circ \tau = I \circ f|_U$. But $\text{inc}_*\xi$

is constant in \mathbb{R}^{n+p+1} along γ , so $\xi \circ \tau = -I_*\xi$ and $A_{\xi \circ \tau} \circ \tau_* = -\tau_* \circ A_\xi$. Hence $\sigma(A_\xi(\gamma(\pi))) = -\sigma(A_\xi(\gamma(0)))$. ■

Corollary 77. *Ric ≥ 1 at some $x \in U \Rightarrow f$ is totally geodesic.*

Proof. Use Theorem 76 and (2). ■

Corollary 78. *If $p \leq n - 1$, the only $f : M_1^n = \mathbb{S}^n/\Gamma \rightarrow \mathbb{S}^{n+p}$ is the totally geodesic inclusion ($\Rightarrow \Gamma = \{Id\}$). In particular, it is rigid.*

Example 79. The product isometric immersion $F : \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{2n+2}$ given by $F(t) = \frac{1}{\sqrt{n+1}}e^{i\sqrt{n+1}t}$ induces $f = F|_{\mathbb{S}^n} : \mathbb{S}^n \rightarrow \mathbb{S}^{2n+1}$ which is not totally geodesic.

What about $p = n$?? Recall Corollary 50...

21.2 Zero extrinsic curvature: The Euclidean case

Theorem 80 (Hartman's extrinsic splitting thm). *M^n complete with $Ric_M \geq 0$ and $f : M^n \rightarrow \mathbb{R}^{n+p}$ containing r independent lines $\Rightarrow f$ is an r -cylinder. In particular, f is an ν_0 -cylinder.*

Proof. (by Johel Beltran) Let $g : I \times \mathbb{R} \rightarrow \mathbb{R}^m$ i.i. containing a straight line L . Write $g(x, y) = (u(x, y), v(x, y))$ with $u(0, y) = 0 \in \mathbb{R}^{m-1}$, $v(0, y) = y$. But $v(x, y) = y$: indeed, if $p = (x, y)$ and $c = v(p) - y$, let $q = (0, y - \lambda c) \in L \subset \mathbb{R}^2$ with $\lambda \gg 1$ so that $d(p, q) - d((0, y), q) \leq |c|/2$. So, $(\lambda + 1)|c| \leq d(g(p), g(q)) \leq d(p, q) \leq (\lambda + 1/2)|c|$, and thus $c = 0$. Since $1 = \|g_y\|^2 = \|u_y\|^2 + 1$, we get $g(x, y) = (u(x), y)$ and $g = u \times Id_{\mathbb{R}}$.

Now, by the splitting theorem, $M = N \times \mathbb{R}^r$. Take $\gamma : I \rightarrow N$ a unit curve and set $f_\gamma : I \times \mathbb{R}^r \rightarrow \mathbb{R}^m$, $f_\gamma(s, v) = f(\gamma(s), v)$. By the above $f_\gamma(x, v) = (g(\gamma(x), v), v)$. But $\|f_*(0, v)\| = \|v\| \Rightarrow g_*(0, v) = 0$. ■

Corollary 81. *If $f : \mathbb{R}^n \rightarrow \mathbb{R}^{n+p}$ is an i.i. with $p < n$, then f is a $(n - p)$ -cylinder.*

§22. The Gauss Parametrization

Motivation. Let $g : I \times \mathbb{R} \rightarrow \mathbb{R}^m$ a non-cylindrical ruled surface, with rulings $R = \text{span}\{Z\} \Rightarrow g(t, s) = \beta(t) + sZ(t)$, where $Z : I \rightarrow \mathbb{S}^{m-1}$, $\|Z'\| = 1$, W.L.G. $\langle \beta', Z' \rangle = 0$ (β is called the *striction curve*). Let $J = \{t : \beta'(t) \parallel Z(t)\}$. Then, $K \leq 0$, and $K^{-1}(0) = \{\nu > 0\} = \{\nu = 1\} = \{\Delta = R\} = J \times \mathbb{R}$, and $g(\text{sing}(g)) = \beta(J)$. In particular $K \equiv 0 \iff g(\text{sing}(g)) = \beta$. But $\text{sing}(g)$ is not just the singular set of the map g , but of the submanifold, since $C_Z = s^{-1}Id$. We just gave another proof of Hartman's Theorem 80, certainly much less elegant and elementary, but the parametrization idea is much more powerful!

In fact, we classified all ruled flat surfaces in \mathbb{R}^n , and hence all flat surfaces in \mathbb{R}^3 : *each connected component of an open dense subset* is either a cylinder over a curve, or a cone over a spherical curve (with $\beta = \text{constant}$ as the vertex), or the surface of tangents of the regular curve β : $g = \beta + s\beta'$. Moreover, all these connected components are glued together along rulings. Observe that looking at the problem with the singularities actually helped!

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Let $f : M^n \rightarrow \mathbb{R}^{n+1}$ be a submanifold with constant relative nullity $n - k$ and Gauss map $\eta : M^n \rightarrow \mathbb{S}^n$. Let $\gamma = \langle f, \eta \rangle$ be the *support function* of f . Then, locally, we have a projection $\pi : M^n \mapsto V^k := M^n / \Delta$ onto the leaf space, which is a k -dimensional manifold. We thus have that η and γ depend only

on their projections, i.e., $\eta = h \circ \pi$ and $\gamma = r \circ \pi$, for certain

$$h : V^k \rightarrow \mathbb{S}^n \quad \text{and} \quad r : V^k \rightarrow \mathbb{R} : \quad \text{the } \underline{\text{Gauss data}} \text{ of } f.$$

Therefore, at regular points, $f(M)$ is locally parametrized by

$$\hat{f} : M \cong T_h^\perp V \rightarrow \mathbb{R}^{n+1},$$

$$\hat{f} \circ \xi = rh + \nabla r + \xi, \quad \xi \in \Gamma(T^\perp V).$$

Observe that, if $w = \xi(x) \in T_{h(x)}^\perp V$ and since $h_{*x}(T_x V)$ and $\hat{f}_{*w}(\Delta^\perp(w))$ are parallel, we identify $T_x V$ with $\Delta^\perp(w)$ with the isometry $j = j_w : T_{h(x)} V \rightarrow \Delta^\perp(w)$ given by $h_{*x} = \hat{f}_{*w} \circ j_w$, i.e., $X \cong X' = jX \circ \pi$. In particular, $j_\xi : \mathfrak{X}(V) \rightarrow \mathfrak{X}_\xi(\Delta^\perp)$ satisfies $h_* = \hat{f}_* \circ j_\xi$ and is parallel, namely, $\nabla j_\xi = 0$. Notice also that $\nabla_\Delta j = 0$. Set

$$P_w := rI + \text{Hess}_r - A_w^h \in \text{EndSim}(T_x V).$$

Hence, $j_w \circ P_w = (\xi_{*x})_{\Delta^\perp(w)}$, $\pi_{*w} \circ j_w = P_w^{-1}$, and j conjugates all operators. Note that $\nabla_\Delta j = 0$ and set $\hat{\xi} = \xi \circ \pi \in \Delta$. Thus:

- i) $\Delta(w) = T_{h(x)}^\perp V$ and $\Delta^\perp(w) = T_{h(x)} V$ by construction;
- ii) w is a regular point of $\hat{f} \iff P_w$ is invertible;
- iii) $\forall X \neq 0$, $(\xi_* X)_{\Delta^\perp(w)} \neq 0$ and $\|(\xi_* X)_{\Delta^\perp(w)}\|_{\hat{f}} = \|P_w X\|_h$;
- iv) The shape operator of f in $\Delta^\perp(w)$ is $A_w = -P_w^{-1}$;
- v) The singular points of \hat{f} are singular points of $\text{Im}(\hat{f})$ itself;
- vi) The connections of \hat{f} and h are related: $(\nabla_{P_w X}^M Y)_{\Delta^\perp} = \nabla_X^h Y$;
- vii) The normal connection ∇^\perp of h is related to the Levi-Civita connection of M along Δ by $(\nabla_{P_w X}^M \hat{\xi})_\Delta = \nabla_X^\perp \hat{\xi}$;

viii) The splitting tensor of Δ for $\hat{\xi}$ is $C_{\hat{\xi}} = A_{\hat{\xi}}^h P_w^{-1}$.

Proof. vi) Formally, $\hat{f}_*(\nabla_{(P_w X)}^M Y')_{\Delta^\perp} = (\bar{\nabla}_{(P_w X)} h_* Y \circ \pi)_{TV} = h_*(\nabla_X^V Y) \circ \pi = \hat{f}_*(\nabla_X^V Y)'$.

vii + viii) $\hat{f}_*(\nabla_{P_w \hat{X}}^M \hat{\xi}) = \bar{\nabla}_X^h \xi = -\hat{f}_* j A_\xi^h X + \nabla_X^\perp \xi$. ■

Corollary 82. *Local classification of $f : U \subset \mathbb{Q}_c^n \rightarrow \mathbb{Q}_c^{n+1}$.*

Corollary 83. Δ^\perp is integrable $\iff h$ has flat normal bundle and $[\text{Hess}_r, A_w] = 0 \ \forall w \in T^\perp V$.

