

Riemannian Geometry



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M392C NOTES: RIEMANNIAN GEOMETRY

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These notes were taken in UT Austin's M392C (Riemannian Geometry) class in Spring 2017, taught by Dan Freed. I live-TeXed them using vim, so there may be typos; please send questions, comments, complaints, and corrections to a.debray@math.utexas.edu. Thanks to Martin Bobb, Gill Grindstaff, and Jonathan Johnson for some corrections.

The cover image is the Cosmic Horseshoe (LRG 3-757), a gravitationally lensed system of two galaxies. Einstein's theory of general relativity, written in the language of Riemannian geometry, predicts that matter bends light, so if two galaxies are in the same line of sight from the Earth, the foreground galaxy's gravity should bend the background galaxy's light into a ring, as in the picture. The discovery of this and other gravitational lenses corroborates Einstein's theories. Source: <https://apod.nasa.gov/apod/ap111221.html>.

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Lecture 1.

Geometry in flat space: 1/17/17

"Do you have all these equations?"

Before we begin with Riemannian manifolds, it'll be useful to do a little geometry in flat space.

Definition 1.1. Let V be a real vector space; then, an *affine space over V* is a set A with a simply transitive right V -action.

That this action is simply transitive means for any $a, b \in A$, there's a unique $\xi \in V$ such that $a \cdot \xi = b$.

Definition 1.2. A set with a simply transitive (right) V -action is called a (*right*) V -torsor.

V -torsors look like copies of V without a distinguished identity.

One of the distinct features of affine space is *global parallelism*: if I have a vector ξ at a point a , I immediately get a vector at every point, which defines a vector field on the entire space.

What is the analogue of a basis for an affine space? This is a collection of points a_0, \dots, a_n such that any $a \in A$ is uniquely written as

$$(1.3) \quad a = \lambda^0 a_0 + \lambda^1 a_1 + \dots + \lambda^n a_n$$

for some $\lambda^i \in \mathbb{R}$ with $\lambda^0 + \dots + \lambda^n = 1$.

Equation (1.3) may be written more concisely with *index notation*: any variable written as both a superscript and a subscript is implicitly summed over. That is, we may rewrite (1.3) as

$$a = \lambda^i a_i.$$

Note that in an affine space, we don't know how to add vectors (since we don't have an origin), but we can take weighted averages.

Theorem 1.4 (Giovanni Ceva, 1678). *Let A be an affine plane and $a, b, c \in A$ be a triangle (i.e. three distinct, noncollinear points). Suppose $p \in \overline{bc}$, $q \in \overline{ca}$, and $r \in \overline{ab}$. Then, \overline{ap} , \overline{bq} , and \overline{cr} are coincident iff*

$$[ar : rb][bp : pc][cq : ca] = 1.$$

Typically, this is thought of as a ratio of lengths, but we don't necessarily have lengths: instead, we can use barycentric coordinates. There is a unique λ such that if $r = (1 - \lambda)a + \lambda b$, then $[ar : rb] = \lambda / (1 - \lambda)$.

Proof. Let

$$r := (1 - \lambda)a + \lambda b$$

$$p := (1 - \mu)b + \mu c$$

$$q := (1 - \nu)c + \nu a.$$

Set

$$(1.5) \quad x := \alpha a + \beta b + \gamma c,$$

where $\alpha + \beta + \gamma = 1$. Since $x \in \overline{ap}$, then

$$(1.6) \quad x = \alpha a + C((1 - \mu)b + \mu c).$$

Comparing (1.5) and (1.6), $\mu / (1 - \mu) = \gamma / \beta$.

⊠

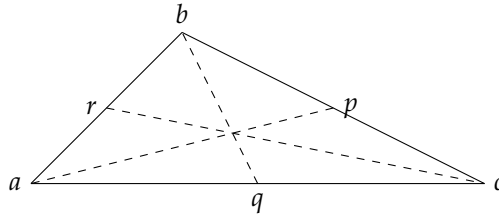


FIGURE 1. Depiction of Ceva's theorem (Theorem 1.4).

Standard affine space $\mathbb{A}^n := \{(x^1, \dots, x^n) \in \mathbb{R}^n \mid x^i \in \mathbb{R}\}$. You may complain this is the same as \mathbb{R}^n , but \mathbb{A}^n only comes with an affine structure, not a vector-space structure.

Definition 1.7. Let A be an affine space modeled on V and B be an affine space modeled on W . Then, a map $f : A \rightarrow B$ is *affine* if there exists a linear map $T : V \rightarrow W$ such that $f(a + \xi) = f(a) + T\xi$ for all $a \in A$ and $\xi \in V$.

In other words, an affine map is a linear map plus some constant, which is not uniquely defined.

Definition 1.8. An *affine coordinate system* on A is an affine isomorphism $x = (x^1, \dots, x^n) : A \rightarrow \mathbb{A}^n$.

Then, the differentials dx_a^1, \dots, dx_a^N are independent of basepoint a and form a basis for V^* , the dual vector space and dual basis to V and $\frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^n}$, the tangent space to any $a \in A$.

But affine space is not the only flat geometry we could consider: more generally, we consider a structure on a vector space V which can be promoted to a translationally invariant structure on A . This leads to metric geometry, symplectic geometry, etc.

Definition 1.9. An *inner product* on a (finite-dimensional) vector space V is a bilinear map $\langle -, - \rangle : V \times V \rightarrow \mathbb{R}$ which is symmetric and positive definite, i.e. for all $\xi, \eta \in V$, $\langle \xi, \eta \rangle = \langle \eta, \xi \rangle$, $\langle \xi, \xi \rangle \geq 0$, and $\langle \xi, \xi \rangle = 0$ iff $\xi = 0$.

Since $\langle -, - \rangle$ is bilinear, then this can be determined in terms of n^2 numbers: let v_1, \dots, v_n be a basis for V and define $g_{ij} := \langle v_i, v_j \rangle$ for $i, j = 1, \dots, n$. Of course, these numbers aren't independent: $g_{ij} = g_{ji}$, so there are really only $n(n+1)$ choices of information.

Definition 1.10. A basis e_1, \dots, e_n for V is *orthonormal* if

$$\langle e_i, e_j \rangle = \delta_{ij} := \begin{cases} 1, & i = j \\ 0, & i \neq j. \end{cases}$$

Our first major result of flat Euclidean geometry is that these exist.

Theorem 1.11. *There exist orthonormal bases.*

Proof. Let v_1, \dots, v_n be any basis of V . Let

$$e_1 = \frac{v_1}{\langle v_1, v_1 \rangle^{1/2}},$$

and for $i = 2, \dots, n$, let

$$v'_i = v_i - \langle v_i, e_1 \rangle e_1.$$

Then, $\langle e_1, e_1 \rangle = 1$ and $\langle e_1, v'_i \rangle = 0$. Then, repeat with v'_2, \dots, v'_n . \square

This explicit algorithm is called the *Gram-Schmidt process*.

In an inner product space, we get some familiar geometric constructions: the *length* of a vector $\xi \in V$ is $|\xi| = \langle \xi, \xi \rangle^{1/2}$, and the *angle* between $\xi, \eta \in V \setminus 0$ is the θ such that

$$\cos \theta = \frac{\langle \xi, \eta \rangle}{|\xi||\eta|}.$$

Definition 1.12. A *Euclidean space* E is an affine space over an inner product space V .

This has a notion of distance: $d_E : E \times E \rightarrow \mathbb{R}^{\geq 0}$, where $a, b \mapsto |\xi|$, where $b = a + \xi$. This generalizes to notions of area, volume, etc.

Theorem 1.13 (Napoleon, 1820). *Let abc be a triangle in a plane and attach an equilateral triangle to each edge. The centers of these three triangles form an equilateral triangle.*

Exercise 1.14. Prove this.



We want to understand curved analogues of this classical material, and will pick up where differential topology left off. We work on smooth manifolds: a *smooth manifold* is a space X together with an atlas of charts $U \subset X$ with homeomorphisms $x : U \rightarrow \mathbb{A}^n$ such that every point is contained in the domain of some chart and the transition maps are smooth. We do not require a manifold to have a global dimension: the different connected components may have different dimensions, e.g. $S^1 \amalg S^2$.¹

A chart map $x : U \rightarrow \mathbb{A}^n$ is a set of n continuous maps (x^1, \dots, x^n) . If p is in the domain of both x and y , we can consider $x \circ y^{-1} : \mathbb{A}^n \rightarrow \mathbb{A}^n$; calculus as usual tells us what it means for this transition map to be smooth.

At any $x \in X$, we have a tangent space $T_x X$ and a cotangent space $T_x^* X$: a chart defines a basis of the tangent space $\frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^n}$ and a basis of the cotangent space dx_x^1, \dots, dx_x^n . This depends strongly on x : unlike for flat space, we may not be able to parallel-transport these globally, even on something as simple as S^2 .

In this course, we will study what happens when we go from a curved analogue of affine space to a curved analogue of Euclidean space, whence the following central definition.

Definition 1.15. A *Riemannian metric* on a smooth manifold X is a choice of inner product $\langle -, - \rangle_x$ on $T_x X$ for all $x \in X$ which varies smoothly in x .

¹This is important for, e.g. a space of solutions of certain PDEs.

Now, we can compute lengths of tangent vectors and the angle that two smooth curves intersect at (or rather, the angle their tangent vectors intersect at). We also obtain a notion of distance between points, and can develop analogues of Euclidean geometry on manifolds.

What does “varying smoothly” mean, exactly? Suppose x^1, \dots, x^n is a set of local coordinates on $U \subset X$; then, for $i, j = 1, \dots, n$, define

$$g_{ij} := \left\langle \frac{\partial}{\partial x^i} \Big|_x, \frac{\partial}{\partial x^j} \Big|_x \right\rangle_{T_x X}.$$

One can check that if the metric is smoothly varying in one chart, then it’s smoothly varying in all charts.

We’ll write the metric as

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

This again uses the summation convention, and it’s useful to think about where exactly this lives: it identifies the metric as a tensor.

Many manifolds arise as embedded submanifolds of Euclidean space, and the Whitney embedding theorem shows that all may be embedded. Many authors say it’s best to meet manifolds as embedded submanifolds first, but there are some which arise without a natural embedding, e.g. the Grassmanian $\text{Gr}_2(\mathbb{R}^4)$, the space of two-dimensional subspaces of \mathbb{R}^4 .

In any case, if $X \subset \mathbb{E}^N$ is embedded, then X inherits a metric, since $T_x X \subset \mathbb{R}^N$ is also a subspace, and we can restrict the inner product. Classical Riemannian geometry is the study of *plane curves* (one-dimensional submanifolds of \mathbb{R}^2), *space curves* (one-dimensional submanifolds of \mathbb{R}^3), and *surfaces* (two-dimensional submanifolds of \mathbb{R}^3).

To study Riemannian manifolds, we should begin with the simplest cases. The zero-dimensional manifolds are disjoint unions of points with zero-dimensional tangent spaces and the trivial Riemannian metric. In the one-dimensional case, there is a little more to tell. A smooth map $X \rightarrow Y$ of Riemannian manifolds is an *isometry* if it’s a map that preserves the inner product on each tangent space. This automatically implies it’s injective.

Theorem 1.16. *Let C be a (complete) Riemannian 1-manifold which is diffeomorphic to \mathbb{R} . Then, C is isometric to \mathbb{E}^1 .*

Before we prove this, we need a change-of-coordinates lemma. (We’ll address completeness later, to avoid finite intervals.)

Remark. Let x^1, \dots, x^n and y^1, \dots, y^n be coordinate systems and suppose a metric can be written as

$$g = g_{ij} dx^i \otimes dx^j = h_{ab} dy^a \otimes dy^b.$$

Then,

$$(1.17) \quad g_{ij} = h_{ab} \frac{\partial y^a}{\partial x^i} \frac{\partial y^b}{\partial x^j}.$$

This is n^2 equations: there is no implicit summation here. ◀

Proof of Theorem 1.16. Let $x : C \rightarrow \mathbb{R}$ be a diffeomorphism, which defines a global coordinate on C . Let $g(x) = \langle \frac{\partial}{\partial x}, \frac{\partial}{\partial x} \rangle$. We seek a new coordinate $y : C \rightarrow \mathbb{R}$ such that $h(y) = \langle \frac{\partial}{\partial y}, \frac{\partial}{\partial y} \rangle = 1$ everywhere. By (1.17),

$$(1.18) \quad g = \left(\frac{dy}{dx} \right)^2,$$

so fix an $x_0 \in C$ and define

$$y(x) = \int_{x_0}^x \sqrt{g(t)} dt.$$

This y satisfies (1.18) and therefore is an isometry. ⊠

The analogue to Theorem 1.16 in n dimensions (where $n > 1$) is as follows: if x^1, \dots, x^n is a local coordinate system and g_{ij} is the Riemannian metric in these coordinates, is there a local change of coordinates $y^a(x^1, \dots, x^n)$ such that $h_{ab} = \delta_{ab}$? This is the analogue in Riemannian geometry to finding orthonormal coordinates, guaranteed by Theorem 1.11.

This requires solving an analogue to (1.17), but this time it's a PDE

$$g_{ij} = \sum_a \frac{\partial y^a}{\partial x^i} \frac{\partial y^a}{\partial x^j}.$$

This time, we need to ask whether there are solutions. The only thing we know how to do is differentiate:

$$(1.19a) \quad \frac{\partial g_{ij}}{\partial x^k} = \sum_a \frac{\partial^2 y^a}{\partial x^k \partial x^i} \frac{\partial y^a}{\partial x^j} + \frac{\partial y^a}{\partial x^i} \frac{\partial^2 y^a}{\partial x^k \partial x^j}.$$

By permuting indices, we obtain

$$(1.19b) \quad \frac{\partial g_{ik}}{\partial x^j} = \sum_a \frac{\partial^2 y^a}{\partial x^j \partial x^i} \frac{\partial y^a}{\partial x^k} + \frac{\partial y^a}{\partial x^i} \frac{\partial^2 y^a}{\partial x^j \partial x^k}$$

$$(1.19c) \quad \frac{\partial g_{jk}}{\partial x^i} = \sum_a \frac{\partial^2 y^a}{\partial x^i \partial x^j} \frac{\partial y^a}{\partial x^k} + \frac{\partial y^a}{\partial x^j} \frac{\partial^2 y^a}{\partial x^i \partial x^k}.$$

Taking (1.19a) + (1.19b) - (1.19c), we obtain

$$\frac{1}{2} \left(\frac{\partial g_{ij}}{\partial x^k} + \frac{\partial g_{ik}}{\partial x^j} - \frac{\partial g_{jk}}{\partial x^i} \right) = \sum_a \frac{\partial y^a}{\partial x^i} \frac{\partial^2 y^a}{\partial x^j \partial x^k}.$$

Now we multiply by $\frac{\partial y^b}{\partial x^\ell} g^{\ell i}$, concluding

$$\frac{\partial y^b}{\partial x^\ell} g^{\ell i} \underbrace{\left(\frac{\partial g_{ij}}{\partial x^k} + \frac{\partial g_{ik}}{\partial x^j} - \frac{\partial g_{jk}}{\partial x^i} \right)}_{\Gamma_{jk}^\ell} = \sum_a \frac{\partial y^a}{\partial x^i} \frac{\partial^2 y^a}{\partial x^j \partial x^k} g^{\ell i} \frac{\partial y^b}{\partial x^\ell}.$$

These Γ_{jk}^ℓ symbols therefore satisfy

$$\frac{\partial^2 y^b}{\partial x^j \partial x^k} = \Gamma_{jk}^i \frac{\partial y^b}{\partial x^i}.$$

If we differentiate once again (with respect to x^ℓ), we get

$$\begin{aligned} \frac{\partial^3 y^b}{\partial x^\ell \partial x^j \partial x^k} &= \frac{\partial \Gamma_{jk}^i}{\partial x^\ell} \frac{\partial y^b}{\partial x^i} + \Gamma_{jk}^i \frac{\partial^2 y^b}{\partial x^\ell \partial x^i} \\ &= \left(\frac{\partial \Gamma_{jk}^i}{\partial x^\ell} + \Gamma_{jk}^m \Gamma_{m\ell}^i \right) \frac{\partial y^b}{\partial x^i}. \end{aligned}$$

Since mixed partials commute, then one discovers that if such an isometry exists, the *Riemannian curvature tensor*

$$(1.20) \quad R_{jkl}^i := \frac{\partial \Gamma_{j\ell}^i}{\partial x^k} - \frac{\partial \Gamma_{jk}^i}{\partial x^\ell} + \Gamma_{jk}^m \Gamma_{m\ell}^i - \Gamma_{j\ell}^m \Gamma_{mk}^i$$

must vanish. In simple cases, one can calculate that it's not always zero, so we don't always have global parallelism.

Riemann derived this in the middle of the 1800s. It's possible to see the glimmer of special relativity in them, though of course this was discovered later.

There's no text, though there is a website: <http://www.ma.utexas.edu/users/dafr/M392C/index.html>. There are problem sets, so undergraduates have to do some problem sets, and graduate students should. Feel free to talk to the professor about the problems, and especially to establish groups to work on the problem sets. Office hours are Wednesdays 2 to 3.

Existence of Riemannian metrics: 1/19/17

“There are so many of you... so quiet... I’ll be more provocative until I get questions. Or I’ll go faster.”

Due to the large size of the class, it’s being moved to RLM 6.104 starting next week. This means everyone who wants to sign up should be able to.

Some readings are up on the website, including a translation of Riemann’s original work on curvature.

Last time, we defined affine space, which leads to the notion of a smooth manifold, and then introduced Euclidean space, an affine space over an inner product space. The curved version of that is a Riemannian manifold.

Recall that a Riemannian metric g on a smooth manifold X is a smoothly varying family of inner products on $T_x X$, and a Riemannian manifold is a smooth manifold together with a Riemannian metric. We also defined an isometry: if X and Y are Riemannian manifolds, then a diffeomorphism $f : X \rightarrow Y$ is an isometry if for all $x \in X$ and $\xi_1, \xi_2 \in T_x X$,

$$\langle f_* \xi_1, f_* \xi_2 \rangle_{T_{f(x)} Y} = \langle \xi_1, \xi_2 \rangle_{T_x X}.$$

Here, $f_* : T_x X \rightarrow T_{f(x)} Y$ is the linear pushforward of tangent vectors, also called the *differential*. If f is merely a smooth function, this is called an *isometric immersion* (the inverse function theorem automatically implies it’s an immersion). If f is an embedding, this is called an *isometric embedding*.

