Manifold Theory

- **Def.** (preliminary)
  A smooth n-manifold M is an n-dimensional surface inside $\mathbb{R}^m$. $(M \subset \mathbb{R}^m)$
  This means: for every point $m \in M$ there is $\varepsilon > 0$ and a diffeomorphism
  $\varphi : B(m, \varepsilon) = \{x \in \mathbb{R}^m / \|x - m\| < \varepsilon\} \to \mathbb{R}^n$
  s.t. $\varphi(M)$ is a vector subspace of $\mathbb{R}^m$

There is $U_{\ni m} \subset \mathbb{R}^m$ open and $V \subset \mathbb{R}^m$ open diffeo $\varphi : U \to V$ such that $\varphi(U \cap M) = V \cap W$, $W \subset \mathbb{R}^m$ vector subspace.

- **Def.** Suppose $\mathcal{U} \subset \mathbb{R}^m$, $V \subset \mathbb{R}^n$ are open subsets. A map $\varphi : \mathcal{U} \to V$ is a diff if φ is a bijection and φ and φ^{-1} are smooth

- **Def.** A subset $\mathcal{U} \subset \mathbb{R}^m$ is open for every point $u \in \mathcal{U}$ there is $\varepsilon > 0$ such that $B(u, \varepsilon) \subset \mathcal{U}$.

- **Ex.**
  a.) $\mathbb{R} \xrightarrow{\varphi} \mathbb{R}$ is not a diffeomorphism
  $x \mapsto x^3$. However, φ^{-1} is not smooth
  $x \to x^{1/3}$

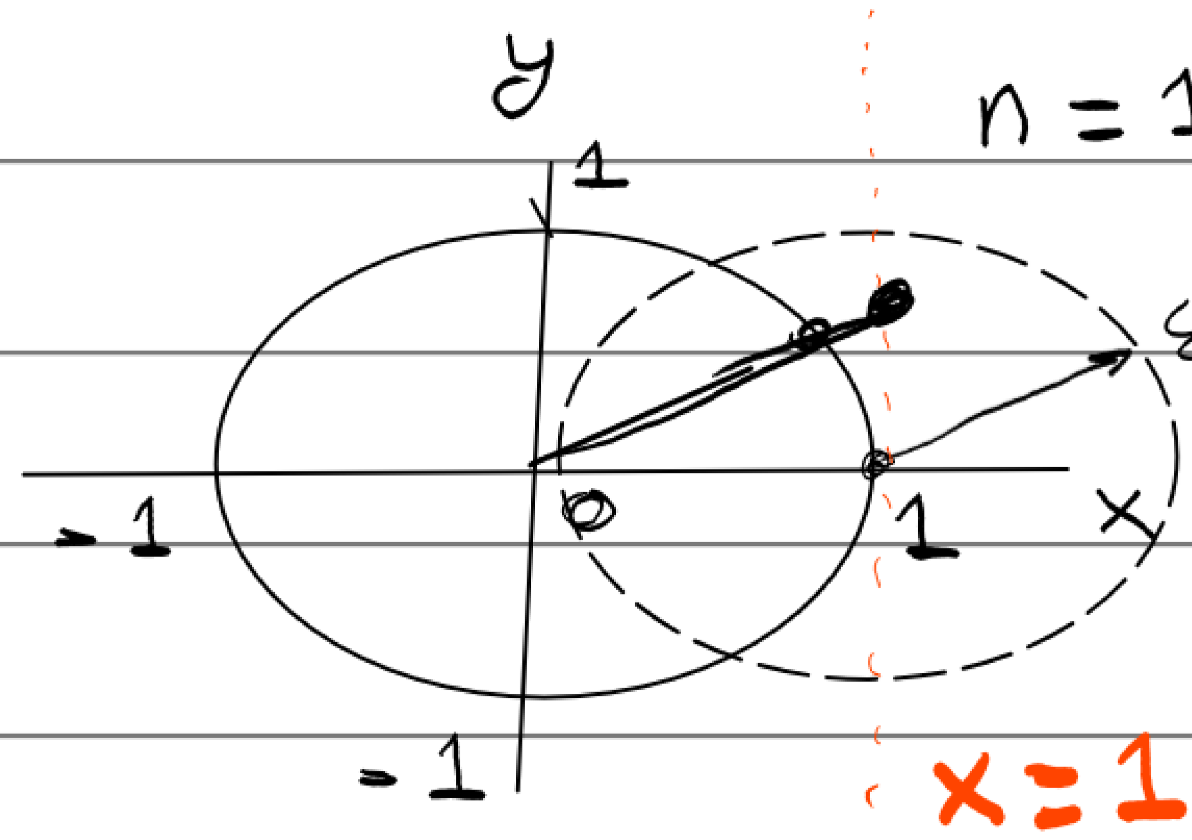
  b.) $(0, \infty) \xrightarrow{\varphi} (0, \infty)$ is a diffeomorphism
  $x \mapsto x^2$ ✓
  $x \mapsto \sqrt{x}$.

  c.) $\mathbb{R}^m \xrightarrow{A} \mathbb{R}^n$ where A is a linear map
  A is a diffeomorphism $\Leftrightarrow m = n$ and the matrix of A is inv. (i.e. $\det A \neq 0$).

  d.) The inverse function theorem: if $\varphi : \mathbb{R}^m \to \mathbb{R}^n$ is a smooth bijective map, then φ^{-1} is smooth
  $\Leftrightarrow \forall x \in \mathbb{R}^m : (D\varphi)(x)$ is an inv. Linear map (matrix)

• **Exa.** $S^1 = \{(x,y) \mid x^2+y^2=1\}$

$n=1$



$\{(x,y) \mid x>0\}$

$\to \{(x,y) \mid x>0\}$

$(x,y) \mapsto t\cdot(x,y),\ t = \sqrt{\tan^2(\frac{y}{x})+1}$

Implicit function Theorem!

Suppose $f: \mathbb{R}^m \to \mathbb{R}^p$ is a smooth map and

$Df(0)$ has rank p.

Then, $\exists \varepsilon > 0 : f^{-1}(f(0)) \cap B(0,\varepsilon)$ which satisfies

0, $0 \in \mathbb{R}^m$ s.t. $f(0)=0$.

• **Exa.** $m=2,\ p=1 \quad f: \mathbb{R}^2 \to \mathbb{R}$

$(x,y) \mapsto x^2+y^2=1$

Let $a=(x,y)$.

$$Df = \left(\frac{\partial f}{\partial x}(x,y) \quad \frac{\partial f}{\partial y}(x,y) \right)$$

$$= (2x \quad 2y)$$

$$\operatorname{rank}(Df)(x,y) = \begin{cases} 0, & \text{if } x=y=0 \\ 1, & \text{otherwise} \end{cases}$$

rank $=1=p$, IFT applies.

• **Exa.** $S^n = \{(x_0,\dots,x_n) \mid x_0^2+\dots+x_n^2=1\}$

is also a smooth manifold.

• **Exa.** $T^n = \{(x_1, \dots, x_{2n}) \mid x_1^2 + x_2^2 = 1,$
$x_3^2 + x_4^2 = 1 \dots \}$

$f: \mathbb{R}^{2n} \longrightarrow \mathbb{R}^n$

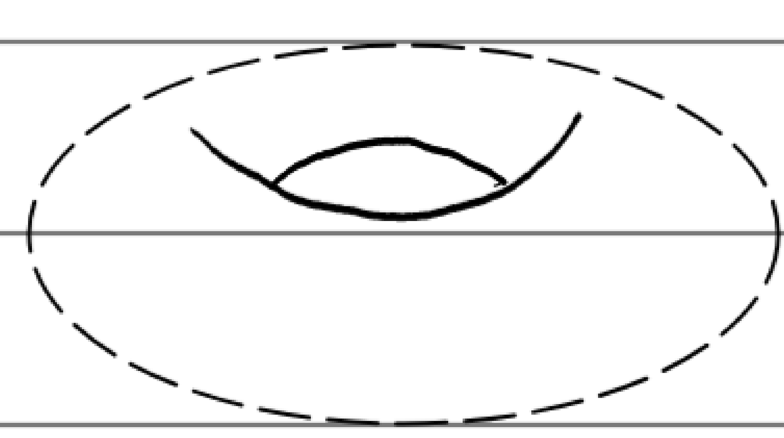
$(x_1, \dots, x_{2n}) \xmapsto{f} (x_1^2 + x_2^2 - 1, \dots, x_{2n-1}^2 + x_{2n}^2 - 1)$

$$Df(x_1, \dots, x_{2n}) = \begin{pmatrix} 2x_1 & 2x_2 & 0 & \cdots & \cdots & 0 \\ 0 & 0 & 2x_3 & 2x_4 & 0 \cdots & 0 \\ 0 & 0 & \cdots & \cdots & 2x_{2n-1} & 2x_{2n} \end{pmatrix}$$

rank n iff

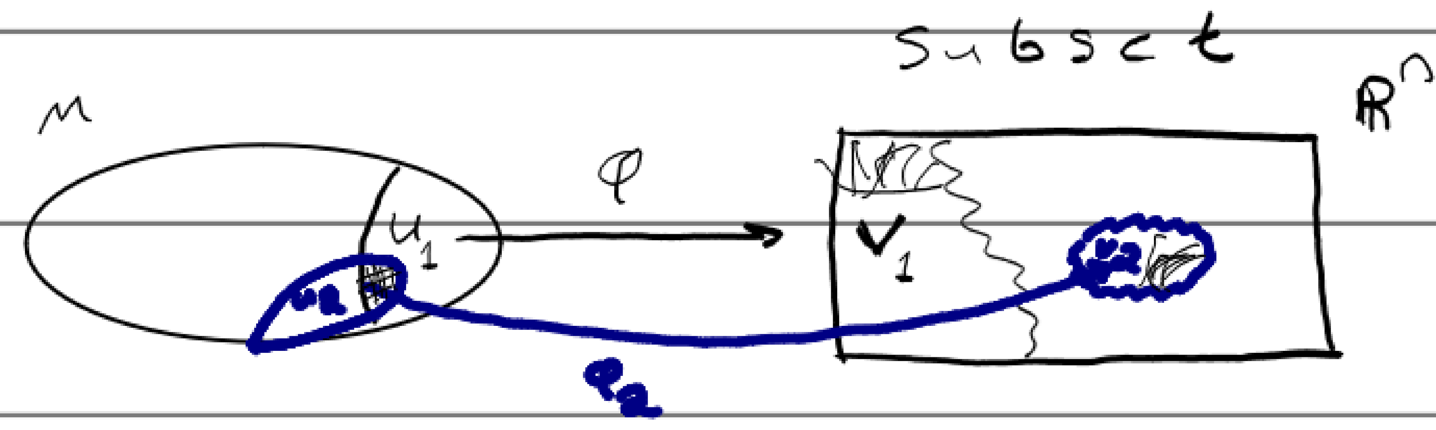
$(x_1, x_2) \neq 0$. Basically no zeroes, we have LID so rank $= n$, number of columns.

• **Exa.** $T^2 = \{(x, y, z) \mid \left(x - \frac{x}{\sqrt{x^2+y^2}}\right)^2 + \left(y - \frac{y}{\sqrt{x^2+y^2}}\right)^2 + z^2 = \left(\frac{1}{2}\right)^2 \}$.



• **Def.** Suppose M is a set

a.) A chart on M is a bijection $\varphi: U \longrightarrow V$ where $U \subset M$ and $V \subset \mathbb{R}^n$ open.
subset



Two charts are compatible

$\varphi_1: U_1 \longrightarrow V_1 \subset \mathbb{R}^{n_1}$ $\wedge$ $\varphi_2: U_2 \longrightarrow V_2 \subset \mathbb{R}^{n_2}$

if $\varphi_1(U_1 \cap U_2) \subset \mathbb{R}^{n_1}$ is open

$\varphi_2(U_1 \cap U_2) \subset \mathbb{R}^{n_2}$ is open

and $\varphi_2 \circ \varphi_1^{-1}: \varphi_1(U_1 \cap U_2) \longrightarrow \varphi_2(U_1 \cap U_2)$ is smooth

and $\varphi_1 \circ \varphi_2^{-1}: \varphi_2(U_1 \cap U_2) \longrightarrow \varphi_1(U_1 \cap U_2)$ is smooth.

c) An atlas is a compatible family of charts $(\varphi_i : U_i \longrightarrow V_i)_{i\in I}$

s.t. $\bigcup_{i\in I} U_i = M$.

d.) A smooth manifold is a set (M) w/ an atlas $\mathcal{A}$ $(M, \mathcal{A})$.

Notes (08/29/24)

- Recall:

(a) A chart on M is $\varphi : U \longrightarrow V$ (bijection)

$V \subset \mathbb{R}^n$ open, $U \subset M$

(b) $\varphi_1 \sim \varphi_2$ (compatible)

$\varphi_1 : U_1 \longrightarrow V_1$

$\varphi_2 : U_2 \longrightarrow V_2$

if $\varphi_1(U_1 \cap U_2) \subset \mathbb{R}^n$ open

if $\varphi_2(U_1 \cap U_2) \subset \mathbb{R}^n$ open

$\alpha = \varphi_2 \circ \varphi_1^{-1}$ is smooth, $\beta = \varphi_1 \circ \varphi_2^{-1}$ is smooth

(c) An atlas on M is a compatible family

$\{\varphi_i : U_i \to V_i\}_{i\in I}$

such that $\bigcup_{i\in I} U_i = M$

(d) • def. A smooth manifold is a set M equipped with an atlas.

- Exa. If $U \subset \mathbb{R}^n$, then U is a smooth manifold w/ a single chart $\varphi : U \xrightarrow[\text{id}]{} U$. In particular, $\emptyset, \mathbb{R}^n, B(c, \varepsilon)$
identity are all smooth manifolds.

(b) $S^n = \{ x \in \mathbb{R}^{n+1} \mid \|x\| = 1 \ (x_0^2 + \dots + x_n^2 = 1) \}$

North pole, $N = \{1, 0, \dots, 0\}$

South Pole, $S = \{-1, 0, \dots, 0\}$

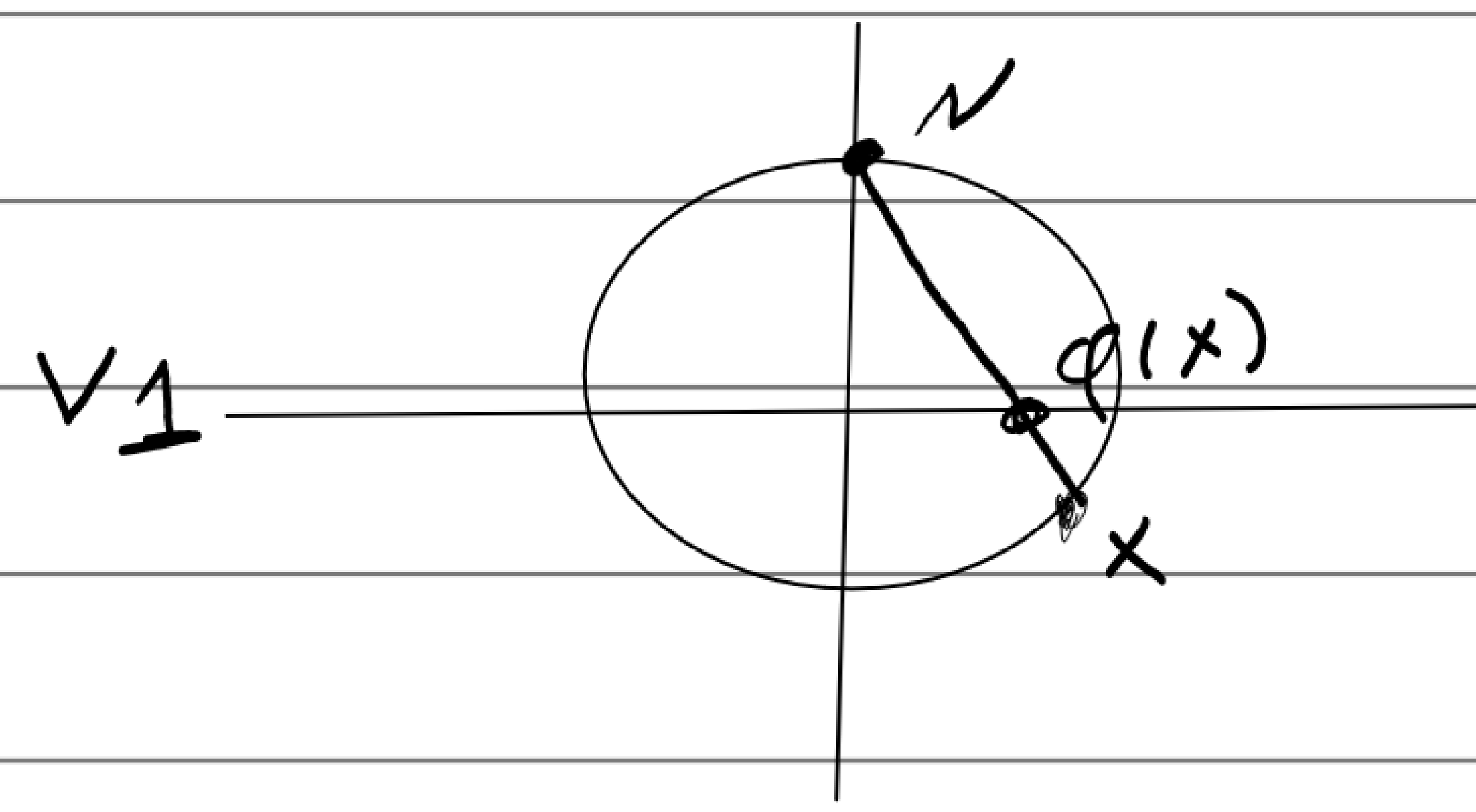
$\varphi_1 : U_1 \to V_1$

$S^n \setminus \{N\} \longrightarrow \mathbb{R}^n$

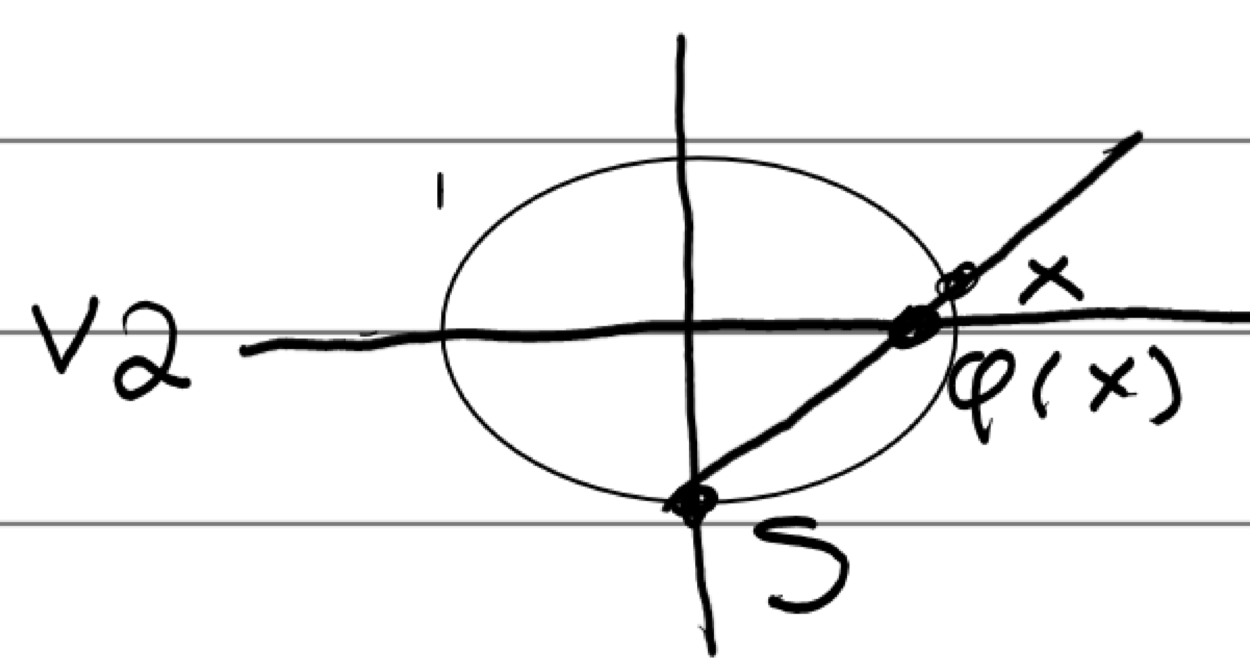
Stereographic projection

$\varphi_2 : U_2 \to V_2$

$S^n \setminus \{S\} \longrightarrow \mathbb{R}^n$



Kind of like ungluing a point and unravelling into a line.



$\varphi_1(x_0, \dots, x_n) = \gamma \cdot (x_1, \dots, x_n)$

$t \mapsto N + t(x - N) = (1 + t\cdot(x_0 - 1), t\cdot x_1, \dots, t\cdot x_n)$

where $t = \dfrac{1}{1 - x_0}$

$\varphi_2(x_0, \dots, x_n) = \dfrac{1}{1 + x_0} \cdot (x_1, \dots, x_n)$

cont. on next page

$\varphi_1^{-1}(y_1,\dots,y_n) =$

$t \longmapsto N + t\cdot\big((0,y_1,\dots,y_n) - N\big) = (1-t, ty_1, \dots)$

$(1-t)^2 + t^2(y_1 + \dots + y_n^2) = 1 \qquad = N - t\cdot y$

$t^2\cdot(1+y_1^2+\dots+y_n^2) - 2t = 0$

Assuming, $t \neq 0$

$\Rightarrow \qquad t = \dfrac{2}{1+y_1^2+\dots+y_n^2}$

$\varphi^{-1}_1(\dots) = N + \dfrac{2}{1+y_1^2+\dots+y_m^2}(-1, y_1, \dots, y_n)$

$\varphi_2^{-1}(y_1,\dots,y_n) = S + \dfrac{2}{1+y_1^2+\dots+y_n^2}(1, y_1, \dots, y_n)$

$\varphi_2 \circ \varphi_1^{-1}$

$= \varphi_2\left(N + \dfrac{2}{1+y_1^2+\dots+y_m^2}(-1, y_1, \dots, y_n)\right) \qquad \dfrac{2}{\|y\|^2}\cdot\dfrac{1}{2-\frac{2}{\|y\|^2}}$

$= \dfrac{1}{1+1-\frac{2}{1+y_1^2+\dots+y_n^2}} \cdot \dfrac{2}{1+y_2^2+\dots+y_n^2}(y_1,\dots,y_n) \to \text{smooth}$

$1 - x_0 = \dfrac{1}{t}, \qquad x_0 = 1 - \dfrac{1}{t}, \quad t = \dfrac{2}{1+y_1^2+\dots+y_n^2}$

This guy is smooth because $1+y_1^2+\dots > 1.$

$= \dfrac{y}{\|y_2\|}, \quad y = (y_1,\dots,y_n)$ w.L.O.G on $\varphi_1 \circ \varphi_2^{-1}$.

$\square$

$\left(\dfrac{y_1}{\|y\|^2}, \dfrac{y_2}{\|y_2\|^2},\right.$

HW 1: Prove T^n is a smooth manifold

Hint: $T^n = \mathbb{R}^n/\sim$

$(x_1,\dots,x_n) \sim (y_1,\dots,y_n)$

if $(x_1-y_1,\dots,y_1-y_n) \in \mathbb{Z}^n$

- Recall equivalence relations:

(a) A relation on a set S is a subset $R \subset S \times S$ we write xRy or $x \sim y$ instead of $(x,y) \in R$.