Corollary 84. *Any submanifold $h : V^k \rightarrow \mathbb{S}^n$ is a Gauss map. The set of hypersurfaces with Gauss map h is parametrized by $\mathcal{F}(V^k)$.*

Corollary 85. *In \mathbb{Q}_c^{n+1} we also have Gauss parametrization.*

Corollary 86. f is a cylinder $\iff h$ reduces codimension.

Corollary 87. $f : M^n \rightarrow \mathbb{R}^{n+1}$ with $\mu \equiv n - 2$ and complete leaves of Δ along which the mean curvature of f does not change sign. Then, $h : V^2 \rightarrow \mathbb{S}^n$ is minimal and f is a cylinder over $g : N^{2+\epsilon} \rightarrow \mathbb{R}^{3+\epsilon}$ and $\nu_g = \epsilon$, where $\epsilon = 0, 1$.

The last one and Theorem 32 give:

Corollary 88. $f : M^n \rightarrow \mathbb{R}^{n+1}$ complete minimal without euclidean factors, $n \geq 4 \implies f$ is rigid in \mathbb{R}^{n+p} among minimal.

Corollary 89. $f : M^n \rightarrow \mathbb{R}^{n+1}$ with $\mu \equiv n - 2$ and scal_M constant. Then f is locally a cylinder over a surface. If in addition M^n is complete $\implies f(M) = \mathbb{S}_c^2 \times \mathbb{R}^{n-2} \subset \mathbb{R}^3 \times \mathbb{R}^{n-2}$.

Proof. Need to prove that h is totally geodesic (global part then follows from Hilbert's $\mathbb{H}^2 \not\subset \mathbb{R}^3$ and the rigidity of $\mathbb{S}^2 \subset \mathbb{R}^3$). Otherwise $\implies \nu_h = 1$ and $K_{V^2} = 1$ in some open subset $U \subset V^2$.

Let $\{X, Y\}$ o.n.b. of TU and $Y \in \Delta_h$. So, $\nabla_Y X = \nabla_Y Y = 0$. Moreover $YY(r) + r = 0$ and $YX(r) = \text{scal}_M^{-1} \neq 0$ is constant $\Rightarrow 0 = X(r) + XY(r) = 2\langle \nabla_{[X,Y]} \nabla r, Y \rangle = 2\langle \nabla_X Y, X \rangle YX(r) \Rightarrow \nabla Y = 0 \Rightarrow K_{V^2} = 0$, contradiction. ■

§23. Homogeneous hypersurfaces

Def.: $f: M^n \rightarrow \mathbb{Q}_c^{n+1}$ is *isoparametric* if it has constant principal curvatures $(\lambda_1 < \dots < \lambda_g$ with multiplicity m_i).

Lemma 90. $f: M^n \rightarrow \mathbb{Q}_c^{n+1}$ with M^n homogeneous \Rightarrow Either $\tau \leq 1$ or τ is constant. If $\tau \geq 3$, then f is isoparametric.

Theorem 91 (Cartan fund. formula). $\forall i, \sum_{j \neq i}^g m_j \frac{c + \lambda_i \lambda_j}{\lambda_i - \lambda_j} = 0$.

Proof. $Ae_i = \lambda_i e_i, E_i = \text{Ker}(A - \lambda_i I), \Gamma_{ij}^k = \langle \nabla_{e_i} e_j, e_k \rangle = -\Gamma_{ik}^j$. Codazzi: $(\lambda_j - \lambda_k)\Gamma_{ij}^k = (\lambda_i - \lambda_k)\Gamma_{ji}^k \Rightarrow E_i$ totally geodesic \Rightarrow WLG $g \geq 3$. Gauss: $c + \lambda_i \lambda_j = \sum_k (\Gamma_{ij}^k \Gamma_{ji}^k + \Gamma_{ij}^k \Gamma_{ki}^j + \Gamma_{ji}^k \Gamma_{kj}^i) = 2 \sum_k \Gamma_{ij}^k \Gamma_{ji}^k = \sum_{i \neq k \neq j} \frac{(\lambda_i - \lambda_j)^2}{(\lambda_i - \lambda_k)(\lambda_j - \lambda_k)} (\Gamma_{ki}^j)^2$. Now just sum. ■

Corollary 92. Suppose that $f: M^n \rightarrow \mathbb{R}^{n+1}$ is isoparametric. Then, $f(M) \subset \mathbb{S}_c^k \times \mathbb{R}^{n-k}$ for some $0 \leq k \leq n$.

Proof. Let i in Theorem 91 s.t. λ_i is the smallest positive one \Rightarrow all others are 0, $E_{\lambda_i} = \Delta^\perp$ is tot. geod., done by Proposition 69. ■

Remark 93. Similar result holds for \mathbb{H}^{n+1} , also proved by Cartan. So the only interesting case is for \mathbb{S}^{n+1} . Münzner showed that $g = 1, 2, 3, 4$ or 6 , and for g odd all multiplicities are equal, while if g is even $m_i = m_{i+2} (i \bmod g)$. Using representations of Clifford algebras, Ferus-Karcher-Münzner gave a beautiful construction of a large family with $g = 4$. Lots of things are understood, but the full classification is still an important open problem.

Theorem 94. $f: M^n \rightarrow \mathbb{R}^{n+1}$ with M^n homogeneous $\Rightarrow f$ is either a complete cylinder over a plane curve, or $\mathbb{S}_c^k \times \mathbb{R}^{n-k}$.

23.1 Curvature homogeneous hypersurfaces

There are weaker (and local!) notions than the above:

Definition 95. A Riemannian manifold M is said to be *curvature homogeneous* if $\forall x, y \in M \exists$ a linear isometry $\tau_{xy}: T_x M \rightarrow T_y M$ such that its curvature tensor satisfies $R_x = J_{xy}^* R_y$.

Definition 96. We say that $f: M^n \rightarrow \mathbb{Q}_c^{n+p}$ is *weakly isoparametric* if $\forall x, y \in M \exists$ linear isometries $\tau_{xy}: T_x M \rightarrow T_y M$ and $\hat{\tau}_{xy}: T_x^\perp M \rightarrow T_y^\perp M$ such that $\hat{\tau}_{xy} \circ \alpha_x = \tau_{xy}^* \alpha_y$.

By Gauss eqn, weakly isoparametric \Rightarrow curvature homogeneous. WLOG, we can fix $y = x_0$ and work with just $\tau_x = \tau_{xx_0}$, $\hat{\tau}_x = \hat{\tau}_{xx_0}$. For $f: M^n \rightarrow \mathbb{Q}_c^{n+p}$ with M^n curvature homogeneous, define

$$\beta_x = (\alpha_x, \tau_x^* \alpha_{x_0}) : T_x M \times T_x M \rightarrow W_x^{p,p} = T_x M \oplus T_{x_0} M.$$

Then, β_x is flat $\forall x$, and f is weakly isoparametric if and only if β_x is null $\forall x$. The Main Lemma 45 then immediately implies:

Proposition 97. $f: M^n \rightarrow \mathbb{Q}_c^{n+1}$ is curvature homogeneous if and only if either it is isoparametric, or has constant curvature c , or has rank two and constant scalar curvature $\neq c$.

Besides the isoparametric case, Corollary 82 and Corollary 89 tell us that what is left are the rank two hypersurfaces with constant scalar curvature for $c \neq 0$. By the Gauss parametrization, this is equivalent to the classification of $V^2 \subset \mathbb{S}_{\pm 1}^{n+1}$ for which all shape operators of unit vectors have constant determinant $\neq 0$. Tsukada proved in 1988 that the only case for $n \geq 4$ was a single complete

hypersurface $M^4 \subset \mathbb{H}^5$ related to the unit normal bundle of the Veronese surface. Now, the case $n = 3$ has just been solved:

Theorem 98 ([Bryant-Florit-Ziller]). *Let \mathcal{M} be the set of immersed rank two hypersurfaces in \mathbb{Q}_c^4 , $c = \pm 1$, whose induced metrics have constant scalar curvature. Then, \mathcal{M} contains a one parameter family of hypersurfaces admitting no continuous symmetries, and an isolated rotationally symmetric hypersurface. None of these examples is complete, and any connected hypersurface in \mathcal{M} is congruent to an open subset of one of them.*

§24. Immersions of Riemannian products

Orthogonal nets. Ex: Riemannian products. Adapted tensors. Recall: if $X_i \in \mathfrak{X}(M_i)$ we have lifts $\tilde{X}_i \stackrel{\pi_i}{\sim} X_i$, and for the injections $\tau_j = \tau_j^{x_{j+1}} : M_j \rightarrow M_1 \times M_2$ we have $X_i \stackrel{\tau_i}{\sim} \tilde{X}_i$. We conclude that $T_{(x_1, x_2)}(M_1 \times M_2) \cong T_{x_1}M_1 \oplus T_{x_2}M_2$ canonically.

Theorem 99 (Moore). *If the second fundamental form of $f : M_1 \times M_2 \rightarrow \mathbb{R}^m$ is adapted, then f is an extrinsic product.*

Proof. Taking lifts of vector fields in each factors we see that $f_*T_xM_1 \perp f_*T_yM_2 \quad \forall (x, y) \in M_1 \times M_2$. Thus, $V_1 \perp V_2$, where

$$V_i := \text{span}\{f_{*(x_1, x_2)}(T_{x_i}M_i) : (x_1, x_2) \in M_1 \times M_2\}.$$

Decomposing $\mathbb{R}^m = V_0 \oplus^\perp V_1 \oplus^\perp V_2$ and $f = f_0 + f_1 + f_2$, we conclude that $f_1 = f_1(x_1)$, $f_2 = f_2(x_2)$, and that f_0 is constant. ■

Remark 100. The decomposition is unique (if f_i is substantial).