Existence of Riemannian metrics. Suppose V is a real vector space and $g_0, g_1 : V \times V \rightarrow \mathbb{R}$ are inner products. Then for $t \in [0, 1]$, $(1 - t)g_0 + tg_1$ is also an inner product (you can check this directly).

The set of bilinear maps $V \times V \rightarrow \mathbb{R}$, denoted $\text{Bil}(V \times V, \mathbb{R})$, is a real vector space, naturally isomorphic to $\text{Hom}(V \otimes V, \mathbb{R})$ and to $V^* \otimes V^*$. Here, “natural” means this works for all finite-dimensional vector spaces at once, and commutes with linear maps.

Inner products are elements of this vector space, and our observation above means that if g_0 and g_1 are inner products, the line between them in $\text{Bil}(V \times V, \mathbb{R})$ consists of inner products. In particular, *inner products form a convex set*. This only uses the affine structure on $\text{Bil}(V \times V, \mathbb{R})$, since we can take convex combinations in an affine space.

This is used to generalize to the curved case, showing Riemannian metrics always exist.

Theorem 2.1. *Let X be a smooth manifold. Then, there is a Riemannian metric on X .*

Proof. Let $\mathcal{U} = \{(U, x)\}$ be a cover of X by coordinate charts $x : U \rightarrow \mathbb{A}^n$, and let g_U denote the metric on U such that $\frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^n}$ are orthonormal. That is, take the standard metric on \mathbb{A}^n making it into Euclidean space \mathbb{E}^n , and pull it back to U , where it becomes a metric (you can check that metrics pull back along closed immersions).

Now, the bases on two different charts in \mathcal{U} don’t agree, and don’t necessarily differ by orthonormal bases. Thus, we use a standard argument in differential geometry to globalize local objects living in a convex set: let $\{\rho_U\}_{U \in \mathcal{U}}$ be a partition of unity subordinate to \mathcal{U} ; then,

$$g = \sum_{U \in \mathcal{U}} \rho_U g_U$$

is a Riemannian metric. □

Remark. Global existence is *not* assured for every geometric structure. For example, a *complex structure* on a real vector space V is an endomorphism $J : V \rightarrow V$ such that $J^2 = -\text{id}_V$. This is akin to multiplication by i in a complex vector space, which squares to -1 and commutes with addition.

You can place this structure on affine space, and there’s an immediate obstruction: $\dim_{\mathbb{R}} V$ must be even. Now we globalize: given an even-dimensional manifold, do we have such a structure? That is, can we place a smoothly varying complex structure on $T_x X$ for all $x \in X$? This is called an *almost complex structure*, and not every even-dimensional manifold admits one.

Exercise 2.2. Show that S^4 has no almost complex structure.

There is an almost complex structure on S^6 , and it's a famous open question whether there's a complex structure (i.e. complex coordinates with holomorphic transition functions). The known almost complex structure does not work.

Another local structure that doesn't automatically globalize is a mixed-signature metric (e.g. a Minkowski metric). In such a metric, the *null vectors*, those ξ for which $\langle \xi, \xi \rangle = 0$, form a cone whose interior is the *positive vectors* (for which the metric is positive). Trying to globalize this produces, more or less, a line in each tangent space $T_x X$. Passing to a double cover, one can choose an orientation, and therefore a nonzero vector field on X , and this can't be done in general. For example, a surface of genus 2 admits no metric of signature $(1, 1)$. These kinds of metrics arise in general relativity. ◀

In this class, we care about Riemannian metrics, which do globalize.

Let x^1, \dots, x^n be local coordinates; then, we defined some local quantities in the metric in terms of these coordinates. Namely,

$$g_{ij} = \left\langle \frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j} \right\rangle,$$

so that $g = g_{ij} dx^i \otimes dx^j = g_{ij} dx^i dx^j$. We then used this to define symbols Γ_{jk}^i and the Riemann curvature tensor R_{jkl}^i . We proved Theorem 1.16; here's a better version.

Theorem 2.3. *Let C be a Riemannian 1-manifold diffeomorphic to \mathbb{R} . Then, there exists an isometry $C \rightarrow I$, where $I \subset \mathbb{E}^1$ is an open interval.*

The argument we gave defining the Riemann curvature tensor generalizes this.

Theorem 2.4. *Suppose (U, g) is a Riemannian manifold and $x : U \rightarrow \mathbb{A}^n$ is a global coordinate such that*

$$g = \sum_{i=1}^n (dx^i)^2.$$

Then, $R_{jkl}^i = 0$ on U .

One important thing to check here is that

$$R = R_{jkl}^i \frac{\partial}{\partial x^i} \otimes dx^j \otimes dx^k \otimes dx^\ell$$

is independent of the coordinate system (which is not clear from its definition). This means that the Riemann curvature tensor is a tensor, i.e. $R \in T_x X \otimes T_x^* X \otimes T_x^* X \otimes T_x^* X$. In the next few weeks, we will add some geometry to this discussion.

Example 2.5. Let $X = \mathbb{E}^2$ be Euclidean space with the standard metric g . Then, we have global coordinates $(x, y) : \mathbb{E}^2 \rightarrow \mathbb{A}^2$, so $g = dx^2 + dy^2$.

We can also introduce *polar coordinates*, another coordinate system which isn't global. This is a coordinate map $(r, \theta) : \mathbb{E}^2 \setminus \{(x, 0) : x \leq 0\} \rightarrow \mathbb{A}^2$ (so $r > 0$, $-\pi < \theta < \pi$). In this case, the metric has the form

$$g = dr^2 + r^2 d\theta^2.$$

This means that the vector field $\frac{\partial}{\partial r}$ has constant length 1, but the vector field $\frac{\partial}{\partial \theta}$ has length r at (r, θ) . ◀

Symmetry. We've now seen vector spaces, affine spaces, Euclidean spaces, and Riemannian manifolds. As in any mathematical context, it's important to ask what the proper notion of symmetry is for these objects.

If V is a vector space, its *general linear group* is $GL(V) = \text{Aut}(V) := \{T : V \rightarrow V \text{ invertible}\}$. The standard example is $GL_n(\mathbb{R}) := GL(\mathbb{R}^n)$, the group of invertible $n \times n$ matrices, acting on the column vectors of \mathbb{R}^n by scalar multiplication. For example $GL_1(\mathbb{R}) = \mathbb{R}^\times$, the group of nonzero numbers under multiplication.

What about affine space? Affine space on V is a V -torsor, as V acts by translation. The symmetry group is the group of *affine transformations*

$$\text{Aff}(A) := \{\alpha : A \rightarrow A \mid \alpha \text{ is invertible and affine}\}.$$

Recall that an affine map is one that preserves the affine structure: the image of a finite weighted average is the weighted average of the images. The derivative of an affine map is a linear map, so if A is an affine

space modeled by V , the derivative defines a group homomorphism $d : \text{Aff}(A) \rightarrow \text{GL}(V)$, whose kernel is the translations, a group isomorphic to V . Thus, we have a *group extension* (short exact sequence of groups)

$$(2.6) \quad 1 \longrightarrow V \longrightarrow \text{Aff}(A) \xrightarrow{d} \text{GL}(V) \longrightarrow 1.$$

The key is that in affine space, there's no canonical origin. However, (2.6) splits, if noncanonically: choose an $a \in A$. Then, any $b \in A$ can be uniquely written as $a + \zeta$ for some $\zeta \in V$, so for any linear transformation T , $a + \zeta \mapsto a + T\zeta$ is an affine transformation of A .

(2.6) is a sequence of manifolds with smooth group homomorphisms, making it a short exact sequence of *Lie groups*; we'll discuss Lie groups more later.

If V is an n -dimensional vector space, its bases are the set $\mathcal{B}(V) = \{b : \mathbb{R}^n \xrightarrow{\cong} V\}$. If $V = \mathbb{R}^n$, this is $\text{GL}_n(\mathbb{R})$. In general, this makes $\mathcal{B}(V)$ into a right $\text{GL}_n(\mathbb{R})$ -torsor, defined by the simply transitive action $\mathcal{B}(V) \times \text{GL}_n(\mathbb{R}) \rightarrow \mathcal{B}(V)$ sending $\beta, g \mapsto \beta \circ g$. (There is a corresponding left action by $\text{GL}(V)$). The action on the right is akin to numbering elements of the basis, and the action on the left is more geometric; this is an instance of a general idea that internal actions tend to be from the right, and geometric ones from the left.

What's the analogue for an affine space A modeled on V ? Let $\mathcal{B}(A)$ denote the collection of pairs (a, β) where $a \in A$ and $\beta \in \mathcal{B}(V)$, identified with the set of affine isomorphisms $\alpha : A \xrightarrow{\cong} \mathbb{A}^n$. These are the bases at specific points of A . There is a forgetful map $\pi : \mathcal{B}(A) \rightarrow A$ sending $(a, \beta) \rightarrow a$, and the fiber is $\mathcal{B}(V)$, the bases at a . In a similar way, there is a left action of $\text{Aff}(A)$ on $\mathcal{B}(A)$, and a right action of $\text{Aff}_n := \text{Aff}(\mathbb{A}^n)$ on $\mathcal{B}(A)$.

We'll use these torsors of bases a lot in this class. In this way, we're enacting Felix Klein's *Erlangen* program, where the kind of geometry we do is reflected by the symmetry group we place on the geometric structures.

Let's see what happens to these ideas in the Euclidean and Riemannian cases. If V is an inner product space, its *orthogonal group* $O(V) \subset \text{GL}(V)$ is the group of linear isomorphisms preserving the inner product, i.e. $T : V \rightarrow V$ such that $\langle T\xi_1, T\xi_2 \rangle = \langle \xi_1, \xi_2 \rangle$ for all $\xi_1, \xi_2 \in V$. For $V = \mathbb{R}^n$, we let $O_n := O(\mathbb{R}^n)$.

Example 2.7. If $n = 1$, $O_1 \subset \text{GL}_1$ is $\{\pm 1\} \subset \mathbb{R}^\times$, so it's isomorphic to the cyclic group of order 2.

If $n = 2$, we can rotate by angles θ or reflect across lines, and playing with an orthonormal basis shows that all elements of O_2 must be rotations or reflections. Since O_2 is a Lie group, we can draw a picture as in Figure 2.

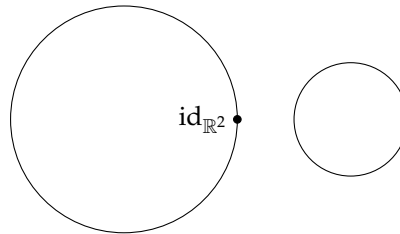


FIGURE 2. A picture of O_2 . The left circle is the rotations; the right circle is the reflections, which in a sense form a circle half as long.

As with the affine symmetries, there's an extension

$$1 \longrightarrow \text{SO}_2 \longrightarrow O_2 \longrightarrow \{\pm 1\} \longrightarrow 1.$$

◀

Similarly, the isomorphisms of Euclidean space E , denoted $\text{Euc}(E)$, are the affine isomorphisms preserving the inner product at each point. This again fits into an extension sequence

$$1 \longrightarrow V \longrightarrow \text{Euc}(E) \longrightarrow O(V) \longrightarrow 1.$$

All this is nice, but let's talk about manifolds. If X is a smooth manifold, we no longer have translations, and the linear symmetries talk about the tangent space. We'll see what kind of structures we get in this case.

The analogue of the torsor of bases is $\mathcal{B}(X) := \{(x, \beta) : x \in X, \beta : \mathbb{R}^n \xrightarrow{\sim} T_x X\}$. This admits a right action of $\mathrm{GL}_n(\mathbb{R})$ by precomposition, as on a vector space, and there is again a forgetful map $\pi : \mathcal{B}(X) \rightarrow X$ that ignores the basis.

If $x : U \rightarrow \mathbb{A}^n$ is a chart, then it defines a local section $U \rightarrow \mathcal{B}(X)$ sending

$$(x^1, \dots, x^n) \mapsto \left((x^1, \dots, x^n), \left(\frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^n} \right) \right).$$

If X is a Riemannian manifold, then we can also speak of orthonormal bases:

$$\mathcal{B}_O(X) := \{(x, \beta) : x \in X, \beta : \mathbb{R}^n \xrightarrow{\cong} T_x X \text{ is an isometry}\}.$$

Again there is a forgetful map to X , but now a coordinate does *not* always determine a section: if the Riemann curvature tensor doesn't vanish, the image of an orthonormal basis of the tangent space at a point might not be orthonormal.

$\mathcal{B}(X)$ and $\mathcal{B}_O(X)$ are not just sets but smooth manifolds, and the forgetful maps back to X are called fiber bundles (even principal bundles). We'll go back and discuss this in more detail.

Curvature. Let's end with something concrete. Let E be a Euclidean plane, an affine space with an underlying 2-dimensional inner product space.

Let $C \subset E$ be a 1-dimensional submanifold. Let's choose a *co-orientation* of C : an orientation of C is an orientation of its tangent bundle, so a co-orientation is an orientation of its normal bundle. In essence, this is choosing a side of the curve.² We'll use this to define a function $\kappa : C \rightarrow \mathbb{R}$ called the (*signed*) *curvature*. Intuitively, this should be positive if C is curved towards the side chosen by the co-orientation, and negative if it curves away, and a larger magnitude means a stronger curvature.

The Euclidean structure on E induces an inner product structure on $T_x C$ for all $x \in C$ that varies smoothly, so C becomes a Riemannian manifold. Theorem 1.16 means there's nothing intrinsic about C we can measure, but the way in which it sits inside E is what κ will measure. This is an important dichotomy, between intrinsic geometry and extrinsic geometry. The Riemann curvature tensor is intrinsic, since it doesn't depend on an embedding, but the signed curvature will be extrinsic.

Lecture 3.

The curvature of a curve: 1/24/17

"And if you follow your nose... well, Euler's nose..."

In the next two lectures, we'll march through the theory of extrinsic curvature (which can fill an entire undergraduate course).

Let E be a Euclidean plane modeled on an inner product space of V , which acts on E by translations, and let $i : C \hookrightarrow E$ be an immersed 1-manifold.³ Suppose C is co-oriented, meaning we've oriented its normal bundle (picking a side of C , so to speak). This determines a unit co-oriented normal vector e_1 at every $x \in C$, meaning the unique unit vector in $(\nu_{C \hookrightarrow E})_x$ with a positive orientation. We can also choose a unit tangent vector e_2 perpendicular to e_1 , and there are two choices. Together they define an orthonormal basis at each point: $(e_1, e_2) : C \rightarrow \mathcal{B}_O(V)$.

You learned how to do calculus with real-valued differential forms; in exactly the same way, it's possible to do calculus with vector-valued differential forms $\Omega_C^*(V)$, the forms modeled on functions $C \rightarrow V$. For $i, j \in \{1, 2\}$, we can define $e_i \in \Omega_C^0(V)$ and $de_i \in \Omega_C^1(V)$, such that $\langle e_i, e_j \rangle = \delta_{ij}$ and the Leibniz rule is satisfied:

$$\langle de_i, e_j \rangle + \langle e_i, de_j \rangle = 0.$$

Thus, there exists an $\alpha \in \Omega_C^1$ such that

$$de_1 = -\alpha e_2 \quad \text{and} \quad de_2 = \alpha e_1.$$

²If $N \hookrightarrow M$ is an embedding and M is oriented, an orientation of N and a co-orientation of N determine each other.

³Especially if C is immersed but not embedded, it is helpful to remember i : when C self-intersects, remembering i is necessary for computing curvature.

In other words, applying d to the row vector $(e_1 \ e_2)$ multiplies it by a skew-symmetric matrix:

$$d \begin{pmatrix} e_1 & e_2 \end{pmatrix} = \begin{pmatrix} e_1 & e_2 \end{pmatrix} \begin{pmatrix} 0 & \alpha \\ -\alpha & 0 \end{pmatrix}.$$

Let $\theta^1, \theta^2 : C \rightarrow V^*$ define the dual basis at each point, i.e. at every $x \in C$, $\theta^i(e_j) = \delta_j^i$ as functions $C \rightarrow \mathbb{R}$. Then, $i^*\theta^2 \in \Omega_C^1$ and we can write

$$\alpha = k \cdot i^*\theta^2$$

for some function $k : C \rightarrow \mathbb{R}$.

Definition 3.1. The *curvature* of C is the function k .

Example 3.2. Let C denote the circle of radius R in the Euclidean plane \mathbb{E}^2 . It's parameterized by coordinates $x = R \cos \phi$ and $y = R \sin \phi$, so

$$\begin{aligned} dx &= -R \sin \phi \, d\phi \\ dy &= R \cos \phi \, d\phi. \end{aligned}$$

Let's choose the co-orientation in which the inward-pointing unit normal is positively oriented. Then,

$$e_1 = -\cos \phi \frac{\partial}{\partial x} - \sin \phi \frac{\partial}{\partial y}.$$

We also have to choose e_2 : suppose it points clockwise along the circle. Then,

$$e_2 = \sin \phi \frac{\partial}{\partial x} - \cos \phi \frac{\partial}{\partial y}.$$

Thus, the dual basis is defined by

$$\begin{aligned} \theta^1 &= -\cos \phi \, dx - \sin \phi \, dy \\ \theta^2 &= \sin \phi \, dx - \cos \phi \, dy, \end{aligned}$$

so $i^*\theta^2 = R \, d\phi$. Then,

$$de_2 = \cos \phi \, d\theta \frac{\partial}{\partial x} + \sin \phi \, d\theta \frac{\partial}{\partial y} = -d\theta e_1.$$

Thus, $de_2 = (1/R)i^*\theta^2(e_1)$. In particular, the curvature is $1/R$. It has units of $1/\text{length}$.

If we chose e_2 to point counterclockwise, there would be a sign change in θ^2 , and another one in α , so they would cancel out to give the same result. \blacktriangleleft

Since the unit vector always has unit length in V , you can think of e_1 as a map $C \rightarrow S(V)$ (called the *Gauss map*), where $S(V)$ is the unit sphere inside V . At a point $p \in C$, we can define the tangent line $T_p C$ at $i(p)$; the tangent line is a subspace of V . We can also consider the tangent line to $e_1(p) \in S(V)$, $T_{e_1(p)} S(V)$; both of these are the same space, the space of vectors in V perpendicular to $e_1(p)$.

This means the differential

$$(3.3) \quad (de_1)_p : T_p C \longrightarrow T_{e_1(p)} S(V)$$

is a map from a line to itself.