† (b) A relation is reflexive if $\forall x: xRx$

† (c) " " " symmetric if $\forall x,y$ $xRy \Leftrightarrow yRx$

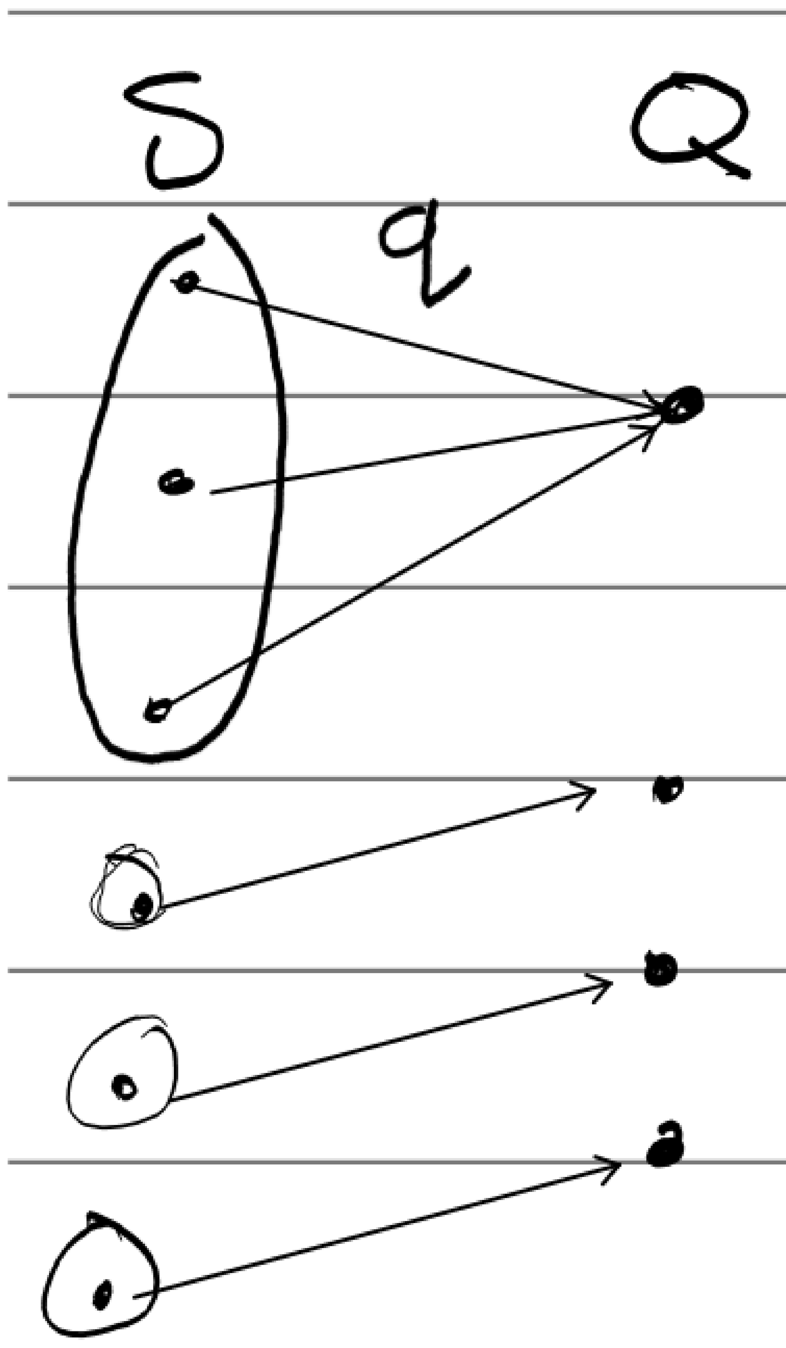
† (d) " " " transitive if $\forall x,y,z$: $(xRy \wedge yRz) \Rightarrow xRz$

if † hold, then R is an equivalence relation. "x is equivalent to y"

(e) • **Thm.** R is an equivalence relation iff $\exists$ a surjective function $q: S \longrightarrow Q$ such that $\forall x,y$: $xRy \Leftrightarrow q(x) = q(y)$

$q: S \to Q$

$Q := S/R$



These groups in S are called equivalence classes...

$q: S \to S/R$

• **Thm.** R is an equivalence relation $\Leftrightarrow \exists P \subset 2^S$, $2^S = \{u \mid u \subset S\}$. "powerset"

Quotients in essence induce the establishment of equivalence classes.

2^S

- $\forall p \in P : p \neq \emptyset$
- $\forall p, q \in P : (p \neq q) \Rightarrow (p \cap q = \emptyset)$
- $S = \bigcup_{p \in P} p$.

Also $\forall x, y : xRy \Longleftrightarrow \exists p \in P :$
$(x \in p) \wedge (y \in p)$.

- **Rem.** P is unique (i)

elements of P are eq. classes (ii)

q is called a quotient map (iii) $\quad q : S \to Q$

Q is called a quotient (iv) $\quad Q = S/R$

of S by R. $Q = S/R$ (v) $\quad q : S \to S/R$

we also might write $[x]$ instead $q(x)$

$[x]_R$

- **Rem.** we can take $Q = P$

$q(x) = \{ y \in S \mid yRx \}$. $\longrightarrow$ causes a lot of suffering!

- **Exa.** $S = \mathbb{R}$, $\sim = R \subset S \times S$

$x \sim y$ if $x - y \in \mathbb{Z}$

easy to check equivalence relation.

$P = \{ \{ -, \ldots, -2, -1, 0, 1, 2, \ldots \}, \{ \ldots, -3/2, -1/2, 1/2, 3/2 \},$
$\{ \ldots, x-2, x-1, x, x+1, x+2, \ldots \} \}$.

$P \overset{iso}{\cong} [0,1)$. Take $x \in [0,1)$

• **Prop.** $\mathbb{R}/\sim$ is a smooth manifold

• ~~Proof~~ → Two charts

$$\varphi_1 : \underset{(0,1)}{U_1} \longrightarrow V_1 \subset \mathbb{R} \quad \text{open}$$

$U_1 = (0,1)$

$U_2 = [0, 1/2) \cup (\frac{1}{2}, 1)$

$U_1 \cup U_2 = [0,1)$.

$$\varphi_2 : U_2 = [0, 1/2) \cup (\tfrac{1}{2}, 1) \to (-\tfrac{1}{2}, \tfrac{1}{2}) \text{ open} \subset \mathbb{R}$$

$$\varphi_2(x) = \begin{cases} x, & x < 1/2 \\ x-1, & x > 1/2 \end{cases}$$

$\boxed{\text{check compatibility and if this forms an Atlas} \quad \text{HW (Hint)}}$

Next time: more on diffeomorphisms, etc.

FIN!

Show that $\mathbb{R}/\sim$ torii smooth manifold!
where $x \sim y$ by $(x-y) \in \mathbb{Z}$.

$P \cong [0,1)$

$\varphi_1 : \underset{(0,1)}{U_1} \longrightarrow V_1 \subset \mathbb{R}$

$\varphi_2 : U_2$
$\quad\quad \shortparallel$
$[0,1/2) \cup (\frac{1}{2}, 1) \to (-\frac{1}{2}, \frac{1}{2})$

$$\varphi_2(x) = \begin{cases} x, & x < 1/2 \\ x-1, & x > 1/2 \end{cases}.$$

x when $x < \frac{1}{2}$, $x - 1$ $x > \frac{1}{2}$

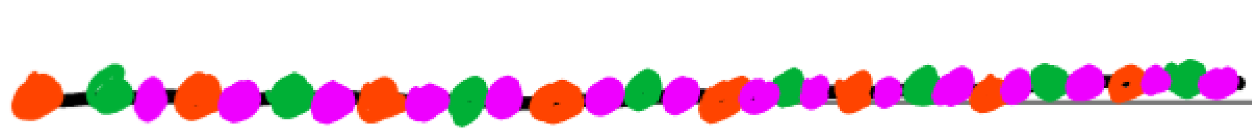
Thus, $x = \varphi_2^{-1}(x)$
$x < \frac{1}{2}$

$$x = \begin{cases} \varphi_2^{-1}(x), & x < 1/2 \\ \varphi_2^{-1}(x-1), & x > 1/2 \end{cases}.$$

$\varphi_2^{-1}(x) = \varphi_2(x)$, $\varphi_2(x)$ id.

$\varphi_1(x)$

This equivalence relation is the set that contains sets of units



$\mathbb{R}$

$\{\ldots -1, 0, 1, \ldots\}$

$\{\ldots -1/2, 0, 1/2\}$.

$\{\ldots x-1, x, x+1\}$.

How is the power set $P \cong [0,1)$?

well, all of the sets repeat themselves.

we can essentially just copy

$\{\ldots, x-1, x, x+1, \ldots\}$ a bunch of times in a row...

why in particular does this help define a Torus?

$\mathbb{R} \setminus \sim$. This quotient sends all of the real numbers to these equivalence classes. Sends

$$\{\ldots, -1, 0, 1, \ldots\}$$

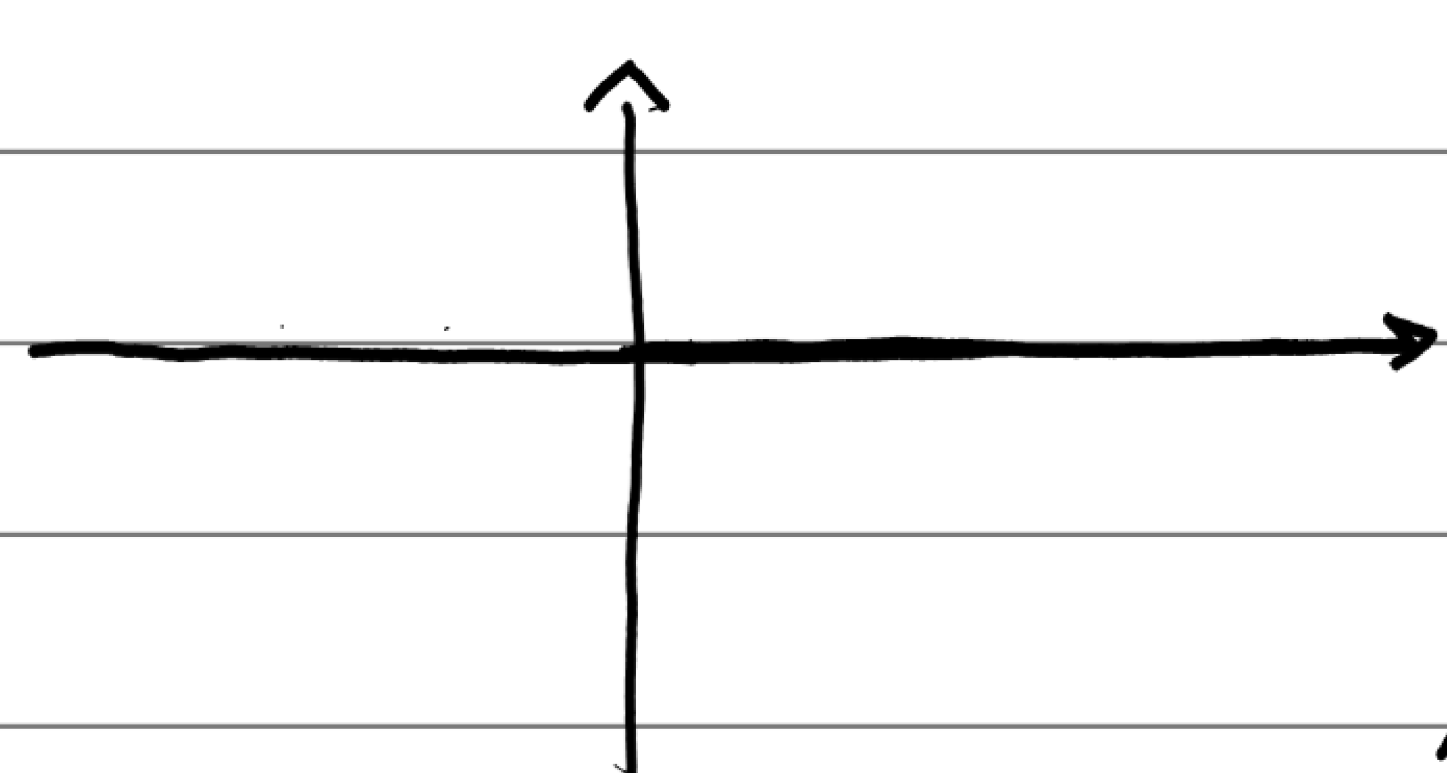
$$p \cong [0,1).$$

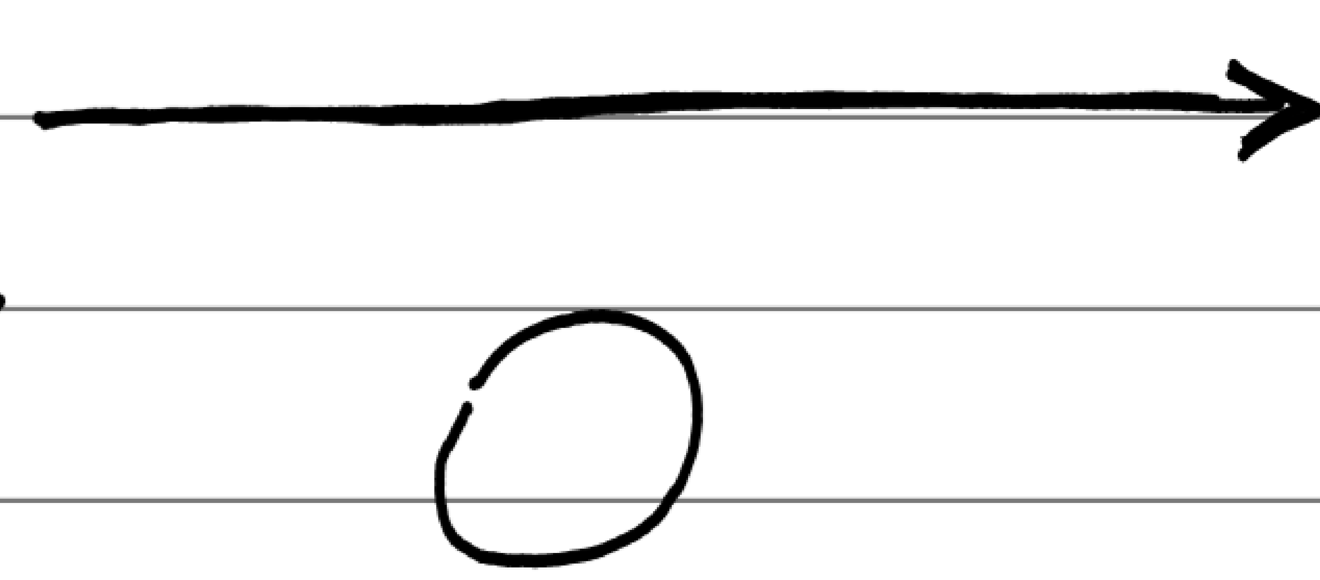
$$\varphi_1 : \underset{(0,1)}{U} \longrightarrow V \subset \mathbb{R} \text{ open}$$

$$\varphi_2 : [0, \tfrac{1}{2}) \cup (\tfrac{1}{2}, 1) \longrightarrow (-1/2, 1/2) \subset \mathbb{R} \text{ open}$$

$$[0, 1/2) \cup (\tfrac{1}{2}, 1) \to (-\tfrac{1}{2}, \tfrac{1}{2})$$

$$\varphi_2(x) = \begin{cases} x, & x < 1/2 \\ x-1, & x > 1/2 \end{cases}.$$





$$T^1 = S^1 \,!!$$

$(0,1) \longrightarrow \mathbb{R}$

uc

$\varphi_1^{-1} : \mathbb{R} \longrightarrow (0,1)$

$\frac{1}{2} \rightarrow 0, \quad 0 \rightarrow -n, \quad 1 \longrightarrow n$

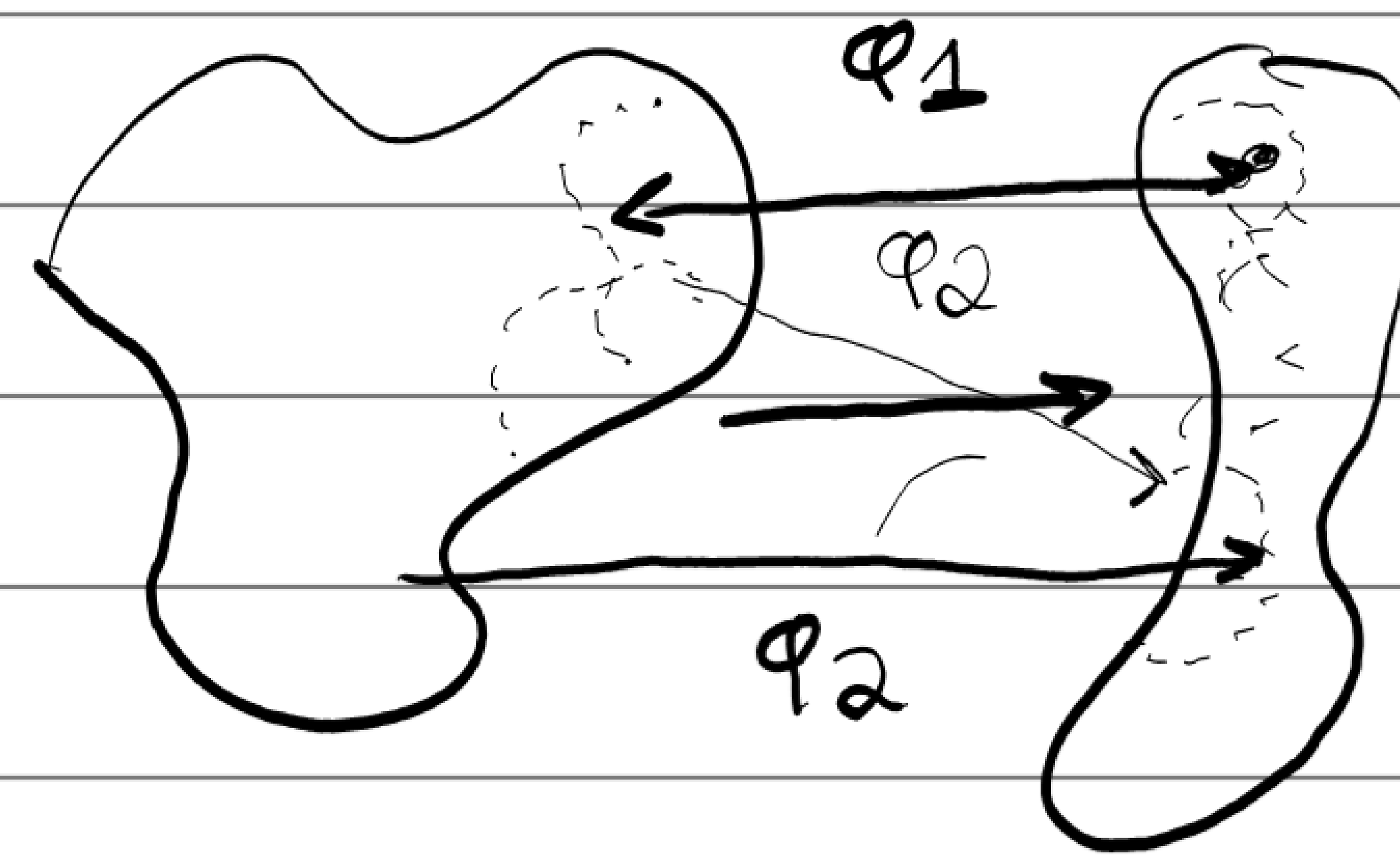
$$\varphi_2 : \begin{cases} x & \text{if } x < 1/2 \\ x-1 & \text{if } x > 1/2 \end{cases}$$

cont too! smooth!

$[0, 1/2) \cup (\frac{1}{2}, 1)$.

Thus, $\longrightarrow (-1/2, 1/2)$

$(\varphi_2 \circ \varphi_1^{-1}) = \varphi_2$



$$\varphi_2 = \begin{cases} x & \text{if } x < 0 \\ x - n & \text{if } x > 0 \end{cases}$$

$x \in [-n, 0) \cup (0, n)$.

Take $x = -n \quad -n$. Let $x = n-1$

$\varphi_2 = -1$? $\quad n \longrightarrow -n$?

no. $n \longrightarrow -n$.

$\varphi_2' = \begin{cases} 1 \\ 1 \end{cases}$

Smooth?

$\varphi_1 : (0,1) \longrightarrow \mathbb{R}$

$\varphi_1 \circ \varphi_2^{-1}$ Smooth

$\varphi_1 [(-1/2, 1/2)] \longrightarrow \mathbb{R}$

$\varphi_1 : -1/2 \longrightarrow -n \; ; \varphi_2 : 1/2 \longrightarrow n$. //

Lecture 4: Diffeomorphisms

Last time

A smooth manifold is

- M : set
- $\varphi_i : U_i \longleftrightarrow V_i$, with $U_i \subset M$ and $V_i \subset \mathbb{R}^n$ open

Atlas!

$i \in I$ - a set

$\forall\, i, j$

- φ_i is compatible w/ φ_j : $\varphi_j \circ \varphi_i^{-1}$ is smooth
- $\bigcup_{i \in I} U_i = M$.

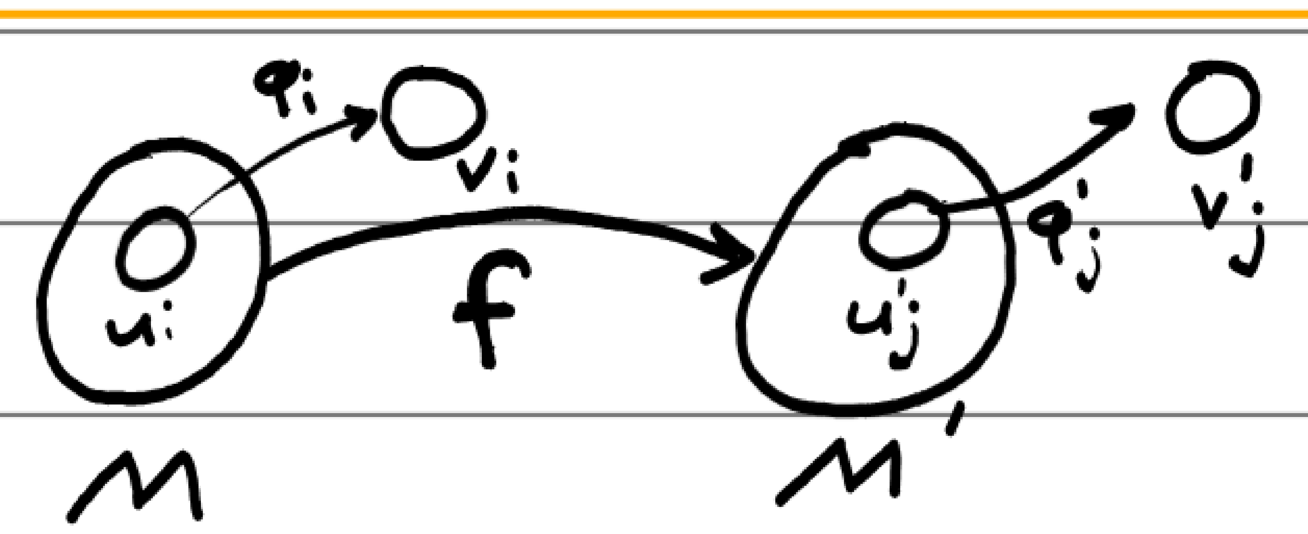
Today

- **Def.** A smooth map

$$\text{if}: \underset{\dim = m}{(M, (\varphi_i : U_i \to V_i)_{i \in I})} \longrightarrow \underset{\dim m'}{(M', (\varphi_j' : U_j' \to V_j')_{j \in J})}$$

is a map of sets $f: M \to M'$ such that ...

$U_i \subset \mathbb{R}^m,\ V_j \subset \mathbb{R}^{m'}$.



... such that for every $i \in I, j \in J$ the map

$$\varphi_j' \circ f \circ \varphi_i^{-1} : \underset{\mathbb{R}^n \text{ open}}{\hat{V}_i} \longrightarrow \hat{V}_j' \subset \mathbb{R}^m \text{ open}.$$

is smooth.

$\hat{V}_i \subset V_i$

$\hat{V}_i = \varphi_i(f^{-1} U_j')$ is open in $\mathbb{R}^m$.

• Exa.

(a) pick some $q \in M'$. set $f(p) = q$ $\forall p \in M$. Then f is smooth.