Corollary 101. *Same in \mathbb{S}^m . Almost the same in \mathbb{H}^m .*

24.1 Splitting under a curvature condition

Theorem 102. *Let $f : M^n = \times_{i=0}^k M_i^{n_i} \rightarrow \mathbb{R}^{n+k}$ such that the set of flat points of M_j has empty interior, $\forall 1 \leq j \leq k$. Then, $M_0^{n_0}$ is flat and $f(M)$ is an open subset of a n_0 -cylinder over an extrinsic product of k hypersurfaces.*

Proof. Fix $1 \leq j \neq j' \leq k$, and let $\sigma_j = \text{span}\{e_{2j-1}, e_{2j}\} \subset T_{x_j} M_j$ with $k_j := K(\sigma_j) \neq 0$, $L_j := \text{span } \alpha(e_{2j}, e_{2j}) \neq 0$, and $T_x^\perp M = L_1 \oplus^\perp \cdots \oplus^\perp L_k$. By Gauss equation, if $V^{2k} = \sigma_1 \oplus \cdots \oplus \sigma_k$,

$$\beta := \alpha \oplus B_1 \oplus \cdots \oplus B_k : V^{2k} \times V^{2k} \rightarrow T_x^\perp M \oplus \mathbb{R}^k = W^{2k,0}$$

is flat, where $B_j = \sqrt{|k_j|}(e^{2j-1} \otimes e^{2j-1} - \text{sign}(k_j)e^{2j} \otimes e^{2j})$. By Proposition 49, there is a basis $\{e'_1, \dots, e'_{2k}\}$ of V^{2k} such that $\beta(e'_r, e'_s) = 0$, $\forall 1 \leq r \neq s \leq 2k$. In particular, $\text{Ker } B_i$ and $\text{Im } B_i$ are spanned by vectors in this basis. Hence, up to order, $e'_{2j-1}, e'_{2j} \in \sigma_j$, $\alpha(\sigma_j, \sigma_{j'}) = 0$, and $\alpha(\sigma_j, \sigma_j) = L_j$. So, for the conullities $\Gamma_j^\perp \subset T_{x_j} M_j$ we get $\alpha(\Gamma_j^\perp, \Gamma_{j'}^\perp) = 0$ and $\alpha(\Gamma_j^\perp, \Gamma_j^\perp) = L_j$. Now it's just Gauss equation:

Since $\Gamma_j \subset \Gamma$, $\langle \alpha(\Gamma_j, \Gamma_j^\perp), \alpha(\Gamma_{j'}^\perp, \Gamma_{j'}^\perp) \rangle = 0$ and then $\alpha(\Gamma_j, \Gamma_j^\perp) \subset L_j$. But if $X \in \Gamma_j^\perp$, there is $Y \in \Gamma_j^\perp$ such that $\alpha(X, Y) = 0$ and $0 \neq \alpha(Y, Y) \in L_j$. So $\langle \alpha(\Gamma_j, X), \alpha(Y, Y) \rangle = 0$, and then $\alpha(\Gamma_j, \Gamma_j^\perp) = 0$. Similarly, $\alpha(\Gamma_j, \Gamma_{j'}^\perp) = 0$. Therefore $\Gamma_j \subset \Delta(x)$, $\alpha(T_{x_j} M_j, T_{x_j} M_j) = L_j$, and $\alpha(T_{x_j} M_j, T_{x_{j'}} M_{j'}) = 0$. The same argument gives $\alpha(T_{x_0} M_0, T_{x_j} M_j) = \alpha(T_{x_0} M_0, T_{x_0} M_0) = 0$ and hence $T_{x_0} M_0 \subset \Delta(x)$ and $\alpha(x)$ is adapted. Therefore α is everywhere adapted to the product structure and the result follows from Proposition 69. ■

Remark 103. Similar in \mathbb{Q}_c^{n+k} . If $k = 2$ we can say a bit more.

24.2 Splitting under an algebraic condition

Lemma 104. *Let $\beta : V^n \times V^n \rightarrow W^{p,0}$ symmetric, $V = V_1 \oplus V_2$ and $R_\beta(V_1, V_i, V_j, V_2) = 0$ for $1 \leq i, j \leq 2$. If $\nu_s < n - 2s$ $\forall 1 \leq s \leq p$, then $\beta(V_1, V_2) = 0$.*

Proof. For $i \neq j$, let $\beta_{ij} := \beta|_{V_i \times V_j} : V_i \times V_j \rightarrow S^s$ surjective and $\Delta_{ij} := \text{Ker } \beta_{ij} \subset V_i \Rightarrow \langle \beta(\Delta_{12}, V_j), \beta(V_i, V_2) \rangle = 0 \Rightarrow \beta(\Delta_{12}, V) \perp S^s$. Similarly, $\beta(V, \Delta_{21}) \perp S^s \Rightarrow \Delta_{12} \oplus \Delta_{21} \subset \text{Ker } \beta_S$, and $\dim(\Delta_{12} \oplus \Delta_{21}) \geq \dim V_2 - s + \dim V_1 - s = n - 2s \Rightarrow s = 0$. ■

Corollary 105. *If $f : M^n := \times_{i=1}^k M_i^{n_i} \rightarrow \mathbb{Q}_c^{n+p}$ satisfies $\nu_s < n - 2s \quad \forall 1 \leq s \leq p$, then f is an extrinsic k -product.*

24.3 Splitting under a global condition

The following is a generalization of Chern-Kuiper Theorem 36:

Theorem 106. *Given $f : M^n \rightarrow \tilde{M}^{n+p}$, decompose $\Gamma^\perp(x)$ as $\Gamma^\perp(x) = T_1 \oplus^\perp \dots \oplus^\perp T_s$, where all T_i 's are non-zero and $(R - f^* \tilde{R})$ -invariant. Then, $\nu(x) \leq \mu(x) \leq \nu(x) + p - s$.*

Proof. If $S = (\Gamma \cap \Delta^\perp) \oplus \text{span}\{Y_1, \dots, Y_s\}$ for $0 \neq Y_i \in T_i \Rightarrow (R - f^* \tilde{R})(S, S) = 0$. Now, if $Z \in RE(\alpha|_{TM \times S})$ then $\text{Ker}(\alpha_Z|_S) = 0$ since $S \cap \Delta = 0$. Hence, $p \geq \dim S = \mu - \nu + s$. ■

Corollary 107. *We always have that $s \leq p$ and, if $\mu = \nu + p$, then $R = f^* \tilde{R}$ and α_f is flat.*

Corollary 108. *Let $f : M^n = \times_{i=1}^p M_i^{n_i} \rightarrow \mathbb{R}^{n+p}$, $n_i \geq 2$. If $\alpha_f(x)$ is not adapted, then $0 < r(x) \leq \mu(x) - r(x) \leq \nu(x) \leq \mu(x)$, where $r(x)$ is the number of factors that are flat at x .*

Proof. By Theorem 102 at least one factor M_i is flat at $x_i = \pi_i(x)$, so $r(x) > 0$. Moreover, $\mu(x) \geq 2r(x)$ since $n_i \geq 2$. The third inequality follows from Theorem 106. ■

Theorem 109. *Let $M_i^{n_i}$ be compact with $n_i \geq 2$. Then, every $f: M^n = \times_{i=1}^p M_i \rightarrow \mathbb{R}^{n+p}$ splits as a product of p hypersurfaces.*

Proof. Let $U \subset M$ be the open subset where α_f is not adapted, and $U_0 \subset U$ where the relative nullity of $f|_U$ is minimum $\nu_0 \Rightarrow \nu_0 \geq \mu - r \geq r > 0$ by Corollary 108. Since M^n is compact and U is open, by Proposition 70 a maximal geodesic in a leaf of Δ in U_0 has to leave U . At the end point α is adapted, hence it is adapted inside U by Proposition 66.6; see also the proof of Proposition 70. So $U = \emptyset$ and the result follows from Theorem 99. ■

Questions: If $f_i: M_i^{n_i} \rightarrow \mathbb{R}^{n_i+p_i}$ with p_i the minimal codimension, is $q = p_1 + p_2$ the minimal codimension for an is.im. $f: M_1^{n_1} \times M_2^{n_2} \rightarrow \mathbb{R}^{n_1+n_2+q}$? If yes, is it necessarily a product?

Remark 110. Similar results to those in this section exist for *warped products*; see [DT].

§25. Conformal immersions

General philosophy: $\mathbb{Q}_c^m \cong \mathbb{R}^m$; conformal immersions in $\mathbb{R}^m \cong$ isometric immersions in the *light cone* $\mathbb{V}^{m+1} \subset \mathbb{L}^{m+2}$.