Theorem 3.4. The map in (3.3) is multiplication by $-k(p)$.

Proof.

$$de_1(e_2) = \alpha(e_2) \cdot d_2 = -ki^*\theta^2(e_2)e_2 = -k \cdot e_2. \quad \square$$

Remark (History). The curvature may have been initially defined by Nicole Oresme in about 1350. It was again discovered by Huygens in c. 1650 and Newton in c. 1664. \blacktriangleleft

Here's a third approach to curvature. Let $i : C \hookrightarrow E$ be a co-oriented curve as usual, and assume C is embedded. For some $p \in C$, we can identify the normal line to $i(p)$ with \mathbb{R} , letting the positive numbers point into the positively oriented direction. Call this coordinate y . Given a choice of a unit tangent vector e_2 , we can identify the tangent line with \mathbb{R} , again pointing the positive numbers in the x -direction. Call this coordinate x .

Lemma 3.5. *There exists an open set $U \subset E$ about p such that $C \cap U$ is the graph of a function $f : \mathbb{R} \rightarrow \mathbb{R}$ in the above xy -coordinate system such that*

- $f(0) = f'(0) = 0$, and
- $f''(0) = k(p)$.

Proof. The x -coordinate map $x|_C : C \rightarrow \mathbb{R}$ satisfies $dx_p = \text{id}_{T_p C}$; in particular, it's invertible. By the inverse function theorem, there's a local inverse $g : I \rightarrow C$, where $I \subset \mathbb{R}$ is an open interval. Define f to be $y \circ i \circ g$: since $i : C \hookrightarrow E$ and $y : E \rightarrow \mathbb{R}$, this is a map $I \rightarrow \mathbb{R}$. Write

$$e_1 = \frac{(-f', 1)}{\sqrt{1 + (f')^2}} \quad \text{and} \quad e_2 = \frac{(1, f')}{\sqrt{1 + (f')^2}}.$$

Then,

$$de_1 = \left(\frac{(-f'', 0)}{\sqrt{1 + (f')^2}} + \frac{(-f', 1)}{(1 + (f')^2)^{3/2}} f' \right) dt.$$

At p ,

$$de_1 = (-f''(0), 0) dt = (-f''(0) dt) e_2. \quad \square$$

In calculus, we think of the tangent line as the best linear approximation to a function at a point, which only requires an affine space. Curvature is the process that goes one degree higher: you could ask for the *osculating parabola* to a curve at a point, the parabola that best approximates a curve at a point, or for the *osculating circle*, the circle that best approximates the curve at that point. Then, the curvature can be read off of the constants, e.g. it's 1 over the radius of the osculating circle. But knowing these parameters requires an inner product, hence a Euclidean space.

Prescribing curvature. We aim to solve the following problem: given an abstract curve C and a function $k : C \rightarrow \mathbb{R}$, construct an immersion $i : C \rightarrow E$ and a co-orientation such that k is the curvature of i .

Curvature requires thinking about a frame at each point of $i(C)$, so we should think about the bundle of orthonormal frame $\pi : \mathcal{B}_O(E) \rightarrow E$. A point in $\mathcal{B}_O(E)$ is a triple $(p; e_1, e_2)$, where $p \in E$ and (e_1, e_2) is an orthonormal basis of V . In particular, $\mathcal{B}_O(E)$ is naturally a product $E \times \mathcal{B}_O(V)$. We want to construct a lift $\tilde{i} : C \rightarrow \mathcal{B}_O(E)$ making the following diagram commute:

$$\begin{array}{ccc} & \mathcal{B}_O(E) & \\ \tilde{i} \nearrow & \downarrow \pi & \\ C & \xrightarrow{i} & E. \end{array}$$

This \tilde{i} is specified as a triple of functions on C , $\tilde{i} = (p, e_1, e_2)$. Prescribing the curvature means we need this to satisfy

$$(3.6) \quad d \begin{pmatrix} p & e_1 & e_2 \end{pmatrix} = \begin{pmatrix} p & e_1 & e_2 \end{pmatrix} \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & k dt \\ dt & -k dt & 0 \end{pmatrix}}_{A(t)}.$$

We'll interpret A as a time-varying vector field on the manifold $\mathcal{B}_O(E)$; then, we can evoke the basic theory of ordinary differential equations to prove there's a solution.

Digression. Let's recall what this basic theory of ordinary differential equations says. Let X be a smooth manifold and $(a, b) \subset \mathbb{R}$ be an interval. Projection onto the second factor defines a map $\pi_2 : (a, b) \times X \rightarrow X$, and we can pull the tangent bundle back along it:

$$\begin{array}{ccc} \pi_2^* TX & \longrightarrow & TX \\ \downarrow p & & \downarrow \\ (a, b) \times X & \xrightarrow{\pi_2} & X. \end{array}$$

Definition 3.7.

- A *time-varying vector field* is a section $\xi : (a, b) \times X \rightarrow \pi_2^*TX$ of $p : \pi_2^*TX \rightarrow (a, b) \times X$.
- An *integral curve* of ξ is an open interval $I \subset (a, b)$ and a function $\gamma : I \rightarrow X$ such that

$$\dot{\gamma}(t) = \xi_{(t, \gamma(t))}.$$

Time-varying vector fields correspond to ODEs and integral curves correspond to their solutions.

Theorem 3.8. *Given $(t_0, x_0) \in (a, b) \times X$, there exists an $\varepsilon > 0$ and an integral curve $\gamma : (t_0 - \varepsilon, t_0 + \varepsilon)$ such that $\gamma(t_0) = x_0$, and any two choices for γ agree on their common domain. Moreover, there is a maximal domain $J \subset (a, b)$ on which a solution exists and an integral curve $\gamma : J \rightarrow X$*

That is, solutions exist and are unique given an initial condition. However, they may not be globally defined.⁴

Just as $\mathcal{B}_O(V)$ is a torsor for a right action of O_2 (an orthogonal basis composed with an orthogonal transformation is again an orthogonal basis), $\mathcal{B}_O(E)$ is a torsor for the right action of Euc_2 , the group of Euclidean transformations of \mathbb{E}^2 . This torsor structure means the derivative of a curve in any neighborhood of the origin of the group defines a vector field on the torsor.

If $P(t)$ is a curve in O_2 such that $P(0) = \text{id}$, then ${}^tP \cdot P = I$, so differentiating this condition, ${}^t \cdot P + \cdot P = 0$. That is, $T_e O_2$ is the line of 2×2 skew-symmetric matrices over \mathbb{R} . Looking again at (3.6), the lower right entries of $A(t)$ are exactly such a matrix, so $A(t)$ is in fact a time-varying vector field on $\mathcal{B}_O(E)$.

Now, using Theorem 3.8, given an initial $p \in E$ and an initial frame (e_1, e_2) on $T_p E$, there is a local and in fact a maximal solution to the prescribed curvature problem. This solution is unique up to the choice of (p, e_1, e_2) , and this is usually expressed by saying that the group of symmetries of Euclidean space acts transitively on the solutions (so there's only one up to rotations and translations).

This is a somewhat elementary context for this material, but we'll adopt this perspective again and again. Eventually there will also be second-order conditions, e.g. when we define geodesics later.

Now, let's step up a dimension: let E be a Euclidean 3-space modeled on an inner product space V and $i : S \hookrightarrow V$ be an immersion of a 2-manifold together with a co-orientation. We can again define the unit co-oriented normal $\nu : S \rightarrow S(V)$. How can we define the curvature of this surface?

Euler solved this problem in 1760 by reducing it to something we've already done: let $L \in \mathbb{P}(T_p S)$ be a 1-dimensional subspace of the tangent space. There's a unique affine plane $\Pi(L)$ passing through p and containing L , and $\Pi(L) \cap S$ is a co-oriented curve in $\Pi(L)$. Let $k_p : \mathbb{P}(T_p S) \rightarrow \mathbb{R}$ be the function assigning to L the curvature of the curve $\Pi(L) \cap S$. Euler studied this function.

As before, locally we can write S as the graph of a function $f : T_p S \rightarrow \mathbb{R}$ with $f(0) = 0$ and $df_0 = 0$. The function k_p encodes the second derivative of f . This is expressed through the Hessian

$$\text{Hess } f_0 : T_p S \times T_p S \longrightarrow \mathbb{R},$$

which is a symmetric bilinear form. In the context of geometry of surfaces, this Hessian is called the *second fundamental form* and denoted Π_p .

Corollary 3.9. *For any $L \in \mathbb{P}(T_p S)$, $k_p(L) = \Pi_p(\xi, \xi)$, where $|\xi| = 1$ and $\xi \in L$.*

The *first fundamental form* is the inner product

$$I_p := \langle -, - \rangle : T_p S \times T_p S \rightarrow \mathbb{R},$$

The second fundamental form may be nondegenerate (e.g. if S is flat), but we know the first is nondegenerate. This means the second fundamental form may be expressed in terms of the first fundamental form and some other operator S , called the *shape operator*:

$$\Pi_p(\xi, \eta) = I_p(\xi, S(\eta)) = \langle \xi, S(\eta) \rangle.$$

Since Π_p is symmetric, then S is self-adjoint. This means it has two real eigenvalues, so we can look at the eigenspaces, which are called the *principal lines* of S at p — unless the curvature is constant at p , in which case p is called an *umbilic point*.

Interestingly, we started with a very extrinsic notion of curvature of surfaces, but from this we've obtained some intrinsic geometry.

⁴In this class, we assume everything is smooth, but Theorem 3.8 is true in much greater generality, requiring only *Lipschitz continuity*, a condition slightly stronger than continuity. Many other things in this class may be relaxed, e.g. to C^2 .

Curvature for surfaces: 1/26/17

"I didn't go into comedy, because I thought I would be safe here. . ."

Last time, we talked about the curvature of surfaces in a Euclidean plane; today, we will consider surfaces in a 3-dimensional Euclidean space E modeled on an inner product space $(V, \langle -, - \rangle)$, the vector space of translations of E .

Though E is abstractly isomorphic to \mathbb{R}^3 , we won't fix an isomorphism by choosing coordinates; later, we'll want to pick special coordinates for E , so this would only complicate things.

Let $\Sigma \subset E$ be an embedded 2-manifold (some of our results will still apply when Σ is immersed), and assume Σ is co-oriented. Let $\nu : \Sigma \rightarrow V$ be the co-oriented positive unit normal.

Given a $p \in \Sigma$ and a plane $L \subset V$, $\Pi(L)$ denotes the plane through p containing L and ν . Then, $\Sigma \cap \Pi(L)$ is a curve, which is intuitively the curve "pointing in the L -direction at p ."

The map assigning to L the curvature of $\Sigma \cap \Pi(L)$ at p is a function

$$k_p : \mathbb{P}(T_p \Sigma) \rightarrow \mathbb{R}.$$

Here, $\mathbb{P}(V)$ is the manifold of 1-dimensional subspaces of a vector space V .

We're going to get some information out of k_p . Let's first introduce special coordinates: choose an orthonormal basis in $\mathcal{B}_O(E)$, so we obtain coordinates x^1 and x^2 in $T_p \Sigma$. As in the last lecture, the inverse function theorem provides for us an open set $U \subset T_p \Sigma$ containing 0, a function $f : U \rightarrow \mathbb{R}$, and an open $J \subset \mathbb{R}$ containing 0 such that $\Sigma \cap ((p + U) \times (p + J\nu))$ is the graph of f .

That is, there's a box inside E with an " xy -plane" $p + U$ and a " z -axis" pointing in the ν -direction, and inside this box, Σ is the graph of a function $f(x, y)$ on $p + U$. Furthermore, $f(p) = 0$ and $df_p = 0$, which is easy to check.

Last time, we defined the second fundamental form at p , $II_p = \text{Hess}_p f : T_p \Sigma \times T_p \Sigma \rightarrow \mathbb{R}$. Based on what we proved last time, using the third incarnation of curvature, we got Corollary 3.9: $k_p(L) = II_p(\xi, \xi)$, where $\xi \in L$ is a unit vector.

This says the Hessian on the diagonal determines the curvature. This is because this is the second derivative of f , and we showed that if $df_p = 0$ for an f parameterizing a plane curve, then its second derivative computes the curvature.

On $T_p \Sigma$ we have two fundamental forms: the inner product, also known as the first fundamental form I_p , and the second fundamental form defined above. Since the first fundamental form is nondegenerate, then we can (and did) define the shape operator $S_p \in \text{End}(T_p \Sigma)$ to satisfy the relation

$$\langle \xi, S_p(\eta) \rangle = II_p(\xi, \eta).$$

Since the inner product is nondegenerate, this uniquely defines $S_p(\eta)$. Moreover, since II_p is symmetric, then S_p is self-adjoint, i.e. $\langle \xi, S_p(\eta) \rangle = \langle S_p(\xi), \eta \rangle$ for all ξ and η . In particular, it's diagonalizable, and since $T_p \Sigma$ is two-dimensional, there are two possibilities:

- (1) If there's only one eigenvalue $\lambda \in \mathbb{R}$, then $S_p = \lambda \cdot \text{id}_{T_p \Sigma}$. In this case, p is called an umbilic point.
- (2) If there are two eigenvalues λ_1 and λ_2 (suppose without loss of generality $\lambda_1 > \lambda_2$), then the two eigenspaces L_1 and L_2 form an orthogonal direct-sum decomposition $T_p \Sigma = L_1 \oplus L_2$. In this case, $S_p|_{L_i}$ is multiplication by λ_i . The L_i are called the *principal directions*, and the λ_i are called the *principal curvatures*. For any plane L ,

$$k_p(L) = \frac{II_p(\xi, \xi)}{I_p(\xi, \xi)}.$$

The maximum of k_p is at L_1 , and the minimum is at L_2 . $II_p(\xi, \xi) I_p(\xi, \xi)$.

If you reverse the co-orientation, then $k \mapsto -k$ and $\lambda_i \mapsto -\lambda_i$. From this we get the *mean curvature* (named after one Mr. Mean)

$$H := \frac{\lambda_1 + \lambda_2}{2} = \frac{1}{2} \text{Tr}(S_p),$$

a function $\Sigma \rightarrow \mathbb{R}$. Reversing the co-orientation sends $H \mapsto -H$. The *Gauss curvature* (named after Gauss) is

$$K := \lambda_1 \lambda_2 = \det S,$$

also a function $\Sigma \rightarrow \mathbb{R}$. This is unchanged when you reverse the co-orientation, which suggests that it comes from an intrinsic invariant! The units of the Gauss curvature has units $1/\text{length}^2$.

We also have the unit normal vector field $\nu: \Sigma \rightarrow S(V) \subset V$, and it tells us things about the curvature too.

Proposition 4.1. $d\nu_p: T_p\Sigma \rightarrow T_p\Sigma$ equals $-S_p$.

Proof. Introduce “Euclidean coordinates” x^1, x^2 on $p + T_p\Sigma$, and let $f = f(x^1, x^2)$ be such that near p , Σ is the graph of f . Then,

$$\nu = \nu(x^1, x^2) = \frac{(-f_1, -f_2, 1)}{\sqrt{1 + f_1^2 + f_2^2}},$$

where $f_i = \frac{\partial f}{\partial x^i}$.

Exercise 4.2. Check that this is in fact a unit normal vector.

You can then calculate

$$d\nu_p = \begin{pmatrix} -\partial_{11}f & -\partial_{12}f \\ -\partial_{21}f & -\partial_{22}f \end{pmatrix} \Big|_p,$$

and this is $-\text{Hess}_p f = -II_p$ as desired. (Here, it may help to remember that p is identified with $(0, 0)$.) \square

Many people bemoan computations and coordinates, but certainly computations are useful, and coordinates are useful for computations. The solution is to judiciously choose coordinates to make computations simpler.

Now we can cover two beautiful theorems of Gauss, one global, one local.

Theorem 4.3 (Gauss-Bonnet). Let $\Sigma \subset E$ be a closed, co-oriented surface and $K: \Sigma \rightarrow \mathbb{R}$ be its Gauss curvature. Let $|dA|$ denote its Riemannian measure. Then,

$$(4.4) \quad \int_{\Sigma} K |dA| = 2\pi\chi(\Sigma).$$

Some of these words merit an explanation.

- A *closed manifold* is not the same thing as a closed subset: it means Σ is compact and has no boundary. It turns out all closed surfaces in E are co-orientable, but this is not necessarily true for immersed surfaces (e.g. the standard immersion of the Klein bottle).
- The Riemannian measure is discussed in the homework, but the essential idea is that on a Riemannian manifold, we know the lengths and angles of vectors, and therefore of the volume of the parallelogram that a basis v_1, \dots, v_n of a tangent space spans, namely $|\det(\langle v_i, v_j \rangle_{ij})|$. Thus, we know how to compute volumes, which defines a measure that we can use to integrate functions.
- $\chi(\Sigma)$ is the Euler characteristic of Σ .

Though the proof we’ll see uses the embedding (and implicitly the fact that Σ is orientable), all of the notions in (4.4) turn out to be extrinsic, and the theorem holds for abstract closed surfaces with a Riemannian metric, orientable or not.

Example 4.5. Consider a sphere $S^2(R)$ of radius R inside E . Then, every point is umbilic, and the Gauss curvature is $1/R^2$ everywhere. The surface area of the sphere is $4\pi R^2$, so

$$\int_{S^2} K |dA| = 4\pi = 2\pi \cdot 2,$$

and indeed $\chi(S^2) = 2$. \blacktriangleleft

Theorem 4.3 is the first of many theorems which relate local and global geometry. It can be used to calculate global quantities, and to constrain local ones: for example, the sphere cannot have a metric with negative curvature, because its Euler characteristic is positive. The torus T^2 has Euler characteristic $\chi(T^2) = 0$, so any metric on it is either everywhere flat (no curvature) or has points of both positive and negative curvature. The standard embedding into \mathbb{E}^3 has points of both positive and negative curvature, but the flat torus can’t be embedded isometrically into \mathbb{E}^3 . It can be embedded into \mathbb{E}^4 , as the product of two copies of the unit circle in \mathbb{E}^2 .