Indeed $f^{-1} U'_j = \begin{cases} M, & \text{if } q \in U'_j \\ \emptyset, & \text{if } q \notin U'_j \end{cases}$

$\widehat{V_i} = \begin{cases} V_i, & \text{if } q \in U'_j \\ \emptyset, & \text{if } q \notin U'_j \end{cases}$

$\varphi'_j \circ f \circ \varphi_i^{-1} = \begin{cases} V_i \to V'_j, \; v \mapsto \varphi'_j(q) & \text{if } q \in U'_j \\ \emptyset \to V'_j & \text{if } q \notin U'_j. \end{cases}$

(b) $(M, (\varphi_i : U_i \to V_i)_{i \in I})$. Pick some $k \in I$. Then $f = \varphi_k^{-1} : V_k \to U_k \subset M$ is a smooth map. ($V_k \subset \mathbb{R}^m$)

• Proof. Have to check that $\forall j \in I$ the map $\varphi_j \circ \varphi_k^{-1} \circ (id_{V_i})^{-1} = \varphi_j \circ \varphi_k^{-1}$ is smooth.

This follows simply by definition of M being a smooth manifold.

• Riemann Def. 18.., Veblen, whitehead 1931.

• Def. Given a $\hat{n}$-manifold $(M, (\varphi_i : U_i \to V_i)_{i \in I})$

A subset $W \subset M$ is open if for every $i \in I$: $\varphi_i(W \cap U_i)$ is an open subset of $\mathbb{R}^n$.

• Recall A topological space is a pair (X, U)

X is a set

$U \subset 2^X = \{S \mid S \subset X\}$. Elements of U are known as open subsets of X...

- $\mathcal{U}$ is closed under finite intersections: $\forall A, B \in \mathcal{U}$: $A \cap B \in \mathcal{U}$, <u>and</u> $X \in \mathcal{U}$.
- $\mathcal{U}$ is closed under arbitrary union: If W is a subset of $\mathcal{U}$ $W \subset \mathcal{U}$, then $\bigcup W = \{x \in X \mid \exists w \in W : x \in w\} \in \mathcal{U}$.

<u>• Exa.</u> $W = \emptyset$, $\bigcup W = \emptyset \in \mathcal{U}$.

<u>• Exa.</u> $\mathcal{U} = \{ S \subset \mathbb{R}^n \mid S = \bigcup_{B(s,\varepsilon) \subset S} B(s,\varepsilon) \}$.

$(\mathbb{R}^n, \mathcal{U})$ is a topological space.

Unions are given basically all by definition.

$A, B \in \mathcal{U}$, $A = \bigcup_{B(a,\varepsilon)} B(a,\varepsilon)$

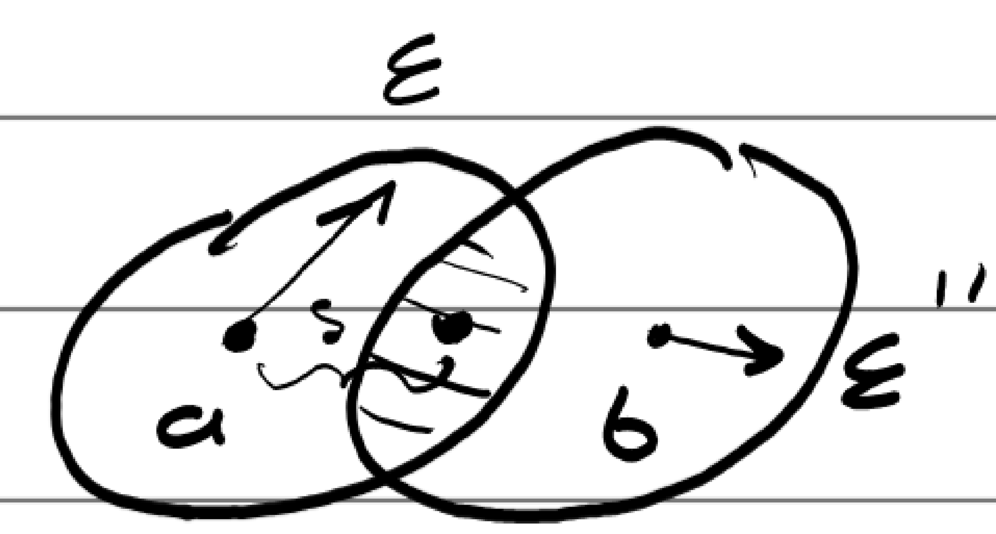
$B = \bigcup_{B(b,\varepsilon') \subset B} B(b,\varepsilon')$

can I use demorgans law here?

$\bigcup (B(a,\varepsilon) \cap B(b,\varepsilon''))$

$B(a,\varepsilon) \subset A$

$B(b,\varepsilon') \subset B$.



Suppose $s \in B(a,\varepsilon) \cap B(b,\varepsilon)$

Set $\varepsilon'' = \min(\varepsilon - \|s-a\|, \varepsilon' - \|s-b\|)$

Then $B(s,\varepsilon'') \subset B(a,\varepsilon) \cap B(b,\varepsilon')$

Pick some $x \in B(s,\varepsilon'')$.

Then $\|x-a\| \leq \|x-s\| + \|s-a\| < \varepsilon'' + \|s-a\|$

$\leq \varepsilon - \|s-a\| + \|s-a\| = \varepsilon$.

• **Prop.** $(M, \{W \subset M \mid W \text{ is open}\})$.
is a topological space

• **Proof.** a) M is open:

$$\forall_{i \in I} \quad \varphi_i(M \cap U_i) = \varphi_i(U_i) = V_i \subset \mathbb{R}^m$$

by def.

b) $W_1, W_2 \subset M$ open

$$\varphi_i(W_1 \cap W_2 \cap U_i)$$

$$\varphi_i((W_1 \cap U_i) \cap (W_2 \cap U_i))$$

$$\underbrace{\varphi_i(W_1 \cap U_i)}_{\text{open.}} \subset \mathbb{R}^m \cap \underbrace{\varphi_i(W_2 \cap U_i))}_{\text{open.}} \subset \mathbb{R}^m$$

Thus, open. $\qquad W_k \subset M$ open

c) unions $\bigcup_{k \in I} W_k$

$$\forall i \in I : \varphi_i\left(\left(\bigcup_{k \in \cancel{I}} W_k\right) \cap U_i\right) = \varphi_i\left(\bigcup_{k \in K} (W_k \cap U_i)\right)$$

$$\bigcup_{k \in K} \underbrace{\varphi_i(W_k \cap U_i)}_{\text{open.}} \subset \mathbb{R}^m$$

This verifies smooth manifolds have an underlying topological space

---

• **Def.** A continuous map $f : (X, \mathcal{U}) \longrightarrow (Y, \mathcal{V})$
is a map of sets $f : X \to Y$ s.t.
$\forall V \in \mathcal{V} : f^{-1}(V) \in \mathcal{U}$.

• **Prop.** Every smooth map of smooth manifolds of smooth manifolds is continuous

• **Proof.** (next time...)

• **Def.** A topological space is $(X, \mathcal{U})$ X set, $\mathcal{U} \subset 2^X$ closed under finite $\cap$, arbitrary $\cup$.

• **Def.** A continuous map $(X, \mathcal{U}) \longrightarrow (Y, \mathcal{V})$ is a map of sets $f: X \to Y$ s.t. $\forall v \in V$: $f^{-1} v \in \mathcal{U}$.

• **Rem.** $U \subset \mathbb{R}^m \xrightarrow{f} V \subset \mathbb{R}^n$ is continuous
$\Longleftrightarrow \forall u \in U \; \forall \varepsilon > 0, \exists \delta > 0 \; \forall x \in U$:
$$\|x - u\| < \delta \Rightarrow \|f(x) - f(u)\| < \varepsilon.$$

• **Proof.**
$\Rightarrow$ assume f is continuous, $u \in U$, $\varepsilon > 0$.
Also, $B(f(u), \varepsilon) \subset \mathbb{R}^n$ (open). Also $\underbrace{f^{-1}(B(f(u), \varepsilon))}_{u \in} \overset{\text{open}}{\subset} U$.
For some $\delta > 0$

$B(u, \delta) \cap U$, $\forall x \in U : \|x - u\| < \delta$
$\Longleftrightarrow x \in B(u, \delta) \Rightarrow \|f(x) - f(u)\| < \varepsilon$
$\Longleftrightarrow f(x) \in B(f(u), \varepsilon) \Longleftrightarrow x \in f^{-1}(B(f(u)), \varepsilon)$.

$\Leftarrow$ try other side at home.

• **Prop.** $(M, (\varphi_i : U_i \to V_i)_{i \in I}) \xrightarrow{f} (N, (\psi_j : W_j \to X_j)_{j \in J})$.
The underlying map of topological spaces is continuous

• **Proof.** Suppose $S \underset{\text{open}}{\subset} N$. w.t.s.

$f^{-1}(S) \subset M \iff \forall i \in I \quad \varphi_i(U_i \cap f^{-1}(S)) \overset{\text{open}}{\subset} \mathbb{R}^n$

$S = S \cap N = S \cap \bigcup_{j \in J} W_j = \bigcup_{j \in J} (S \cap W_j)$

$\varphi_i\left(U_i \cap f^{-1}\left(\bigcup_{j \in J} (S \cap W_j)\right)\right)$

$= \varphi_i(U_i \cap \bigcup_{j \in J} (S \cap W_j)) = \varphi_i\left(\bigcup_{j \in J} U_i \cap f^{-1}(S \cap W_j)\right)$

$= \bigcup_{j \in J} \underbrace{\varphi_i(U_i \cap f^{-1}(S \cap W_j))}$

$= \bigcup_{j \in J} \varphi_i(U_i \cap f^{-1} S \cap f^{-1} W_j)$

$= \bigcup_{j \in J} \underbrace{(\psi_j \circ f \circ \varphi^{-1})}^{-1}(S \cap W_j)$

$\varphi_i \circ f^{-1} \circ \psi_j^{-1} \circ (\psi_j(S \cap W_j))$

smooth!

Now, but why is $\psi_j(S \cap W_j)$ open?

$\psi_j(S \cap W_j)$ is open $\quad S \cap W_j$ is open.

$\uparrow$ by ass $\uparrow$ open. $\quad = (\psi^{-1})^{-1}(S \cap W_j)$

W_j is open $\iff \forall k : \varphi_k(W_j \cap W_k) \subset X_k$.

• **Prop.** $(X, U) \xrightarrow{f} (Y, V) \xrightarrow{g} (Z, W)$

If f and g are continuous, then $f \circ g$ is too.

• **Proof.** suppose $w \in W$, then $(g \circ f)^{-1} w = f^{-1} \underbrace{g^{-1} w}_{\text{open}} . \underset{\text{open.}}{\subset} X$

What is a tangent vector?

Three different points of view:

- Transfer tangent vectors in $\mathbb{R}^n \to M$ using charts
- kinematic tangent vector: an equivalence class of trajectories with the same velocity.

  - $\mathbb{R} \xrightarrow[\text{smooth}]{p} M$ $\quad \mathbb{R} \xrightarrow{p} M$ $\quad p \sim q$ if $p'(0) = q'(0)$ (in a chart)

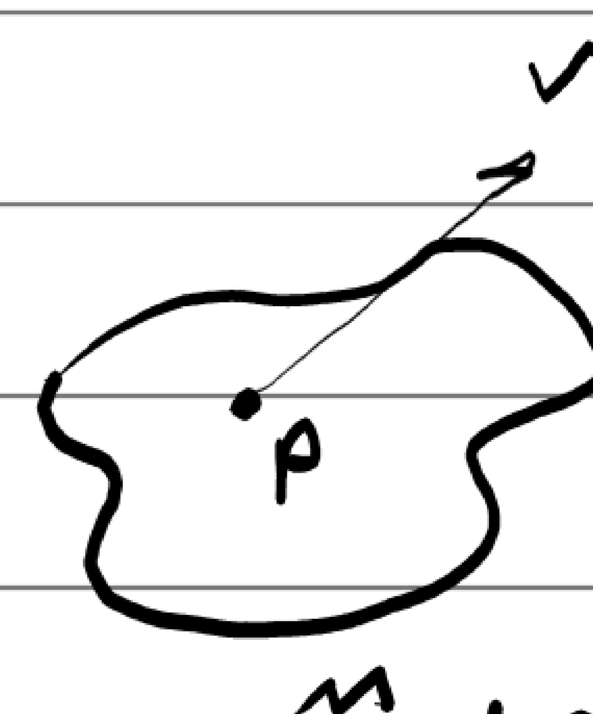
- Algebraic/observational:

$$C^\infty(M,\mathbb{R}) = \{ f : M \to \mathbb{R} \mid f \text{ smooth} \}.$$

$\downarrow$ directional derivative

$\mathbb{R}$

- If $\underset{\text{open}}{M \subset} \mathbb{R}^m$, $p \in M$, $v \in \mathbb{R}^m$



$f : M \longrightarrow \mathbb{R}$

$$\nabla_v f(p) = v_p(f) = \nabla_{(p,v)} f = \nabla_v f = \frac{d f(p+t\cdot v)}{dt}$$

Leibniz rule: $v_p(fg) = v_p \cdot g(p) + f(p) \cdot v_p(g)$

Banach manifolds... charts

$(0,1) \to \mathbb{R}$

uc

$\varphi_1^{-1} : \mathbb{R} \to (0,1)$

$\frac{1}{2} \to 0, \quad 0 \to -n, \quad 1 \to n$

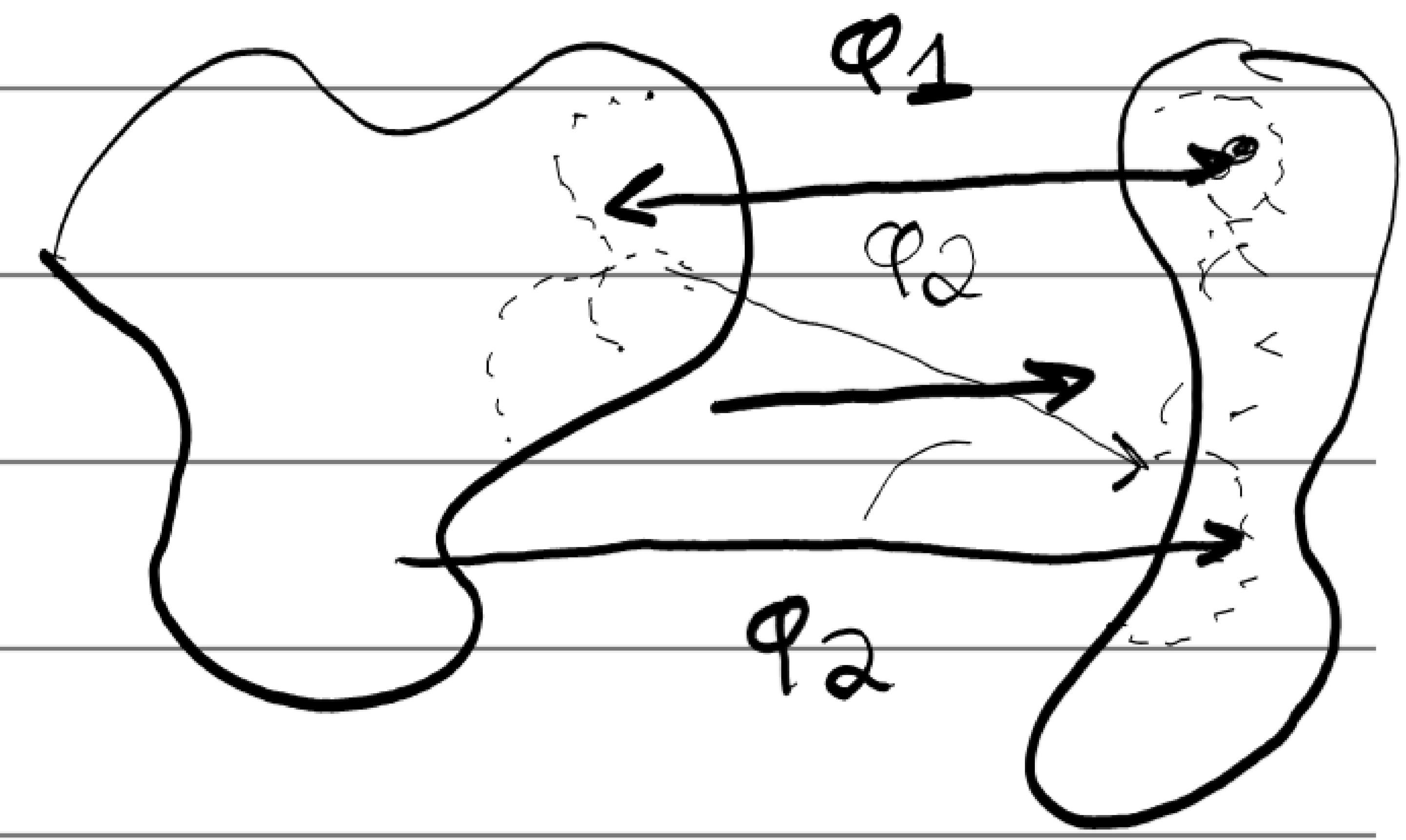
$$\varphi_2 : \begin{cases} x & \text{if } x < 1/2 \\ x-1 & \text{if } x > 1/2 \end{cases}$$

cont too! smooth!

$[0, 1/2) \cup (\frac{1}{2}, 1).$

Thus, $\to (-1/2, 1/2)$

$(\varphi_2 \circ \varphi_1^{-1}) = \varphi_2$



$$\varphi_2 = \begin{cases} x & \text{if } x < 0 \\ x - n & \text{if } x > 0 \end{cases}$$

$x \in [-n, 0) \cup (0, n).$

$(x_1, x_2, \dots, x_n)$

$\varphi_1(x_1, x_2, \dots, x_n) = (\varphi_1(x_1), \varphi_1(x_2), \dots \varphi_1(x_n))$

$\varphi_2 \circ \varphi_1^{-1}(x_1, x_2, \dots, x_n)$

$\varphi_2(\varphi_1^{-1}(x_1), \varphi_1^{-1}(x_2), \varphi_1^{-1}(x_3), \dots, \varphi_1^{-1}(x_n))$

$\varphi_1^{-1}(x_1)$ smooth

$\varphi_2(\varphi_1^{-1}(x_1))$ smooth.

Hint: $T^n = \mathbb{R}^n / \sim$

$(x_1, \dots, x_n) \sim (y_1, \dots, y_n)$

if $\quad (x_1 - y, \dots, y_1 - y_n) \in \mathbb{Z}^n$

$\mathbb{R} / \sim$ is a smooth manifold.

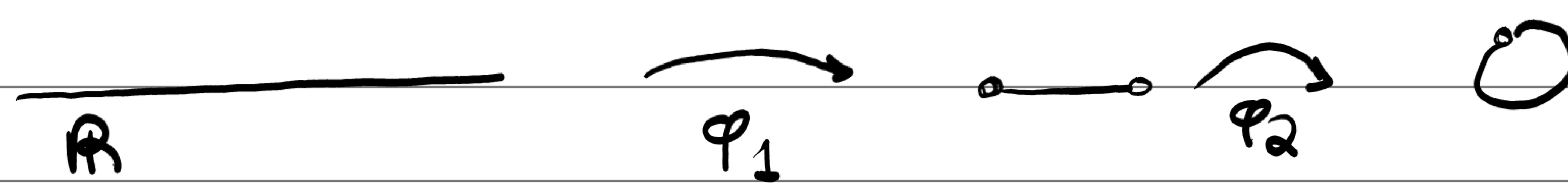
i.e. $\quad T^1 = S^1 = \mathbb{R}^1 / \sim$.

xRY if $\quad x - y \in \mathbb{Z}$.

Thus,

$\varphi_1 \circ \varphi_2^{-1}(x_1)$ is smooth

$\varphi_1(x_1, \dots, x_n) = \gamma \cdot (x_1, \dots, x_n)$.



$\mathbb{R} \setminus \sim \; = T^1 = S^1$. Shown to be a smooth manifold

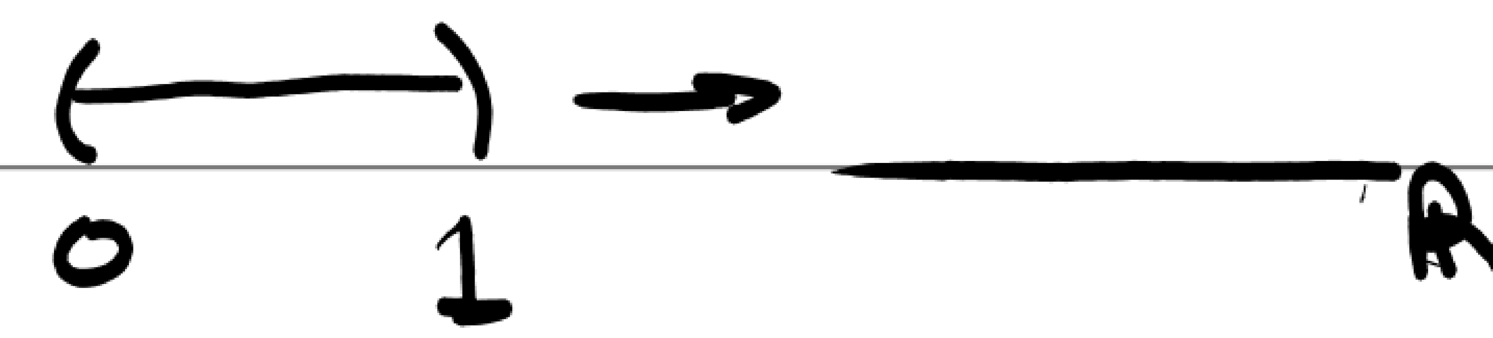
$\varphi_1 \circ \varphi_2^{-1}(x_1, x_2, \dots, x_n)$

$\varphi_1 : (0,1) \longrightarrow V_1 \subset \mathbb{R}$
open

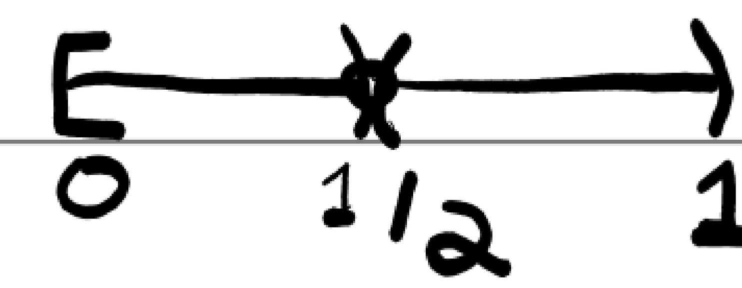
$\varphi_2 : [0, 1/2) \cup (\frac{1}{2}, 1) \longrightarrow (-1/2, 1/2)$

$$\varphi_2(x) = \begin{cases} x, & x < 1/2 \\ x-1, & x > 1/2. \end{cases}$$

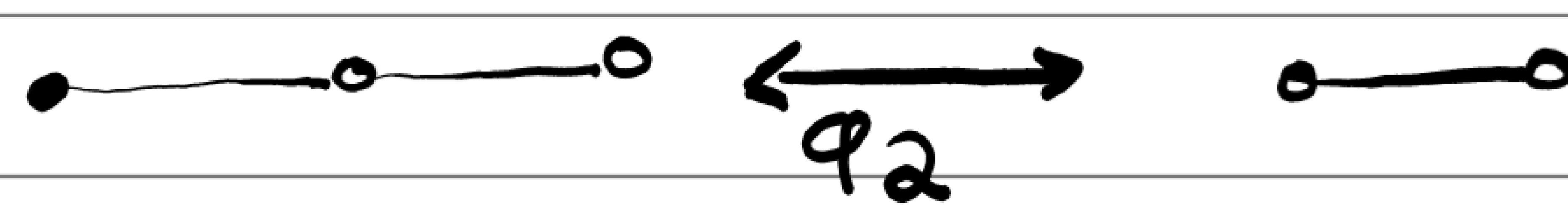
<u>$\varphi_1 \circ \varphi_2^{-1}$</u>



$$x = \begin{cases} \varphi_2^{-1}(x), & x < 1/2 \\ \varphi_2^{-1}(x-1), & x > 1/2 \end{cases}$$



$$\varphi_2(x) = \begin{cases} x & x < 1/2 \\ (x-1) & x > 1/2 \end{cases}$$



$\varphi_1 \circ \varphi_2^{-1} : (-1/2, 1/2) \longrightarrow V_1 \subset \mathbb{R}$

$$\varphi_1 \circ \varphi_2^{-1} = \begin{cases} x & \text{if } x < 0 \\ x - \sup(V) & \text{if } x > 0 \end{cases}$$ smooth

$\varphi_2 \circ \varphi_1^{-1} : V_1 \subset \mathbb{R} \longrightarrow (-1/2, 1/2)$

$\varphi_1^{-1} : V_1 \subset \mathbb{R} \to (0,1) \longrightarrow (-1/2, 1/2)$

$$\varphi_2 = \begin{cases} x, & x < 1/2 \\ x-1, & x > 1/2 \end{cases}$$ Smooth

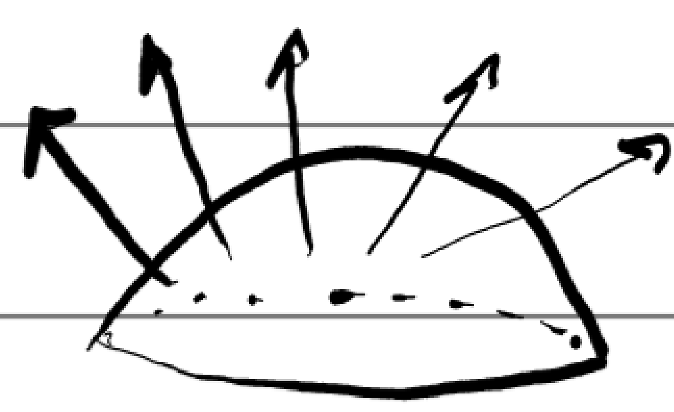
Last time

A tangent vector in M is
1) A tangent vector in a chart
2) An equivalence class of curves
3) A derivation of the ring of smooth functions on M.