If $w \in \mathbb{V}^{m+1}$ and $v \in \mathbb{E}^m = \mathbb{E}_w := \{v \in \mathbb{V}^{m+1}: \langle v, w \rangle = 1\} \cong \mathbb{R}^m$, and $C: \mathbb{R}^m \rightarrow \text{span}\{v, w\}^\perp \subset \mathbb{L}^{m+2}$ is a linear isometry, then

$$\psi(x) = v + Cx - \frac{1}{2}\|x\|^2 w: \mathbb{R}^m \rightarrow \mathbb{E}^m$$

is an isometric embedding in \mathbb{L}^{m+2} . In fact, if $z \in \mathbb{L}^{m+1}$ with $\langle z, z \rangle = -1/c$, then $\mathbb{Q}_c^m \cong \{u \in \mathbb{V}^{m+1} : \langle u, z \rangle = -1/c\}$.

The set of transformations $(v, w, C) \mapsto (v', w', C')$ is $\mathbb{O}_1(m+2)$.

Remark 111. Given a hypersurface $f: M^n \rightarrow \mathbb{V}^{n+1}$ we have that $f \in T_f^\perp M$ is parallel and $A_f^f = -I$. Hence, if η is the normal parallel with $\langle \eta, \eta \rangle = 0$, $\langle \eta, f \rangle = 1$, Gauss equation gives

$$\alpha_f(X, Y) = -\langle X, Y \rangle \eta - \langle LX, Y \rangle f,$$

where

$$L := \frac{n-1}{n-2} Ric - \frac{n}{2(n-2)} scal_M Id.$$

In particular, $T_\psi^\perp \mathbb{R}^m = \text{span}\{\psi, w\}$, $A_w^\psi = 0$, and $\alpha_\psi = -\langle \cdot, \cdot \rangle w$.

25.1 The light cone representative

Conformal structure. Pull back.

Proposition 112. *Let M^n be a Riemannian manifold, and $f: M^n \rightarrow \mathbb{R}^m \cong \mathbb{E}_w^m$ a conformal immersion with conformal factor φ . Then, $\hat{f} := \varphi^{-1} \psi \circ f: M^n \rightarrow \mathbb{V}^{m+1}$ is an isometric immersion. Conversely, if $\hat{f}: M^n \rightarrow \mathbb{V}^{m+1} \setminus \mathbb{R}w$ is an isometric immersion, then $f := \psi^{-1}(\langle \hat{f}, w \rangle^{-1} \hat{f}): M^n \rightarrow \mathbb{R}^m$ is a conformal immersion with conformal factor $\varphi = \langle \hat{f}, w \rangle^{-1}$. We call \hat{f} the *isometric light cone representative of f* .*

Corollary 113. *M^n simply connected, $n \geq 3$, is conformally flat if and only if it is a hypersurface of the light cone.*

Remark 114. The space of curvature tensors can be decomposed in three $O(n)$ -invariant subspaces: the one generated by the inner product (manifolds of constant curvature), the one

spanned by the Ricci flat tensor (conformally flat manifolds), and the complement of these. So, we define the *Weil tensor* W by

$$\begin{aligned} \langle W(X, Y)Z, V \rangle &= \langle R(X, Y)Z, V \rangle - \langle LX, V \rangle \langle Y, Z \rangle - \langle LY, Z \rangle \langle X, V \rangle \\ &\quad + \langle LX, Z \rangle \langle Y, V \rangle + \langle LY, V \rangle \langle X, Z \rangle. \end{aligned}$$

A well-known theorem by Schouten states that, for $n \geq 4$, M^n is conformally flat if and only if $W = 0$. In fact, this can be easily seen using Corollary 113: $W = 0$ is precisely the Gauss equation of an hypersurface in the light-cone; see Remark 111.

Exercise. If $R(u) := u - 2\langle u, z \rangle z \in \mathbb{O}_1(m+2)$ is the reflection with respect to the space-like vector z with $\langle z, w \rangle \neq 0$ in \mathbb{E}_w^m , then \hat{R} is the inversion with respect to the hypersphere $\mathbb{E}_w^m \cap \{z\}^\perp$.

It turns out that \mathbb{R}^m is locally rigid in \mathbb{V}^{m+1} for $m \geq 3$:

Theorem 115. *If $F : U \subset \mathbb{R}^m \rightarrow \mathbb{V}^{m+1}$ is an isometric immersion with $m \geq 3$, then $F = \psi|_U$ for some (v, w, C) .*

Proof. By Remark 111, $\alpha(X, Y) = -\langle X, Y \rangle \eta$. But $\tilde{\nabla}_X \eta = -LX = 0 \Rightarrow \eta$ is a constant vector and $F(U) \subset \mathbb{E}_\eta^m$. ■

Corollary 116. *For any conformal map $f : U \subset \mathbb{R}^m \rightarrow \mathbb{R}^m$, there is $T \in \mathbb{O}_1(m+2)$ such that $\hat{f} = T \circ \psi|_U$.*

Conformal congruence can be regarded as a special case of isometric congruence (so we can use the isometric methods!):

Proposition 117. *$f', f : M^n \rightarrow \mathbb{R}^{n+p}$ are conformally congruent $\iff \hat{f}'$ and \hat{f} are isometrically congruent.*

Proof. Observe that the conformal factor of a composition $i \circ j$ satisfies $\varphi_{i \circ j} = \varphi_j \varphi_i \circ j$. If $f' = \mathcal{T} \circ f$ for a conformal diffeo

\mathcal{T} of \mathbb{R}^{n+p} $\Rightarrow \hat{\mathcal{T}} = T \circ \psi$ for $T \in \mathbb{O}_1(n + p + 2)$, and $\hat{f}' = \varphi_{\mathcal{T} \circ f}^{-1} \psi \circ \mathcal{T} \circ f = \varphi_f^{-1}(\varphi_{\mathcal{T}}^{-1} \psi \circ \mathcal{T}) \circ f = \varphi_f^{-1} T \circ \psi \circ f = T \circ \hat{f}$. ■

Remark 118. See [DT] for equations relating the second fundamental forms, normal connections, etc, between a conformal immersion and its light-cone representative, and the Fundamental Theorem in Moebius geometry. Not surprisingly, by Proposition 117 many isometric results have natural conformal counterparts, that usually can be proved adapting isometric methods.

25.2 The conformal Gauss parametrization

Motivation. Classify conformally flat Euclidean hypersurfaces in terms of curves, as in the flat case (Corollary 82). The first step:

Theorem 119. *Let $f: M^n \rightarrow \mathbb{R}^{n+1}$ with $n \geq 4$. Then, M^n is conformally flat and if and only if f has a principal curvature of multiplicity at least $n - 1$.*

Proof. We can assume f is not umbilic. By Proposition 112, there is a local i.i. $g: M^n \rightarrow \mathbb{V}^{n+1}$. By Remark 111 $\beta = (\alpha_f, \alpha_g) = (A^f, I, L)$ is flat with $\nu_\beta = 0$. By the Main Lemma 45 β is degenerate, so $L \in \text{span}\{A^f, Id\}$ and $\dim \text{Ker}(A^f - \lambda I) \geq n - 1$. The converse is left as an exercise (show that $W = 0$). ■

Remark 120. Cartan's examples: Theorem 119 false for $n = 3$.

Proposition 121. *If $f: M^n \rightarrow \mathbb{R}^{n+p}$ is conformally flat and $n \geq p+3$, then f has a Dupin principal normal of multiplicity at least $n - p \geq 3$.*

Proof. Adapt the proof of Theorem 119 (exercise). ■

So let's classify hypersurfaces with umbilic distributions:

~ · ~

Let $f: M^n \rightarrow \mathbb{R}^{n+1}$ be orientable with Gauss map η and a Dupin principal curvature $\lambda \neq 0$ of multiplicity $n - k$. Since the corresponding eigendistribution E_λ is umbilical (hence integrable), we have the leaf space $V^k := M^n/E_\lambda$ and a submersion $\pi: M^n \rightarrow V^k$. The map

$$h = f + \lambda\eta$$

is constant along the leaves of E_λ , hence it descends to the quotient and we have an immersion $g: V^k \rightarrow \mathbb{R}^{n+1}$ and a function $r \in \mathcal{F}(V)$ given by

$$g \circ \pi = h, \quad r \circ \pi = \lambda^{-1}.$$

We endow V^k with the metric induced by g . In particular, $f = g \circ \pi - (r \circ \pi) \eta$. Since η is normal to f , $\eta^\top = (\nabla r) \circ \pi$ and therefore, by dimension reasons, we can parametrize f over the unit normal bundle $T_1^\perp V$ of g by

$$f \circ \xi = g - r \left(\nabla r + \sqrt{1 - \|\nabla r\|^2} \xi \right), \quad \xi \in \Gamma(T_1^\perp V).$$

§26. Deformable hypersurfaces

Let Δ an integrable distribution on M , and $L = M/\Delta$ the (local) space of leaves with projection $\pi: M \rightarrow L$. A vector field $X \in \mathfrak{X}(M)$ is called *projectable* if there is $\bar{X} \in \mathfrak{X}(L)$ π -related to X . Equivalently, the *horizontal lift* \bar{X}^h of \bar{X} agrees with X_{Δ^\perp} .

Lemma 122. $X \in \mathfrak{X}(M)$ is projectable $\iff [X, \Delta] \subset \Delta$.

Proof. Use the usual flux formula for the Lie bracket: $[X, T] = \lim_{t \rightarrow 0} \frac{1}{t} (X \circ \varphi_t - \varphi_{t*} X)$, where $\varphi_t' = T \circ \varphi_t$ ($\implies \pi \circ \varphi_t = \pi$). ■

Lemma 123. $S \subset \text{End}(\mathbb{R}^2)$ a subspace, and $D \in \text{End}(\mathbb{R}^2)$, $D \notin \text{span}\{I\}$ such that $[D, C] = 0 \ \forall C \in S \Rightarrow \dim S \leq 2$.