Proof of Theorem 4.3. The proof will use the language of differential topology. Recall that if M and M' are oriented manifolds of the same dimension n , we can define the degree of a smooth map $\nu : M' \rightarrow M$, and if $\omega \in \Omega_{M'}^n$, then

$$\int_{M'} \nu^* \omega = (\deg \nu) \int_M \omega.$$

In our case, ν is the unit vector map $\nu : \Sigma \rightarrow S(V)$; we computed that $d\nu = -S$ (where S is the shape operator) in Proposition 4.1. Thus,

$$\det(d\nu) = \det(-S) = K.$$

Let $\omega \in \Omega_{S(V)}^2$ be the area form; then,

$$\nu^* \omega = (\det d\nu) \cdot dA = K dA.$$

Thus, when we integrate,

$$\int_{\Sigma} K dA = \int_{\Sigma} \nu^* \omega = (\deg \nu) \int_{S(V)} \omega = 4\pi \deg \nu,$$

since the area of the unit sphere is 4π . Thus, it suffices to show $\deg \nu = \chi(\Sigma)/2$.

The Euler number emerges from the Poincaré-Hopf theorem, that if \mathbf{v} is a vector field with isolated zeroes on Σ , the sum of the indices of \mathbf{v} at its zeroes produces $\chi(\Sigma)$.

Compose ν with the quotient map $S(V) \rightarrow \mathbb{P}(V)$, and let q be a regular value of this composition, with two preimages $\pm\eta \in S(V)$. η pulls back to a vector field on Σ (constantly pointing in the direction η with unit length). Let ξ_p denote the vector field produced by projecting η onto $T\Sigma$; this has isolated zeros x_1, \dots, x_n .

You can do the computation without coordinates, but it's not hard in them: if $\eta = (0, 0, 1)$ (which is true up to a rotation), then at any x_i ,

$$\xi = \frac{(f_1, f_2, f_1^2 + f_2^2)}{1 + f_1^2 + f_2^2},$$

and you don't have to worry about the denominator in the derivative, so

$$d\nu_p = d\xi_p = \begin{pmatrix} \partial_{11}f & \partial_{12}f \\ \partial_{21}f & \partial_{22}f \end{pmatrix} \Big|_p. \quad \square$$

This is the first connection between topology and geometry.

You might wonder how this can be generalized. In odd dimensions, the Euler characteristic is zero, but for even dimensions, Chern proved the Gauss-Bonnet-Chern theorem in the 1940s which expresses the Euler characteristic in more complicated terms involving the Riemann curvature tensor.

Lecture 5.

Extrinsic and intrinsic curvature: 1/31/17

On the first day, we derived some equations as to when a Riemannian manifold is locally isometric to Euclidean space. Namely, if

$$A_{ijk} := \frac{\partial g_{\ell j}}{\partial x^k} + \frac{\partial g_{\ell k}}{\partial x^j} - \frac{\partial g_{jk}}{\partial x^\ell}$$

and

$$\Gamma_{jk}^i := \frac{1}{2} g^{i\ell} A_{\ell jk},$$

then we derived in (1.20)

$$E_{jkl}^i = \frac{\partial \Gamma_{j\ell}^i}{\partial x^k} - \frac{\partial \Gamma_{jk}^i}{\partial x^\ell} + \Gamma_{j\ell}^m \Gamma_{mk}^i - \Gamma_{jk}^m \Gamma_{m\ell}^i,$$

and the Riemann curvature tensor

$$R = R_{ijkl}^i \frac{\partial}{\partial x^i} \otimes dx^j \otimes dx^k \otimes dx^\ell$$

is an obstruction to a Riemannian manifold being locally isometric to flat, Euclidean space. There's an exercise in the homework to show this is invariant under change of coordinates, and therefore R is an intrinsic object.

Today, we will tie this to the study of curvature of a surface Σ embedded in Euclidean 3-space E . Suppose Σ is co-oriented; then, at any $p \in \Sigma$, we defined the second fundamental form $II_p : T_p \Sigma \times T_p \Sigma \rightarrow \mathbb{R}$ and the shape operator $S_p : T_p \Sigma \rightarrow T_p \Sigma$ satisfying $II_p(\xi, \eta) = \langle \xi, S_p(\eta) \rangle$. The Gauss curvature is $k_p = \det S_p$, and the normal curvature is $II_p(\xi, \xi) / I_p(\xi, \xi)$.

Locally, Σ is the graph of a function $f = f(x^1, x^2)$ defined on an open neighborhood U in the $x^1 x^2$ -plane; here, x^1 and x^2 are special coordinates determined up to an element of O_2 .

Theorem 5.1 (Gauss' *Theorema egregium*, c. 1823). *In any of these special local coordinates at p ,*

$$R_{212}^1(p) = k_p.$$

The right-hand side is defined extrinsically, determining how curves contained in orthogonal planes bend when embedded in the surface. But the left-hand side is defined intrinsically, depending only on the metric. Thus, the Gauss curvature is an intrinsic quantity, and does not depend on the co-orientation or embedding.

Corollary 5.2. *If Σ, Σ' are two surfaces embedded in E and $\varphi : \Sigma' \rightarrow \Sigma$ is an isometry, then $\varphi^* k = k'$.*

This is because the isometry preserves the metric, and the Gauss curvature can be computed only from the metric. This version is closer to how Gauss stated it.

Looking at Corollary 5.2, we know one embedding of the sphere of radius R into E such that the Gauss curvature is $k = 1/R^2$, and that the flat plane has curvature 0. Thus, map projections must be inaccurate: there's no way to map a plane onto any part of the sphere without distorting some length or angle.

The Riemannian curvature tensor on a Riemannian manifold X has a lot of symmetry. From (1.20), one can show that $R_{jkl}^i = -R_{\ell k}^i$: it's skew-symmetric in these arguments. Thus,

$$R = \frac{1}{2} R_{jkl}^i \left(\frac{\partial}{\partial x^i} \otimes dx^j \right) \otimes dx^k \wedge dx^\ell.$$

That is, $R \in \Omega_X^2(\text{End } TX)$: the i and j indices give you an endomorphism of each tangent space. In fact, $R \in \Omega^2(\text{SkewEnd } TX)$: the endomorphism is skew-symmetric.

Applying this to when $\dim X = 2$, if $V := T_p X$, then $R_p \in \text{SkewEnd}(V) \otimes \Lambda^2 V^*$. The second component is the top exterior power, hence the *determinant line* $\text{Det } V^*$. Moreover, $\text{SkewEnd}(V) \xrightarrow{\cong} \Lambda^2 V^*$ through the map sending

$$T \longmapsto (\xi, \eta \longmapsto \langle \xi, T\eta \rangle).$$

This is akin to the way we got the shape operator out of the second fundamental form.

Anyways, this means $R_p \in (\text{Det } V^*)^{\otimes 2} = (\text{Det } V^{\otimes 2})^*$. What is this determinant line? The idea is that for every pair of vectors ξ, η , $\xi \wedge \eta$ can be identified with its area. We don't know what area 1 is *per se*, but we know given ξ', η' how to figure out the ratio of the area of $\xi' \wedge \eta'$ to that of $\xi \wedge \eta$, giving us a one-dimensional subspace.

But we do have an orthonormal basis produced by the metric, so we obtain a distinguished unit vector $e \in \text{Det } V$. Thus, we can express $R_{212}^1(p)$ coordinate-independently, by evaluating $R_p \in ((\text{Det } V)^{\otimes 2})^*$ on $e \otimes e \in (\text{Det } V)^{\otimes 2}$.

Proof of Theorem 5.1. Near p , the surface is the graph of a function $(x^1, x^2) \mapsto (x^1, x^2, f(x^1, x^2))$. Let $f_i := \frac{\partial f}{\partial x^i}$, so

$$\begin{aligned} \frac{\partial}{\partial x^1} \Big|_{(x^1, x^2)} &= (1, 0, f_1) \in T_{(x^1, x^2, f(x^1, x^2))} \Sigma \subset V \\ \frac{\partial}{\partial x^2} \Big|_{(x^1, x^2)} &= (0, 1, f_2). \end{aligned}$$

Let $\Delta := 1 + f_1^2 + f_2^2$. Then, you can calculate that the metric and its inverse satisfy

$$\begin{aligned} g_{11} &= 1 + f_1^2 & g^{11} &= \frac{1 + f_2^2}{\Delta} \\ g_{12} &= f_1 f_2 & g^{12} &= -\frac{f_1 f_2}{\Delta} \\ g_{22} &= 1 + f_2^2 & g^{22} &= \frac{1 + f_1^2}{\Delta}. \end{aligned}$$

The right-hand side is obtained from the left by inverting the 2×2 matrix for g_{ij} .

Exercise 5.3. Check that $A_{\ell jk} = 2f_\ell f_{jk}$.

Recall that $f(0,0) = f_\ell(0,0) = 0$, so $A_{\ell ij}(0) = 0$ and $\Gamma_{jk}^i(0) = 0$. Thus,

$$R_{212}^1(0,0) = \left. \frac{\partial \Gamma_{22}^1}{\partial x^1} \right|_{(0,0)} - \left. \frac{\partial \Gamma_{21}^1}{\partial x^2} \right|_{(0,0)}.$$

Another plug-and-chug shows that

$$\begin{aligned} \Gamma_{22}^1 &= \frac{1}{2} g^{11} A_{122} + \frac{1}{2} g^{12} A_{222} \\ &= \frac{2}{2\Delta} \left((1 + f_2^2) f_1 f_{22} - f_1 f_2 f_{22} \right) \\ &= \frac{f_1 f_{22}}{\Delta}. \end{aligned}$$

A similar calculation shows

$$\Gamma_{21}^1 = \frac{f_1 f_{21}}{\Delta}.$$

Therefore

$$\begin{aligned} R_{212}^1(0,0) &= (f_{11} f_{22} - f_{12} f_{21})|_{(0,0)} \\ &= \det \text{Hess}_{(0,0)} f \\ &= k_p. \end{aligned}$$

□

You should run through these calculations to make sure you understand them.

This provides us an interpretation of R , measuring curvature in different directions on the manifold. If it's equal to 0, the manifold is flat. We'd also like to interpret the Γ_{jk}^i symbols. This should be easier because they're built from first derivatives, whereas R was built from second derivatives.

Let's think about parallelism. In the Euclidean plane E , we have *global parallelism*, that given a vector field $\eta; E \rightarrow V$, we can compute its directional derivatives by considering the function $t \mapsto p + t\zeta_p$ along a direction ζ_p (thought of as rooted at p). That is, the directional derivative of η in the direction ζ_p is

$$D_{\zeta_p} \eta := \lim_{t \rightarrow 0} \frac{\eta(p + t\zeta_p) - \eta(p)}{t}.$$

If $\gamma : (-\varepsilon, \varepsilon) \rightarrow E$ is a curve with $\gamma(0) = p$ and $\dot{\gamma}(0) = \zeta_p$, then

$$D_{\zeta_p} \eta = \left. \frac{d}{dt} \right|_{t=0} \eta(\gamma(t)).$$

This doesn't work quite so well on embedded surfaces $\Sigma \hookrightarrow E$. There's a "poor man's parallelism" that translates a vector using the ambient parallelism on E , but there are lots of issues with this: it does not preserve tangency. So you project down onto $T\Sigma$, you say, but then sometimes you get the zero vector, and it feels like parallelism should preserve lengths and angles, right?

Let's ask a smaller question: given an immersed curve $\gamma : (-\varepsilon, \varepsilon) \rightarrow \Sigma$ with $\gamma(0) = p$ and $\dot{\gamma}(0) = \zeta_p$, can we parallelize?

Definition 5.4. The *covariant derivative* $\nabla_{\zeta_p} \eta$ is the orthogonal projection of $D_{\zeta_p} \eta \in V$ onto $T_p \Sigma$.

Here, η is a section of the vector bundle $T\Sigma \rightarrow \Sigma$, and $\xi_p \in T_p\Sigma$, so $D_{\xi_p}\eta$ is in $T_pE = V$.

Definition 5.5. We say η is *parallel along* $\gamma : (a, b) \rightarrow \Sigma$ if $\nabla_{\dot{\gamma}}\eta = 0$ for all $t \in (a, b)$. If $\nabla_{\dot{\gamma}}\dot{\gamma} = 0$ (i.e. $\dot{\gamma}$ is parallel along γ), then γ is called a *geodesic*.

Here, η is a *vector field along* γ , meaning a section of the pullback bundle $\gamma^*T\Sigma \rightarrow (a, b)$. That is, at each t , $(\gamma^*T\Sigma)_t := T_{\gamma(t)}\Sigma$, and these fit together smoothly. So at each t , η chooses a tangent vector in $T_{\gamma(t)}\Sigma$. Thus, if γ is self-intersecting, we get a different tangent vector each time $\gamma(t)$ reaches the intersection point, so everything is still well-behaved.

Geodesics are the curves which have no acceleration along the curve, so the only acceleration is normal to the surface. For example, if you have a geodesic on a sphere (which is a great circle), it's only accelerating perpendicular to the sphere, the minimal acceleration necessary to stay on the sphere.

One of the first things we prove in multivariable calculus is that the directional derivative is linear in the direction. This is still true here, where we derived it from parallelism, among the oldest notions in geometry.

Lemma 5.6.

(1) $\nabla_{\xi_p}\eta$ is linear in ξ_p , i.e. $\nabla\eta \in T_p^*\Sigma$.

(2) ∇_{ξ_p} satisfies a Leibniz rule:

$$\nabla_{\xi_p}(f\eta) = (\xi_p \cdot f)\eta + f\nabla_{\xi_p}\eta.$$

(3)

$$\nabla_{\xi_p}(\eta + \eta') = \nabla_{\xi_p}\eta + \nabla_{\xi_p}\eta'.$$

(4)

$$\xi_p \langle \eta, \eta' \rangle = \langle \nabla_{\xi_p}\eta, \eta' \rangle + \langle \eta, \nabla_{\xi_p}\eta' \rangle.$$

Though we've defined geodesics extrinsically, they are intrinsic, and we'll be able to describe them using the symbols Γ_{jk}^i .

Theorem 5.7. Let η be a vector field on Σ . Then, $\nabla\eta$ is intrinsic, i.e. determined solely by the metric.

In particular, $\nabla\eta \in \Omega_\Sigma^1(T\Sigma)$.

Proof. Use coordinates $(x^1, x^2, f(x^1, x^2))$ as before, so Σ is the graph of f . A basis for the tangent space is $\frac{\partial}{\partial x^1} = (1, 0, f_1)$ and $\frac{\partial}{\partial x^2} = (0, 1, f_2)$ as before.

Write $\eta = \eta^i \frac{\partial}{\partial x^i}$ with $\eta^i = \eta^i(x^1, x^2)$ for $i = 1, 2$. Thus, $\eta = (\eta^1, \eta^2, \eta^i f_i)$, so by a Leibniz rule

$$D\eta = (d\eta^1, d\eta^2, f_i d\eta^i + \eta^i df_i).$$

In particular, $D\eta_p = (d\eta_p^1, d\eta_p^2, *)$ and $\nabla\eta_p = (d\eta_p^1, d\eta_p^2, 0)$, or

$$\nabla\eta = d\nabla^i \cdot \frac{\partial}{\partial x^i},$$

so $\nabla \frac{\partial}{\partial x^i} = 0$ at p .

We used special coordinates x^1, x^2 ; let's change to arbitrary coordinates y^1, y^2 . Calculus on manifolds (or, for grade students, canceling fractions) shows that

$$\frac{\partial}{\partial y^a} = \frac{\partial x^i}{\partial y^a} \frac{\partial}{\partial x^i},$$

so at p ,

$$\begin{aligned} \nabla \frac{\partial}{\partial y^a} &= \frac{\partial^2 x^i}{\partial y^b \partial y^a} dy^b \cdot \frac{\partial}{\partial x^i} \\ &= \underbrace{\frac{\partial^2 x^i}{\partial y^b \partial y^a} \frac{\partial y^c}{\partial x^i}}_{Q_{ab}^c} dy^b \cdot \frac{\partial}{\partial y^c}. \end{aligned}$$

We'll finish the proof by showing $Q_{ab}^c = \Gamma_{ab}^c$ as computed in the (y^1, y^2) -coordinate system. Since Γ_{ab}^c doesn't depend on the metric, neither can $\nabla\eta$.

At p ,

$$\begin{aligned} g_{ab} &= \left\langle \frac{\partial}{\partial y^a}, \frac{\partial}{\partial y^b} \right\rangle = \frac{\partial x^i}{\partial y^a} \frac{\partial x^j}{\partial y^b} g_{ij} \\ &= \sum_i \frac{\partial x^i}{\partial y^a} \frac{\partial x^i}{\partial y^b}, \end{aligned}$$

so (again at p),

$$\frac{\partial g_{ab}}{\partial y^c} = \sum_i \frac{\partial^2 x^i}{\partial y^c \partial y^a} \frac{\partial x^i}{\partial y^b} + \frac{\partial x^i}{\partial y^a} \frac{\partial^2 x^i}{\partial y^c \partial y^b}.$$

Therefore

$$A_{dab} = 2 \sum_i \frac{\partial^2 x^i}{\partial y^a \partial y^b} \frac{\partial x^i}{\partial y^d}$$

and

$$g^{cd} = \sum_j \frac{\partial y^c}{\partial x^j} \frac{\partial y^d}{\partial x^j}.$$

Thus,

$$\Gamma_{ab}^c = \frac{1}{2} \gamma^{cd} A_{dab} = \sum_{i,j} \frac{\partial y^c}{\partial x^j} \underbrace{\frac{\partial y^d}{\partial x^j} \frac{\partial x^i}{\partial y^d}}_{\delta_j^i} \frac{\partial^2 x^i}{\partial y^a \partial y^b}.$$

Thus, we can collapse to when $i = j$, which recovers Q_{ab}^c . □

Embedded in this proof is the calculation as to how the Γ_{ij}^k change when the coordinates change.

This allows us to define a differential equation for geodesics: if $\eta = \eta^a \frac{\partial}{\partial y^a}$, so that

$$\nabla\eta = \left(\frac{\partial \eta^c}{\partial y^b} + \Gamma_{ab}^c \eta^a \right) dy^b \frac{\partial}{\partial y^c},$$

then the *geodesic equation* for $\dot{\gamma} = \xi = \xi^b \frac{\partial}{\partial y^b}$ is

$$(5.8) \quad \nabla_{\xi} \xi = \left(\dot{y}^a + \Gamma_{ab}^c y^a y^b \right) \frac{\partial}{\partial y^c} = 0.$$

That is, for surfaces, we have intrinsic notions of parallelism and geodesics. This holds in more generality. Next time, we'll say one more thing about surfaces in space (looking at the normal component of the directional derivative), and recover the second fundamental form on it. Then, we'll do some background lectures on differential geometry.

Lecture 6.