TM denotes the tangent bundle. $TM \to M$ is a vector bundle
$\downarrow$ Projection map
M base space

The tangent bundle of an open subset $U \subset \mathbb{R}^n$

finite dimensional real vector-space.



$$\begin{array}{c} TU = U \times \mathbb{R}^n \\ p \downarrow \quad p(u,v) = u \\ U \end{array}$$

$(u, v_1) + (u, v_2)$, $t \cdot (u,v) = (u, t \cdot v)$
$(u, 0)$

Then $u \in U$, then $\{(u,v) \mid v \in \mathbb{R}^n\} \subset TU$ is a vector space.

- Products of manifolds

What do we want?

Given $M, N \in$ Man, want $M \times N \in$ Man,
$\pi_1 : M \times N \longrightarrow M$, $\pi_2 : M \times N \longrightarrow N$ (smooth maps)
Given $L, M, N \in$ Man, $f_1 : L \to M$, $f_2 : L \to N$
want $(f_1, f_2) : L \longrightarrow M \times N$
(For sets: $(f_1, f_2)(l) = (f_1(l), f_2(l))$.

$\pi_1 \circ (f_1, f_2) = f_1$, $\pi_2 \circ (f_1, f_2) = f_2$

- Given some $g : L \to M \times N$, we have $g = (\pi_1 \circ g, \pi_2 \circ g)$.

For sets

$M \times N = \{ (m,n) \mid m \in M, n \in N \}$

$\pi_1(m,n) = m$, $\pi_2(m,n) = n$

$(f_1, f_2)(l) = (f_1(l), f_2(l))$

$\pi_1((f_1,f_2)(l)) = \pi_1(f_1(l), f_2(l)) = f_1(l)$

$(\pi_1 \circ g, \pi_2 \circ g)(l) = (\pi_1(g(l)), \pi_2(g(l)))$

$g(l) = (m,n)$ for unique $m \in M$, $n \in N$

$= (\pi_1(m,n), \pi_2(m,n)) = (m,n) = g(l)$.

- **Def.** $M = (M, (\varphi_i : U_i \to V_i)_{i \in I})$

$N = (N, (\psi_j : U'_j \to V'_j)_{j \in J})$

$M \times N = (M \times N, (\varphi_i \times \psi_j : U_i \times U'_j \to V_i \times V'_j)_{(i,j) \in I \times J})$

$(\varphi_i \circ \pi_1, \psi_j \circ \pi_2) = (\varphi_i(u), \psi_j(u'))$

$\bigcup_{i,j} U_i \times U'_j$

$\bigcup_i U_i \times \left(\bigcup_j U'_j \right) = \bigcup_i (U_i \times N) = \left(\bigcup_i U_i \right) \times N$

$= M \times N$

$(i,j),(k,l) \in I \times J$

$\varphi_i \times \psi_j : \mathcal{U}_i \times \mathcal{U}'_j \longrightarrow V_i \times V'_j$

$\varphi_k \times \psi_l : \mathcal{U}_k \times \mathcal{U}'_l \longrightarrow V_k \times V'_l$

$(\varphi_k^{-1} \times \psi_l^{-1}) \circ (\varphi_i \times \psi_j)$

$= \underbrace{(\varphi_k^{-1} \circ \varphi_i)}_{\text{smooth}} \times \underbrace{(\psi_l^{-1} , \psi_j)}_{\text{smooth}}$

$D(f \times g)$

$$\begin{pmatrix} Df & 0 \\ 0 & Dg \end{pmatrix}.$$

• **Prop.** $\pi_1 : M \times N \longrightarrow M$ is a smooth map.

• **proof.** pick $i \in I$, $j \in J$

passing to the corresponding chart (i,j) in $M \times N$, i in M, j in N, π_1 becomes $V_i \times V'_j \longrightarrow V_i$

restriction of a linear map to open subset, smooth

• **Proof.** $L = (L, (x_k : W_k \to X_k)_{k \in K})$

pick $k \in K$, $(i,j) \in I \times J$

(f_1, f_2) becomes $X_k \xrightarrow[(f_1,f_2)]{} V_i \times V'_j$

$(\underbrace{\varphi_i \circ f_1 \circ x_k^{-1}}_{\text{smooth}}, \underbrace{\psi_j \circ f_2 \circ x_k^{-1}}_{\text{smooth}})$ $D(f,g) = \begin{pmatrix} Df \\ Dg \end{pmatrix}$

• **Def.** $M = (M, (\varphi_i : U_i \longrightarrow V_i))$

$TM = (\ldots, (\psi_i : \ldots \longrightarrow V_i \times \mathbb{R}^n)_{i \in I}).$

The underlying set $TM = (\ldots, (\psi_i : U_i \times \mathbb{R}^n \to V_i \times \mathbb{R}^n)_{i \in I}).$

$\left(\bigsqcup_{i\in I} U_i \times \mathbb{R}^n\right)/\sim$

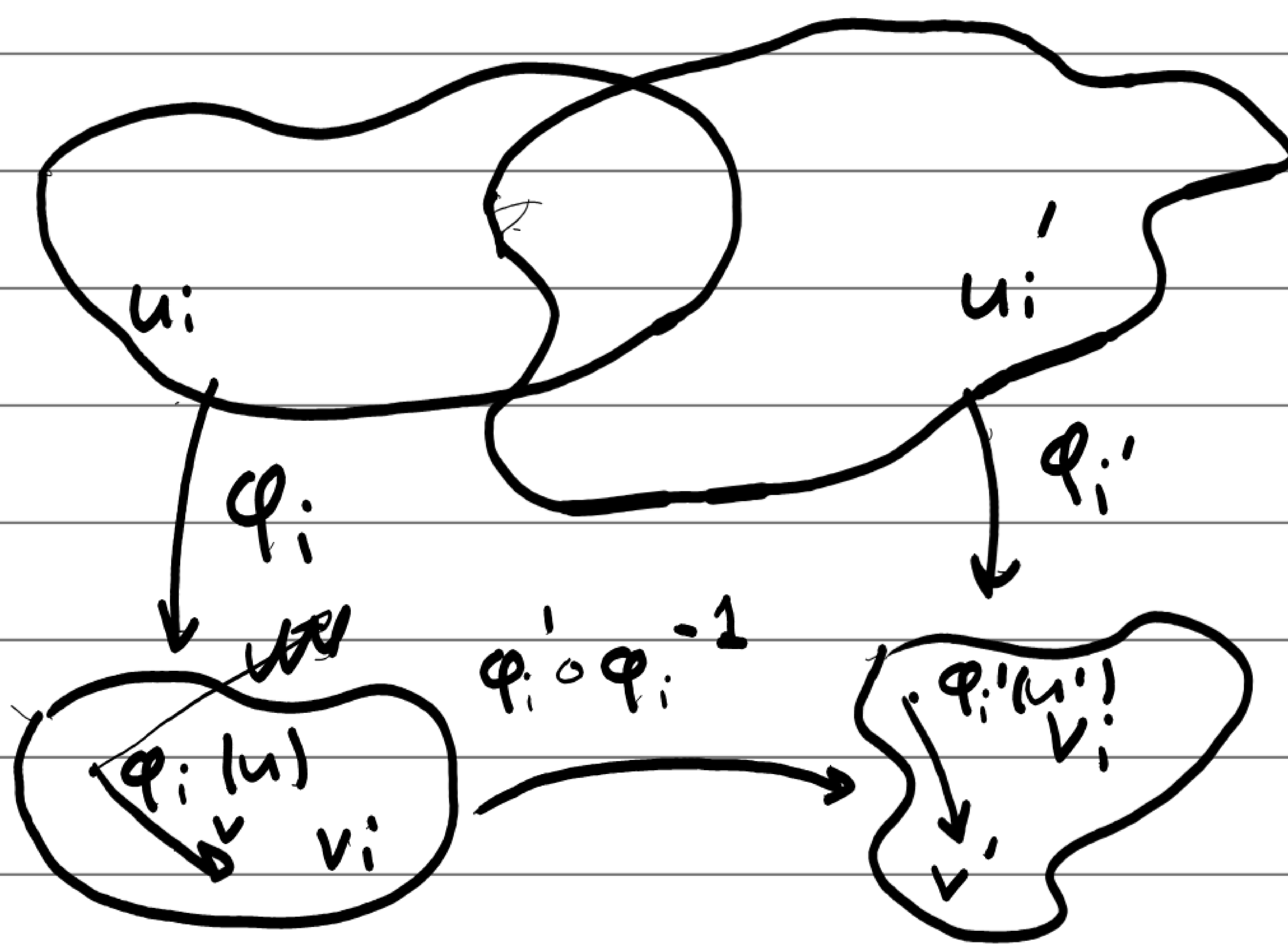
• <u>Def.</u> I: set, $i \in I$: A_i: set

$$\bigsqcup_{i\in I} = \bigcup_{i\in I} \{i\} \times A_i$$

coproduct of sets.

$\sim$: $i, i' \in I$ $\quad u \in U_i$ $\quad u' \in U_{i'}$
$\quad v \in \mathbb{R}^n$ $\quad v' \in \mathbb{R}^n$

$(i,(u,v)) \sim (i,(u',v'))$
if $u = u'$ and $D(\varphi_{i'} \circ \varphi_i^{-1})(v) = v'$



$\varphi_1 : (0,1) \longrightarrow V_1 \subset \mathbb{R}$

$\varphi_2 : [0,1/2) \cup (1/2,1) \longrightarrow \overset{V_2}{(-1/2, 1/2)}$

$\varphi_1 \circ \varphi_2^{-1} : \varphi_2(U_1 \cap U_2) \longrightarrow \varphi_1(U_1 \cap U_2)$

$\varphi_2 \circ \varphi_1^{-1} : \varphi_1(U_1 \cap U_2) \longrightarrow \varphi_2(U_1 \cap U_2)$.

$\varphi_1(U_1 \cap U_2)$

$U_1 = (0,1) \cap U_2 = [0,1/2) \cup (1/2,1)$

$U_1 \cap U_2 = (0,1/2) \cup (1/2,1)$

$\varphi_1(U_1 \cap U_2)$

maps $0 \to \inf(V_1)$

$1 \to \sup(V_1)$

$(\inf(V_1), 0) \cup (0, \sup(V_1))$

$\longrightarrow (\inf(V_1), 0) \cup (0, \sup(V_1))$

$$\begin{cases} x & x < 0 \\ x + \inf(V_1) & x > 0 \end{cases}$$

$$Df(x) = \begin{cases} 1 & x < 0 \\ 1 & x > 0 \end{cases}$$

smooth for domain.

$$\varphi_1 \circ \varphi_2^{-1} : \varphi_2(u_1 \cap u_2) \longrightarrow \varphi_1(u_1 \cap u_2)$$

$$\varphi_2 : [0, 1/2) \cup (1/2, 1) \longrightarrow (-1/2, 1/2)$$

$$\varphi_2 = \begin{cases} x & \text{if } x < 0 \\ x-1 & \text{if } x > 0 \end{cases}$$

$= x \quad \text{if } x < 0$

$= x - 1 \text{ if } x > 0$

$x = \varphi_2^{-1}(x) \quad \text{if } x < 0$

$x = \varphi_2^{-1}(x-1) \text{ if } x > 0$

$\varphi_2^{-1} = id \text{ if } x < 0$

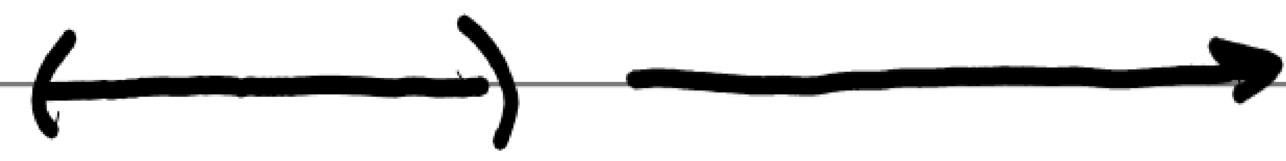
$\varphi_2^{-1} =$

$x - 1 \overset{\varphi_2^{-1}}{\longmapsto} x$, thus $x \overset{\varphi_2^{-1}}{\longmapsto} x + 1$

$\circ$

$\varphi_1 : (0,1) \longrightarrow V \subset \mathbb{R}$

$(0,1)$



$f(x) = 1/x$, $\quad y = 1/x$, $x = 1/f(x)$

$\varphi_1(x) = 1/x - 1/2 \quad = -\frac{1}{x}$

$\tan(\pi x - \pi/2)$ is a suitable map.

$\varphi_1 = \tan(\pi x - \pi/2)$

Last time:

$\mathbb{R}^n$ need to write a homeomorphism

$M = (M, (\varphi_i : U_i \to V_i)_{i\in I})$ transition map

$TM = \left(\coprod_{i \in I} U_i \times \mathbb{R}^n \right) / (u_i, v_i) \sim (u_j, v_j)$ φ

$\iff (u_i = u_j) \wedge (D(\varphi_j \circ \varphi_i^{-1})(v_i) = v_j$

$(\varphi_i \times id_{\mathbb{R}^n} : U_i \times \mathbb{R}^n \to V_i \times \mathbb{R}^n)_{i \in I}.$

$\bigcup_i U_i \times \mathbb{R}^n = TM$ / compatibility of charts

$(\varphi_j \times id_{\mathbb{R}^n} \circ (\varphi_i \times id_{\mathbb{R}})^{-1} = (\varphi_j \times \varphi_i)^{-1} \times id_{\mathbb{R}^n}.$

co(dom) =

- Exa. a) $T\mathbb{R}^n = \mathbb{R}^n \times \mathbb{R}^n$

$TV = V \times V$ $\qquad V \in \mathrm{Vect}_{\mathbb{R}}^{f.d.}$

$U \underset{open}{\subset} V$: $\quad TU = U \times V$

b.) S^n: start with $V \in \mathrm{Vect}^{f.d.}_{\mathbb{R}, \langle -,- \rangle}$

$S^V = \Big(V \cup \{\infty\}, \quad \varphi_1 : V \xrightarrow{id} V$

$\varphi_2 : V \cup \{\infty\} \setminus \{0\} \to V$

$v \longmapsto \frac{1}{\|v\|} \cdot v \Big)$

$\varphi_2 = \varphi_2 : V \setminus \{0\} \to V \setminus \{0\}$

$v \longmapsto \frac{1}{\|v\|^2} \cdot v$

$\varphi_1 \circ \varphi_2^{-1} : \varphi_2^{-1} : V \setminus \{0\} \to V \setminus \{0\}$

$$\frac{1}{\|v\|^2} \cdot \|v\| = \|w\|$$

$$\|v\| = \frac{1}{\|w\|}$$

$$v = w \cdot \|v\|^2 = \frac{w}{\|w\|^2}.$$

$$T(S^V) = (TV \sqcup V, \varphi \times id_V, \varphi_2 \times id_V)$$

In general $TS^V \cong V \times S^V$

However $TS^1 \cong \mathbb{R} \times S$, $TS^2 \cong \mathbb{R}^2 \times S^2$?

HW 2: write a smooth map that

assigns $S^2 \xrightarrow{s} TS^2$

s.t.

$$\begin{tikzcd} S^2 \arrow[r, "s"] \arrow[rr, bend right, "id"'] & TS^2 \arrow[r, "p"] & S^2 \end{tikzcd}$$

section at most at one point, i.e

$\forall v \in S^2 \setminus \{\infty\}$ $s(v) \neq 0$, $0 \in TS^2$.

HW 4: $T(T^n) = T^n \times \mathbb{R}^n$?

HW 3: $V \in Vect_{\mathbb{R}}^{f.d.}$

a lattice $L \subset V$: $L = \varphi(\mathbb{Z}^n)$

$L = \mathbb{Z}^n \subset \mathbb{R}^n = V$ $\qquad \varphi: \mathbb{R}^n \xrightarrow[iso]{\cong} V$

$V/L = V/\sim$, $v_1 \sim v_2$ if $v_1 - v_2 \in L$.

quotient group. abelian L is normal

a.) equip the quotient V/L with a structure of smooth manifold

b.) Prove $V/L \times V/L \xrightarrow{+} V/L$ is a smooth map. (elliptic curve)

c.) Prove that $V/L \xrightarrow[\varphi]{\cong} V'/L'$ $\dim V = \dim V'$

elliptic curve vector bundle.

• Proposition $M \in \mathrm{Man}$

$TM \in \mathrm{Man}$

$\downarrow p$ smooth

M

$V \in \mathrm{Vect}_{\mathbb{R}}$ $0 \in V$

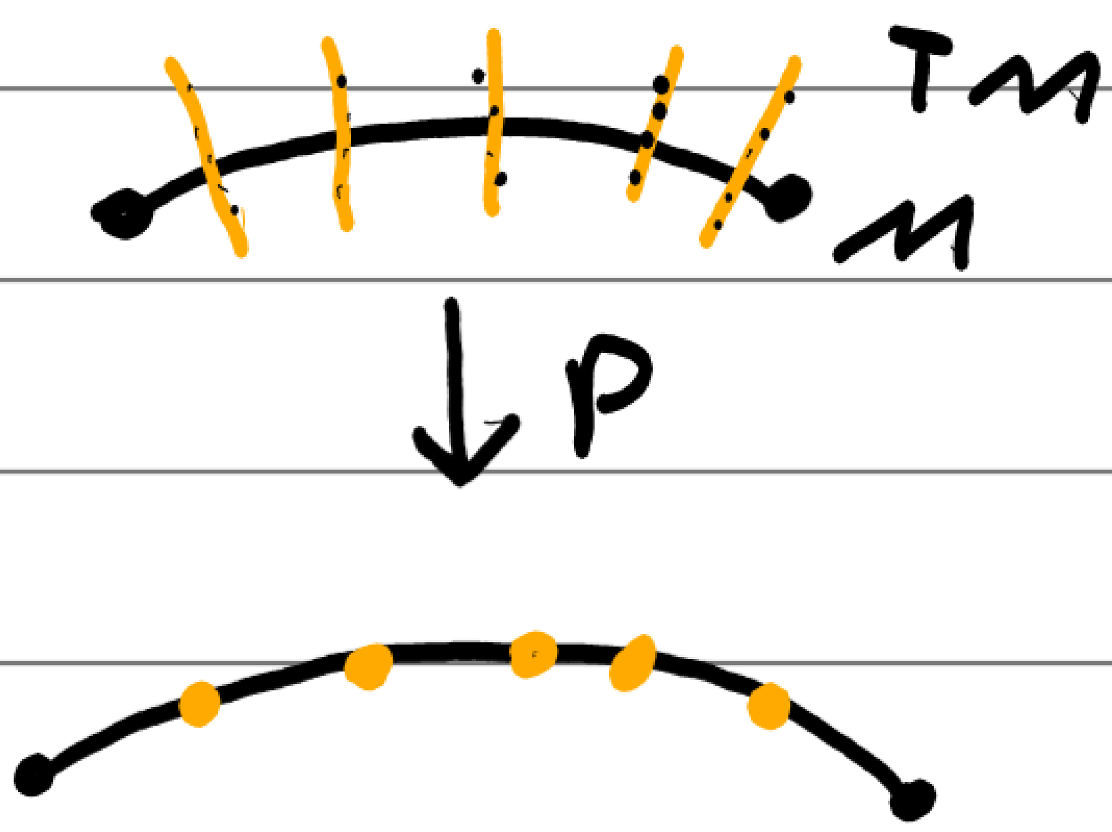
$0 : 1 \longrightarrow V$

$\cdot : \mathbb{R} \times V \longrightarrow V$

$+ : V \times V \longrightarrow V$

$|A \times B| = |A| \cdot |B|$

$|\prod_{\emptyset}| = 1$, $|A| = |A|$



smooth

$0 : M \longrightarrow TM$

$\cdot : \mathbb{R} \times TM \longrightarrow TM$

$+ : TM \times TM \not\longrightarrow TM$ Naive!

$: \underbrace{TM \times TM}_{M} \longrightarrow TM$

"

$\{(v_1, v_2) \in TM \times TM \mid p(v_1) = p(v_2)\}$.

In a lecture, submersion will come in handy.

• Proof.

— Prop. — Suppose we have two smooth manifolds $M = (M, (\varphi_i : U_i \longrightarrow V_i)_{i \in J})$

$N = (N, (\psi_i : U_i' \longrightarrow V_i')_{i \in I})$

If $f : M \longrightarrow N$ is a map of sets such that $\forall i : f(U_i) \subset U_i'$.

Then f is smooth iff $\forall i$ $\psi_i \circ f \circ \varphi_i^{-1} : V_i \longrightarrow V_i'$ is a smooth map.

<u>Proof</u> $\psi_j \circ f \circ \varphi_i^{-1} = (\psi_j \circ \psi_i^{-1}) \circ (\psi_i \circ f \circ \varphi_i^{-1})$

a) $0: M \to TM$ is smooth

$M = (M, (\varphi_i : U_i \to V_i))$

$TM = (TM, (\varphi_i \times id_{\mathbb{R}^n} : U_i \times \mathbb{R}^n \to V_i \times \mathbb{R}^n)_{i \in I})$

$0: M \to TM$ is smooth $\Leftrightarrow \forall i$

$m \mapsto (m, 0)$ $(\varphi_i \times id) \circ 0 \circ \varphi_i^{-1})(v)$

$= (\varphi_i \times id_{\mathbb{R}^n})(\varphi_i^{-1}(v), 0)$

$= (\varphi_i(\varphi_i(v)), id\, 0) = (v, 0).$

exercise for b) and c)

a) $V_i \to V_i \times \mathbb{R}^n$ in the Ith chart.