Proof. If there is $C \in S$ symmetric such that $C \neq aI$, then D and all elements in S diagonalize in the same basis. ■

Definition 124. We say that a nowhere flat Euclidean hypersurface f is a *Sbrana-Cartan hypersurface* if there is another \hat{f} nowhere congruent to f (i.e., f is *locally deformable*).

Example: Associated family of a minimal rank 2 hypersurface.

Nowhere flat surfaces in \mathbb{R}^3 are locally deformable, but no classification exists. Nadirashvili's example.

Proposition 69: Surface-like hypersurfaces $\iff \text{Im } C \subset \text{span}\{I\}$.

From now on in this section, assume that $f: M^n \rightarrow \mathbb{R}^{n+1}$ is a nowhere surface-like Sbrana-Cartan hypersurface with deformation \hat{f} , and A and \hat{A} their shape operators in Δ^\perp . Then:

- (a) $\hat{\Delta} = \Gamma = \Delta$ agree and are intrinsic (since $\hat{\nu} = \mu = \nu \equiv n-2$);
- (b) Hence, the splitting tensor C of Δ is the same and intrinsic!
- (c) Gauss $\iff D := A^{-1}\hat{A} \in \text{End}(\Delta^\perp)$ satisfies $\det D = 1$;
- (d) Noncongruent $\iff D \notin \text{span}\{I\}$ on an open dense $U \subset M^n$;
- (e) $[D, C_T] = 0 \ \forall T \in \Delta$ (by Proposition 66.7);
- (f) $\nabla_\Delta D = 0$ (by the last and 2 Codazzi's in $\nabla_\Delta \hat{A} = \nabla_\Delta AD$);
- (g) $\dim(\text{span}\{I\} + \text{Im } C) = 2$ a.e. on U (by (e)) \Rightarrow
- (h) Up to sign, $\exists! J \in \text{End}(\Delta^\perp)$ such that $J^2 = \epsilon I$, $\epsilon = 1, 0, -1$, $\|J\| = 1$ if $\epsilon = 0$, satisfying $\text{span}\{I\} \neq \text{Im } C \subset \text{span}\{I, J\}$;

(i) $AJ = J^t A$ (by (h) and Proposition 66.7);

(j) $(e)+(h) \Rightarrow D \in \text{span}\{I, J\}$ (same computation as (g)) \Rightarrow

(k) $\nabla_\Delta J = 0$ (by (f), since also $J \in \text{span}\{I, D\}$).

Def.: A Riemannian manifold M^n with $\mu \equiv n - 2$ is called *parabolic* ($\epsilon=0$), *hyperbolic* ($\epsilon=1$), *elliptic* ($\epsilon=-1$) if there is $J \in \text{End}(\Gamma^\perp)$ satisfying (h) + (k) ($\Rightarrow M^n$ is nowhere surface-like).

Proposition 125. *Both D and J project to $V^2 := M^n/\Delta$, i.e., $\exists \bar{D}, \bar{J}$ such that $\bar{D} \circ \pi_* = \pi_* \circ D$ and $\bar{J} \circ \pi_* = \pi_* \circ J$ on Δ^\perp .*

Proof. Since D is parallel along Δ it projects, since $[D\bar{X}^h, \Delta]_{\Delta^\perp} = D[\bar{X}^h, \Delta]_{\Delta^\perp} = 0$. Same for J . ■

Parabolic, hyperbolic and elliptic surfaces: existence of real or complex conjugate coordinates, first normal space of dimension 2.

Set

$$\mathcal{D}_M := \{f : M^n \rightarrow \mathbb{R}^{n+1}\} / \text{congruence}.$$

Proposition 126. *$f : M^n \rightarrow \mathbb{R}^{n+1}$ rank two nowhere surface-like. Then, M^n is parabolic (resp hyperbolic, elliptic) w.r.t. $J \iff$ the Gauss data is parabolic (resp. hyperbolic, elliptic) w.r.t. \bar{J} . In particular, every member of \mathcal{D}_M is parabolic (resp. hyperbolic, elliptic).*

Proof. Since $\bar{J} \circ \pi_* = \pi_* \circ J$, and $AJ = J^t A$, by Section 22 $P_w^{-1} = \pi_* = -A$ and $\bar{J}P_w^{-1} = P_w^{-1}J = J^t P_w^{-1}$. So, $\bar{J} = J^t$ and $\bar{J}^t P_w = P_w \bar{J}$. ■

Corollary 127. *By (h), (i) and Proposition 126, the Gauss data is parabolic, hyperbolic or elliptic with respect to \bar{J} : $Q(h) = 0$ and $Q(r) = 0$.*

We first deal with the easiest parabolic case:

Proposition 128. *M^n is parabolic $\iff f$ is ruled. In this case $\mathcal{D}_M = \mathbb{R}$ and every $g \in \mathcal{D}_M$ is ruled with the rulings of f .*

Proof. Let $\{X, Y\}$ o.n.b. of Δ^\perp such that $JX = Y$, $JY = 0$, and $R = \Delta \oplus^\perp \text{span}\{Y\}$. $J^t A = AJ \implies \langle AY, Y \rangle = 0$. $\nabla_\Delta J = 0 \implies \nabla_\Delta Y \subset \Delta$. $\text{Im } C \subset \text{span}\{I, J\} \implies \nabla_Y \Delta \subset R$. Write $D = I + \theta J$. AD Codazzi $\iff \theta AJ$ Codazzi $\iff \nabla_Y Y \in R$, $\Delta(\theta) = 0$, and $Y(\theta\mu) = \theta\mu \langle \nabla_X X, Y \rangle$ where $\mu := \langle AX, Y \rangle$. ■

Def.: Gauss data (h, r) of *first or second species* (with conjugate coordinate system (u, v)): hyperbolic (resp. elliptic) h and r , such that

$$\tau(\Gamma_v^v - 2\Gamma^u \Gamma^v) = (\Gamma_u^u - 2\Gamma^u \Gamma^v)$$

(resp. $\text{Im}(\rho(\Gamma_z - 2\Gamma\bar{\Gamma})) = 0$).

Proposition 129. *Assume M^n is hyperbolic or elliptic. Then, \hat{A} is Codazzi $\iff \bar{D}$ is Codazzi \iff the Gauss data is of first or second species.*

Proof. Use Section 22: $(\nabla_X^h \bar{D}Y)' = j\nabla_{X \circ \pi}^h \bar{D}Y = j\nabla_{X^h}^h \bar{D}Y \circ \pi = j\nabla_{X^h}^h \pi_*(DY) = (\nabla_{X^h}^M (j \circ \pi_*)(DY^h))_{\Delta^\perp} = -(\nabla_{X^h}^M A DY^h)_{\Delta^\perp}$. ■

Finally, we can give the complete classification:

Theorem 130. *Let M^n be any Riemannian manifold. Then, each connected component U of an open dense subset of M^n falls, even locally, exactly into one of these categories:*

- i) $\mathcal{D}_U = \emptyset$, i.e., U is not even locally a Eucl. hypersurface;
- ii) U is rigid, i.e., \mathcal{D}_U is a point;
- iii) U is flat, and $\mathcal{D}_U = \mathcal{F}(\mathbb{R}, \mathbb{S}^n) \times \mathcal{F}(\mathbb{R})$;
- iv) U is nonflat surface-like and \mathcal{D}_U is the one of the surface;
- v) U is parabolic and ruled, $\mathcal{D}_U = \mathcal{F}(\mathbb{R})$, and every element in \mathcal{D}_U is ruled with same rulings as U ;
- vi) The Gauss data is of first species, and $\mathcal{D}_U = \mathbb{R}$;
- vii) The Gauss data is of second species, and $\mathcal{D}_U = \mathbb{Z}_2$.

Case (vi) is called the *continuous type* (e.g., g minimal), while case (vii) is called the *discrete type* (e.g....??????????).

Remark 131. Recently, Diego Navarro Guajardo extended Sbrana-Cartan Theory to higher codimension ([**Gu1**]).

§27. Intersections

These were the first known Sbrana-Cartan hypersurfaces of the discrete type. They can be obtained intersecting two flat hypersurfaces, or, better, as in [**FF**] as rank two hyperbolic submanifolds in codimension two that extend as flat hypersurfaces in two ways. We briefly describe this work.

Let $f: M^n \rightarrow \mathbb{R}^{n+2}$ be a hyperbolic rank two submanifold. It is easy to see that f has a (hyperbolic) *polar surface* that “integrates” its normal bundle, i.e, there is $g: V^2 = M/\Delta \rightarrow \mathbb{R}^{n+2}$ such that

$$g_{*[x]}(T_{[x]}V) = T_{f(x)}^\perp M \quad \forall x \in M^n.$$

In [FF] it was shown that f extends as a flat hypersurface in two different ways $\iff \Gamma^u = \Gamma^v = 0$ for g , i.e., if

$$g(u, v) = c_1(u) + c_2(v),$$

with c'_1, c''_1, c'_2, c''_2 pointwise L.I.. The *shared dimension* $I(c_1, c_2) \in \mathbb{N}_0$ is the smallest integer k for which there is an orthogonal decomposition in affine subspaces, $\mathbb{R}^{n+2} = \mathbb{V}_1 \oplus^\perp \mathbb{V}^k \oplus^\perp \mathbb{V}_2$, satisfying that $\text{span}(c_i) \subset \mathbb{V}_i \oplus^\perp \mathbb{V}^k$, $i = 1, 2$. It turns out that:

- $I(c_1, c_2) = 0 \iff M^n$ is flat;
- $I(c_1, c_2) = 1 \iff M^n$ is of the continuous type;
- $I(c_1, c_2) \geq 2 \iff M^n$ is of the discrete type.