Vector fields and integral curves: 2/2/17

We've talked about how for surfaces, the sectional curvature at a point p is a map $k_p : \mathbb{P}(V) \rightarrow \mathbb{R}$. More generally, the Riemann curvature tensor is $R \in \Omega_X^2(\text{SkewEnd } TX)$, so for any $x \in X$, if $V = T_x X$, $R_x : \Lambda^2 V \rightarrow \text{SkewEnd}(V) \cong \Lambda^2 V^*$, hence determined by a bilinear map $\Lambda^2 V \times \Lambda^2 V \rightarrow \mathbb{R}$. If $\Pi \subset V$ is a two-dimensional subspace, we can evaluate $R_x(\Pi, \Pi) \in \mathbb{R}$, so letting Π vary, we obtain the *sectional curvature* $K_x : \text{Gr}_2(T_x X) \rightarrow \mathbb{R}$. Here, $\text{Gr}_2(V)$ is the *Grassmannian*, the manifold of 2-dimensional subspaces of V .

Let's return to the case of a co-oriented surface Σ embedded in a 3-dimensional Euclidean space E , and let η be a vector field on Σ . Then, the directional derivative in the direction ξ_p (a vector ξ rooted at p) is $D_{\xi_p}^{(E)} \eta \in \mathbb{R}^3$. This has tangential and normal components:

$$D_{\xi_p} \eta = \underbrace{\nabla_{\xi_p} \eta}_{\text{tangential}} + \underbrace{B(\xi_p, \eta) \cdot \nu}_{\text{normal}}.$$

Last time, we showed in Theorem 5.7 that the tangential part is intrinsic to Σ . If $\gamma : (-\varepsilon, \varepsilon) \rightarrow \Sigma$ is a curve, then $\nabla_{\dot{\gamma}} \eta$ is the covariant derivative of η along γ . We said η is parallel along γ if $\nabla_{\dot{\gamma}} \eta = 0$, and γ is a geodesic if $\dot{\gamma}$ is parallel along γ .

Last time, we saw that geodesics are the solutions to the ODE (5.8); by the general theory of ODEs, solutions exist and are unique. Given a smooth curve $\gamma : (a, b) \rightarrow \Sigma$, a $t_0 \in (a, b)$, and an $\eta_0 \in T_{\gamma(t_0)} \Sigma$, there exists a unique parallel vector field η along γ such that $\eta_{\gamma(t_0)} = \eta_0$.

But local parallelism doesn't imply global parallelism. Consider a geodesic triangle on a sphere,⁵ as in Figure 3. If you start with a vector tangent along the upper left piece and parallel-transport it to the lower

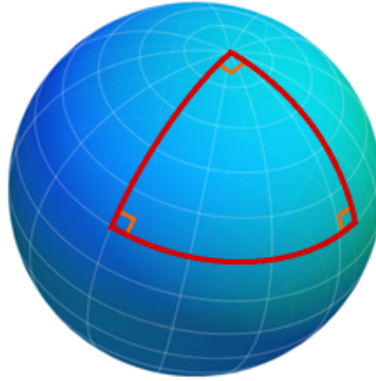


FIGURE 3. A geodesic triangle on the sphere. Each line is a piece of a great circle, and all three angles are right angles. Source: http://world.mathigon.org/Dimensions_and_Distortions.

left corner, then parallel-transport it to the lower-right corner, then parallel-transport it back up to the pole, you'll end up with a different vector than you started with.

Parallel-transport can be thought of as a way of isometrically identifying tangent spaces (which we can canonically do in Euclidean space, but not always on manifolds).

Proposition 6.1. *Let $\gamma : (a, b) \rightarrow \Sigma$ be a curve and η_1, η_2 be parallel vector fields along γ . Then, $\gamma \eta_1, \eta_2 : \gamma \rightarrow \mathbb{R}$ is constant.*

Proof. Let $\xi = \dot{\gamma}$, so

$$\xi \langle \eta_1, \eta_2 \rangle = \langle \nabla_{\xi} \eta_1, \eta_2 + \eta_1, \nabla_{\xi} \eta_2 \rangle = 0. \quad \square$$

If γ is closed, traveling along γ from a point p to itself will produce an isometry of $T_p \Sigma$, but not always the identity: in the above example, it was a nontrivial rotation. This is called the *holonomy* around the loop. If the top angle is θ (and the sphere has radius 1), the area of the triangle is θ .

~ . ~

Now let's discuss the geometry of the normal component $B(\xi_p, \eta)$.

Lemma 6.2.

- (1) If $f \in \Omega_{\Sigma}^0$, $B(\xi_p, f\eta) = fB(\xi_p, \eta)$.
- (2) B is the second fundamental form.

⁵There are other surfaces than spheres, of course! Check out the homework for some examples.

Remark. If X is a manifold, $\mathcal{X}(X)$ denotes the space of vector fields on X . We say T is linear if it's \mathbb{R} -linear, i.e. for all $\xi, \xi' \in \mathcal{X}(X)$ and $\lambda \in \mathbb{R}$,

$$T(\lambda\xi + \xi') = \lambda T(\xi) + T(\xi').$$

We say T is *linear over functions* if it's Ω_X^0 -linear, i.e. for any $f \in \Omega_X^0$ (i.e. $C^\infty(X)$), $T(f\xi) = fT(\xi)$. This means T doesn't differentiate f or anything like that, e.g. $\nabla_{\xi_p}(f\xi) = (\xi_p f)\xi + f\nabla_{\xi_p}\xi$ is not linear over functions. If T is linear over functions, it defines a cotangent vector field. \triangleleft

Proof of Lemma 6.2. For the first part, $B(\xi_p, \eta) = \langle D_{\xi_p}\eta, \nu \rangle$, so at p ,

$$\begin{aligned} B(\xi_p, f\xi) &= \langle D_{\xi_p}f\xi, \nu \rangle = \langle (\xi_p f)\xi + fD_{\xi_p}\xi, \nu \rangle \\ &= f(p)\langle D_{\xi_p}\xi, \nu \rangle = f(p)B(\xi_p, \xi). \end{aligned}$$

So B determines a bilinear map $B : T_p\Sigma \times T_p\Sigma \rightarrow \mathbb{R}$.⁶ Let's see that it agrees with Π .

Choose coordinates (x^1, x^2) such that Σ is the graph of $f(x^1, x^2)$. Then, $\frac{\partial}{\partial x^1} = (1, 0, f_1)$ and $\frac{\partial}{\partial x^2} = (0, 1, f_2)$ as normal. Write

$$\xi_p = \xi^i \frac{\partial}{\partial x^i} \Big|_p \quad \text{and} \quad \eta = \eta^i \frac{\partial}{\partial x^i} \Big|_p,$$

for $\xi^i, \eta^i \in \mathbb{R}$, we want to extend η_p to a map on local vector fields. We have liberty in this extension, so let's make our life easier and set $\eta^i(x^1, x^2) = \eta^i$, so it's constant. Thus, $\eta = (\eta^1, \eta^2, \eta^i f_i)$, so at $(x^1, x^2) = (0, 0)$,

$$D_{\xi_p}\eta = (0, 0, \eta^i(\xi_p f_i)) = (0, 0, \eta^i \xi^j f_{ij}).$$

Since $\nu_p = (0, 0, 1)$,

$$B(\xi_p, \eta_p) = f_{ij} \xi^i \eta^j = \Pi(\xi_p, \eta_p). \quad \square$$

This provides a coordinate-free interpretation of the second fundamental form, which is nice.

The first chapter of Warner's "Foundations on Differentiable Manifolds and Lie Groups" is a good reference for a lot of this material.

Anyways, this means the directional derivative is

$$D_{\xi_p}\eta = \nabla_{\xi_p}\eta + \Pi_p(\xi_p, \eta_p)\nu_p.$$

We can use this to derive a coordinate-free interpretation of the shape operator:

$$\begin{aligned} \Pi(\xi, \eta) &= \langle D_{\xi}\eta, \nu \rangle = \xi \langle \eta, \nu \rangle - \langle \eta, D_{\xi}\nu \rangle \\ &= -\langle \eta, D_{\xi}\nu \rangle = -\langle \eta, d\nu(\xi) \rangle, \end{aligned}$$

so $S_p = -d\nu_p$.

~ . ~

Though we'll begin talking about abstract Riemannian manifolds, these concrete examples, which you can draw, make these ideas clearer, and have fairly direct analogues in the abstract setting.

The choice of a unit tangent vector on a curve is discrete: on each connected component, you can flip between e_1 and $-e_1$. On a surface, though, it's possible to rotate a local frame $\{e_1, e_2, e_3\}$ (where e_1 is normal and e_2 and e_3 are tangential), so there's a continuous choice, and this continues to be true in higher dimensions.

In mathematics, a common approach to studying a situation where one needs to make a choice is to study all choices (sometimes you can make a convenient choice). Thus, we'll have to study this and other structures attached to smooth manifolds, including Lie groups, Lie derivatives, and a little geometry of smooth manifolds. But the payoff is that understanding how the frames change determines a lot of the Riemannian geometry.

⁶Equivalently, $B(\xi_p, \eta)$ only depends on the value of η at p .

Vector fields. Let X be a smooth manifold and ξ be vector field on X .

Definition 6.3. A piecewise-smooth curve $\gamma : (a, b) \rightarrow X$ is an *integral curve* of ξ if for all $t \in (a, b)$, $\dot{\gamma}(t) = \xi_{\gamma(t)}$.

That is, ξ is tangent along γ . We'd like to impose some constant-velocity constraint on this, but need a Riemannian metric to do that. It's possible to show that integral curves always exist, by starting with a finite approximation, iterating in a nice manner, and using some soft analysis (the contraction mapping theorem) to show there's a solution.

Theorem 6.4. Given an $x_0 \in X$ and a vector field ξ on X , there's a unique maximal integral curve $\gamma : (a(x_0), b(x_0)) \rightarrow X$ (where $a, b \in [-\infty, \infty]$), such that $\gamma(0) = x_0$ and if $\mu(a, b) \rightarrow X$ is an integral curve for ξ with $\mu(0) = x_0$, then $a(x_0) \leq a < 0 < b \leq b(x_0)$ and $\mu = \gamma|_{(a,b)}$.

This curve will be called γ_{x_0} .

Definition 6.5. With notation as in the above definition, γ is *complete* if for all $x_0 \in X$, $a(x_0) = -\infty$ and $b(x_0) = \infty$.

Here's a useful sufficient condition:

Theorem 6.6. If for some Riemannian metric $\langle -, - \rangle$, $\|\xi\| : X \rightarrow \mathbb{R}^{\geq 0}$ is bounded, then ξ is complete.

Corollary 6.7. If X is a compact manifold, all ξ are complete.

We would like to travel along a vector field. Let $\varphi(t, x) := \gamma_x(t)$; if ξ is complete, then $\varphi : \mathbb{R} \times X \rightarrow X$ is well-defined. Otherwise, you may find yourself flowing off the end of the world!

Definition 6.8. A *flow* on a manifold X is a (discrete) group homomorphism $\hat{\varphi} : \mathbb{R} \rightarrow \text{Diff}(X)$ (the latter group is under composition) such that the action map $\varphi : \mathbb{R} \times X \rightarrow X$ is C^∞ .

That is, we ask for $\hat{\varphi}(t_1 + t_2) = \hat{\varphi}(t_2) \circ \hat{\varphi}(t_1)$ and $\varphi(t_1 x) = \hat{\varphi}(t)(x)$. We don't know how to express smoothness on $\text{Diff}(X)$, so the smoothness criterion is stated in terms of the finite-dimensional manifolds \mathbb{R} and X .

Given a vector field ξ , define for some $t \in \mathbb{R}$ the set

$$\mathcal{D}_t := \{x \in X \mid t \in (a(x), b(x))\}.$$

The following theorem rests on a proof of Theorem 6.4. This is often left unproven in geometry textbooks, but can be found, e.g. in Lang's ODE book or in Coddington-Levinson.

Theorem 6.9.

- (1) \mathcal{D}_t is open.
- (2) The map $\varphi_t : \mathcal{D}_t \rightarrow \mathcal{D}_{-t}$ is a diffeomorphism.
- (3) The domain of $\varphi_{t_2} \circ \varphi_{t_1}$ is a subset of the domain of $\varphi_{t_1+t_2}$, and on that domain, $\varphi_{t_2} \circ \varphi_{t_1} = \varphi_{t_1+t_2}$.
- (4) If $x \in X$ and $U \subset X$ is an open set containing x , then there's a $V \subset U$ and an $\varepsilon > 0$ such that $\varphi(-\varepsilon, \varepsilon) \times V$ maps into U .
- (5) If ξ is complete, then $\mathcal{D}_t = X$ for all t , and φ is a global flow.

This all relies on ξ being fixed with time (an *autonomous system*). If $\xi = \xi(t)$ varies with time, then a lot of these arguments don't work; in particular $\varphi_{t_2} \circ \varphi_{t_1} \neq \varphi_{t_1+t_2}$. Fortunately, we can use a neat technique to dispatch these.

A vector field ξ is a section of the tangent bundle $p : TX \rightarrow X$, and a time-varying vector field $\xi(t)$ is a section of the pullback: if $\pi_2 : (a, b) \times X \rightarrow X$ denotes projection onto the second component, $\tilde{\xi}$ is a section of the pullback $\pi_2^* TX \rightarrow (a, b) \times X$. That is, on each time-slice, you get a section of TX , and these vary smoothly.

Let $\tilde{\xi} = \frac{\partial}{\partial t} + \xi$, so $\tilde{\xi}$ is a vector field on $(a, b) \times X$. Given an initial condition (t_0, x_0) , Theorem 6.4 says there's an integral curve $\hat{\gamma} : (\hat{a}, \hat{b}) \rightarrow (a, b) \times X$. Letting $\hat{\gamma}(t) = (t, \gamma(t))$, then $\hat{\gamma}(t) = \tilde{\xi}_{\hat{\gamma}(t)}$. This is $(1, \dot{\gamma}(t)) = (1, \tilde{\xi}(t))$, so $\gamma(t)$ is what we were looking for, and the solution exists, at least locally!

Once we have this flow, we're going to look at what happens if you carry various objects along the flow, e.g. vector fields or differential forms.

Lecture 7.

Tangential structures of manifolds: 2/7/17

Today, we'll talk about tangential structures: vector fields, subspaces of the tangent bundle, etc. We'll later dualize and look at functions and differential forms, and still later use this to understand Lie groups.

Let X be a smooth manifold and $\zeta \in \mathcal{X}(X)$ be a vector field on it. Let φ_t be the (local) flow generated by ζ : given a vector field, traveling along its integral curves moves points along the flow, and we can therefore flow all sorts of other objects: functions, vectors, differential forms, connections. . .

The Lie derivative is the instantaneous change in a quantity as you flow it. By a *covariant* object we mean something which pushes forward along maps, e.g. vectors. Similarly, *contravariant* things are those which pull back under maps.

Definition 7.1. Let T be a covariant object. Then, the *Lie derivative* of T is

$$\mathcal{L}_\zeta T := \left. \frac{d}{dt} \right|_{t=0} (\varphi_{-t})_* T.$$

If T is a contravariant object, then the Lie derivative of T is

$$\mathcal{L}_\zeta T := \left. \frac{d}{dt} \right|_{t=0} (\varphi_t)^* T.$$

Example 7.2. Let $f \in \Omega_X^0$ be a function. Functions pull back, so this is contravariant: $\varphi_t^* f(p) = f(\varphi_t(p))$. Thus, the Lie derivative of f is

$$\mathcal{L}_\zeta f(p) = \left. \frac{d}{dt} \right|_{t=0} \varphi_t^* f(p) = \left. \frac{d}{dt} \right|_{t=0} f(\varphi_t(p)).$$

Thus, this is the directional derivative along a curve $\gamma : t \mapsto \varphi_t(p)$, since $\gamma(0) = p$ and $\dot{\gamma}(p) = \zeta_p$. In symbols, $\mathcal{L}_\zeta f(p) = df|_p(\zeta_p)$. ◀

Example 7.3. Let $\eta \in \mathcal{X}(X)$ be a vector field. To compute its Lie derivative, let's introduce local coordinates x^1, \dots, x^n , so $\zeta = \zeta^i \frac{\partial}{\partial x^i}$, $\eta = \eta^j \frac{\partial}{\partial x^j}$, and $\varphi(t, x) = (\varphi^1(t, x), \dots, \varphi^n(t, x))$. Since φ_t is the flow, it satisfies

$$\dot{\varphi}(t, x) = \zeta_{\varphi(t, x)}, \quad \left. \frac{\partial \varphi^i}{\partial x^j} \right|_{t=0} = \delta_{j^i}, \quad \text{and} \quad \left. \frac{\partial^2 \varphi^i}{\partial x^k \partial x^k} \right|_{t=0} = 0.$$

Therefore we compute

$$(\varphi_{-t})\eta = (\varphi_{-t})_* \left(\eta^i \frac{\partial}{\partial x^i} \right) = (\varphi_t^* \eta^i) (\varphi_{-t})_* \frac{\partial}{\partial x^i}.$$

This pullback and pushforward are

$$\begin{aligned} \varphi_t^* \eta^i &= \eta^i(\varphi^1(t, x), \dots, \varphi^n(t, x)) \\ (\varphi_{-t})_* \frac{\partial}{\partial x^i} &= \left. \frac{d}{ds} \right|_{s=0} \varphi_{-t}(x^1, \dots, x^i + s, \dots, x^n) \\ &= \left. \frac{d}{ds} \right|_{s=0} \left(\varphi^j(-t, x^1, \dots, x^i + s, \dots, x^n) \right)_j \\ &= \frac{\partial \varphi^j}{\partial x^i}(\varphi(-t, x)) \cdot \frac{\partial}{\partial x^j}. \end{aligned}$$

Putting these together,

$$(\varphi_{-t})\eta = \eta^i(\varphi(t, x)) \cdot \frac{\partial \varphi^j}{\partial x^i}(\varphi(-t, x)) \frac{\partial}{\partial x^j}$$

and

$$\begin{aligned} \frac{d}{dt} \Big|_{t=0} (\varphi_{-t})_* \eta &= \left(\frac{\partial \xi^i}{\partial \eta^j} \phi^k \frac{\partial \phi^j}{\partial x^i} \frac{\partial}{\partial x^j} - \eta^i \frac{\partial^2 \phi^j}{\partial x^k \partial x^i} \phi^k \frac{\partial}{\partial x^j} - \eta^i \frac{d}{dt} \left(\frac{\partial \phi^j}{\partial x^i} \right) \frac{\partial}{\partial x^j} \right) \Big|_{t=0} \\ &= \frac{\partial \eta^i}{\partial x^k} \xi^k \delta_i^j \frac{\partial}{\partial x^j} - \eta^i \frac{\partial \xi^j}{\partial x^i} \frac{\partial}{\partial x^j} \\ &\quad - \left(\xi^i \frac{\partial \eta^j}{\partial x^i} - \eta^i \frac{\partial \xi^j}{\partial x^i} \right) \frac{\partial}{\partial x^j}. \end{aligned}$$

You might think this formula in coordinates is boring; if so, do it yourself. ◀

Therefore we have proven:

Proposition 7.4 (Lie derivative of vector fields in local coordinates).

$$\mathcal{L}_{\xi^i \partial / \partial x^i} \eta^j \frac{\partial}{\partial x^j} = \xi^i \frac{\partial \eta^j}{\partial x^i} \frac{\partial}{\partial x^j} - \eta^j \frac{\partial \xi^i}{\partial \eta^j} \frac{\partial}{\partial x^i}.$$

Notice the almost symmetry between ξ and η in the above result.