$v \mapsto (v, 0)$

b) $\mathbb{R} \times V_i \times \mathbb{R}^n \to V_i \times \mathbb{R}^n$

$(t, v, w) \mapsto (v, t \cdot w)$

c) $V_i \times \mathbb{R}^n \times \mathbb{R}^n \to V_i \times \mathbb{R}^n$

$(v, w_1, w_2) \to (v, w_1 + w_2).$

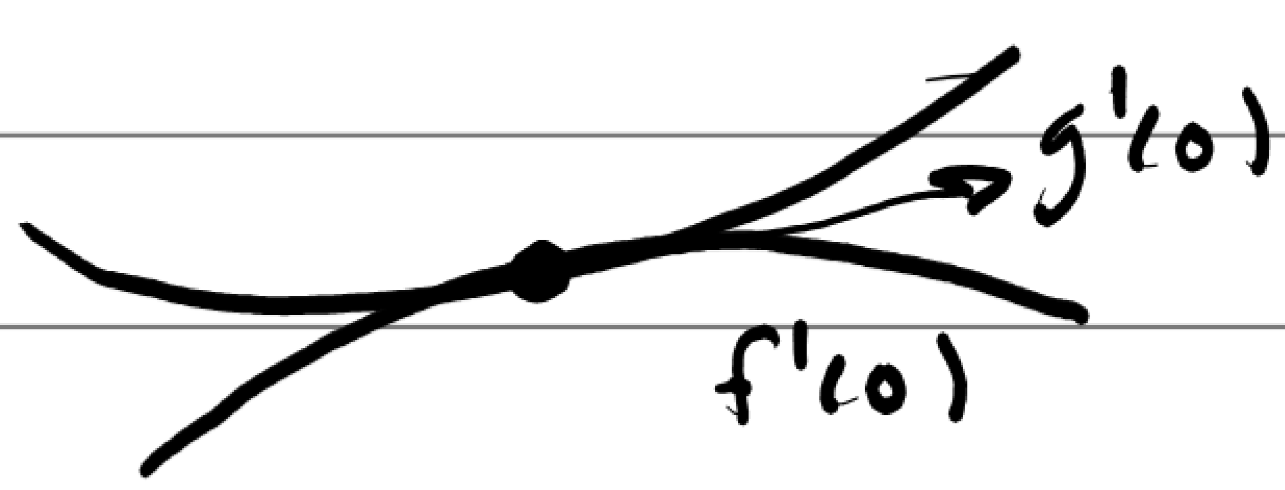
<u>Construction 2:</u>

$TM = C^\infty(\mathbb{R}, M)/\sim$

$f \sim g \Leftrightarrow f(0) = g(0)$ <u>and</u> $f'(0) = g'(0)$

(in some chart)

$C^\infty(\mathbb{R}, \mathbb{S})/\sim$



• Proposition

$$C^\infty(\mathbb{R}, M)/\sim \longrightarrow TM$$

is a bijection

• Recall $X/R \xrightarrow{f} Y$ are in bijection with maps of sets $X \xrightarrow[g]{} Y$ such that g respects R.

$$x_1 R x_2 \Rightarrow g(x_1) = g(x_2).$$

"f is well-defined"

$$f([x]) = g(x).$$

• Proof of Prop. $\underset{f\in}{C^\infty}(\mathbb{R}, M) \longrightarrow TM$

$$TM = \coprod_{i\in I} U_i \times \mathbb{R}^n / \sim$$

$$(u_i, w_i) \sim (u_j, w_j)$$

$$\iff u_i = u_j \text{ and } D(\varphi_j \circ \varphi_i^{-1})(w_i) = w_j.$$

$f(0)$

pick some i s.t. $f(0) \in U_i$.

Set $r(f) = [(f(0), D(\varphi_i \circ f)(0)]$

If

$$[(f(0), D(\varphi_i \circ f)(0)] = [(f(0), D(\varphi_j \circ f)(0)]$$

and $D(\varphi_j \circ \varphi_i^{-1})(w_i) = w_j$.

$$D(\varphi_j \circ \varphi_i^{-1})\left(D(\varphi_i \circ f)(0)\right)$$

$$= D(\varphi_j \circ \underbrace{\varphi_i^{-1} \circ \varphi_i}_{I} \circ f)(0)$$

$$= D(\varphi_j \circ f)(0).$$

Tensors

$D(\varphi_i \circ f)(0) = D(\varphi_i \circ g)(0)$

$$\begin{tikzcd} \mathbb{R} \arrow[r, "f"] \arrow[drr] & M \supset U_i \arrow[r, "\varphi_i"] & V_i \\ & & \mathbb{R}^n \arrow[u, phantom, "\subset" rotate=90] \end{tikzcd}$$

2) suppose $f, g \in C^\infty(\mathbb{R}, M)$, $f \sim g$

$D(\varphi_i \circ f)(0) = D(\varphi_i \circ g)(0)$

$f(0) = g(0)$

want: $r(f) = r(g)$

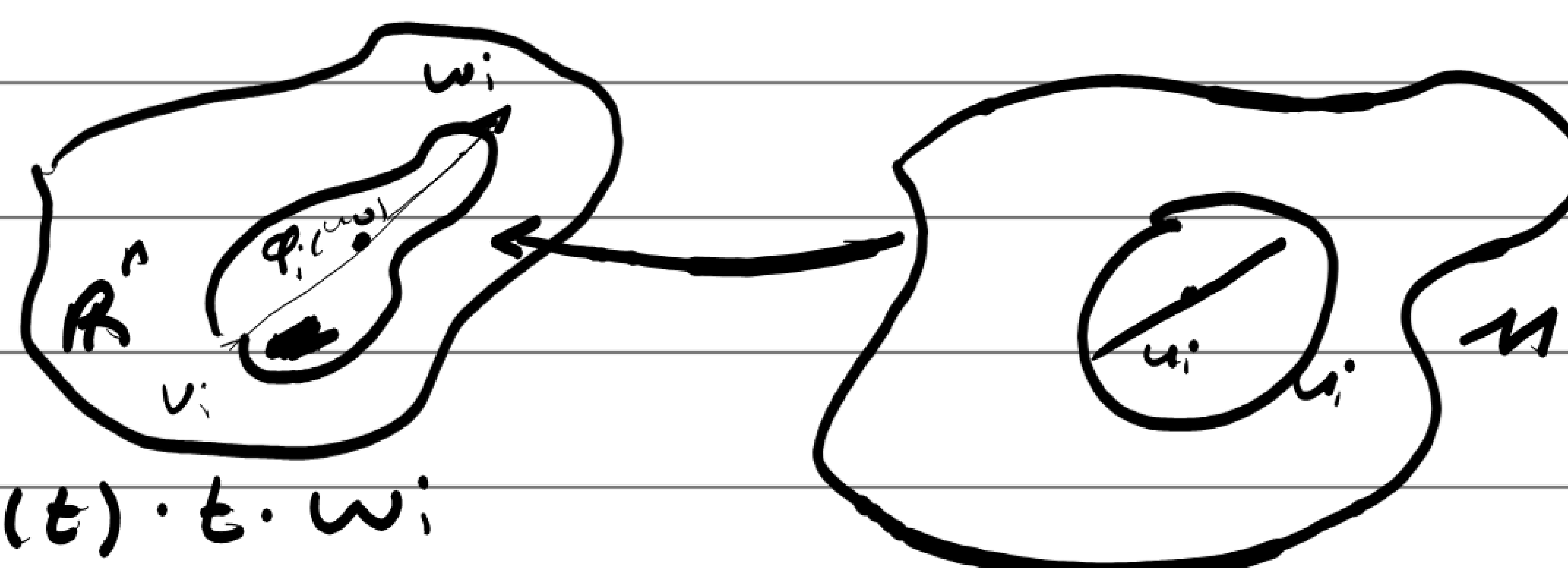
$[(f(0), D(\varphi_i \circ f)(0))] = [(g(0), D(\varphi_i \circ g)(0))]$

$\quad \| \; D(\varphi_i)(f(0)) \cdot (Df(0)) = f'(0).$

3) $s : \left(\bigsqcup_{i \in I} U_i \times \mathbb{R}_n \right) / \sim \; \longrightarrow C^\infty(\mathbb{R}, M)/\sim$

pick some $i \in I$: $U_i \times \mathbb{R}^n \longrightarrow C^\infty(\mathbb{R}, M)/\sim$

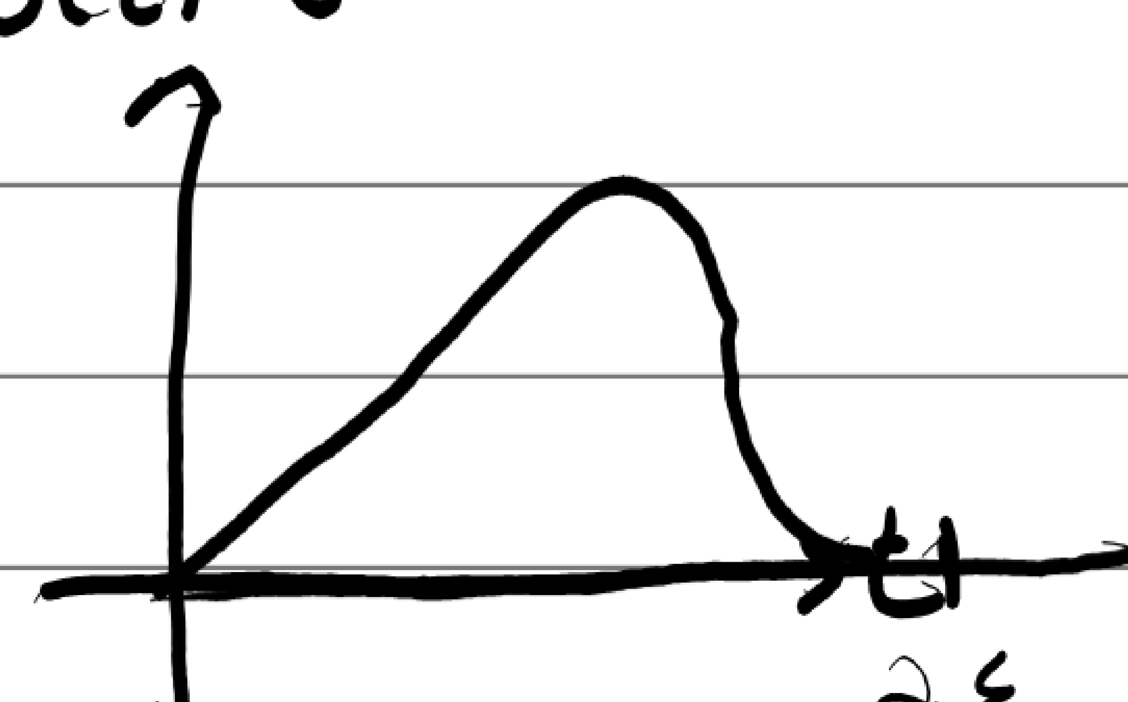
$(u_i, w_i) \longmapsto \varphi_i^{-1} \circ h$



$h : \mathbb{R} \longrightarrow V_i$

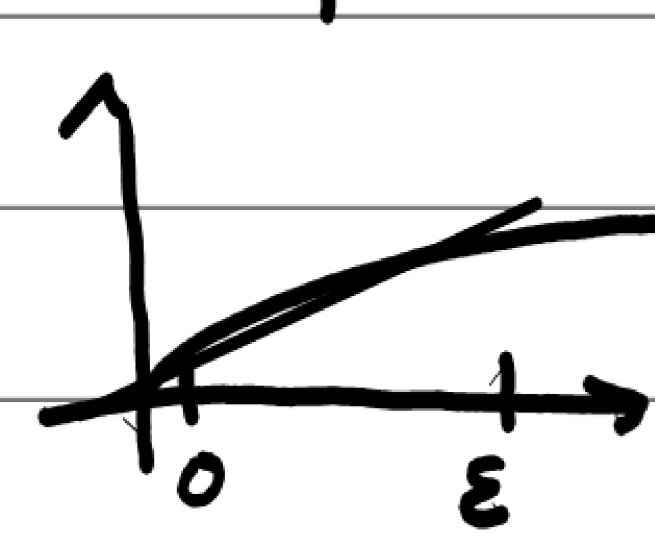
$h(t) = \varphi_i(u_i) + b(t) \cdot t \cdot w_i$

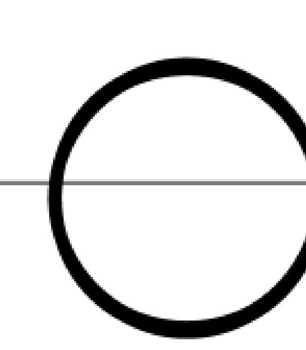
$$b(t) = \begin{cases} 1, & t \in (-\varepsilon, \varepsilon) \\ 0, & |t| \geq 2\varepsilon \end{cases}$$

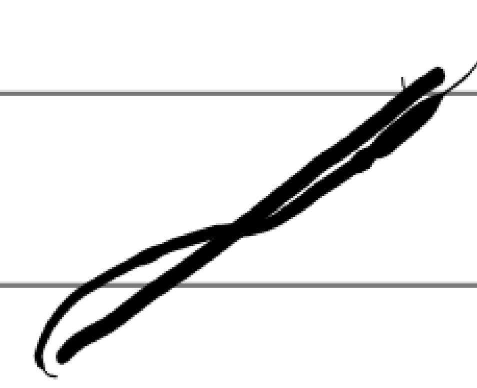


$b(t) \in (0,1)$, $\varepsilon \leq |t| < 2\varepsilon$.

$h(t) = \varphi_i(u_i) + c(t) \cdot w_i$







$(u_i, w_i) \sim (u_j, w_j)$

$u_i = u_j$ **and** $D(\varphi_j \circ \varphi_i^{-1})(\varphi_i(u_i))(w_i) = w_j$

want: $\underset{[\varphi_i^{-1} \circ h_i]}{\underset{\shortparallel}{S(u_i, w_i)}} = \underset{[\varphi_j^{-1} \circ h_j]}{\underset{\shortparallel}{S(u_j, w_j)}}$

$\iff \varphi_i^{-1} \circ h_i \sim \varphi_j^{-1} \circ h_j$

$$\varphi_j^{-1}(h_j(0)) = \varphi_j^{-1}(\varphi_j(u_j)) = u_j = u_i$$

In the J-th chart

$D(\varphi_i \circ \varphi_i^{-1} \circ h_i)(0) = D(\varphi_i \circ \varphi_j^{-1} \circ h_j)(0)$

$= \underset{w_i}{\underset{\shortparallel}{h_i'(0)}}$ $\qquad \underset{\shortparallel}{} D(\varphi_i \circ \varphi_j^{-1})(\underset{\varphi_j(u_j)}{\underset{\shortparallel}{h_j(0)}})(\underset{w_j}{\underset{\shortparallel}{h_j'(0)}})$

5) $r \circ s = id_{TM}$

6) $s \circ r = id_{C^\infty(\mathbb{R}, M)/\sim}$

prove 5 and 6.

Last time:

(1) TM (charts) $\cong_{(2)} TM$ kinematic

$\quad \cong$ TM (derivations) (3)

The algebra of smooth manifolds

what is $C^\infty(M,\mathbb{R})$ in physics " observables

Answer: a commutative real algebra

Better answer a C^∞-ring.

Def. A commutative real algebra is $(A, 0, +, \cdot, \iota)$

A: underlying set

$0 \in A$

$+: A \times A \longrightarrow A$

$\cdot: A \times A \longrightarrow A$

$\iota: \mathbb{R} \to A$

$0 := \iota(0)$, $1 := \iota(1)$

such that $\forall a,b,c \in A$ $\forall r,s \in \mathbb{R}$

$a+(b+c) = (a+b)+c$

$0+a = a$

$a\cdot(b\cdot c) = (a\cdot b)\cdot c$

$a\cdot(b+c) = ab+ac$

$\iota(r+s) = \iota(r)+\iota(s)$

$\iota(rs) = \iota(r)\cdot\iota(s)$

Alternatively a homomorphism of commutative rings $\iota: \mathbb{R} \longrightarrow A$

Exa. $C^\infty(M)$ All operations are defined pointwise $(f+g)(m) = f(m)+g(m)$

$\iota(r)(m) = r$

$\iota(r+s)(m) = r+s = \iota(r)(m) + \iota(s)(m)$

$= (\iota(r)+\iota(s))(m)$

$M = \emptyset : C^\infty(M, \mathbb{R})$ $f: A \to B$

$G \subset A \times B$, $\forall a \in A \; \exists! \, b \in B : (a,b) \in G$.

$A = \emptyset$: $A \times B = \emptyset \times B = \emptyset$

$G = \emptyset$.

$\forall a \in \emptyset \; \exists! \, b \in B : (a,b) \in \emptyset$

Fact: A smooth manifold M can be reconstructed from $C^\infty(M, \mathbb{R})$

suppose A is a commutative real algebra such that $\exists \varphi : A \xrightarrow{\cong} C^\infty(M)$.

Then M can be reconstructed from A as follows:

The underlying set of M is the set of homomorphisms of algebras $A \to \mathbb{R}$

Reference: Jet Nestruev

Smooth manifolds and observables.

Second Edition

- Proposition If M is a hausdorff, second countable smooth manifold, then, the canonical map of sets

$M \xrightarrow{ev} \mathrm{Hom}(C^\infty M, \mathbb{R})$ is a bijection

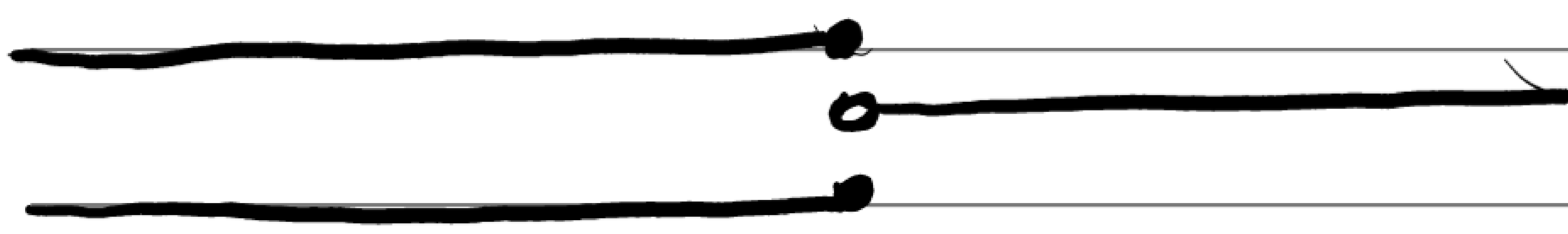
$ev(m)$

- Def. Topological space (X, U) is hausdorff if for any points $x, y \in X$

$(x \neq y) \Rightarrow \exists V, W \in X$ s.t. $x \in V$, $y \in W$ and

$V \cap W = \emptyset$.

• Exa: 1) $\mathbb{R}$ 3) $\mathbb{R}^n$
2) $\mathbb{Q}$ 4) any embedded



$M = (-\infty, 0]_1 \sqcup (-\infty, 0]_2 \sqcup (0, \infty)$

Two charts

$\varphi_1 : (-\infty, 0]_1 \sqcup (0, \infty) \longrightarrow \mathbb{R}$

$\varphi_2 : (-\infty, 0]_2 \sqcup (0, \infty) \longrightarrow \mathbb{R}$

compatibility:

$\varphi_2 \circ \varphi_1^{-1} : (0, \infty) \xrightarrow[id]{} (0, \infty)$

$\varphi_1 \circ \varphi_2^{-1} : (0, \infty) \xrightarrow[id]{} (0, \infty)$

• **Def.** A topological space $(X, \mathcal{U})$ is second countable if $\exists$ countable $\mathcal{B} \subset \mathcal{U}$ such that $\forall V \in \mathcal{U} : V = \bigcup_{B \in \mathcal{B},\, B \subset V} B$

• Exa. a) $\mathbb{R}$ is second countable

$$\mathcal{B} = \{ (a, b) \mid a, b \in \mathbb{Q} \}$$

$$(r, s) = \bigcup_{(a,b) \subset (r,s)} (a, b) \longrightarrow a, b \in \mathbb{Q}$$

b.) $\mathbb{R}^n$ is also second countable

$$\mathcal{B} = \{ B(x, \varepsilon) \mid \varepsilon \in \mathbb{Q}_{>0},\ x \in \mathbb{Q}^n \}$$

c) embedded smooth manifolds

• Non-example

The long line

• Proof of proposition

a) ev is injective

if $m_1 \neq m_2$, then $ev(m_1) \neq ev(m_2)$.

That is, $\exists f \in C^\infty(M)$:

$$\begin{array}{ccc} ev(m_1)(f) & \neq & ev(m_2)(f) \\ \| & & \| \\ f(m_1) & \neq & f(m_2) \end{array}$$

Since M is Hausdorff, $\exists$ open subsets V_1, V_2 s.t. $m_1 \in V_1$, $m_2 \in V_2$, $V_1 \cap V_2 = \emptyset$

must show that

can assume V_1, V_2 are domains of charts

$\varphi_1 : V_1 \longrightarrow W_1$ (compatible w/ M)

$\varphi_2 : V_2 \longrightarrow W_2$

pick $\varepsilon > 0$: $B(\varphi_1(m_1), 2\varepsilon) \subset W_1$

Take $f : M \longrightarrow \mathbb{R}$

$$f = \begin{cases} 0 & \text{if } m \notin V_1 \\ b\left(\|\varphi_1(m) - \varphi_1(m_1)\|^2 \cdot 1/\varepsilon^2 \right), & \text{if } m \in V_1 \end{cases}$$

$b : \mathbb{R} \to \mathbb{R}$ smooth s.t.

$$b(0) = 1 \qquad b\big|_{[1,\infty)} = 0$$

b) Use Whitney's embedding theorem (requires M to be second countable)

Assume M to be embedded $M \subset \mathbb{R}^n$.

Given a homomorphism $\varphi : C^\infty(M) \to \mathbb{R}$,

• **Thm.** $M \xrightarrow{\cong} \mathrm{Hom}(C^\infty(M), \mathbb{R})$

$m \longmapsto ev_m = (f \mapsto f(m))$

• **Proof.** Injectivity ✓

Surjectivity pick a smooth embedding w/ a closed image $M \subset \mathbb{R}^m$, i.e. $\mathbb{R}^m / M$ is open.

$C^\infty(\mathbb{R}^m) \longrightarrow C^\infty(M)$

• Restriction preserves all operations

If $\varphi : C^\infty M \longrightarrow \mathbb{R}$ is a homomorphism

$$\begin{tikzcd}[column sep=small] & C^\infty M \arrow[dr, "\varphi"] & \\ C^\infty \mathbb{R}^m \arrow[ur, "r"] \arrow[rr, "\varphi \circ r"'] & & \mathbb{R} \end{tikzcd}$$

$\exists p \in \mathbb{R}^m$ s.t. $\varphi \circ r = ev_p$.

claim: $p \in M$. (Thus, $\varphi = ev_p$

Suppose $p \notin M$. There $\exists g \in C^\infty(\mathbb{R})$ s.t. $g|_M = 0$ and $g(p) \neq 0$.

(Need: $\mathbb{R}^m \setminus M$ is open).

(★) evaluate at g:

$\varphi(r(g)) = g(p) \neq 0$

$\varphi(r(0))$

$\varphi(0) = 0$ ↯

Therefore, $p \in M$.

- **Prop.** $\mathbb{R}^m \xrightarrow{\cong} \hom(C^\infty \mathbb{R}^m, \mathbb{R})$
- Proof: Injec ✓

Surjectivity: Assume $\varphi : C^\infty \mathbb{R}^m \longrightarrow \mathbb{R}$.

Hadamard's Lemma:

If $f : \mathbb{R}^m \longrightarrow \mathbb{R}$ is smooth, then $\exists\, g_i : \mathbb{R}^m \longrightarrow \mathbb{R}$ smooth $(1 \le i \le m)$

$$f = f(0) + \sum_i x_i \cdot g_i$$

- Example $m = 1$

$$f(x) - f(0) = x \cdot g(x)$$
$$g(x) = \frac{f(x) - f(0)}{x - 0}$$

$f'(0) = g(0)$

$m > 1$ not unique

Set $p_i = \varphi(x_i)$ $\quad x_i : \mathbb{R}^m \longrightarrow \mathbb{R}$ ith coordinate

Now, $p \in \mathbb{R}^m$ and we claim that $\varphi = ev_p$.

Pick $f \in C^\infty M$ $\quad f = f(p) = \sum_i (x_i - p_i) \cdot g_i$

$\exists g_i$: Hadamard's lemma

we have $\varphi(f) = \varphi(f(p) + \sum (x_i - p_i) \cdot g_i)$

$$= f(p) + \sum (\varphi(x_i) - p_i) \cdot \varphi(g_i)) = f(p).$$

Sar's thm? Reference:

Transformations of deformation

HW6 Prove M, N are smooth manifolds

then $C^\infty(M, N) \xrightarrow{\cong} \operatorname{Hom}(C^\infty N, C^\infty M)$

$\overset{\psi}{f} \longmapsto (g^{\in} \longmapsto g \cdot f)$. ☆

Show bijection.