Corollary 132. *Crazy collage of the different types.*

Remark 133. Diego Navarro Guajardo also extended this intersection construction to higher codimension ([Gu2]).

§28. Genuine rigidity ([DF2])

Rigidity in higher codimensions: rigidity and compositions are particular cases of *isometric extensions*. In this context, algebraic rigidity results like Theorem 44 and Theorem 47 disregard information about the normal connections. As such, they should be understood as “generic” without much usefulness for classification. Now we search for more geometry.

Def.: We say that a pair $f: M^n \rightarrow \mathbb{R}^{n+p}$ and $\hat{f}: M^n \rightarrow \mathbb{R}^{n+q}$ of isometric immersions *extends isometrically* when there are an isometric embedding $j: M^n \hookrightarrow N^m$ into a Riemannian manifold

N^m with $m > n$ and isometric immersions $F: N^m \rightarrow \mathbb{R}^{n+p}$ and $\hat{F}: N^m \rightarrow \mathbb{R}^{n+q}$ such that $f = F \circ j$ and $\hat{f} = \hat{F} \circ j$. In other terms, the following diagram commutes:

$$\begin{array}{ccc}
 & & \mathbb{R}^{n+p} \\
 & \nearrow f & \\
 M^n & \xrightarrow{j} & N^m \\
 & \searrow \hat{f} & \\
 & & \mathbb{R}^{n+q}
 \end{array}
 \begin{array}{c}
 \nearrow F \\
 \searrow \hat{F}
 \end{array}
 \quad (1)$$

We want to *discard* deformations \hat{f} that arise in this way, since the deformation problem essentially depends on the codimension, and not on the dimension. This gives rise to the following:

Def.: We say that $\hat{f}: M^n \rightarrow \mathbb{R}^{n+q}$ is a *genuine deformation* of a given $f: M^n \rightarrow \mathbb{R}^{n+p}$ (or that $\{f_\lambda: M^n \rightarrow \mathbb{R}^{n+p_\lambda}\}$ is a *genuine set*) if $\exists U \subset M^n$ s.t. $f|_U$ and $\hat{f}|_U$ extend isometrically.

Def.: We say that $f: M^n \rightarrow \mathbb{R}^{n+p}$ is *genuinely rigid in \mathbb{R}^{n+q}* if every $\hat{f}: M^n \rightarrow \mathbb{R}^{n+q}$ is *nowhere* a genuine deformation of f .

Motivation of the following. Structure of the second fundamental forms and normal connections when a pair extends isometrically: the extensions induce a natural parallel bundle isometry between the normal subbundles $F_*(T_j^\perp M) \rightarrow \hat{F}_*(T_j^\perp M)$ that preserves second fundamental forms. *When is the converse statement true?*

Def.: D^d -ruled submanifolds, mutually ruled (sets!), ruled extensions.

Let $f: M^n \rightarrow \mathbb{R}^{n+p}$ and $\hat{f}: M^n \rightarrow \mathbb{R}^{n+q}$, and τ a **parallel** vector bundle isometry that **preserves second fundamental forms**,

$$\tau: L^\ell \subset T_f^\perp M \rightarrow \hat{L}^\ell \subset T_{\hat{f}}^\perp M. \quad (6)$$

Equivalently, the induced v.b. isometry $\bar{\tau}$ is parallel, where

$$\bar{\tau} = Id \oplus \tau: f_*TM \oplus L \rightarrow \hat{f}_*TM \oplus \hat{L}.$$

Define $\phi_\tau: TM \times (TM \oplus L) \rightarrow (L^\perp \times \hat{L}^\perp, \langle \cdot, \cdot \rangle_{L^\perp} - \langle \cdot, \cdot \rangle_{\hat{L}^\perp})$ by

$$\phi_\tau(X, \eta) = ((\tilde{\nabla}_X \eta)_{L^\perp}, (\tilde{\nabla}_X \bar{\tau} \eta)_{\hat{L}^\perp}).$$

Proposition 134. *The bilinear form ϕ_τ is Codazzi and flat.*

Proof. Exercise. ■

Notice that $\alpha_{L^\perp} \oplus \hat{\alpha}_{\hat{L}^\perp} = \phi_\tau|_{TM \times TM}$. Assume that the subspaces

$$D = D_\tau := \mathcal{N}(\alpha_{L^\perp} \oplus \hat{\alpha}_{\hat{L}^\perp}) \subset TM,$$

$$\Delta = \Delta_\tau := \mathcal{N}_r(\phi_\tau) \subset TM \oplus L$$

have constant dimensions $d_\tau \leq \nu_\tau$ respectively (observe that $\Delta \cap TM = D$). It follows that $\bar{\tau}|_\Delta: \Delta \rightarrow \hat{\Delta}$ is a parallel vector bundle isometry, and hence, we can identify $\hat{\Delta}$ with Δ .

Corollary 135. $\mathcal{N}_l(\phi_\tau) \subset D \subset TM$ is integrable. In particular, if L and \hat{L} are **parallel along D** , namely, if $D = \mathcal{N}_l(\phi_\tau)$, then $D \subset \Delta$ is integrable.

Corollary 136. If L and \hat{L} are **parallel along D** , $\text{Im}(\phi_\tau)$ and Δ are smooth and parallel along its leaves. In particular, the leaf through $x \in M^n$ is also given by $\Delta(x) \cap M^n$.

Let $\pi: \Lambda \rightarrow M^n$ be the vector bundle $\Lambda := D^\perp \subset \Delta \subset TM \oplus L$, and consider the extensions $F: \Lambda \rightarrow \mathbb{R}^{n+p}$ and $\hat{F}: \Lambda \rightarrow \mathbb{R}^{n+q}$,

$$F \circ \xi = f \circ \pi + \xi, \quad \hat{F} \circ \xi = \hat{f} \circ \pi + \bar{\tau}\xi, \quad \forall \xi \in \Gamma(\Lambda), \quad (7)$$

restricted to a neighborhood N of $M^n \cong 0 \subset \Lambda$ to get immersions. Observe that L^\perp , D , Δ , etc, induce natural corresponding bundles over Λ (e.g., $L^\perp(\xi_x) = L^\perp(x)$, namely, $\pi^*(L^\perp)$).

The following is the main result on isometric extensions:

Theorem 137. *If L and \hat{L} are **parallel along D** , then F and \hat{F} are isometric $\pi^*(\Delta)$ -ruled extensions of f and \hat{f} . Moreover, there are orthogonal splittings*

$$T_F^\perp N = \mathcal{L} \oplus^\perp \pi^*(L^\perp), \quad T_{\hat{F}}^\perp N = \hat{\mathcal{L}} \oplus^\perp \pi^*(\hat{L}^\perp),$$

and a parallel vector bundle isometry $\mathcal{T}: \mathcal{L} \rightarrow \hat{\mathcal{L}}$ that preserves second fundamental forms such that $\pi^*(\Delta) = D_{\mathcal{T}}$. In addition, \mathcal{L} and $\hat{\mathcal{L}}$ are parallel along $\pi^*(\Delta)$.

Proof. Let's argue first for F , \hat{F} being similar. Observe first that $\text{Im } F_* \subset \pi^*(T_f M \oplus L)$ which is parallel along $\pi^*(D) \subset T\Lambda$. Thus, $\pi^*(L^\perp) \subset T_F^\perp \Lambda$, and we can write

$$T_F \Lambda \oplus^\perp \mathcal{L} = \pi^*(T_f M \oplus L), \quad \mathcal{L}^\perp = \pi^*(L^\perp). \quad (8)$$

Since D is integrable and $\tilde{\nabla}_D \Delta \subset \Delta$ by Corollary 136, we easily get that F is $\pi^*(\Delta)$ -ruled. (Equivalently, we could have worked on $V := M/D$ and defined F over the bundle $\pi^*(\Delta) \rightarrow V$ instead!). Using (8) we define $\bar{\mathcal{T}}$ by $\bar{\mathcal{T}} \circ \pi^* = \pi^* \circ \bar{\tau}$, which is clearly parallel, and the extensions are isometric since $\hat{F}_{*w_x} = \bar{\tau}_x \circ F_{*w_x}$.