Corollary 7.5. $\mathcal{L}_{\xi} \eta = -\mathcal{L}_{\eta} \xi$.

Let's take a different point of view. Recall that the vector fields on X are alternatively the *derivations* $\xi : \Omega_X^0 \rightarrow \Omega_X^0$, i.e. linear maps satisfying the Leibniz rule

$$\xi(fg) = (\xi f)g + f(\xi g).$$

Hopefully you proved this in a differential topology class; if not, it's an exercise! You could also use the more general criterion that anything tensorial over functions is a tensor.

Definition 7.6. If $\xi, \eta \in \mathcal{X}(X)$, their *Lie bracket* $[\xi, \eta]$ is the derivation

$$(7.7) \quad f \mapsto \xi(\eta f) - \eta(\xi f).$$

Lemma 7.8. (7.7) satisfies the Leibniz rule and hence is actually a derivation.

Proof. Applying it to fg , we get

$$\begin{aligned} \xi(\eta(fg)) - \eta(\xi(fg)) &= \xi(\eta(f) \cdot g - f\eta(g)) - \eta(\xi(f) \cdot g - f\xi(g)) \\ &= \xi\eta f \cdot g + \eta f \cdot \xi g + \xi f \cdot \eta g + f\xi\eta g - \eta\xi f \cdot g - \xi f \cdot \eta g - \eta f \cdot \xi g - f\eta\xi g. \end{aligned}$$

The cross terms cancel, so this is

$$= ([\xi, \eta]f) \cdot g + f \cdot [\xi, \eta]g. \quad \square$$

This is in fact the same thing as the Lie derivative!

Proposition 7.9. Let $\xi, \eta \in \mathcal{X}(X)$.

- (1) The Lie bracket is the Lie derivative: $[\xi, \eta] = \mathcal{L}_{\xi} \eta$.
- (2) The Lie bracket is antisymmetric: $[\eta, \xi] = -[\xi, \eta]$.
- (3) (Jacobi identity)

$$[[\xi, \eta], \zeta] + [[\eta, \zeta], \xi] + [[\zeta, \xi], \eta] = 0.$$

(4)

$$[f\xi, g\eta] = fg[\xi, \eta] + f(\xi g)\eta - g(\eta f)\xi.$$

Parts (2) and (3) follow formally from properties of the commutator in an associative algebra, and parts (1) and (4) can be checked in local coordinates. This uses the fact that mixed partials commute, or for all i and j ,

$$\left[\frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j} \right] = 0.$$

So the Lie bracket vanishes for coordinate vector fields, but may not vanish in general, reflecting yet another obstruction to global parallelism; the Lie bracket measures the failure of vector fields to commute as derivations.

There are a couple of other forms of the Jacobi identity. Some of them say that $\mathcal{L}_\xi = [\xi, -]$ is a derivation, meaning it satisfies the Leibniz rule:

$$\mathcal{L}_\xi[\eta, \zeta] = [\mathcal{L}_\xi\eta, \zeta] + [\eta, \mathcal{L}_\xi\zeta].$$

Let $\xi, \eta \in \mathcal{X}(X)$, and let φ_t, ψ_s be their local flows. Consider flowing along a rectangle: t and s are small, and we flow by $\psi_{-s}\varphi_{-t}\psi_s\varphi_t$. That the Lie bracket isn't always zero means this flow might not get back to where it started.

Specifically, choose local coordinate x^1, \dots, x^n , and let $(t, s) \mapsto x^i(t, s)$ be the map sending $(t, s) \mapsto \psi_{-s}\varphi_{-t}\psi_s\varphi_t(p)$. This maps the rectangle into the manifold. The two axes (where $s = 0$ or $t = 0$) are collapsed onto p .

Proposition 7.10. *In this case,*

$$\mathcal{L}_\xi\eta(p) = \left. \frac{\partial^2 x^i}{\partial t \partial s} \right|_{s=0} \frac{\partial}{\partial x^i}.$$

Proof. The proof is, again, a calculation.

$$\left. \frac{\partial x^i}{\partial s} \frac{\partial}{\partial x^i} \right|_{s=0} = -\eta = (\varphi_{-t})_*\eta.$$

The first term is constant with respect to t , so disappears when we differentiate with respect to r , and the second term becomes $\mathcal{L}_\xi\eta(p)$ by the definition of the Lie derivative. \square

These computations aren't just a nuisance: there's lots of ways to think about them or to choose notation, and these choices of notation are particularly nice for not making mistakes, etc. They also demonstrate how to think about local coordinates.

Now, suppose ξ and η are complete (so the flow exists for all time), so we can make a global statement. Pushing forward a vector field along a map $X' \rightarrow X$ doesn't in general define a vector field: if the map isn't surjective, there's not a vector at every point, and if it's not injective, there may be multiple choices for the vector at a given point. If $\psi: X \rightarrow X$ is a diffeomorphism, however, you can push vector fields forward, and $\psi_*\xi$ generates the flow $\psi \circ \varphi_t \circ \psi^{-1}$. (This is a nice exercise using the existence and uniqueness of ODEs.) Thus, $\psi_*\xi = \xi$ iff $\psi\varphi_t\psi^{-1} = \varphi_t$ for all t , and therefore $(\varphi_s)_*\xi = \xi$ for all s iff $\psi_s\varphi_t\psi_{-s}\varphi_{-t} = \text{id}$ for all s and t . This is one direction of the following.

Proposition 7.11. $[\xi, \eta] = 0$ iff for all s and t , $\psi_s\varphi_t\psi_{-s}\varphi_{-t} = \text{id}$, where ψ_s and φ_t are the flows associated with η and φ , respectively.

The direction we didn't prove follows from observing that $[\eta, \xi] = \frac{d}{ds}(\psi_{-s})_*\xi = 0$. The situation in this proposition might hold more generally, however.

Definition 7.12. Let $\psi: X' \rightarrow X$ be a smooth map, $\xi' \in \mathcal{X}(X')$, and $\xi \in \mathcal{X}(X)$. Then, ξ' and ξ are ψ -related if $(\psi_*)_{p'}\xi'_{p'} = \xi_{\psi(p')}$ for all $p' \in X'$.

The consequence is that this preserves Lie bracket data.

Proposition 7.13. Suppose ξ' and ξ are ψ -related and η' and η are ψ -related. Then, $[\xi', \eta']$ and $[\xi, \eta]$ are ψ -related.

You can (and should) prove this yourself, using the formula for the Lie bracket as the commutator of the derivatives of the flows. This is part of a general principle, that to prove something about vector fields, it's useful to think of them as infinitesimally small curves. Alternatively, you could translate this into the language of derivations and prove it that way.

~ ~ ~

Another useful thing you can do with vector fields is use them to define local coordinate systems.

Theorem 7.14. Let $\xi \in \mathcal{X}(X)$ and $p \in X$ be such that $\xi_p \neq 0$. Then, there exists a local chart U containing p and local coordinates $(x^1, \dots, x^n): U \rightarrow X$ such that $\frac{\partial}{\partial x^1} = \xi$ on all of U .

Proof sketch. Let (y^1, \dots, y^n) be local coordinates about p such that p maps to the origin, so $y^i(p) = 0$, and $\frac{\partial}{\partial y^i} \Big|_p = \xi_p$. Let φ_t be the flow generated by ξ . Then, define

$$(7.15) \quad (x^1, \dots, x^n) \mapsto \varphi_{x^1}(0, x^2, \dots, x^n),$$

where on the right-hand side, the argument of φ_{x^1} is written in y^i -coordinates. Then, using y^i -coordinates, you can check that the differential at 0 is invertible. This means (7.15) defines a local coordinate system, and the computation will show that $\frac{\partial}{\partial x^i} = \xi$. \square

Now let's do this with multiple vector fields.

Theorem 7.16. *Let $k \leq \dim X$ and $\xi_1, \dots, \xi_k \in \mathcal{X}(X)$. If $\{\xi_1|_p, \dots, \xi_k|_p\}$ are linearly independent at a $p \in X$, then there exists a local chart U containing p and local coordinates $(x^1, \dots, x^n) : U \rightarrow X$ with $\frac{\partial}{\partial x^i} = \xi_i$ for $i = 1, \dots, k$ iff $[\xi_i, \xi_j] = 0$ for all $1 \leq i, j \leq k$.*

Proof sketch. Let y^1, \dots, y^n be local coordinates about p such that $y^i(p) = 0$ for all i and $\frac{\partial}{\partial y^i} \Big|_p = \xi_p$ for $i = 1, \dots, k$. Let $\varphi_t^{(i)}$ be the flow generated by ξ_i , and let

$$(x^1, \dots, x^n) \mapsto \varphi_{x^k}^{(k)} \cdots \varphi_{x^2}^{(2)} \varphi_{x^1}^{(1)}(0, \dots, 0, x^{k+1}, \dots, x^n).$$

Again, the argument of φ is in y^i -coordinates. Now, check that the differential is the identity (in y^i -coordinates) and $\frac{\partial}{\partial x^i} = \xi_i$ in the same way. However, this will use that $\varphi^{(i)}$ and $\varphi^{(j)}$ commute, which is true iff the Lie brackets vanish. \square

So defining a coordinate system through vector fields only works if they commute. Think back to Riemannian geometry: we studied surfaces by introducing special coordinates at each point, but we may not be able to promote this to an orthonormal frame. Being a coordinate system and being orthonormal are in tension, and what measures this tension is the Riemann curvature tensor.

You might want to generalize this to plane fields or hyperplane fields at a point instead of just vector fields. Then, you'll get integral manifolds, and this perspective can be useful to define maps between manifolds. Again, there will be a condition about commutators, encoded in a theorem due to Klebsch (and attributed to Frobenius).

Lecture 8.

Distributions and Foliations: 2/9/17

Today, we'll work through distributions, the local Frobenius theorem, foliations, and some other things preparing us for Lie groups. After that, we'll be able to return to Riemannian geometry. Throughout today's lecture, X is a smooth manifold.

Definition 8.1.

- (1) A *distribution* is a vector subbundle $E \subset TX \rightarrow X$.
- (2) If E is a distribution, a vector field $\xi \in \mathcal{X}(X)$ *belongs to* E if ξ is a section of $E \rightarrow X$, i.e. $\xi_p \in E_p$ for all $p \in X$.
- (3) E is *involutive* (or *integrable*) if whenever $\xi, \eta \in E$, $[\xi, \eta] \in E$ as well.
- (4) A submanifold $Y \subset X$ is an *integral manifold* of E if for all $p \in Y$, $T_p Y = E_p$.

You can think of a distribution as a hyperplane field at every point, distinguishing the directions in $T_p X$ that are contained in E_p . If ξ belongs to E , then at every point it's contained in the hyperplane defined at that point. So a distribution is first-order information for constructing a manifold: we've specified the tangent space, and want to find a curved manifold which satisfies it.

Proposition 8.2. *If $\text{rank } E = 1$, E is involutive.*

These E are also called *line fields*.

Proof. We can work locally: choose an open $U \subset X$ and a nonzero section e of $E|_U \rightarrow U$, so that any $\xi, \eta \in \Gamma(E|_U)$ can be written as $\xi = fe$ and $\eta = ge$ for $f, g \in \Omega_U^0$. Then, compute:

$$\begin{aligned} [\xi, \eta] &= [fe, ge] = fg[e, e] + f(e \cdot g)e - g(e \cdot f)e \\ &= [f(e \cdot g) - g(e \cdot f)]e, \end{aligned}$$

which is also a section of $E|_U$. □

Integral manifolds to line fields also exist: locally choose a nonvanishing ξ belonging to E and choose its integral curve.

Remark. However, not every line field admits a global nonvanishing section. Let X be the Möbius band, the total space of a line bundle $\pi: X \rightarrow S^1$ defined by gluing $\mathbb{R} \times [0, 1] \rightarrow [0, 1]$ with degree -1 . We'll let E be the copy of X inside the tangent bundle. That is, π is a submersion, so we have a short exact sequence of vector bundles

$$0 \longrightarrow T(X/S^1) \longrightarrow TX \longrightarrow \pi^*TS^1 \longrightarrow 0.$$

This has no natural splitting (splittings will be called covariant derivatives later). Since the fiber X/S^1 is a vector space V , then its tangent space at each $v \in V$ is identified with V again. We choose E to be this subspace of TX , and ultimately because the Möbius strip isn't orientable, E admits no global nonvanishing section. ◀

Example 8.3. Let $X = \mathbb{A}_{x,y,z}^3$ and

$$E := \text{span} \left\{ \frac{\partial}{\partial x}, \frac{\partial}{\partial y} + x \frac{\partial}{\partial z} \right\}.$$

Then, for any $(x_0, y_0, z_0) \in \mathbb{A}^3$, there's a piecewise smooth map γ from $(0, 0, 0)$ to (x_0, y_0, z_0) with $\dot{\gamma} \in E$. The idea is to zigzag from varying x to varying y and z .

However, E is not involutive:

$$\left[\frac{\partial}{\partial x}, \frac{\partial}{\partial y} + x \frac{\partial}{\partial z} \right] = \frac{\partial}{\partial z} \notin E. \quad \blacktriangleleft$$

Checking involutivity seems kind of hard, but there's a nice criterion. We know $\text{span}\{\frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^n}\}$ is involutive, and this turns out to be the key.

Theorem 8.4 (Local Frobenius). *Let $E \subset TX$ be a distribution of rank k .*

- (1) *E is involutive iff about every $p \in X$, there exist local coordinates x^1, \dots, x^n on some $U \subset X$ containing p such that*

$$(8.5) \quad E|_U = \text{span} \left\{ \frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^k} \right\}.$$

- (2) *If this is true, then any connected integral manifold $Y \subset U$ has the form $x^m = c^m$, for $m = k+1, \dots, n$, for some $c^{k+1}, \dots, c^n \in \mathbb{R}$.*

One can imagine a structure on a manifold which is an atlas only of charts satisfying (8.5). This is a geometric structure in the same way that a Riemannian metric is a geometric structure. Part (2) says that in this case, the integral manifolds are parallel to the $x^1 \cdots x^k$ -plane on U .

Proof. It suffices to prove the forward direction; the reverse direction is a computation. Choose local coordinates y^1, \dots, y^n about p such that

- (1) $y^i(p) = 0$ for each i ,
- (2) $y(U)$ has the form $-\varepsilon < y^i < \varepsilon$ for some $\varepsilon > 0$ (i.e. it's a cube),⁷ and
- (3) $E_p = \text{span} \left\{ \frac{\partial}{\partial y^1}, \dots, \frac{\partial}{\partial y^k} \right\}.$

⁷This is easy to accomplish: given any local coordinates, we can pick the open cube of side length ε around 0 and restrict y to it.

Let $\pi : \mathbb{A}^n \rightarrow \mathbb{A}^k$ be projection onto the first k coordinates; then, shrinking ε if necessary, $\pi_* : \mathbb{R}^n \rightarrow \mathbb{R}^k$ sends E_y isomorphically onto \mathbb{R}^k for all $y \in y(U)$. Let ξ_1, \dots, ξ_k be defined to satisfy $\pi_* \xi_i = \frac{\partial}{\partial y^i}$.

Now we have a basis ξ^1, \dots, ξ^k in E that is π_* -related to $\frac{\partial}{\partial y^i}$. In particular,

$$\pi_*[\xi_i, \xi_j] = \left[\frac{\partial}{\partial y^i}, \frac{\partial}{\partial y^j} \right] = 0.$$

If E is involutive, then we conclude that $[\xi_i, \xi_j] = 0$, so by Theorem 7.16, we can find local coordinates x^1, \dots, x^n (shrinking ε if necessary) such that $\frac{\partial}{\partial x^i} = \xi_i$ for $i = 1, \dots, k$. \square

This is a very geometric approach to a question originally motivated by systems of differential equations; involutivity is the analogue of mixed partials commuting.

The coordinate system guaranteed by Theorem 8.4 for an involutive E is called an *E-coordinate system* or a *slice*.

Example 8.6. Consider \mathbb{A}^2 and E be a one-dimensional constant distribution. Then, the integral submanifolds of \mathbb{A}^2 are the lines parallel to E . Quotient out by $\mathbb{Z}^2 \subset \mathbb{R}^2$ and let $X = \mathbb{A}^2/\mathbb{Z}^2$ be the torus. The integral manifolds project to integral submanifolds of the torus, but their structure depends on the embedding $\mathbb{Z}^2 \subset \mathbb{R}^2$.

If the images of $(1,0)$ and $(0,1)$ are related by rational numbers, then each integral manifold has finite length and closes up to a circle. For example, it could be a circle that traverses each direction of the torus once, or more than once. If the integral manifolds traverse one direction p times and the other q times, this characterizes the homology class $(p,q) \in H_1(\mathbb{A}^2/\mathbb{Z}^2) \cong \mathbb{Z}^2$. This is a *foliation*, and the integral submanifolds are called *leaves*. In this case, the quotient space parameterizing the leaves is a manifold, specifically S^1 .

If instead the images of $(1,0)$ and $(0,1)$ aren't related by rational numbers, then each integral manifold has infinite length, and is in fact dense in the torus! So we get an immersed submanifold, not an embedded one. This is a more pathological case, and is one of the reasons we require manifolds to be second countable. The quotient space is still a topological space, but not Hausdorff. \blacktriangleleft

Example 8.7. The *Hopf fibration* is a map $\pi : S^3 \rightarrow S^2$. Identify S^3 as the unit sphere in \mathbb{C}^2 , the set $\{(\tilde{\zeta}^1, \tilde{\zeta}^2) \in \mathbb{C}^2 \mid |\tilde{\zeta}^1|^2 + |\tilde{\zeta}^2|^2 = 1\}$. Then, identify $S^2 = \mathbb{CP}^1$, the space of 1-dimensional subspaces in \mathbb{C}^2 . The Hopf fibration sends an $x \in S^2$ to the line containing it.