• **Remark** $M = \mathbb{R}^0 \cong$
$$N \cong C^\infty(\mathbb{R}^0, N) \xrightarrow{\cong} \hom(C^\infty N, \mathbb{R}).$$

$N \cong C^\infty(\mathbb{R}^0, N)$, $M \cong C^\infty(\mathbb{R}^0, M) \Rightarrow \hom(C^\infty N, \mathbb{R}) \times \hom(C^\infty M, A)$

• **Remark** The functor

$$C^\infty : Man^{op} \longrightarrow CommAlg_{\mathbb{R}} \supset F$$

$\mathrm{Ob}\, F = \{ A \in (Alg_{\mathbb{R}}) \mid \exists M : A \cong C^\infty(M, \mathbb{R}) \}$

is fully faithful. In particular,
$$C^\infty : Man^{op} \longrightarrow F$$
is an equivalence of categories

• **Remark** constructions of differential geometry continue to make sense for commutative real algebras
$$A \in CAlg_{\mathbb{R}}, \quad A \notin F.$$

• **Exa.**

a) Take $G \subset \mathbb{R}^m$ closed (i.e. $\mathbb{R}^m \setminus G$ is open.)

Take $I = \{ f \in C^\infty \mathbb{R}^m \mid f|_G = 0 \}$

Then $A = C^\infty(\mathbb{R}^m) / I$ is the algebra of smooth functions on G.

• **Exa.** $f'(a)$
$$f(a+\varepsilon) = f(a) + \varepsilon \cdot f'(a) + \varepsilon^2 \cdot g(a+\varepsilon)$$

Take $\varepsilon^2 = 0$
$$= f(a) + \varepsilon \cdot f'(a)$$

$$f'(a) : f(a+\varepsilon) - f(a) = \varepsilon \cdot f'(a)$$

$A \in CAlg_{\mathbb{R}}$

$A = \mathbb{R}[\varepsilon]/\varepsilon^2 = \{a + b\cdot\varepsilon \mid a, b \in \mathbb{R}\}$

$(a_1 + b_1 \cdot \varepsilon) + (a_2 + b_2 \cdot \varepsilon) = (a_1 + a_2) + (b_1 + b_2)\cdot\varepsilon$

$(a_1 + b_1 \cdot \varepsilon)(a_2 + b_2 \cdot \varepsilon) = a_1 a_2 + (a_1 b_2 + a_2 b_1)\cdot\varepsilon$

$(\cdots\bullet\cdots)$ infinitesimal neighborhood / fuzz

geometry $\longleftrightarrow$	algebra
M: smooth manifold	$C^\infty M$: comm real algebra
$p \in M$ $\xrightarrow{p \mapsto ev_p}$	$C^\infty M \xrightarrow{p} \mathbb{R}$: homomorphism
$M \to N$ smooth map	$C^\infty N \to C^\infty M$: homomorphism
$v \in TM$	$C^\infty M \to \mathbb{R}$: derivation
$C^\infty M \xrightarrow{d} \Omega^1 M$	$C^\infty M \to \Omega^1 C^\infty M$ kahler C^∞-diff
$M \to TM$ vectorfield	$C^\infty M \to C^\infty M$: derivation

Recall A module over a commutative real algebra A is a real vector space M together with a homomorphism of commutative real algebras $A \longrightarrow End(M)$. where $End M$ is the algebra of endomorphisms are $\mathbb{R}$-linear maps $M \to M$ $+, -, 0$ defined pointwise. $1 = id_M$ $\quad L(a)m = a\cdot m$

$f \cdot g = f \circ g$

Unfold: M is a real vector space with addit

$A \times M \longrightarrow M$: scalar multiplication

$(a_1 + a_2)m = a_1 m + a_2 m$; $0 \cdot m = 0$

$a \cdot (m_1 + m_2) = a \cdot m_1 + a \cdot m_2$; $a \cdot 0 = 0$

$(a_1 \cdot a_2) \cdot m = a_1 \cdot (a_2 \cdot m)$; $1 \cdot m = m$

$(r \cdot a) \cdot m = a \cdot (r \cdot m) = r \cdot (a \cdot m)$ $\quad r \in \mathbb{R}$

$V \cong \mathbb{R}^n$

• **Exa.** $A = C^\infty M$, $V = \mathbb{R}$

An A-module structure on V is a homomorphism of $\mathbb{R}$-algebras $C^\infty(M) \longrightarrow \mathrm{End}(M) \cong \mathbb{R}$

i.e, a point $p \in M$

$f \in C^\infty M$, $r \in V = \mathbb{R}$, $f(r) = f(p) \cdot r$

• **Exa.** $A = \mathbb{R}$, $V \in \mathrm{Vect}_{\mathbb{R}}$

$l(r) = l(r \cdot 1) = r \cdot l(1) = r \cdot \mathrm{id}_V$

An $\mathbb{R}$ module $\equiv$ $\mathbb{R}$-vector space

Recall $C^\infty(M)$-module structures on $\mathbb{R}$

$\equiv$ homomorphisms $C^\infty M \longrightarrow \mathbb{R}$

$\equiv$ points in M.

$p \in M$: $\underset{C^\infty M}{f} \cdot \underset{\mathbb{R}}{r} = f(p) r$

• **Def.** Suppose A is a commutative real algebra, M is an A-module. A derivation of A w/ values in M is an $\mathbb{R}$ linear map $A \xrightarrow{d} M$ s.t. Leibniz rule holds

$$d(a_1 a_2) = \underbrace{d(a_1)}_{M} \cdot \underbrace{a_2}_{a} + \underbrace{a_1}_{a} \cdot \underbrace{d(a_2)}_{M}$$

• Exa. $A = C^\infty S$, $M = C^\infty S$

$f \longmapsto f'$ is a derivation

• Exa. $f \longmapsto D_v f(s)$
$\qquad\qquad \overset{\shortparallel}{} \quad (t \longmapsto f(s+t\cdot v))'_{t=0}$

$$\begin{array}{ccc} C^\infty S & \xrightarrow[\text{derivation}]{} & \mathbb{R} \\ \shortparallel & & \shortparallel \\ A & & M \end{array} \longleftarrow \text{A-module structure by } ev_s.$$

Leibniz rule: $d(fg) = d(f)g + f d(g)$

$D_v(f \cdot g)(s) = (D_v f(s)) \cdot g(s) + f(s) \cdot D_v g(s)$.

$\underset{A}{\underset{\shortparallel}{f}} \cdot \underset{\in \mathbb{R}}{m} = f(s) \cdot m$

arbitrary module structure

• Prop. The map $S \times \mathbb{R}^n \longrightarrow Der(C^\infty S, \mathbb{R})$
$(s,v) \longmapsto (f \longmapsto D_v f(s))$.

is a bijection

• Proof.

Injectivity: Suppose we have (s_1, v_1) and $(s_2, v_2) \in S \times \mathbb{R}^n$ map to the same derivation $C^\infty S \to \mathbb{R}$. The module structures on $\mathbb{R}$ must coincide $\Rightarrow s_1 = s_2$. Take $f \in C^\infty S$:

$f(s) = \langle w, s - s_1 \rangle$ where $w \in \mathbb{R}^n$.

$D_{v_1} f(s_1) = \langle w, v_1 \rangle \quad \forall\, w \in \mathbb{R}^n$
$\qquad\qquad\qquad \shortparallel$
$D_{v_2} f(s_2) = \langle w, v_2 \rangle \qquad \langle w, v_1 - v_2 \rangle = 0$

$w = v_1 - v_2 \qquad \Rightarrow \quad v_1 - v_2 = 0 \Rightarrow v_1 = v_2$

Surjectivity: Suppose $d: C^\infty S \longrightarrow \mathbb{R}$ is a derivation.
The $C^\infty S$-module structure on $\mathbb{R} \equiv$ a unique $s \in S$
$f \cdot m := f(s) \cdot m$. Now $d(H_{s,w}) \in \mathbb{R}$ $\forall w \in \mathbb{R}^n$
we get a $\mathbb{R}$-linear map $\quad w \longmapsto d(H_{s,w})$

$$\mathbb{R}^n \longmapsto \mathbb{R}.$$

$d(H_{s,w}) = \langle w, v \rangle$; w.t.s. that
$D_v f(s) = d(f)$ $\forall f \in C^\infty S$.

Recall Hadamard Lemma

$$f(t) = f(s) + \sum_{1 \leq i \leq n} (t_i - s_i) \cdot g_i(t)$$

$$d(f(s)) + \sum_i \left[d(t_i - s_i) \cdot g_i + (t_i - s_i) \cdot d(g_i) \right]$$

prove derivation vanishes constants

$$H_{s, e_i}(t) = \langle e_i, t - s \rangle = t_i - s_i$$

$$= \sum dH_{s,e_i} \cdot g_i + \underbrace{(t_i - s_i) \cdot dg_i}_{\text{vanishes if } t = s}$$

$$= \sum \langle e_i, v \rangle \cdot g_i + (t_i - s_i) \cdot dg_i = \sum_i \langle e_i, v \rangle g_i(s)$$

$$= \sum v_i \cdot \partial_i f(s) = D_v f(s).$$

$$\partial_i f = \frac{\partial f}{\partial x}(s) = g_i(s).$$

Corollary: Every derivation is also a C^∞ derivation

• Def. A map of sets $C^\infty S \longrightarrow M$ is a C^∞ derivation if the chainrule holds

$g_i \in C^\infty S$ $\qquad d(f(g_1, \dots, g_i)) = \sum_i \frac{\partial f}{\partial x_i}(g_1, \dots, g_m) \cdot d(g_i)$

$f \in C^\infty \mathbb{R}^m$

• Remark Every C^∞ derivation is a derivation.

Take $f_1(x_1, x_2) = x_1 + x_2$ (additivity)

$f_2(x_1, x_2) = x_1 \cdot x_2$ (Leibniz)

$f_3(x_1) = r \cdot x_1$

$f_1 : d(g_1 + g_2) = dg_1 + dg_2$

$f_2 : d(g_1 \cdot g_2) = g_2 \cdot dg_1 + g_1 \cdot dg_2$

• Def. $S \in Man, w \in TS \xrightarrow{D} Der(C^\infty S, \mathbb{R})$

(i) $W = [(\underset{\in S}{s}, \underset{\in \mathbb{R}^n}{v}, \underset{\in I}{i})]$ $\quad S = (S, (\varphi_i : U_i \to \underset{\text{open } \subset \mathbb{R}^n}{V_i})_{i \in I})$

$s \in U_i$. $D_w f = D_v (f \circ \varphi_i^{-1})(\varphi_i(s))$

HW hint it's chain rule.

HW 7: Show well-defined.

(ii) $W = [\gamma]$ $\quad \gamma : \mathbb{R} \to S$

$D_w f = (f \circ \gamma)'(0)$

$$\begin{tikzcd} \mathbb{R} \arrow[r, "\gamma"'] \arrow[rr, bend right, "f \cdot \gamma"'] & S \arrow[r, "f"'] & \mathbb{R} \end{tikzcd}$$

• Proposition D is a bijection HW8

• Def. A tangent vector in $S \in man$ is a point derivation $C^\infty S \to \mathbb{R}$.

Today
$$\begin{tikzcd} M \arrow[r] \arrow[d, "p_M"'] \arrow[dr, phantom, "\#"] & N \arrow[d, "p_N"] \\ TM \arrow[r, "Tf"'] & TN \end{tikzcd}$$
$p_N \circ Tf = f \circ p_M$

Example $M \overset{open}{\subset} \mathbb{R}^n$

$TM = M \times \mathbb{R}^n$

$Tf(m, v) = Df(m)(v) = \partial_v f(m)$

Def. ① $f : M \to N$

$M = (M, (\varphi_i : U_i \to V_i)_{i \in I})$

$N = (N, (\psi_j : W_j \to X_j)_{j \in J})$

$m \in M, v \in \mathbb{R}^m, i \in I$

$Tf([(m, v, i)]) = [(f(m), D_v(\psi_j \circ f \circ \varphi_i^{-1})(\varphi_i(m)),$
$j)]$ pick $j \in J$ s.t. $f(m) \in W_j$

$\to$ Independence of the choice of j

$[(f(m), D_v(\psi_j \circ f \circ \varphi_i^{-1})(\varphi_i(m))] = \star$

$\overset{?}{=} [(f(m), D_v(\psi_{j'} \circ f \circ \varphi_i^{-1})(\varphi_i(m)), j')]$

$\star = [(f(m), D_v(\psi_{j'} \circ \psi_j^{-1} \circ \psi_j \circ f \circ \varphi_i^{-1})(\varphi_i(m), j')]$

Independence of i: similar.

Def. ② $f([\gamma]) = [f \circ \gamma]$, $\gamma : \mathbb{R} \to M$

independent of γ : chart } chain rule

Def. ③ $f : M \to N$

$C^\infty M \xrightarrow{v} \mathbb{R}$ $\star$ derivation $C^\infty f : C^\infty N \to C^\infty M$

$Tf(v)$ $v \circ C^\infty f$ $g \longmapsto (g \circ f) \cdot r$ $\star$

$v \circ C^\infty f : C^\infty N \to \mathbb{R}$ $g \cdot r = (g \circ f) \cdot r$

Claim: $v \circ C^\infty f$ is a derivation

$\mathbb{R}$-linear ✓

$$(v\circ C^\infty f)(h_1\cdot h_2) = v\left(C^\infty f(h_1\cdot h_2)\right)$$

$$v\left((C^\infty f)(h_1)\cdot_* (C^\infty f)(h_2)\right) = v\left((C^\infty f)(h_1)\right)$$

$$\cdot\, C^\infty f(h_2) + (C^\infty f)(h_1)\cdot_* v\left((C^\infty f)(h_2)\right)$$

$$= (v\circ C^\infty f)(h_1)\cdot_\square h_2 + h_1 \cdot_\square (v\circ C^\infty f)(h_2)$$

①: why are these def. equivalent?

Tf ① = Tf ② = Tf ③

Pass to a single chart in M and N.

① = ②

$$\begin{array}{ccc} [f\circ\gamma] & \longmapsto & (f\circ\gamma)'(0) \\ \downarrow & & \parallel \\ Tf(\gamma'(0)) & & D_{\gamma'(0)} f(\gamma(0)) \end{array}$$

① = ③

$$M\subset\mathbb{R}^m \longrightarrow N\subset\mathbb{R}^n$$

$$(m,v) \longmapsto (f(m), D_v f(m))$$

$$\downarrow$$

$$(g\longmapsto D_v g(m)) \longmapsto (h\longmapsto D_v(h\circ f)(m))$$

$$\overset{\text{chain rule}}{=} D_{D_v f(m)}\, h(f(m))$$

• **Example.** $M = N = \mathbb{C}$ $\qquad TM = M\times\mathbb{R}^2 = M\times\mathbb{C}$

HW 9: $\qquad TN = N\times\mathbb{R}^2 = N\times\mathbb{C}$

$$f: M\longrightarrow N$$

$$z \longmapsto z^2$$

$$x+iy \longmapsto x^2-y^2+2xyi$$

$$Tf(z, \underbrace{a\cdot\partial_x + b\cdot\partial_y}_{\begin{pmatrix}a\\b\end{pmatrix}}) = \begin{pmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} \\ \frac{\partial f_1}{\partial x} & \frac{\partial f_2}{\partial y}\end{pmatrix}\begin{pmatrix}a\\b\end{pmatrix} = \begin{pmatrix} 2x & -2y \\ 2y & 2x\end{pmatrix}$$

$= 2 \cdot (xa - yb, ya + xb)$

$= 2 \cdot z \cdot v$

$v = a + ib$

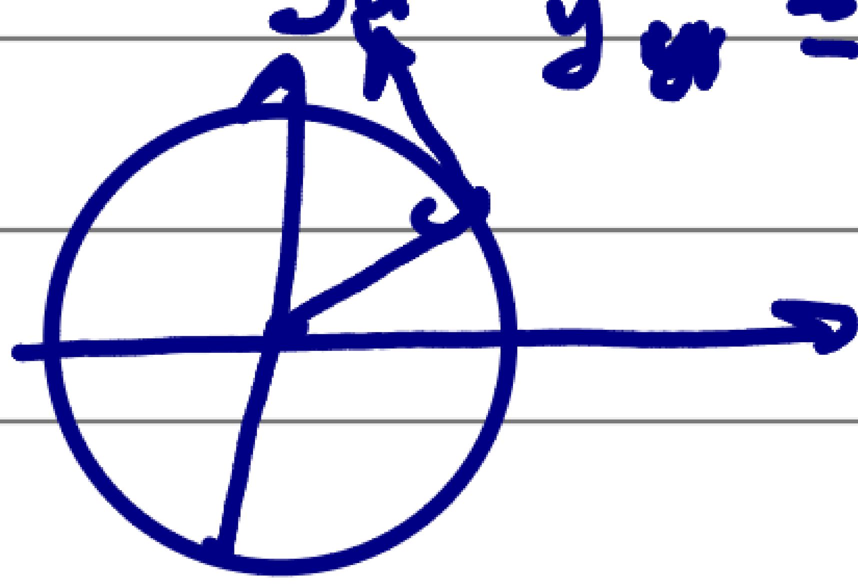
Example $S^1 < \mathbb{R}^2$ $\quad S^1 = \{(x,y) \mid x^2 + y^2 = 1\}$

$S^1 \xrightarrow{f} S^1$

$f(x,y) = (x^2 - y^2, 2xy)$

sidenote $M < \mathbb{R}^a$ $\quad$ HW9: ④ $\Longleftrightarrow TM, Tf$

$TM = (m, u)$ $m \in M, u \in \mathbb{R}^a$ $\quad$ ① $\vee$ ② $\vee$ ③



y_u $\quad y_u = (u_x, u_y)$

$\langle (x,y), (u_x, u_y) \rangle = 0$

$= x u_x + y u_y = 0 \Longleftrightarrow Re(z \bar{u}) = 0$

$(u_x, u_y) = \lambda (y - x)$

$z = x + iy$

$Tf(z, u) = (f(z), 2z \cdot u)$

$= (\underset{S^1}{\uparrow}{z^2}, 2zu)$

$Re(z^2 \cdot 2z\bar{u})$

$= Re(z \cdot z \cdot \bar{z} \cdot \bar{u} \cdot 2)$

$= Re(z \cdot \bar{u} \cdot 2) = 0$

• Example : V real vectorspace : V_1, V_2

$f: V_1 \longrightarrow V_2$

$TV_i = V_i \times V_i$

$$\begin{array}{ccccc} Tf: & TV_1 & \longrightarrow & TV_2 \\ & \| & & \| \\ & V_1 \times V_1 & & V_2 \times V_2 \end{array}$$

$$Tf(p,v) = (f(p), f(v)) = f(p,v)$$

• Exa.

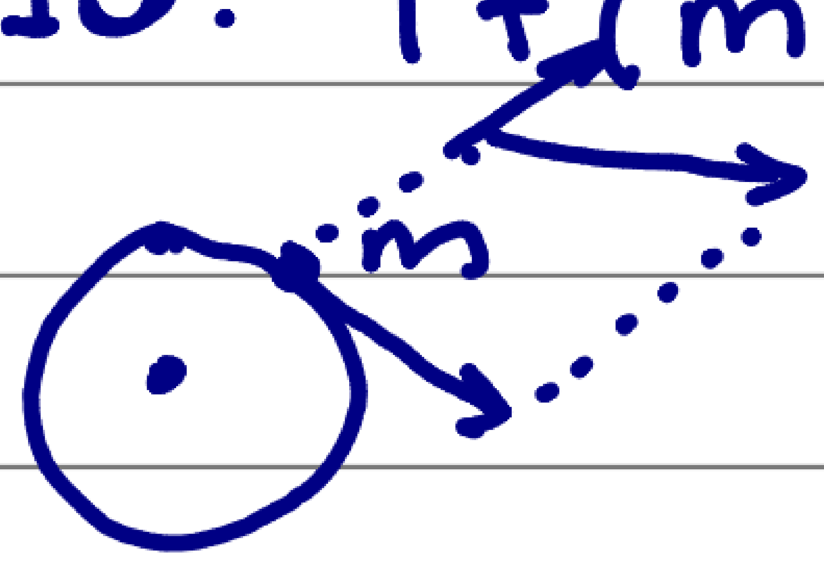
$$S^n = \{ v \in \mathbb{R}^{n+1} \mid \|v\| = 1$$

$$f: \mathbb{R}^{n+1}/0 \longrightarrow S^n$$
$$v \longmapsto \frac{1}{\|v\|} \cdot v$$

$$T\mathbb{R}^{n+1} = \mathbb{R}^{n+1} \times \mathbb{R}^{n+1}$$

$$TS^n = \{ (m,u) \mid m \in S^n, u \in \mathbb{R}^{n+1}, \langle m,u \rangle = 0 \}$$

HW 10: $Tf(m,v) = \left(f(m), v - \frac{\langle m,v \rangle \cdot v}{\|v\|}\right)$



Last time

tangent vector	tangent map	vector field
$v \in TM$	$Tf : TM \to TN$	$v : M \to TM$
$v = (u,w) \in U \times \mathbb{R}^n$ (in a chart)	$Tf(u,w) = D_w f(u)$	$x_i : U_i \to \mathbb{R}^n$
$v = [\gamma : \mathbb{R} \to M]$ $= [\gamma : U \to M]$	$Tf(v) = Tf([\gamma])$ $= f \circ \gamma$	$x = [\Gamma]_i$ $\Gamma : W \to M$ $W \subset_{open} M \times \mathbb{R}$
$v : C^\infty M \to \mathbb{R}$ endomorphisms?	$Tf(v) = v \circ C^\infty f$ $C^\infty f : C^\infty N \to C^\infty M$ $g \mapsto g \circ f$	$X : C^\infty M \to C^\infty M$ deriv.
$v = [(u,w,i)]$		

1

• **Def.** A vector field X on a smooth manifold M is a smooth map $X : M \to TM$ s.t.

$$\begin{tikzcd} M \arrow[r, "X"] \arrow[dr, "id_M"'] & TM \arrow[d, "p"] \\ & M \end{tikzcd} \quad \#$$

• **Example** $M \subset_{open} \mathbb{R}^n$ $\qquad TM \cong M \times \mathbb{R}^n \xrightarrow{p} M$

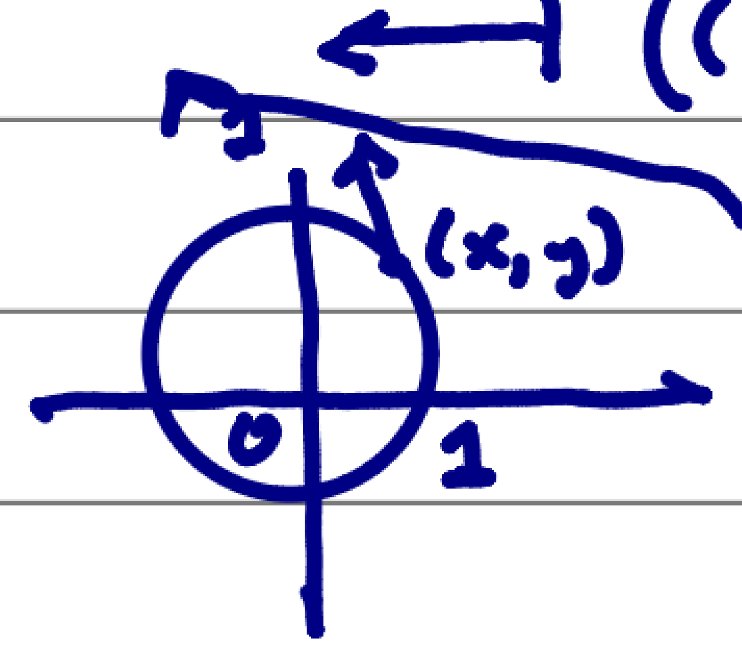
$$\begin{tikzcd} M \arrow[r, "X"] \arrow[dr, "id_M"'] & TM = M \times \mathbb{R}^n \arrow[d] \\ & M \end{tikzcd} \quad \#$$

$$X(m) = (m, \bar{x}(m))$$
$$\bar{x} : M \to \mathbb{R}^n$$

• **Example** $M = S^1$ $\qquad TS^1 \cong S^1 \times \mathbb{R}$

$$S^1 \subset \mathbb{R}^2$$
$$S^1 = \{(x,y) \mid x^2 + y^2 = 1\}$$

$$((x,y),t) \longmapsto ((x,y),(-ty,tx))$$



$X(x,y) = ((x,y), x, (-xy, x^2))$

② $\underline{\text{• Def.}}$ $M = (M, (\varphi_i : \underset{\subset M}{U_i} \xrightarrow{\cong} \underset{\subset \mathbb{R}^n}{V_i})_{i\in I})$