Now, take $\eta \in \Gamma(L^\perp)$ and $Z \in \Gamma(\Delta)$. Since $\pi^*(\Delta) = \pi_*^{-1}(D)$,

$$(\tilde{\nabla}_{Z \circ \pi} \eta \circ \pi)_{T_F \Lambda \oplus \mathcal{L}} = (\tilde{\nabla}_Z \eta \circ \pi)_{T_f M \oplus L} = (\tilde{\nabla}_{\pi_* Z} \eta)_{T_f M \oplus L} = 0.$$

This proves the last assertion and $\pi^*(\Delta) \subset D_{\mathcal{T}}$. For the opposite inclusion, since $\alpha_{L^\perp} \oplus \hat{\alpha}_{\hat{L}^\perp} = \alpha_{\mathcal{L}^\perp}^F \oplus \hat{\alpha}_{\hat{\mathcal{L}}^\perp}^{\hat{F}}|_{T_j M \times T_j M}$, equality holds along M^n , and hence in a neighborhood by semicontinuity. ■

Corollary 138. *The extensions F and \hat{F} are trivial $\iff f$ and \hat{f} are mutually D -ruled.*

Lemma 139. *Let $f: M^n \rightarrow \mathbb{R}^{n+p}$ be a D -ruled submanifold. $\Rightarrow L_D := S(\alpha|_{D \times TM})$ is parallel along D (constant dimension).*

Corollary 140. *$\{f, \hat{f}\}$ is genuine $\Rightarrow f$ and \hat{f} are mutually D -ruled and we have:*

$$\begin{array}{ccc}
 T_f^\perp M = L_D \oplus L_D^\perp & & L_D := \text{span} \{ \alpha(D, TM) \} \\
 \mathcal{T}_D : & \searrow & \\
 (\nabla^\perp)_{L_D} = (\hat{\nabla}^\perp)_{\hat{L}_D} & & D = \mathcal{N} \left(\alpha_{L_D^\perp} \oplus \hat{\alpha}_{\hat{L}_D^\perp} \right) \text{ are rulings!!} \\
 \alpha_{L_D} = \hat{\alpha}_{\hat{L}_D} & & \\
 \downarrow & \nearrow & \\
 T_{\hat{f}}^\perp M = \hat{L}_D \oplus \hat{L}_D^\perp & & \hat{L}_D := \text{span} \{ \hat{\alpha}(D, TM) \}
 \end{array}$$

In other words, if $\{f, \hat{f}\}$ is genuine, then they have a “*partial relative nullity*” in common, which, if not relative nullity ($L_D \neq 0$), then it is much bigger than it should be, i.e.: *if we lose relative nullity we gain dimension*.

There are always isometries such as τ as in (6), e.g., $\tau = 0$! In this case $D^d = \Delta_f \cap \Delta_{\hat{f}}$, where the result is obvious. But we have no estimate on d for $\tau = 0$, since ϕ_0 may be degenerate...

Yet, in [DF2] we explicitly constructed τ , L , and D^d for which the rulings are **big**:

Theorem 141. *Let $f: M^n \rightarrow \mathbb{R}^{n+p}$ and $\hat{f}: M^n \rightarrow \mathbb{R}^{n+q}$ a genuine pair with $p+q < n$ and $\min\{p, q\} \leq 5$. Then, $\{f, \hat{f}\}$ are mutually D^d -ruled a.e., with $d \geq n - p - q + 3 \dim L_D$. Moreover, the isometry τ_D is parallel and preserves second fundamental forms.*

Just the proof of the above (sharp!) estimate on d takes 5 pages and it is quite delicate. But as we will see in the next section, the above generalizes all known result about compositions, rigidity with s -nullities, etc, i.e., the ones we studied so far (exercise).

Not surprisingly, we get several corollaries, like:

Corollary 142. *Let $f: M^n \rightarrow \mathbb{R}^{n+p}$ and q a positive integer with $p+q < n$. If $\min\{p, q\} \leq 5$ and f is not $(n-p-q)$ -ruled on any open subset of M^n , then f is genuinely rigid in \mathbb{R}^{n+q} .*

Corollary 143. *Let $f: M^n \rightarrow \mathbb{R}^{n+p}$ and q a positive integer with $p+q < n$. If $\min\{p, q\} \leq 5$ and $\text{Ric}_M > 0$ then f is genuinely rigid in \mathbb{R}^{n+q} .*

Corollary 144. *Any $f: U \subset \mathbb{S}^N \rightarrow \mathbb{R}^{2n-2}$ is a composition a.e.*

We even get topological criteria for genuine rigidity in line with the rigidity question proposed by M. Gromov in *Partial Differential Relations* p.259 (and answered in [DG]):

Corollary 145. *Let M^n be a compact manifold whose first Pontrjagin class satisfies that $[p_1]^2 \neq 0$. If $n > p+q$ and*

$p + q \leq 6$, then any analytic immersion $f: M^n \rightarrow \mathbb{R}^{n+p}$ is (with the induced metric) genuinely rigid in \mathbb{R}^{n+q} .

§29. Better s -nullities

Since L_D is always parallel along D by Lemma 139, Corollary 138 screams to use the s -nullity of another bilinear form instead of the ones for the second fundamental form. Indeed, given $V^s \subset T^\perp M$ a normal subbundle of rank s of an isometric immersion $f: M^n \rightarrow \mathbb{R}^{n+p}$, define as in [FG] the tensor

$$\phi_V: TM \times (TM \oplus V^\perp) \rightarrow V, \quad \phi_V(X, v) = (\tilde{\nabla}_X v)_V.$$

Notice that $\phi_\tau = (\phi_{L^\perp}, \hat{\phi}_{\hat{L}^\perp})$. As before, since ϕ_V is Codazzi, its left nullity

$$\mathcal{N}_l(\phi_V) = \{X \in \mathcal{N}(\alpha_V): \nabla_X^\perp V \subset V\}$$

is integrable where it has constant dimension. Set

$$\bar{\nu}_s^f := \max_{V^s \subset T^\perp M} \dim \mathcal{N}_l(\phi_V).$$

Thus Lemma 139, Corollary 138 and Theorem 141 imply that $D = \mathcal{N}_l(\phi_\tau) \subset \mathcal{N}_l(\phi_{L_D^\perp}) \Rightarrow$

Corollary 146. *Let $f: M^n \rightarrow \mathbb{R}^{n+p}$, and $q \in \mathbb{N}$ such that $\min\{p, q\} \leq 5$. If $\bar{\nu}_s^f < n + 2p - q - 3s$ almost everywhere for all $1 \leq s \leq p$, then f is genuinely rigid in \mathbb{R}^{n+q} .*

Remark 147. This result is stronger than all the ones with s -nullities cited before (and probably all the ones not cited too...):

- We can work with $q \neq p$;

- $\bar{\nu}_s^f \leq \nu_s^f$ since $\mathcal{N}_l(\phi_V) \subset \mathcal{N}(\alpha_V)$;
- The bound on $\bar{\nu}_s^f$ is weaker than the usual one for ν_s^f by $p-s$;
- $\mathcal{N}_l(\phi_V)$ is always integrable, and ‘almost’ totally geodesic;
- We can require in the definition of $\bar{\nu}_s^f$ to $\mathcal{N}_l(\phi_V)$ be totally geodesic, or asymptotic, since the leaves of D are rulings, which makes $\bar{\nu}_s^f$ even smaller. That is:

We define the (local) *rulling index* $\nu_R(f)$ for $f: M^n \rightarrow \mathbb{R}^{n+p}$ by

$$\nu_R(f) = \max\{d - 3\ell_D : f|_U \text{ is } D^d\text{-ruled for some } U \subset M^n\}.$$

Corollary 148. *Let $f: M^n \rightarrow \mathbb{R}^{n+p}$ and let q be a positive integer such that $p + q < n$ and $\min\{p, q\} \leq 5$. If $\nu_R(f) \leq n - p - q - 1$, then f is genuinely rigid in \mathbb{R}^{n+q} .*

§30. Global rigidity

Global rigidity results in submanifold theory are *way* more scarce than local ones, the most beautiful of which is Sacksteder’s:

Theorem 149. *A compact Euclidean hypersurface of dimension at least 3 is rigid provided its set of non-totally geodesic points is connected. (And we understand if not!). Same for complete bounded.*

Proof. By Proposition 134, $\beta := \phi_0$ is flat and Codazzi. Hence, Propositions 66, 70 and Corollary 71 hold for $\Delta_0 = \mathcal{N}(\beta)$ (see Remark 72). Now use the spirit of the proof of Theorem 109 to show that $A = \pm\hat{A}$ everywhere. ■

Remark 150. Same result and proof hold for $f: M^n \rightarrow \mathbb{H}^{n+1}$. For $f: M^n \rightarrow \mathbb{S}^{n+1}$ complete and $n \geq 4$ it also holds by the proof of Corollary 73 since no leaf of relative nullity with $\nu \geq n - 2$ can be complete: $\{X, \dots, C_{T_\nu} X\}$ would be $n - 1$ L.I. vectors in Δ^\perp . In [DG] the codimension two case was solved by showing that, giving a pair of is.ims., along each connected component of an open dense subset, the immersions are either congruent or extend isometrically to flat hypersurfaces, or to **singular** Sbrana-Cartan hypersurfaces. That singularities are necessary was proved much later in [FF] (also in the flat case, filling a gap in [DG]). In other words, compact codimension two Euclidean submanifolds are *singularly genuinely rigid*, and **singularities are needed!**

§31. Singular genuine rigidity ([FG])

As we saw in Theorem 137, given $\tau: L \rightarrow \hat{L}$ we get isometric (possibly trivial) ruled extensions as in (7). In particular, this holds for $\tau = 0$, in which case $\phi_0 = \beta := (\alpha, \hat{\alpha})$. The key distribution here was thus $\Delta_0 = \text{Ker } \beta$. The extensions in (7) are then obviously isometric since $\hat{F}_* = \bar{\tau} \circ F_*$. This is a sufficient condition, but not a necessary one (!!!). Indeed, a tautology:

Proposition 151. *Let f, \hat{f} and $\tau: L \rightarrow \hat{L}$ parallel that preserves second fundamental forms. Let $\Lambda \subset TM \oplus L$ be any subbundle. Then, F and \hat{F} in (7) are isometric \iff*

$$\phi_\tau(TM, \Lambda) \subset L^\perp \oplus \hat{L}^\perp \text{ is null.} \quad (9)$$

Of course this holds if $\Lambda \subset \Delta_\tau$ as before, but it has two very important advantages:

- No Main Lemma! In particular, no need for $\min\{p, q\} \leq 5$ in an analogous to Theorem 141.
- Null subspaces are much, Much, MUCH easier to get than nullities due to Proposition 34. Thanks J.D.Moore!