Each fiber of π is a circle $S^1 \subset S^3$, which is actually unknotted. Thinking of $S^3 = \mathbb{A}^3 \cup \{*\}$, there's one fiber which is a straight line, and the rest are circles winding around this line. Any two circular fibers are linked with linking number 1. There's a distribution $E = \ker \pi_* \subset TS^3$. The fibers of the Hopf fibration are integral manifolds for E . \blacktriangleleft

The leaf space of a foliation is sometimes a manifold, but not always; in fact, it's an example of a *noncommutative space*, a significant example in Alain Connes' noncommutative geometry.

Definition 8.8. A *k-dimensional foliation* on X is a decomposition of X as

$$X = \coprod_{\alpha \in A} \mathcal{F}_\alpha,$$

where each \mathcal{F}_α is a k -dimensional immersed submanifold, such that for every $p \in X$, there exist local coordinates x^1, \dots, x^n on a $U \subset X$ such that $\mathcal{F}_\alpha \cap U$ is a union of slices $x^m = c^m$ (for $m = k+1, \dots, n$). These \mathcal{F}_α are called the *leaves* of the foliation \mathcal{F} .

The *tangent bundle* to a foliation \mathcal{F}_α is

$$T\mathcal{F} := \coprod_{p \in X} T_p \mathcal{F}_{\alpha(p)},$$

where $p \in \mathcal{F}_{\alpha(p)}$.

$T\mathcal{F} \rightarrow X$ is locally trivial; in particular, it's a vector bundle. Foliations are a richly studied subject.

Theorem 8.9. Let $E \subset TX$ be an involutive distribution. Then, there exists a foliation \mathcal{F} such that $T\mathcal{F} = E$. In particular, the leaves are maximal integral manifolds for E , and there is a unique such maximal integral submanifold through every point.

So this is the solution to the differential equation that E defines; rather than solve it at each point, we solve it at all points at once.

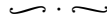
We will often only need one leaf when we apply this, but the full generality of the theorem is too beautiful to pass up.

Proof sketch of Theorem 8.9. Second-countability of X is important in this theorem: we cover X by a sequence of charts U_1, U_2, \dots of E -coordinate systems. If $S \subset U_i$ is a slice, then $\pi_0(S \cap U_j)$ is either empty, finite, or countably infinite.

Introduce an equivalence relation on slices where $S \subset U_i$ and $T \subset U_j$ are equivalent if there's a finite sequence $i_0 = i, i_1, i_2, \dots, i_N = j$ and slices $S_{i_j} \subset U_{i_j}$ such that $S_{i_j} \cap S_{i_{j+1}} \neq \emptyset$, $S_0 = S$, and $S_N = T$. Let \mathcal{F}_α be the union of the slices S in an equivalence class; these will be the leaves in the foliation.

Clearly $\{\mathcal{F}_\alpha\}$ is a decomposition of X into a disjoint union of pieces, but we need each inclusion map $\mathcal{F}_\alpha \rightarrow X$ to be an immersion, which is data. The construction we've defined already does this: it's covered by these U_{i_j} . Then, since there's only countably many charts, \mathcal{F}_α must be second countable. \square

This implies the distribution in Example 8.3 isn't involutive: we saw how to get from the origin to any point, but if it were involutive, there would have to be a foliation, and there would be no way to travel between different leaves in a foliation.



We'll now pass to something more formal, which involves functions on X . This involves drawing fewer pictures, which is maybe a little unfortunate, but the calculations we can make are useful.

Let Ω_X^\bullet denote the algebra of differential forms on X , which is a \mathbb{Z} -graded algebra, graded by

$$\Omega_X^\bullet = \bigoplus_{k \in \mathbb{Z}} \Omega_X^k.$$

The algebra structure is wedge product: $\alpha, \beta \mapsto \alpha \wedge \beta$. It's commutative, in the sense of a \mathbb{Z} -graded algebra: if α and β are homogeneous elements of degrees $|\alpha|$, resp. $|\beta|$, then

$$(8.10) \quad \alpha \wedge \beta = (-1)^{|\alpha||\beta|} \beta \wedge \alpha.$$

This is called the *Koszul sign rule*.

Definition 8.11. Let A^\bullet be a commutative (meaning (8.10) holds) \mathbb{Z} -graded algebra and $T: A^\bullet \rightarrow A^\bullet$. T is a *derivation* if it's a linear map of degree s^8 and T satisfies the Leibniz rule

$$T(\alpha \wedge \beta) = T\alpha \wedge \beta + (-1)^{s|\alpha|} \alpha \wedge T\beta.$$

Example 8.12.

- (1) The *Cartan-de Rham differential* $d: \Omega_X^\bullet \rightarrow \Omega_X^{\bullet+1}$ is a derivation of degree 1.
- (2) Let $\xi \in \mathcal{X}(X)$. If $\alpha \in \Omega_X^\bullet$ and ξ generates the flow φ_t , then the Lie derivative is a derivation of degree 0. This boils down to it satisfying the Leibniz rule: to verify this, use the fact that the pullback commutes with wedge product:

$$\varphi_t^*(\alpha \wedge \beta) = \varphi_t^*\alpha \wedge \varphi_t^*\beta.$$

Now, you can differentiate this with the usual Leibniz rule. There's no sign here, but that's okay, because the degree is 0. \triangleleft

Given a vector field ξ , there's a derivation of degree -1 called contraction ι_ξ , which can be defined somewhat algebraically. We'll talk about this next time; so we now have three operators on differential forms of degrees 1, 0, and -1 ; under Lie bracket, we get some interesting relations between them, namely

$$\mathcal{L}_\xi = [d, \iota_\xi].$$

There's one more operation on differential forms, integration over the fiber in the context of a fiber bundle. If you know all the brackets between these four operators, you can recover the calculus of differential forms and therefore calculus in the usual sense on X .

⁸A linear map of \mathbb{Z} -graded algebras has *degree* s if it sends homogeneous elements of degree n to homogeneous elements of degree $n + s$ for all $n \in \mathbb{Z}$.

Lecture 9.

Lie algebras and Lie groups: 2/14/17

Let $A = \bigoplus_{n \in \mathbb{Z}} A_n$ be a \mathbb{Z} -graded algebra. (That is, multiplication sends $A_m \cdot A_n$ into A_{m+n} .) For example, if V is a real vector space, $\Lambda^\bullet V$ is a commutative \mathbb{Z} -graded algebra, because we specified commutativity by the Koszul sign rule

$$z \wedge w = (-1)^{|z||w|} w \wedge z.$$

Last time, we defined a derivation of degree d to be a linear map $T : A \rightarrow A$ of degree d (so $A_n \rightarrow A_{n+d}$ on homogeneous elements) such that

$$T(\alpha \wedge \beta) = T\alpha \wedge \beta + (-1)^{|T||\alpha|} \alpha \wedge T\beta.$$

Definition 9.1. Let V be a vector space and $\zeta \in V$. Define $\iota_\zeta : \Lambda^k V^* \rightarrow \Lambda^{k-1} V^*$ by

$$(\iota_\zeta \alpha)(\zeta_2, \dots, \zeta_k) := \alpha(\zeta, \zeta_2, \zeta_3, \dots, \zeta_k).$$

This is called *contracting with the first index*.

There is a natural identification $\Lambda^k V^*$ with $(\Lambda^k V)^*$ defined through a pairing $\Lambda^k V^* \otimes \Lambda^k V \rightarrow \mathbb{R}$ sending

$$\alpha_1 \wedge \dots \wedge \alpha_k \otimes \zeta_1, \dots, \zeta_k \longmapsto \det(\alpha_i(\zeta_j)_{i,j}),$$

for $\alpha_i \in V^*$ and $\zeta_j \in V$.

Proposition 9.2.

- (1) ι_ζ is adjoint to left exterior multiplication $\varepsilon_\zeta : \Lambda^{k-1} V \rightarrow \Lambda^k V$, the map sending $z \mapsto \zeta \wedge z$.
- (2) $\iota_\zeta : \Lambda^\bullet V^* \rightarrow \Lambda^\bullet V^*$ is a derivation of degree -1 .
- (3) If $\zeta, \eta \in V$, then $\iota_\zeta \iota_\eta + \iota_\eta \iota_\zeta = 0$.

If we define the *commutator* of $a, b \in A$ to be

$$[a, b] := ab - (-1)^{|a||b|} ba,$$

then (3) can be restated as $[\iota_\zeta, \iota_\eta] = 0$. For any odd-degree element a , $[a, a] = 2a^2$.

In a basis, $\zeta = \zeta^i e_i$ and

$$\alpha = \frac{1}{k!} \alpha_{i_1 \dots i_k} e^{i_1} \wedge \dots \wedge e^{i_k},$$

so that contraction is

$$\iota_\zeta \alpha = \frac{1}{(k-1)!} \zeta^i \alpha_{i i_2 \dots i_k} e^{i_2} \wedge \dots \wedge e^{i_k}.$$

Proof sketch of Proposition 9.2. Part (1) is immediate from the definition.

For part (2), let $\alpha_1, \dots, \alpha_{k+\ell} \in V^*$, let $\alpha = \alpha_1 \wedge \dots \wedge \alpha_k$ and $\beta = \alpha_{k+1} \wedge \dots \wedge \alpha_{k+\ell}$. Then,

$$\iota_{\zeta_1}(\alpha \wedge \beta)(\zeta_2 \wedge \dots \wedge \zeta_{k+\ell}) = \det(\alpha_i(\zeta_j)),$$

and you can finish the proof by expanding along $j = 1$.

For part (3),

$$(\iota_\zeta \iota_\eta \alpha)(z) = \iota_\eta \alpha(\zeta \wedge z) = \alpha(\eta \wedge \zeta \wedge z).$$

$$(\iota_\eta \iota_\zeta \alpha)(z) = \iota_\zeta \alpha(\eta \wedge z) = \alpha(\zeta \wedge \eta \wedge z) = -\alpha(\eta \wedge \zeta \wedge z). \quad \square$$

Now suppose X is a smooth manifold and $\zeta \in \mathcal{X}(X)$. Then, $\iota_\zeta : \Omega_X^\bullet \rightarrow \Omega_X^{\bullet-1}$ defined pointwise is a derivation of degree -1 . Now we have three kinds of derivations on differential forms: d has degree 1, ι_ζ has degree -1 , and \mathcal{L}_ζ has degree 0.

The vector space of derivations on Ω_X^\bullet is closed under commutators, so it's worth asking what derivations we obtain from commutators of our three amigos. By symmetry, there are six ones to consider.

Theorem 9.3.

- $[\iota_\zeta, \iota_\eta] = 0$.
- $[\mathcal{L}_\zeta, \iota_\eta] = \iota_{[\zeta, \eta]}$.
- $[d, \iota_\eta] = \mathcal{L}_\eta$ (the Cartan formula).

- $[\mathcal{L}_{\xi}, \mathcal{L}_{\eta}] = \mathcal{L}_{[\xi, \eta]}$.
- $[\mathcal{L}_{\xi}, d] = 0$.
- $[d, d] = 0$.

Some of these we've proven before; others are new, but can be computed from the definitions. You can quickly check that the degree of a commutator is the sum of the degrees of its two arguments.

The calculations above are in a sense generators and relations for a \mathbb{Z} -graded Lie algebra (with the Koszul sign rule).

Definition 9.4. A *Lie algebra* is a (real) vector space \mathfrak{g} together with a bilinear form $[-, -]: \mathfrak{g} \times \mathfrak{g} \rightarrow \mathfrak{g}$ such that $[\xi, \eta] = -[\eta, \xi]$ and the *Jacobi identity* holds:

$$[[\xi, \eta], \zeta] + [[\eta, \zeta], \xi] + [[\zeta, \xi], \eta] = 0$$

for all $\xi, \zeta, \eta \in \mathfrak{g}$.

To define a graded Lie algebra, one must insert signs corresponding to the Koszul sign rule, e.g. the bracket satisfies

$$[\xi, \eta] = (-1)^{|\xi||\eta|} [\eta, \xi],$$

and there are additional signs in the graded Jacobi identity.

The commutation relations either follow directly or have been already proven, except for the second and third ones. Let's prove those. To check that two derivations on Ω_X^\bullet agree, it suffices to check on Ω_X^0 and $d\Omega_X^0$, since every element of Ω_X^\bullet is (locally) a sum of wedges of these forms, and the Leibniz rule behaves the same for both derivations.

Let's prove that $[\mathcal{L}_{\xi}, \iota_{\eta}] = \iota_{[\xi, \eta]}$. If $f \in \Omega_X^0$, the right-hand side is 0 and the left-hand side is

$$[\mathcal{L}_{\xi}, \iota_{\eta}]f = -\iota_{\eta}\mathcal{L}_{\xi}f = 0.$$

Now let's check on df :

$$\begin{aligned} [\mathcal{L}_{\xi}, \iota_{\eta}]df &= \mathcal{L}_{\xi}\iota_{\eta}df - \iota_{\eta}\mathcal{L}_{\xi}df \\ &= \mathcal{L}_{\xi}(\eta \cdot f) - \iota_{\eta}d\mathcal{L}_{\xi}f \\ &= \xi\eta \cdot f - \eta\xi \cdot f \\ &= \iota_{[\xi, \eta]}df. \end{aligned}$$

The Cartan formula is proved in a similar manner.

Corollary 9.5. Let $\alpha \in \Omega_X^1$ and $\xi, \eta \in \mathcal{X}(X)$. Then,

$$d\alpha(\xi, \eta) = \xi \cdot \alpha(\eta) - \eta \cdot \alpha(\xi) - \alpha([\xi, \eta]).$$

This is a very useful formula, and sometimes is used to define d !

Proof.

$$\begin{aligned} d\alpha(\xi, \eta) &= \iota_{\eta}\iota_{\xi}d\alpha \\ &= -\iota_{\eta}d\iota_{\xi}\alpha + \iota_{\eta}\mathcal{L}_{\xi}\alpha \\ &= -\eta \cdot \alpha(\xi) + \mathcal{L}_{\xi}\iota_{\eta}\alpha - \iota_{[\xi, \eta]}\alpha \\ &= -\eta \cdot \alpha(\xi) + \xi \cdot \alpha(\eta) - \alpha([\xi, \eta]). \end{aligned}$$

□

Let X be a smooth manifold and $E \subset TX$ be a distribution as last time. Let

$$\mathcal{I}(E) := \{\alpha \in \Omega_X^\bullet : \alpha|_E = 0\}.$$

That is, $\mathcal{I}(E)$ is the annihilator of E . For example, on \mathbb{A}^3 , if

$$E = \text{span}\left\{\frac{\partial}{\partial x}, \frac{\partial}{\partial y} + x\frac{\partial}{\partial z}\right\},$$

$$\mathcal{I}(E) = \text{span}\{x dy - dz\}.$$

Lemma 9.6. $\mathcal{I}(E)$ is closed under d iff E is involutive.

We defined integrability in terms of vector fields, and the dual condition on differential forms is a little simpler. The key step in the proof is showing that if ξ and η belong to E and $\alpha \in \Omega_X^1 \cap \mathcal{I}(E)$, Corollary 9.5 shows that

$$d\alpha(\xi, \eta) = \xi \cdot \alpha(\eta) - \eta \cdot \alpha(\xi) - \alpha([\xi, \eta]) = -\alpha([\xi, \eta]).$$

In the example, it's easy to check that E isn't involutive: $d(x dy - dz) = dx \wedge dy \notin \mathcal{I}(E)$.

~ . ~

Let's talk about Lie groups.

Definition 9.7. A Lie group G is a smooth manifold equipped with a group structure such that multiplication $G \times G \rightarrow G$ and inversion $G \rightarrow G$ are smooth.

Like many definitions in mathematics, this is a marriage of two structures, with compatibility conditions (the group structure is smooth). There should be a compatibility condition for the identity, that inclusion of the identity is smooth, but this follows automatically for manifolds. It is needed for defining topological groups more generally, however.

Example 9.8. We have already seen many examples of Lie groups.

- If V is a finite-dimensional, real vector space, $(V, +)$ is an abelian Lie group.
- $GL(V) = \text{Aut}(V)$ is a Lie group, in general nonabelian. If $V = \mathbb{R}^n$, $GL(\mathbb{R}^n)$ is called $GL_n(\mathbb{R})$, and is the group of invertible $n \times n$ matrices. As a manifold, it's an open subset of the space of all $n \times n$ matrices (inversion is the preimage of an open subset of \mathbb{R} under a polynomial, hence smooth, map).
- If V has an inner product, we can look at its orthogonal group $O(V)$. If $V = \mathbb{R}^n$ and the inner product is standard, this is called O_n .
- If A is an affine space modeled on V , then the group of affine transformations $\text{Aff}(A)$ is a Lie group, and fits into a short exact sequence of Lie groups

$$1 \longrightarrow V \longrightarrow \text{Aff}(A) \longrightarrow GL(V) \longrightarrow 0.$$

Similarly, if E is a Euclidean space modeled on V , the Euclidean transformations $\text{Euc}(E)$ form a Lie group. If $A = \mathbb{A}^n$, $\text{Aff}(\mathbb{A}^n)$ is denoted Aff_n , and similarly $\text{Euc}(\mathbb{E}^n)$ is called Euc_n . ◀

Observe that on any manifold X , $\mathcal{X}(X)$ is a Lie algebra under Lie bracket, but it's infinite-dimensional, which makes life hairy.

Lie groups have extra geometric structure: the identity is a distinguished point, and there are distinguished symmetries given by left and right multiplication and conjugation: for each $g \in G$, let

- $L_g: G \rightarrow G$ send $x \mapsto gx$,
- $R_g: G \rightarrow G$ send $x \mapsto xg$, and
- $A_g: G \rightarrow G$ send $x \mapsto gxg^{-1}$.

Definition 9.9.

- Let $\xi \in \mathcal{X}(G)$ be a vector field. Then, ξ is *left-invariant* if $(L_g)_*\xi = \xi$ for all $g \in G$.
- Let $\alpha \in \Omega_G^\bullet$ be a differential form. Then, α is *right-invariant* if $(L_g)^*\alpha = \alpha$ for all $g \in G$.