A vector field X on M is

$$(X_i : U_i \longrightarrow \mathbb{R}^n)_{i\in I}$$

such that $\forall\, i,j \in I$

$$D(\varphi_j \circ \varphi_i^{-1})(X_i|_{U_i\cap U_j}) = X_j|_{U_i\cap U_j}$$

$$D_{X_i(u)}(\varphi_j \circ \varphi_i^{-1})(\varphi_i(u)) = X_j(u) \quad \text{or}$$

$$D(\varphi_i \circ \varphi_j^{-1})|_{\varphi(u)} \cdot X_i(u) = X_j(u)$$

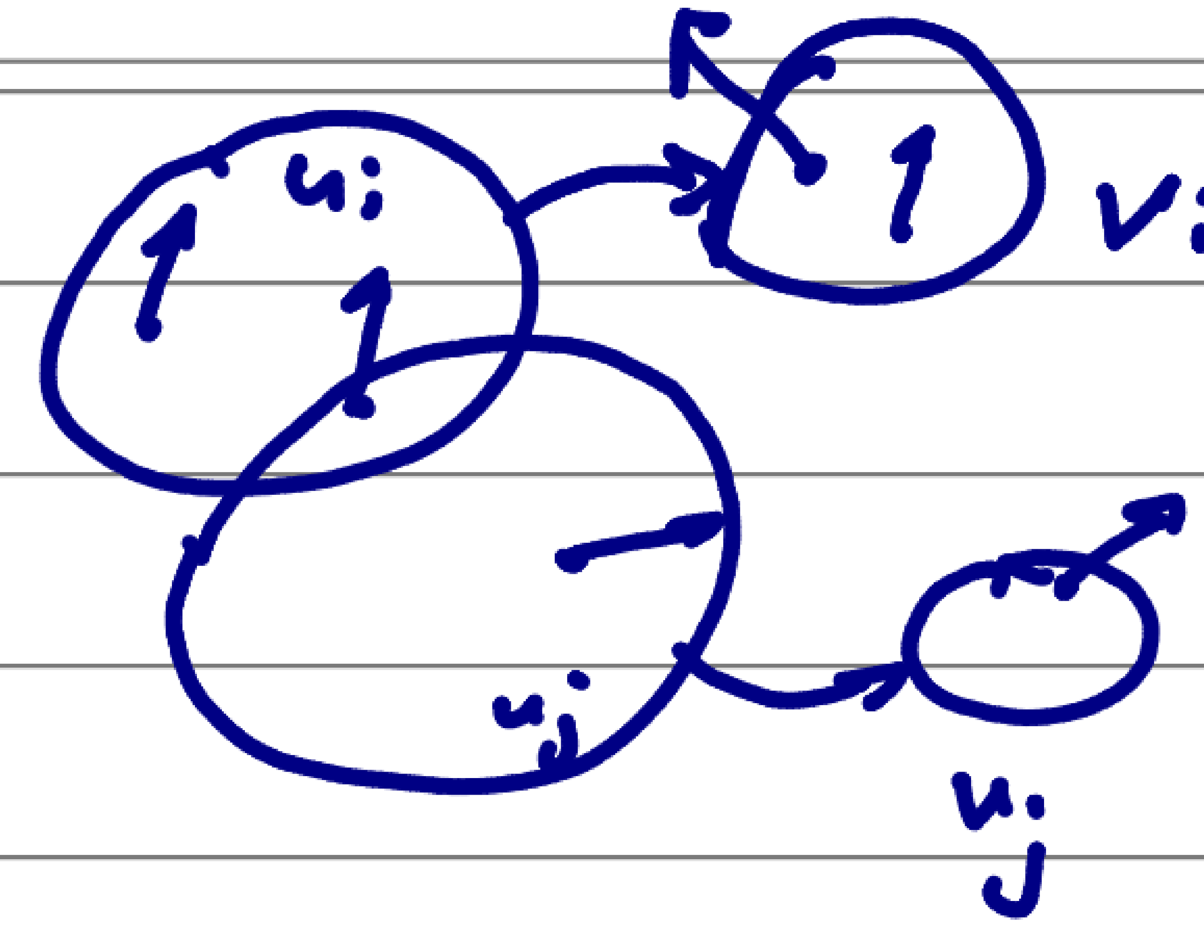
① ⟶ ②

$$X : M \to TM \longmapsto (X_i : U_i \longrightarrow \mathbb{R}^n)_{i\in I}$$

$$\begin{tikzcd} U_i \arrow[r, "X|_{U_i}"] \arrow[dr] \arrow[drrr, bend right, "(\varphi_i, X_i)"'] & TM \\ & TU_i \arrow[u, "T\iota_i"'] \arrow[r, "T\varphi_i"'] & TV_i \arrow[r, phantom, "\cong"] & V_i \times \mathbb{R}^n \end{tikzcd}$$

$$U_i \xrightarrow{\iota_i} M$$

Compatibility



$$D(\varphi_j \circ \varphi_i^{-1})(\varphi_i(u))(x_i(u))$$

$$D(\varphi_j \circ \varphi_i^{-1})(\varphi_i(u))(T\varphi_i(x(u)))$$

$$= D(\varphi_j)(u)(T(x(u)))$$

• **Prop.** (chain rule)

$$\begin{tikzcd} L \arrow[r, "f"] \arrow[dr, "g\circ f"'] & M \arrow[d, "g"] \\ & N \end{tikzcd}$$

$$\begin{tikzcd} TL \arrow[r, "Tf"] \arrow[dr, "T(g\circ f) = Tg\circ Tf"'] & TM \arrow[d, "Tg"] \\ & TN \end{tikzcd}$$

"T is a functor"
$T: \mathrm{Man} \to \mathrm{Man}$

• **Proof.** ③ $T(g\circ f)([\gamma: \mathbb{R} \to L])$
$= [g\circ f\circ \gamma: \mathbb{R} \to N]$
$= Tg([f\circ\gamma])$
$= Tg(Tf([\gamma]))$.

precomposition

④ $T(g\circ f)(v) = v\circ C^\infty(g\circ f) = v\circ(C^\infty f\circ C^\infty g)$
$= (Tf(v))\circ C^\infty g = Tg(Tf(v))$

$$T(\varphi_j\circ\varphi_i^{-1})(T\varphi_i(X_i(u)))$$
$$T(\varphi_j\circ\varphi_i^{-1}\circ\varphi_i)(X_i(u))$$
$$T(\varphi_j)(X_i(u)) = X_j(u).$$

Last time: vectorfield on M.

(1) $M \xrightarrow{v} TM \qquad p\circ v = id_M$

(2) $M = (M, (\varphi_i : U_i \to V_i)_{i\in I})$

$X_i : V_i \to \mathbb{R}^n$

$T(\varphi_j \circ \varphi_i^{-1})(x, X_i(x)) = (\varphi_j(\varphi_i^{-1}(x)), X_j(\varphi_j(\varphi_i^{-1}(x))))$

(3) $W \subset M\times\mathbb{R}\;, \; W \supset M\times\{0\}$

$F : W \to M \qquad [F]$

$F(F(x,s),t) = F(x, s+t)$

$F_1 \sim F_2$ if $\exists\; W_3 \subset W_1 \cap W_2$

$F_1|_{W_3} = F_2|_{W_3}$

"Local semigroup, Local action of Lie group..."

(4) Derivation

(2) $\to$ (1)

$p \in TM$, $p = [(m, w, i)]$. Fix $i \in I$

$U_i \xrightarrow{Y_i} TM$

$m \mapsto [(m, \;_i(\varphi_i(m)), i]$

$Y_i|_{U_i\cap U_j} = Y_j|_{U_i \cap U_j}$

$[(m, X_i(\varphi_i(m)), i)] = [(m, X_j(\varphi_j(m)), j)]$

$Y : \bigcup_i U_i \to TM$

$$\begin{tikzcd}
\mathbb{R}^m \arrow[d, phantom, "\cup"] & \mathbb{R}^n \arrow[d, phantom, "\cup"] \\
U \arrow[r, "f"] & V \\
TU = U\times\mathbb{R}^m \arrow[u] \arrow[r, bend left, "Tf"] & TV = V\times\mathbb{R}^n \arrow[u]
\end{tikzcd}$$

$Tf(u, w) = (f(u), D_w f(u))$

• Example

$M = \mathbb{R}$

$X : M \longrightarrow \mathbb{R}\ , \quad X(t) = t^2$

$$\frac{\partial F}{\partial t}(m,t) = X(F(m,t))$$

$$\frac{\partial F}{\partial t}(m,t) = F(m,t)^2$$

Assume $F(m,t) \neq 0$ $\qquad F(m,t)^{-2} \cdot \frac{\partial f}{\partial t}(m,t) = 1$

$$\frac{\partial}{\partial t}\left(\frac{F(m,t)^{-1}}{-2} \right) = \frac{\partial}{\partial t}(t)$$

$- F(m,t)^{-1} = t + c \qquad F(m,t)^{-1} = -t + c$

$\qquad F(m,t) = -\frac{1}{t+c} = -\frac{1}{t - 1/m}$

$F(m,0) = -\frac{1}{c}\ , \quad c = -1/m$

$$F(m,t) = \begin{cases} 0\ , & m = 0 \\ \dfrac{1}{\frac{1}{m} - t}\ , & m \neq 0 \end{cases}$$

HW 11

$T(M \times N) \cong TM \times TN$

③ $\longrightarrow$ ① $\quad [F] \quad F : \underset{M\times\mathbb{R}}{\underset{\cap}{W}} \longrightarrow M$

①

$M : \xrightarrow{\ V\ } TM$

$TF : TW \xrightarrow{\ TF\ } TM$

$TW \subset T(M \times \mathbb{R}) \cong TM \times T\mathbb{R} \cong TM \times \underbrace{\mathbb{R}}_{t} \times \underbrace{\mathbb{R}}_{\frac{\partial}{\partial t}}$

$V(m) = TF\big((m,0), 0, 1\big)$

$V(m) = \frac{\partial F}{\partial t}(m,0) \in TM$

1, 2 $\longrightarrow$ 3

Theorem $M \in \mathrm{Man}$, $v \in \mathfrak{X}M$

$\mathfrak{X}M = \{ v : M \to TM \mid p \circ v = \mathrm{id}_M \}$

$\exists !$ 3 $\qquad v = \frac{\partial F}{\partial t}(m,0)$

$F : W \to M$ (existence and uniqueness to ODEs)

If $F_1 : W_1 \to M$ 3, then $W_1 \subset W$

$\forall m \in M : W \cap (\{m\} \times \mathbb{R})$ is an interval of the maximal integral curve of M. $\qquad$ MC

Proof. Immediate reduction to $\mathbb{R}^n$ using charts, apply the Banach Fixed Point theorem.

$$\frac{\partial F}{\partial t}(m,t) = G(F(m,t),(m,t))$$

jets

$x_i : M \times \underset{t}{\mathbb{R}} \to V$

$$\frac{dx_i}{dt} = G_i(x_1(t), x_2(t), \dots, x_n(t), t)$$

$$\frac{\partial F}{\partial t}(m,t) \qquad X : M \times \mathbb{R} \to TM$$

$$= X(F(m,t),t) \qquad N = M \times \mathbb{R}$$

$Y : N \to TN$

$$Y(m,t) = (X(m,t),t,1$$

$$\frac{\partial G}{\partial t}(m,t) = Y(G(m,t))$$

Citer manifold thm.

④ **·Def.** A vector field on M is a derivation $X: C^\infty M \to C^\infty M$, i.e., X is an $\mathbb{R}$-linear map s.t.

$$X(fg) = X(f)\cdot g + f\cdot X(g)$$

·ex. think of how to get a derivation using a flow or curve

·Remark The value of a vector field X at some point $p \in M$ $\quad C^\infty M \xrightarrow[ev_m]{} \mathbb{R}$

is the point derivation

$$\begin{tikzcd} C^\infty M \arrow[r, "X_m"] \arrow[dr, "X"'] & \mathbb{R} \\ & C^\infty M \arrow[u, "ev_m"'] \end{tikzcd}$$

$$(ev_m \circ X)(f\cdot g) = ev_m(X(fg)) = ev_m(X(f)g + fX(g))$$
$$= ev_m(Xf)\cdot g(m) + f(m)\cdot ev_m(X(g))$$

④ Given a derivation $X: C^\infty M \xrightarrow{\text{deriv}} C^\infty M$

Given a point $m \in M$: $ev_m \circ X$ is the point derivation corresponding to the tangent vector X_m.

Given point derivations $X_m : C^\infty M \to \mathbb{R}$ $(m \in M)$, we have $X: C^\infty M \to \mathbb{R}^M$ (a derivation)

$$f \longmapsto m \longmapsto X_m(f)$$

X factors as an actual derivation to smooth functions if X_m depends smoothly on $m \in M$.

③ $F: W \to M$

$W \subset M \times \mathbb{R}$ $\quad W \supset W \times \{0\}$

$$F(F(x,t),s) = F(F(m,s),t)$$
$$F(m,0) = m.$$

$$X : C^\infty M \longrightarrow C^\infty M \qquad X = [F]$$
$$f \longmapsto \mathcal{L}_{[F]} f$$

$$= \lim_{t \to 0} \frac{1}{t}\left(f(F(m,t)) - f(m)\right)$$

$$= \left(t \longmapsto f(F(m,t))\right)'(0).$$

• Prop. if $[F]$ ③, then X is a derivation.

• Claim: X is a derivation

$\mathbb{R}$-Linear

Leibniz

$$\mathcal{L}_X(fg)(m) = \left(t \longmapsto (f\cdot g)(F(m,t))\right)'(0)$$
$$= (t \longmapsto f(F(m,t)))'(0) \cdot g(\underbrace{F(m,0)}_{m})$$
$$(t \mapsto g(F(m,t)))'(0) \cdot f(\underbrace{F(m,0)}_{m})$$

$$= \mathcal{L}_{[F]}(f)(m) \cdot g(m) + f(m) \cdot \mathcal{L}_{[F]}(g)(m)$$
$$\mathcal{L}_{[F]}(fg) = \mathcal{L}_{[F]} f \cdot g + f \cdot \mathcal{L}_{[F]} g$$

④ $\longrightarrow$ ①

• Prop. If $X : C^\infty M \xrightarrow{\text{deriv}} C^\infty M$, then
$$S : M \longrightarrow TM \qquad S(m) = ev_m \circ X$$
is a smooth map and a section $p \circ S = id_M$.

•Proof. ① The base point of $ev_m \circ X$ is ev_m.

Thus $p \circ S = id_M$.

② s is smooth. Working in a chart, assume $M \underset{\text{open}}{\subset} \mathbb{R}^n$.

$$s(m)_i = (ev_m \circ X)(x_i)$$

$$x_i \in C^\infty M, \quad x_i : \underset{p}{\mathbb{R}^n} \longrightarrow \underset{p_i}{\mathbb{R}}$$

$$s(m)_i = X(x_i)(m).$$

$s_i \in C^\infty M$ smooth function

Thus s is smooth

$\square$

• Proof ④ $\xrightarrow{\checkmark}$ ① $\xrightarrow{\checkmark}$ ③

Lie derivatives of vector fields
= Lie brackets of vector fields

$$X, Y \in \mathfrak{X}(M)$$

$$\mathcal{L}_X Y = [X, Y] \in \mathfrak{X}(M)$$

• Def. $X, Y : C^\infty M \xrightarrow{\text{deriv}} C^\infty M$

Then, : $[X, Y] : C^\infty M \to C^\infty M$

$$[XY](f) = X(Y(f)) - Y(X(f))$$

Claim: $[X, Y]$ is a derivation. $\mathbb{R}$ linear ✓

$$[X, Y](fg) = X(Y(fg)) - Y(X(fg))$$

$$= X(Y(f) \cdot g + f \cdot Y(g)) - Y(X(f) \cdot g + f \cdot X(g))$$

$$= X(Y(f)) \cdot g + Y(f) \cdot X(g) + X(f) \cdot Y(g) + f \cdot X(Y(g))$$

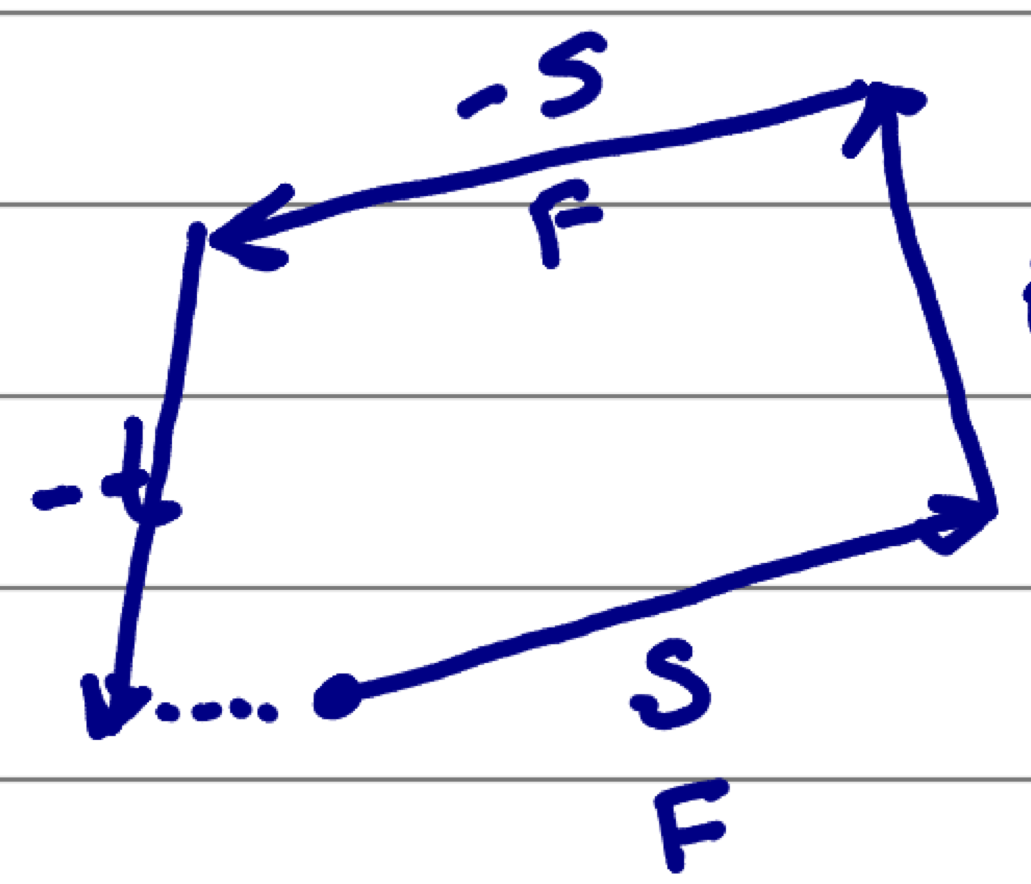
$- Y(X(f))\cdot g - X(f)\cdot Y(g) - Y(f)X(g)$
$- f\cdot Y(X(g))$
$= [X,Y](f)\cdot g + f\cdot [X,Y](g)$

• **Def ②** $[F], [G]$: local flows on M.

$[F,G]$: vector field, Assume $M \subset \mathbb{R}^n$. In a chart,

$$[F,G](m) = \lim_{\substack{(s,t)\to 0 \\ \hat{m}}} \frac{1}{s\cdot t}\Big(\underbrace{G(F(G(F(m,s),t),-s),-t)}_{wc} - m\Big)$$

In general: $\mathbb{R}^2 \xrightarrow{h} M$



$(s,t) \longmapsto G(F(G(F(m,s),t),-s,-t)$

$Th: W \times \mathbb{R}^2 \to TM$
$(s,t),\ (s,0) \to M$
$W \xrightarrow{\frac{\partial h}{\partial s}} M$

$\dfrac{\partial^2 h}{\partial s \partial t} : W \to TM$ evaluated at $(0,0)$

$[F,G]$ $\qquad$ $[F,G]$ product of two
$\dfrac{\partial^2 h}{\partial s \partial t}(0,0)$. $\qquad$ infinitesimal.

Commuting vector fields,
coordinate vector fields.

In coordinates $M = \mathbb{R}^n$

$x_i : \mathbb{R}^n \xrightarrow{i\text{th}} \mathbb{R}$

$$\frac{\partial}{\partial x_i} : C^\infty M \longrightarrow C^\infty M$$
$$f \longmapsto \frac{\partial f}{\partial x_i}$$

$M \longrightarrow TM = M \times \mathbb{R}^n$

$m \longmapsto (m, e_i)$

$$e_i = (0, 0, \dots, 0, \overset{i\text{th}}{1}, 0, \dots, 0)$$

• Remark. $\mathfrak{X}(M) = \{ X : M \to TM \mid p \circ X = \mathrm{id}\, M \}$
is a module over $C^\infty M$

$$f \in C^\infty M,\ X \in \mathfrak{X}(M) : f \cdot X \in \mathfrak{X}(M)$$

$$(f \cdot X)(m) = \underset{\mathbb{R}}{\underset{\Uparrow}{f(m)}} \cdot \underset{T_m M}{\underset{\Uparrow}{X(m)}}$$

$X : C^\infty M \xrightarrow{\text{deriv}} C^\infty M$ $f \cdot X : C^\infty M \to C^\infty M$ $(f X)(g)$
$= f \cdot X(g)$.