Observe that Proposition 151 holds even if Λ is not transversal to M^n . In this case, F and \hat{F} are not immersions along $M^n \subset \Lambda$. Actually, the only problem to extend is when $\Lambda = D \subset TM$, otherwise we just take a subbundle of Λ transversal to M^n .

If f is D -ruled, then F is not an immersion, it has constant rank equal to n , and $F(D) = f(M)$. But what if not?

Def.: We say that $F = F_{\Lambda, f}$ in (7) is a *singular extension* of f if it is an immersion in some open neighborhood of M^n (the 0-section of Λ), except of course at M^n itself.

Def.: We say that \hat{f} is a *strongly genuine deformation* of f , or that $\{f, \hat{f}\}$ is a *strongly genuine pair*, if there is no open subset U where $f|_U$ and $\hat{f}|_U$ singularly extend isometrically.

Def.: Given $q \in \mathbb{N}$, the isometric immersion f is said to be *singularly genuinely rigid in \mathbb{R}^{n+q}* if, for any isometric immersion $\hat{f}: M^n \rightarrow \mathbb{R}^{n+q}$, $\{f, \hat{f}\}$ singularly extend isometrically a.e..

We say that $F = F_{\Lambda, f}$ *nowhere induces a singular extension* of f if, for every open subset $U \subset M^n$ and every subbundle $\Lambda' \subset \Lambda|_U$, the restriction of $F|_{\Lambda'}$ is not a singular extension of $f|_U$.

The key point is that this only happens when f is $\bar{\Lambda}$ -ruled (observe that now $\Lambda \subset TM$ is not necessarily integrable, so $\bar{\Lambda}$ -ruled means that $f_{*x}(\Lambda(x) \cap U) \subset f(M)$):

Proposition 152. *Let $\Lambda \subset TM$ any smooth distribution. Then, $F_{\Lambda, f}$ nowhere induces a singular extension of $f \iff f$ is $\bar{\Lambda}$ -ruled.*

Proof. We only need to prove the direct statement. SPG, $\Lambda \subset TM$ with $\text{rank } \Lambda = 1$. So we may parametrize $F(x, t) = f(x) + tX(x)$ where $\|X\| = 1$. Then, $\forall p \in M$ there is $(p_m, t_m) \rightarrow (p, 0)$ with $t_m \neq 0$ such that $\text{rank } F_*(p_m, t_m) = n$. Define the tensors on M by $K = \nabla_{\bullet} X$ and $H_t = I + tK$. Hence, there is $Y_m \in T_{p_m} M$ such that $F_{*(p_m, t_m)} Y_m = X(p_m)$, i.e., $H_{t_m} Y_m = X(p_m)$ and

$$\alpha(X(p_m), H_{t_m}^{-1} X(p_m)) = 0. \quad (10)$$

Consider a precompact open neighborhood $U \subset M^n$ of p , so $\|\alpha\| < c$ and $\|K\| < c$ for some constant $c > 1$. Hence for $t \in I = (-\frac{1}{c^2}, \frac{1}{c^2})$ we have that H_t is invertible on U , and

$$H_t^{-1} = \sum_{i \geq 0} (-t)^i K^i,$$

since $H_t \circ \sum_{i=0}^N (-t)^i K^i = Id - (-t)^{N+1} K^{N+1}$.

We claim that $\alpha(X, S_X) = 0$ on M^n , where S_X is the K -invariant subspace generated by X , i.e., $S_X = \text{span}\{X, KX, K^2X, \dots\}$. If otherwise, set $j := \min\{k \in \mathbb{N} : \alpha(X(q), K^k(X(q))) \neq 0, q \in M^n\}$ and take $p \in M^n$ such that $\alpha(X(p), K^j(X(p))) \neq 0$. By (10),

$$\sum_{i \geq 0} (-t_m)^i \alpha(X(p_m), K^{j+i}(X(p_m))) = 0.$$

Taking $m \rightarrow \infty$ we get $\alpha(X(p), K^j(X(p))) = 0$, a contradiction. Now, since $\alpha(X, S_X) = 0$ on M^n , for any $t \in I$ and $p \in U$ we

get $F_{*(p,t)}(H_t^{-1}(X)) = X$ since $H_t^{-1}(X) \in S_X$. It follows that $\text{rank}(F_*) = n$ in all $U \times I$, and therefore $F(U \times I) = f(U)$. Hence a segment of the line generated by X is contained in $f(U)$. ■

We have thus shown:

Theorem 153. *Let $\{f, \hat{f}\}$ be a strongly genuine pair and $\tau: L^\ell \subset T_f^\perp M \rightarrow \hat{L}^\ell \subset T_{\hat{f}}^\perp M$ a parallel vector bundle isometry that preserves second fundamental forms. Let $D \subset TM \oplus L^\ell$ be a subbundle such that $\phi_\tau(TM, D)$ is a null subset. Then $D \subset TM$ and f and \hat{f} are mutually \bar{D} -ruled.*

From Proposition 34 we immediately get the following, where

$$i(\phi_\tau)(x) := \max\{\text{rank}(\phi_\tau(X, \cdot)): X \in T_x M\}.$$

Corollary 154. *Under the assumptions of Theorem 153, along each connected component of an open dense subset of M^n , $i(\phi_\tau)$ is constant and f and \hat{f} are mutually \bar{D}_Y^d -ruled for any smooth vector field $Y \in \text{Re}(\phi_\tau)$, where $D_Y^d := \text{Ker}(\phi_\tau^Y) \subset TM$. In particular, f and \hat{f} are mutually d -ruled with*

$$d = n + \ell - i(\phi_\tau) \geq n - p - q + 3\ell.$$

By allowing singular extensions we recover all the corollaries in [DF2], and even without the technical restrictions on the codimensions required there due to the Main Lemma. For example:

Corollary 155. *Any $M^n \subset \mathbb{R}^{n+p}$ with positive Ricci curvature is singularly genuinely rigid in \mathbb{R}^{n+q} , for every $q < n - p$.*

Now, we did all this to apply to global rigidity. Indeed we have:

Theorem 156. *Let $f: M^n \rightarrow \mathbb{R}^{n+p}$ and $\hat{f}: M^n \rightarrow \mathbb{R}^{n+q}$ be isometric immersions of a compact Riemannian manifold with $p+q < n$. Then, along each connected component of an open dense subset of M^n , either f and \hat{f} singularly extend isometrically, or f and \hat{f} are mutually d -ruled, with $d \geq n-p-q+3$.*

This is an immediate consequence of Corollary 154 and the next, which shows that we have $\ell \geq 1$ a.e.:

Lemma 157. *Under the assumptions of Theorem 156, at each point of M^n either $i(\beta) \leq p+q-3$, or $S(\beta)^\perp$ is not definite. The last possibility holds globally if $\min\{p, q\} \leq 5$.*

Proof. Let W be the complement, i.e., where either $S(\beta)^\perp$ is definite, and $i(\beta) \geq p+q-2$ if $\min\{p, q\} \geq 6$. So, $\nu_0 > 0$ on W since this is the easy part of the Main Lemma where no hypothesis is needed; see the first exercise in Section 16. Then, use Sacksteder's trick: not only ν_0 , but also $i(\beta)$ (by the proof of Proposition 70), are constant along a geodesic in Δ_0 . ■

In particular, for $p+q \leq 4$, Theorem 156 easily unifies Sacksteder and Dajczer-Gromoll Theorems above, states that the only way to isometrically immerse a compact Euclidean hypersurface in codimension 3 is through compositions (which in turn were classified in [DF1]), and provides a global version of the main result in [DFT]:

Corollary 158. *Any compact (or complete and bounded) isometrically immersed submanifold M^n of \mathbb{R}^{n+p} is singularly genuinely rigid in \mathbb{R}^{n+q} for all $q < \min\{5, n\} - p$.*

Proof. The only case left is the $(n - 1)$ -ruled one, which is not hard, or you can attack it directly; see Section 3.1 in [FG]. ■

From Theorem 156 we also get the following topological criteria for singular genuine rigidity with the same spirit as Corollary 145, yet without any *a priori* assumption on the codimensions:

Corollary 159. *M^n a compact manifold whose k -th Pontrjagin class $[p_k] \neq 0$ for some $k > \frac{3}{4}(p + q - 3)$. Then, any analytic immersion $f: M^n \rightarrow \mathbb{R}^{n+p}$ (with the induced metric) is singularly genuinely rigid in \mathbb{R}^{n+q} in the C^∞ -category.*

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