In the same way, one can define left-invariance of Riemannian metrics, etc. Replacing L_g with R_g defines *right-invariance* of vector fields, forms, etc. And requiring invariance under any two of L_g , R_g , and A_g forces invariance under the third, and this is called *bi-invariance*.

Since the differential of L_g is an isomorphism (since $L_{g^{-1}}$ is an inverse), then G acts on G transitively by left multiplication. This means in particular the dimension of G is constant (on arbitrary manifolds, such as $S^1 \amalg S^2$, the dimension is only locally constant).

Definition 9.10. Let G be a Lie group. Then, its Lie algebra $\mathfrak{g} \subset \mathcal{X}(G)$ is the subspace of left-invariant vector fields on G .

Evaluation at the identity defines a linear map $\text{ev}_e: \mathfrak{g} \rightarrow T_e G$, sending $\xi \mapsto \xi|_e$. This map is an isomorphism, so $\dim \mathfrak{g} = \dim G$.

Proposition 9.11. \mathfrak{g} is closed under $[-, -]$.

Proof. Let $\xi, \eta \in \mathfrak{g}$ and $g \in G$. Since ξ is left-invariant, it's L_g -related to itself, and similarly for η . We showed in Proposition 7.13 that if ξ and ξ' are related under ψ and η and η' are related under ψ , then so are $[\xi, \eta]$ and $[\xi', \eta']$. Thus, for our ξ and η , $[\xi, \eta]$ is L_g -related to itself for all g , hence is L_g -invariant. \square

In a very weak sense, the bracket is dual to d , so let's see what the corresponding statement is for differential forms.

Proposition 9.12. *The subspace $(\Omega_G^\bullet)^G$ of left-invariant forms is closed under d .*

Proof. Let $\omega \in (\Omega_G^\bullet)^G$, i.e. $L_g^*\omega = \omega$ for all $g \in G$. Then, by the commutation relations,

$$L_g^*d\omega = dL_g^*\omega = d\omega. \quad \square$$

Observe that evaluation at the identity defines a map

$$\text{ev}_e: (\Omega_G^\bullet)^G \longrightarrow \Lambda^\bullet T_e^*G = \Lambda^\bullet \mathfrak{g}^*.$$

Thus one obtains a complex

$$(9.13) \quad 0 \longrightarrow \mathfrak{g} \xrightarrow{d} \Lambda^2 \mathfrak{g}^* \xrightarrow{d} \Lambda^3 \mathfrak{g}^* \longrightarrow \dots$$

The map $d: \mathfrak{g} \rightarrow \Lambda^2 \mathfrak{g}^*$ can be computed with Corollary 9.5 to be the map

$$(9.14) \quad \alpha \longmapsto (\xi, \eta \longmapsto -\alpha([\xi, \eta])).$$

But this makes sense for any abstract Lie algebra, whether or not it came from G , and so one could define the complex (9.13) through the map (9.14). In this way one can talk about Lie algebra cohomology.

Suppose that ξ_1, \dots, ξ_n is a basis for \mathfrak{g} , so that there exist $C_{jk}^i \in \mathbb{R}$ such that

$$[\xi_j, \xi_k] = C_{jk}^i \xi_i.$$

These are called the *structure constants* for \mathfrak{g} in this basis. Skew-symmetry implies that $C_{jk}^i + C_{kj}^i = 0$, and there's a similar formula that comes from the Jacobi identity.

Exercise 9.15. Suppose that $\theta^1, \dots, \theta^n$ is the dual basis to ξ_1, \dots, ξ_n for $\mathfrak{g}^* \subset \Omega_G^1$. Show that

$$d\theta^i + \frac{1}{2}C_{jk}^i \theta^j \wedge \theta^k = 0.$$

If $\theta := \theta^i \xi_i \in \Omega_G^1(\mathfrak{g})$, then θ does not depend on the choice of basis, coming from $\mathfrak{g}^* \otimes \mathfrak{g} \cong \text{End}(\mathfrak{g})$ (as vector spaces): θ maps to $\text{id}_{\mathfrak{g}}$. This θ is a canonical 1-form that restricts to the form corresponding to the identity at each point; θ is called the *Maurer-Cartan 1-form*.

Proposition 9.16. *θ satisfies the Maurer-Cartan equation*

$$(9.17) \quad d\theta + \frac{1}{2}\theta \wedge \theta = 0.$$

Lecture 10.

The Maurer-Cartan form: 2/16/17

Let's continue where we left off, letting G be a Lie group. There are a lot of nice facts about Lie groups, some of which are homework problems (e.g. using the inverse function theorem to prove that if multiplication is smooth, inversion is automatically smooth). The Lie algebra of G , denoted \mathfrak{g} , is the Lie algebra of left-invariant vector fields on G . We also defined a \mathfrak{g} -valued 1-form $\theta \in \Omega_G^1(\mathfrak{g})$, called the Maurer-Cartan 1-form.

If G is a Lie group, the path component of the identity G_e is a subgroup: for any $g, h \in G_e$, there's a path through the identity to g and one from the identity to h , so since multiplication is continuous, we get a path from g to gh . Moreover, all components are diffeomorphic: left translation $L_g: G_e \xrightarrow{\cong} g \cdot G_e$ defines a diffeomorphism from G_e to the component of G containing g . Many Lie groups that we care about aren't connected, e.g. the orthogonal groups O_n and the general linear groups $GL_n(\mathbb{R})$, as well as any nontrivial finite group.

The Maurer-Cartan equation (9.17) encodes a lot of structure about G . For example, if ξ_1, \dots, ξ_n is a basis of \mathfrak{g} and $\theta = \theta^i \xi_i$, so $\theta^i \in \Omega_G^1$ is an ordinary 1-form, then

$$[\theta \wedge \theta] = [\theta^i \xi_i \wedge \theta^j \xi_j] = \theta^i \wedge \theta^j [\xi_i, \xi_j].$$

Proof of Proposition 9.16. We'll compute at $x \in G$, evaluating on $\xi_x, \eta_x \in T_x G$. We can extend them to left-invariant vector fields ξ, η on G ; since the Maurer-Cartan equation is tensorial, its truth or falsity doesn't depend on the choice of extension. Then,

$$\begin{aligned} d\theta_x[\xi_x, \eta_x] &= \xi_x \cdot \theta(\eta) - \eta_x \cdot \theta(\xi) - \theta_x([\xi, \eta]_x) \\ &= -\theta_x([\xi, \eta]_x) = -[\xi, \eta]_x. \\ \frac{1}{2}[\theta \wedge \theta]_x(\xi_x, \eta_x) &= \frac{1}{2}([\theta_x(\xi_x), \theta_x(\eta_x)] - [\theta_x(\eta_x), \theta_x(\xi_x)]) \\ &= [\theta_x(\xi_x), \theta_x(\eta_x)] \\ &= [\xi, \eta]_x. \end{aligned} \quad \square$$

It's locally possible to get from the Lie algebra to the Lie group.

Definition 10.1. If $\xi \in \mathfrak{g}$, then there's a unique integral curve $\gamma_\xi(t)$ such that $\gamma_\xi(0) = e$ and $\dot{\gamma}_\xi(0) = \xi$. Define $\exp: \mathfrak{g} \rightarrow G$ by

$$\exp \xi := \gamma_\xi(1).$$

That is, flow along the curve in the direction of ξ for time 1. In particular, $\gamma_\xi(t) = \exp(t\xi)$, which will also be written $e^{t\xi}$. You can check that the integral curve with initial position $x \in G$ is $t \mapsto xe^{t\xi}$, so the flow φ_t generated by ξ is $\varphi_t = R_{e^{t\xi}}$, i.e. right translation by $\exp(t\xi)$.

A lot of Lie groups arise as matrix groups, in which the exponential map is just the matrix exponential.

Example 10.2. The *general linear group* $GL_n(\mathbb{R})$ is the group of $n \times n$ invertible matrices. This is an open condition in all $n \times n$ matrices, since it's asking the determinant to be nonzero, so this is a Lie group. Inclusion defines a canonical function $g: G \hookrightarrow M_n(\mathbb{R})$. \triangleleft

Since $GL_n(\mathbb{R})$ is an open subset of the vector space $M_n(\mathbb{R})$, then its Lie algebra $\mathfrak{gl}_n(\mathbb{R})$ can be canonically identified with $M_n(\mathbb{R})$.

Theorem 10.3. For $G = GL_n(\mathbb{R})$,

- (1) the Lie bracket on $\mathfrak{gl}_n(\mathbb{R}) = M_n(\mathbb{R})$ is $[A, B] = AB - BA$,
- (2) the exponential is the matrix exponential $\exp: M_n(\mathbb{R}) \rightarrow GL_n(\mathbb{R})$ defined by

$$e^A = I + A + \frac{A^2}{2!} + \dots,$$

- (3) and the Maurer-Cartan form is

$$\theta = g^{-1} dg.$$

As most Lie groups we think about are matrix groups, hence subgroups of $GL_n(\mathbb{R})$ for some n , this makes all of these notions nicely concrete, and Theorem 10.3 holds for them too.

Proof sketch of Theorem 10.3. For (2), first prove that for an $A \in M_n(\mathbb{R})$, the function

$$f(t) := I + tA + \frac{(tA)^2}{2!} + \dots + \frac{(tA)^N}{N!} + \dots$$

converges, and then differentiate term-by-term to show that $\dot{f}(t) = f(t) \cdot A$, which is what we needed.

For (1), the flow generated by ξ_A is $\varphi_t := R_{e^{tA}}$ and for ξ_B it's $\psi_s := R_{e^{sB}}$. Thus,

$$\begin{aligned} [\xi_A, \xi_B]_I &= \frac{\partial^2}{\partial s \partial t} \Big|_{s,t=0} \psi_{-s} \varphi_{-t} \psi_s \varphi_t(I) \\ &= \frac{\partial^2}{\partial s \partial t} \Big|_{s,t=0} e^{tA} e^{sB} e^{-tA} e^{-sB} \\ &= \frac{\partial^2}{\partial s \partial t} \Big|_{s,t=0} (I + tA)(I + sB)(I - tA)(I - sB) \\ &= AB - BA. \end{aligned}$$

The calculation of the Maurer-Cartan form comes directly from its definition. \square

The Maurer-Cartan equation $d\theta + \theta \wedge \theta = 0$ turns into matrix multiplication for G a matrix group; in particular, if θ_j^i denotes the coefficients of the matrix θ in some basis, then matrix multiplication in coordinates implies that

$$d\theta_j^i + \theta_k^i \wedge \theta_j^k = 0.$$

This will be important to us.

Example 10.4. Let's compute the Maurer-Cartan form for Aff_n . The trick is to embed $\text{Aff}_n \hookrightarrow \text{GL}_{n+1}(\mathbb{R})$ as follows: any affine transformation is of the form $x \mapsto Mx + \xi$ for some $M \in \text{GL}_n(\mathbb{R})$ and $\xi \in \mathbb{R}^n$, so it can be represented in $\text{GL}_{n+1}(\mathbb{R})$ as the block matrix

$$\begin{pmatrix} M & \xi \\ 0 & 1 \end{pmatrix},$$

which acts on $x = (x^1, \dots, x^n, 1)$. In other words, looking at the line $\{x^{n+1} = 1\}$ in \mathbb{R}^{n+1} recovers \mathbb{A}^n and Aff_n .

Therefore the Lie algebra also embeds: $\mathfrak{aff}_n \hookrightarrow \mathfrak{gl}_{n+1}(\mathbb{R}) = M_{n+1}(\mathbb{R})$: the affine Lie algebra consists of transformations $x \mapsto Mx + \xi$ where M need not be invertible, and this is sent to the matrix

$$\begin{pmatrix} M & \xi \\ 0 & 0 \end{pmatrix}.$$

With this embedding, the Maurer-Cartan form is

$$\begin{pmatrix} \theta_j^i & \theta^i \\ 0 & 0 \end{pmatrix},$$

and the equations of matrix multiplication inform us that

$$\begin{aligned} d\theta^i + \theta_j^i \wedge \theta^j &= 0 \\ d\theta_j^i + \theta_k^i \wedge \theta_j^k &= 0. \end{aligned} \quad \blacktriangleleft$$

Example 10.5. For curvd space, we care about the orthogonal group $O_n \hookrightarrow M_n(\mathbb{R})$ of orthogonal $n \times n$ matrices, those matrices M such that $M^T M = I$. The Lie algebra \mathfrak{o}_n is the vector space of skew-symmetric matrices, i.e. $M^T + M = 0$. In this case, the Maurer-Cartan form satisfies

$$\theta_j^i + \theta_i^j = 0. \quad \blacktriangleleft$$

Similarly, we can embed $\text{Euc}_n \hookrightarrow M_{n+1}(\mathbb{R})$ through the embedding $\text{Euc}_n \hookrightarrow \text{Aff}_n \hookrightarrow \text{GL}_{n+1}(\mathbb{R}) \hookrightarrow M_{n+1}(\mathbb{R})$, and obtain its Maurer-Cartan formula in that way. The same is true for the *conformal group* $\text{CO}_n \subset \text{GL}_n(\mathbb{R})$ of matrices M such that $\langle M\xi, M\eta \rangle = c\langle \xi, \eta \rangle$ for some $c > 0$ and all $\xi, \eta \in \mathbb{R}^n$. You can play the same game for any kind of geometric structure: symplectic geometry with the symplectic group, spin geometry with the spin group, and so forth.

The adjoint action. Let $g \in G$. Then, the conjugation action $A_g = L_g \circ R_{g^{-1}} = R_{g^{-1}} \circ L_g$ sends $x \mapsto gxg^{-1}$. Therefore A defines a map $G \rightarrow \text{Aut}(G)$.

Definition 10.6. Identifying $\mathfrak{g} \cong T_e G$, the *adjoint action* $\text{Ad}_g \in \text{End}(\mathfrak{g})$ is defined by $\text{Ad}_g = d(A_g)_e$.

Lemma 10.7.

- (1) The adjoint action preserves the Lie algebra, hence is a Lie algebra endomorphism.
- (2) The differential of $\text{Ad}: G \rightarrow \text{Aut}(\mathfrak{g})$ (sending $g \mapsto A_g$) at the identity is

$$d\text{Ad}_g|_e(\xi) = [\xi, -].$$

The Maurer-Cartan form behaves nicely under the left and right actions.

Proposition 10.8. In $\Omega_G^1(\mathfrak{g})$, $L_g^* \theta = \theta$, but $R_g^* \theta = \text{Ad}_{g^{-1}} \theta$.

These equations are simple, but will come up again.

Proof. Let $x \in G$, so that if $\xi_x \in T_x G$,

$$(R_g^* \theta)_x(\xi_x) = \theta_{xg}(R_{g*} \xi_x).$$

Let ξ be a left-invariant extension of $\xi_x = \theta_x(\xi_x)$. Then, at the identity,

$$\begin{aligned} (R_g^* \theta)_x(\xi_x) &= \left. \frac{d}{dt} \right|_{t=0} \theta_{xg}(xe^{t\xi}g) \\ &= \left. \frac{d}{dt} \right|_{t=0} (xg)^{-1}(xe^{t\xi}g) \\ &= \left. \frac{d}{dt} \right|_{t=0} g^{-1}e^{t\xi}g \\ &= \text{Ad}_{g^{-1}} \xi. \end{aligned}$$

□

We've met the Maurer-Cartan form on groups, but it will also arise on G -torsors. This is an instance of the notion that left-invariant objects on G extend to right G -torsors, and right-invariant objects extend to left torsors.

Recall that a *right G -torsor* G is a manifold with a simply transitive right action $T \times G \rightarrow T$, sending $t, g \mapsto t \cdot g$, so the map $T \times G \rightarrow T \times T$ sending $t, g \mapsto t, t \cdot g$ is a diffeomorphism.

Torsors are like groups with multiplication but no preferred origin. Examples include affine space \mathbb{A}^n , a torsor over \mathbb{R}^n ; and $\mathcal{B}(V)$, the space of bases for a vector space V , which is a $\text{GL}(V)$ -torsor.

If $t \in T$, $\varphi_t: GT \rightarrow T$ sending $g \mapsto t \cdot g$ is a diffeomorphism, in fact an isomorphism of right G -torsors. If I have two of these, φ_{t_0} and φ_{t_1} , then the map $\varphi_{t_1}^{-1} \circ \varphi_{t_0}: G \rightarrow G$ is a right-invariant diffeomorphism, and in fact is left multiplication by some $h \in G$, such that $t_1(hg) = t_0g$ for all $g \in G$; in particular, $t_0 = t_1h$. This means that the Maurer-Cartan form, which is left-invariant, can be pulled back along some (well, any) φ_t^{-1} and therefore makes sense on a right G -torsor.

This concludes our crash course on Lie groups; we'll see this stuff again later.

Plane curves. Let E be a Euclidean plane modeled on an inner product space V .⁹ Let $\mathcal{B}_O(E)$ denote the space of affine isometries $\alpha: \mathbb{E}^2 \rightarrow E$. These are ways of choosing an origin and orthonormal coordinates for E . That is, α can be identified with pairs (p, b) where $p \in E$ and b is a basis of V . Forgetting the basis defines a map $\pi: \mathcal{B}_O(E) \rightarrow E$, called the *frame bundle*; it is a right Euc_2 -torsor, where Euc_2 acts by changing the coordinates of b .

Therefore all left-invariant information on Euc_2 comes over to $\mathcal{B}_O(E)$. In particular, there are Maurer-Cartan forms θ^1 and θ^2 with $\theta_2^1 = -\theta_1^2$, coming from the same equation on Euc_2 . This will be useful: differential forms make computations particularly easy compared to coordinate systems and vector fields (though those are not bad). Figuring out what this form actually calculates on a pair (p, b) is the first step towards understanding the Riemann curvature tensor: θ^i is the component of translation in the direction e^i .

Let $\gamma: (a, b) \rightarrow E$ be an embedded curve, which lifts to a map $\tilde{\gamma}$ of frames, so e_1 is normal and e_2 is tangent. What is the pullback $\gamma^* \theta^i$ and $\gamma^* \theta_j^i$? Since there's no translation in direction e^1 , $\gamma^* \theta^1 = 0$, and

⁹Some of what we do here will work for more general Euclidean spaces.

consequently $\gamma^*\theta^1 = dt$. The pullback $\gamma^*\theta_2^1 = -k dt$. So the Maurer-Cartan forms encode curvature on the torsor of frames, even in the simple situation of a plane curve.