• Prop. If $M \underset{\text{open}}{\subset} \mathbb{R}^n$, then $\mathfrak{X}(M)$ is a free $C^\infty M$ module of rank n with a basis $\left(\frac{\partial}{\partial x_1}, \dots, \frac{\partial}{\partial x_n} \right) \in \mathfrak{X}$

• Proof. Given some $X \in \mathfrak{X}(M)$ set $f_i = X(x_i)$
then $X = \sum_i f_i \frac{\partial}{\partial x_i}$

• Proof. $X(g) = \sum_i f_i \cdot \frac{\partial g}{\partial x_i}$. Pick some $m \in M$

$$X(g(m)) = \sum f_i(m) \frac{\partial g}{\partial x_i}(m)$$

$g(p) = g(m) + \sum h_i(p) \cdot (p_i - m_i)$

Hadamard's Lemma: $\exists h_i$

$\measuredangle$

$$X\left(g(m) + \sum_i (p_i - m_i) h_i\right)$$

$$= \left(\sum_i X(p_i - m_i) \cdot h_i + \cancel{(p_i - m_i)} \overset{0}{X} h\right)(m)$$

$p = m$

$$= \left[\sum f_i \cdot h_i\right](m) = \sum_i f_i(m) \cdot h_i(m)$$

$$= \sum_i f_i(m) \cdot \frac{\partial g}{\partial x_i}(m) \quad \star \checkmark$$

• Prop. The Lie bracket

1. $[-,-] : \mathfrak{X} \times \mathfrak{X} \longrightarrow \mathfrak{X}$ is $\mathbb{R}$ - bilinear

$[f \cdot X, g \cdot Y] = f \cdot g [X, Y]$

4. $[X, f \cdot Y] - f[X, Y] = X(f) \cdot Y$

2. $[X, [Y, Z]] - [Y, [X, Z]] + [Z, [X, Y]] = 0$

3. $[X, Y] = -[Y, X]$ ↑ Jacobi Identity

1-3 Lie algebra

• Prop. Derivations of $A \in CAlg_{\mathbb{R}}$ form a Lie algebra over $\mathbb{R}$ $[D_1, D_2] = D_1 D_2 - D_2 D_1$

• Proof. 0) $[D_1, D_2]$ is a derivation

1) $\mathbb{R}$ bilinear $\checkmark$

2) $\checkmark$

3) $\checkmark$

• Prop. 4 is true

• Prop. Evaluate on some $g \in C^\infty M$

$X(f\,Y(g)) + \cancel{f \cdot Y(X(g))} - f \cdot X(Y(g))$
$\cancel{+ f\,Y(X(g))}$

$X(f) \cdot Y(g) + f\,X(Y(g)) - f \cdot X(Y(g))$

$X\ (f) \cdot Y)\ (g)$

• Example $M = \mathbb{R}^n$

$\mathfrak{X}M$: free $C^\infty M$-module
w/basis $\frac{\partial}{\partial x_i}$, $1 \leq i \leq n$

$\forall X \in \mathfrak{X}(M) : \exists!\ (f_i)_{i \leq 1 < n}$

$X = \sum_i f_i \frac{\partial}{\partial x_i}$

$[\sum_i f_i \frac{\partial}{\partial x_i}, \sum_j g_j \cdot \frac{\partial}{\partial x_j}] = \sum_{i,j} [f_i \frac{\partial}{\partial x_i}, g_j \cdot \frac{\partial}{\partial x_j}]$

$\mathcal{L}_X(f \cdot Y) = (\mathcal{L}_X f) \cdot Y + f \cdot \mathcal{L}_X Y$

$= \sum_{ij} \left(f_i \frac{\partial}{\partial x_i} \right) (g)_j \cdot \frac{\partial}{\partial x_j} + g_j [f_i \frac{\partial}{\partial x_i}, \frac{\partial}{\partial x_j}].$

noncommutative

$= \sum_{ij} f_i \cdot \frac{\partial g_j}{\partial x_i} \cdot \frac{\partial}{\partial x_j} + \cancel{g_j f_i \left[\frac{\partial}{\partial x_i}, \frac{\partial}{\partial x_j}\right]} - g_j \frac{\partial f}{\partial x_j} \cdot \frac{\partial}{\partial x_i}$

$$\sum_k \left(\sum_i f_i \frac{\partial g_k}{\partial x_i} - g_i \frac{\partial f_k}{\partial x_i} \right) \cdot \frac{\partial}{\partial x_k}$$

Multi-linear Algebra of Real vector spaces (and modules)

Def. $V_1, \dots, V_n, W \in \mathrm{Vect}_{\mathbb{R}}$:

A multilinear map $V_1, \dots, V_n \to W$ is a map of sets $V_1 \times \dots \times V_n \xrightarrow{t} W$ such that $\forall i\ \forall v_j \in V_j$, $j \neq i$: $V_i \to W$ is an $\mathbb{R}$-linear map
$v_i \mapsto T(v_1, \dots, v_i)$

Def. $V, W \in \mathrm{Vect}_{\mathbb{R}}$ $\quad \mathrm{Hom}(V,W) \in \mathrm{Vect}_{\mathbb{R}}$
$f \qquad f: V \to W \in \mathrm{Vect}_{\mathbb{R}}$

operations are non pointwise $\qquad$ convolution.

$$(f_1 + f_2)(v) = f_1(v) + f_2(v)$$

$$\mathbb{R} \to (r \cdot f)(v) = r \cdot f(v)$$

Def. $V_1, \dots, V_n, W \in \mathrm{Vect}_{\mathbb{R}}$

$$\mathrm{Hom}(V_1, \dots, V_n; W)$$

Prop. $T \in \mathrm{Hom}(V_1, V_2; W) \cong \mathrm{Hom}(V_1, \mathrm{hom}(V_2, W)) \ni Q$

$$\cong \mathrm{Hom}\big(V_2, \mathrm{Hom}(V_1, W)\big)$$

Given T, $Q(v_1)(v_2) = T(v_1, v_2)$

Given Q, $T(v_1, v_2) = Q(v_1)(v_2)$

Example $\qquad$ Terminology $W = \mathbb{R}$

T is a multilinear form

Example $\mathrm{Hom}(V, \mathbb{R}) = V^*$ the dual vector space.

$$\mathrm{Hom}(\mathbb{R}, V) \cong V \qquad \mathrm{Hom}(V, \mathbb{R}^n) \cong V^* \oplus \dots \oplus V^*$$

$$f \mapsto f(1)$$

$\mathrm{Hom}(\mathbb{R}^n \to V) \cong V \oplus \ldots \oplus V$

• Def. $V_1, V_2 \in \mathrm{Vect}\,\mathbb{R}$

$V_1 \otimes V_2 \in \mathrm{Vect}_{\mathbb{R}}$

tensor product of V_1 and V_2

$\mathbb{R}$-bilinear $\quad V_1, V_2 \xrightarrow{\otimes} V_1 \underset{\mathbb{R}}{\otimes} V_2$

$\qquad v_1, v_2 \xmapsto{\otimes} v_1 \underset{\mathbb{R}}{\otimes} v_2$

Essentially, we define tensor product of elements and spaces in the same package.

• Thm. The universal property:

if $V_1, V_2 \xrightarrow[T]{\text{bilinear}} W$, then, there is

a unique $\mathbb{R}$ linear map $S: V_1 \otimes V_2 \longrightarrow W$

such that $\forall v_1, v_2 : T(v_1 + v_2) = S(v_1 \otimes v_2)$

S is only linear, whereas T is multi-linear (bi in this case)

• Prop. $\otimes$ exists and is unique up to a unique isomorphism

• Proof. U_1: real vector space with basis $V_1 \times V_2$

$U_2 \subset U_1$: vector subspace linear, span of $(v_1 + v_1', v_2) - (v_1, v_2) - (v_1', v_2)$

$(v_1, v_2 + v_2') - (v_1, v_2) - (v_1, v_2')$

$(r \cdot v_1, v_2) - r \cdot (v_1, v_2)$

$(v_1, r \cdot v_2) - r \cdot (v_1, v_2)$

set $V_1 \otimes V_2 = U_1 / U_2$
$= U_1$

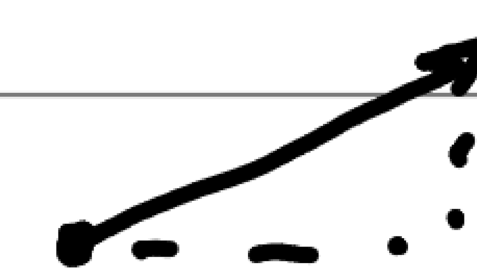
• Recall

$U_1 = \mathrm{Free}(V_1 \times V_2) = \bigoplus_{V_1 \times V_2} \mathbb{R}$

$U_2 = \mathrm{Span} \langle (u_1 + u_1', u_2) - (u_1, u_2) - (u_1', u_2), \dots \rangle$

$V_1, V_2 \longrightarrow \underline{V_1 \otimes V_2}$ $\quad \langle 1, 2 \rangle$

$(v_1, v_2) \longmapsto [(v_1, v_2)] = v_1 \otimes v_2$



bilinear $\searrow$ W $\quad \exists! S$

$\mathbb{R}$

$T(v_1, v_2) = S(v_1 \otimes v_2)$

4

• existence of S

$V_1 \otimes V_2 = U_1 / U_2 \xrightarrow{S} W$

$U_1 \xrightarrow{S_1} W$

vanish on U_2

$V_1 \times V_2 \xrightarrow{S_2} W$

map of sets

$S_1((u_1 + u_1', u_2) - (u_1, u_2) - (u_1', u_2), \dots \rangle$

$T(u_1 + u_1', u_2) - T(u_1, u_2) - T(u_1', u_2) = 0$

$V_1 \otimes V_2 = U_1 / U_2 \overset{S}{\underset{S'}{\rightrightarrows}} W$

$\otimes \uparrow$ $\qquad T$

V_1, V_2 $\qquad S - S' = 0 \Rightarrow S = S'.$

$(S - S')([(v_1, v_2)]) = T(v_1, v_2) - T(v_1, v_2) = 0$

• Proposition

$$U_1 \otimes (V_1 \oplus V_2) \cong U \otimes V_1 \oplus U \otimes V_2$$

a.)

$$\begin{tikzcd}
u \otimes (V_1 \oplus V_2) \arrow[r, "S"] & u \otimes V_1 \oplus u \otimes V_2 \\
u, V_1 \oplus V_2 \arrow[u, "\otimes"] \arrow[ur, "S \circ \otimes"'] &
\end{tikzcd}$$

$$(u, (v_1, v_2)) \longmapsto (u \otimes v_1, u \otimes v_2)$$

$$(u + u', (v_1, v_2)) \overset{S}{\longmapsto} \begin{pmatrix} (u+u') \otimes v_1, \\ (u+u') \otimes v_2 \end{pmatrix} = \begin{pmatrix} u \otimes v_1 + u' \otimes v_1, \\ + u \otimes v_2 + u' \otimes v_2 \end{pmatrix}$$

Bilinearity property

$$(u \otimes v_1, u \otimes v_2) + (u' \otimes v_1, u' \otimes v_2)$$

$$= S(u, (v_1, v_2) + (v_1', v_2'))$$

$$= S(u, (v_1, v_2)) + S(u, (v_1', v_2'))$$

b.) $T : u \otimes v_1 \oplus u \otimes v_2 \to u \otimes (v_1 \oplus v_2)$

$T_1 : u \otimes v_1 \longrightarrow u \otimes (v_1 \oplus v_2)$

$T_2 \quad u \otimes v_2 \longrightarrow u \otimes (v_1 \oplus v_2)$

$T(p_1, p_2) = T_1(p_1) + T_2(p_2)$

$p_1 \in u \otimes V_1, \quad p_2 \in u \otimes V_2$

$$\begin{array}{ccc} u \otimes V_1 & \xrightarrow{T_1} & u \otimes (v_1 \oplus v_2) \\ \uparrow & & \\ u, v_1 & \longrightarrow & u \otimes (v_1, 0) \\ (u, v_1) & \longmapsto & \text{bilinear} \end{array}$$

$T(u \otimes v_1, u \otimes v_2) = u_1 \otimes (v_1, 0) + u_2 \otimes (0v, v_2)$

$T_2(u \otimes v_2) = u \otimes (0, v_2)$

c.) $S(T(u_1 \otimes v_1, u_2 \otimes v_2)) =$

$S(u_1 \otimes (v_1, 0) + u_2 \otimes (0, v_2))$

$= (u_1 \otimes v_1, u_1 \otimes 0) + (u_2 \otimes 0, u_2 \otimes v_2) =$

$(u_1 \otimes v_1, u_2 \otimes v_2)$

d.) $T(S(u \otimes (v_1, v_2)))$

$= T(u \otimes v_1, u \otimes v_2)$

$= u \otimes (v_1, 0) + u \otimes (0, v_2)$

$= u \otimes (v_1, v_2)$ $\quad$ .//

tombstone halmos

• Corollary

a) $\mathbb{R}^m \otimes \mathbb{R}^n \cong \mathbb{R}^{m\cdot n} \xleftarrow{s} \mathbb{R}^m \times \mathbb{R}^n \ni (e_i, f_j) \mapsto g_{(i,j)}$

$\mathbb{R}^m \times \mathbb{R}^n \xrightarrow{\otimes} \mathbb{R}^m \otimes \mathbb{R}^n$

$$\left(\bigoplus_m \mathbb{R}\right) \otimes \left(\bigoplus_n \mathbb{R}\right) = \bigoplus_m \left(\mathbb{R} \times \bigoplus_n \mathbb{R}\right)$$

$$s\left(= \sum_i x^i e_i, \sum y^j f_j\right) = \sum_{i,j} x^i y^j g_{(i,j)}$$

$$= \bigoplus_m \bigoplus_n \mathbb{R} \otimes \mathbb{R} \cong \bigoplus_{m\cdot n} \mathbb{R} \cong \mathbb{R}^{m\cdot n}.$$

• Lemma $\mathbb{R} \otimes \mathbb{R} \xrightarrow{\cong} \mathbb{R}$

$a \otimes b \longmapsto a\cdot b$

$c \cdot 1 \otimes 1 = c \otimes 1 \longleftarrow c$

$a \otimes b \longmapsto a \cdot b$

$(a\cdot 1) \otimes (b \cdot 1) \longleftarrow$

$ab \cdot (1 \otimes 1)$

$c \cdot (1 \otimes 1) \longleftarrow c = c \cdot 1 \cdot 1$

b.) $\dim(V_1 \otimes V_2) = \dim V_1 \cdot \dim V_2$

c.) if $(e_i)_{i\in I}$ is a basis for V_1,

$(f_j)_{j\in J}$ is a basis for V_2,

$(e_i \otimes f_j)_{(i,j)\in I\times J}$ is a basis for $V_1 \otimes V_2$

$V_1 \oplus V_2$

for $(e_i \oplus f_j)$ has

$(e_i, 0) + (0, f_j)$

• Def. $V_1^* \otimes V_2 \xrightarrow{T} \mathrm{Hom}(V_1, V_2)$

$V_1^*, V_2 \xrightarrow{\text{bilinear}} (v_1 \mapsto f(v_1)\cdot v_2)$

$f, v_2 \in V_2$

$f: V_1 \to \mathbb{R}$

$\mathrm{im}\,T$ = finite rank linear maps $V_1 \to V_2$

• Def. $V_1, V_2 \in$ vect

$S \in V_1 \otimes V_2$ S is a tensor, which is a member of the tensor space, which is also a vector space

the rank of S is ☆ $\operatorname{rank} S = \min k$

$$S = \sum_{i=1}^{k} v_i \otimes v_i' \qquad v_i \in V_1,\ v_i' \in V_2$$

• Exa. $\operatorname{rank} S = 0 \iff S = 0$

$\operatorname{rank} S = 1 \iff v \in V_1, v' \in V_2$

$S = v \otimes v'$

tensor   decomposable tensor

• Prop. a) $\mathrm{im}\,T = \{ f: V_1 \to V_2 \mid \dim \mathrm{im} f < \infty \}$

$\underset{\star}{\underset{\|}{\operatorname{rank} f}} = \underset{\dim \mathrm{im} f}{\underset{\|}{\underbrace{\operatorname{rank} f}}}$

b) $\forall g \in V_1^* \otimes V_2$

$\operatorname{rank} g = \dim \mathrm{im}\, T(g)$

Thm. $V^* \otimes W \longrightarrow \mathrm{Hom}(V,W)$

$f \otimes w \longmapsto (v \mapsto \underbrace{f(v)}_{\mathbb{R}} \cdot w)$

$\operatorname{im} T = \{ f : V \to W \mid \dim \operatorname{im} f < \infty \}$ finite rank operators

$\dim T(t) = \operatorname{rank} t = \min k$

$t = \sum_{i=1}^{k} f_i \otimes w_i$

ask for a little more clarification over this guy...

• **Corollary** $\dim V < \infty$

$V^* \otimes W \xrightarrow{\cong} \mathrm{Hom}(V,W)$

$V \otimes W \xrightarrow{\cong} \mathrm{Hom}(V^*, W)$

• **Corollary** $\dim V, W < \infty$

$V \otimes W \cong \mathrm{Bilin}(V^*, W^*; \mathbb{R})$

elements of tensor product have finite rank

i.) $t \in V^* \otimes W$

$t = \sum_{i=1}^{k} f_i \otimes w_i$, k min

$T(t)(v) = \sum_{i=1}^{k} f_i(v) \cdot w_i \in \mathrm{Span}(w_i)_i \ \forall i$

$\dim \leq k$

$\dim = k.$

ii.) $f : V \to W$ $\dim \operatorname{im} f < \infty.$

$\operatorname{im}(f) = \mathrm{Span}(w_1, \dots, w_k)$ $k = \dim \operatorname{im} f$

$$\begin{tikzcd} V \arrow[r, "f"] \arrow[dr, "f"'] \arrow[ddr, bend right, "g_i"'] & W \\ & \operatorname{im} f \arrow[u] \arrow[d, "w_i^*"] \\ & \mathbb{R} \end{tikzcd}$$

$f(v) = \sum_{i=1}^{k} w_i^*(f(v)) \cdot w_i$

$= T\left(\sum_{i=1}^{k} g_i \otimes w_i \right)(v)$

Tensors

$V \in \mathrm{Vect}_{\mathbb{R}}$

k times contravariant

and l times covariant is an element of

$$\underbrace{V \otimes V \otimes V \otimes \dots \otimes V}_{k \text{ times}} \otimes \underbrace{V^* \otimes V^* \otimes \dots \otimes V^*}_{l \text{ times}}$$

$$\dim(\dots\dots) = (\dim V)^{k+l}$$

suppose $\mathbb{R}^n \xrightarrow[\cong]{e} V$ is a basis

$$V \xrightarrow[\cong]{x = e^{-1}} \mathbb{R}^n \qquad v \in V = \sum_i x_i(v) e_i$$

Suppose $t = v_1 \otimes \dots\dots \otimes v_k \otimes f_1 \otimes \dots \otimes f_l$

Then $t = \left(\sum x^i(v_1 e_i)\right) \otimes \dots \otimes \left(\sum e_i^*(f_i) \cdot x^*_i\right)$
$\otimes \dots\dots$

$$\sum_{\substack{i_1, \dots, i_k \\ j_1, \dots, j_l}} \left(x^{i_1}(v_1) \;\cdots\; e^*_{j_1}(f_1)\, x^*_{j_1}\right) \cdot \underbrace{\left(e_{i_1} \otimes \dots \otimes e_{i_k} \otimes f_{j_1} \dots \otimes f_{j_l}\right)}_{\text{basis}}$$

$$\begin{tikzcd} & V & \mathbb{R}^n \arrow[l, "d"'] \\ \mathbb{R} \arrow[ur, "e"] \arrow[urr, "T"'] & & \end{tikzcd}$$

$$e_i = \sum_j T_i^j d_j$$

$$\begin{tikzcd} \mathbb{R}^n & & \mathbb{R}^n \\ & V \arrow[ul, "x = c^{-1}"] \arrow[ur, "y = d^{-1}"'] & \end{tikzcd}$$

$$e = d \circ T$$

$$x_i = \sum T^{-1}{}_i^j \, y_j \qquad e^{-1} = T^{-1} \circ d^{-1}$$

$$x = T^{-1} \circ y$$

• Recall multilinear maps

$\mathrm{Hom}(V, V, \ldots, V; W)$

$\cong \mathrm{Hom}(V \otimes V \otimes \ldots \otimes V, W)$

$= \mathrm{Hom}(V^{\otimes n}, W)$

if $\dim V < \infty$ $\quad \cong V^{*\otimes n} \otimes W$

• <u>Def.</u> A multi-linear map $V, \ldots, V \xrightarrow{T} W$ is symmetric if $T(v_1, \ldots, v_{i-1}, v_j, v_{i+1}, \ldots v_{j-1}, v_i, v_{j+1}) = T(v_1, \ldots, v_n)$.

$T(\ldots) = -T(v_1, \ldots, v_n)$ pairity of transpositions.

• <u>Proposition</u> $V, W \in \mathrm{Vect}$, $n \geq 0$

$\exists \ \mathrm{Sym}^n V \in \mathrm{Vect}$, symmetric multilinear map $V, \ldots, V \longrightarrow \mathrm{Sym}^n V$

such that $\forall\, W \in \mathrm{Vect}$ symmetric multilinear map $V, \ldots, V \xrightarrow{T} W$

$\exists !\ \mathrm{Sym}^n V \xrightarrow[\text{linear}]{S} W$ s.t. $T = S \circ v$

$T(v_1, \ldots, v_n) = S(v_1 \vee v_2 \vee \ldots \vee v_n$

6.) $\exists \Lambda^n V$ exact, antisymmetric multi-linear map $V, \dots, V \xrightarrow{\wedge} \Lambda^n V$

$$v_1, \dots, v_n \overset{\wedge}{\longmapsto} \underbrace{v_1 \wedge v_2 \wedge \dots \wedge v_n}_{\text{multivector}}$$

<u>• Corollary</u> $\mathrm{Hom}_{sym}(V, \dots, V; W)$

$\cong \mathrm{Hom}(\mathrm{Sym}^n V, W)$

$\mathrm{Hom}_{antisym}(V, \dots, V; W) \cong \mathrm{Hom}(\Lambda^n V, W)$.

elements in grassman algebra

<u>• Prop.</u> $\underset{\substack{\shortparallel \\ S_n}}{\Sigma_n}$ = permutation of n elements

$$\sigma \in S^n : V^{\otimes n} \xrightarrow{\sigma} V^{\otimes n}$$

$$v_1, \dots, v_n \longmapsto v_{\sigma(1)} \otimes v_{\sigma(2)} \otimes \dots \otimes v_{\sigma(n)}$$

$$v_1 \otimes \dots \otimes v_n \longmapsto$$

Symmetric Tensor construction.

Set $\mathrm{Sym}^n V = V^{\otimes n} / \mathrm{span}(v_1 \otimes \dots \otimes v_n - v_{\sigma(1)} \otimes \dots \otimes v_{\sigma(n)})$

$$v_1 v \dots v v_n = [v_1 \otimes \dots \otimes v_n]$$

$$\Lambda^n V = V^{\otimes n} / \mathrm{span}\,(v_1 \otimes \dots \otimes v_n) - (-1)^{\sigma} v_{\sigma_1} \otimes \dots \otimes v_{\sigma_n}$$

$v_1 \wedge \dots \wedge v_n = [v_1 \otimes \dots \otimes v_n]$. HW 12

use universal property

Def A tensor $t \in V^{\otimes n}$ is • symmetric

$$\sigma \cdot t = t$$

for all $\sigma \in S^n$ only for fields char $= 0$

• antisymmetric

$$\sigma \cdot t = (-1)^{\sigma} \cdot t$$

Example

$V = \langle e_1, e_2 \rangle$

$$\left.\begin{array}{l} t = e_1 \otimes e_2 + e_2 \otimes e_1 \\ t = e_1 \otimes e_1 \\ t = e_2 \otimes e_2 \end{array}\right\} \text{symmetric}$$

$t = e_1 \otimes e_2 - e_2 \otimes e_1$ } antisymmetric.

$t = 0$ symmetric and anti-symmetric

$V^{\otimes n}_{sym}$ $\quad$ $V^{\otimes n}_{antisym}$

Proposition. working over a field of char 0 (e.g., $\mathbb{Q}, \mathbb{R}, \mathbb{C}$)

$$\mathrm{Sym}^n V \xrightarrow{\cong} V^{\otimes n}_{sym}$$

$$\Lambda^n V \xrightarrow{\cong} V^{\otimes n}_{\Lambda}$$

Proof. $\mathrm{Sym}^n V \underset{B}{\overset{A}{\rightleftarrows}} V^{\otimes n}_{sym}$

$v_1 \vee \dots \vee v_n \quad v_1 \otimes \dots \otimes v_n$

$$v_1, \dots, v_n \longmapsto \sum_{\sigma \in S_n} v_{\sigma_1} \otimes \dots \otimes v_{\sigma_n}$$

$(B \circ A)(v_1 \vee \dots \vee v_n) = B\left(\sum_\sigma v_{\sigma_1} \otimes \dots \otimes v_{\sigma_n}\right)$

$= \sum v_{\sigma_1} \vee \dots \vee v_{\sigma_n} = \sum v_1 \vee \dots \vee v_n = n!\,(v_1 \vee \dots \vee v_n)$

$B \circ A = n! \cdot \mathrm{id}_{\mathrm{Sym}^n_V}$ $\qquad t \in V^{\otimes n}_{\mathrm{sym}} = \sum_{j \in J} v_{j,1} \otimes \dots \otimes v_{jn}$

$(A \circ B)(t)$

$= A\left(\sum_j v_{j1} \vee \dots \vee v_{jn}\right) = \sum_j \sum_{\sigma \in S^n} v_{j\sigma_1} \otimes \dots \otimes v_{j\sigma_n}$

Def. $\mathrm{Hom}(V_1, W_1) \otimes \mathrm{Hom}(V_2, W_2) \to \mathrm{hom}(V_1 \otimes V_2, W_1 \otimes W_2)$

$f_1 \otimes f_2 \longmapsto (v_1 \otimes v_2 \mapsto f_1(v_1) \otimes f_2(v_2))$

Isomorphism iff our vector spaces are finite (V_1, V_2 are $\underbrace{\text{finite dimensional}}_{\text{dualizable}}$ or $\dim W_i < \infty$)

modules: iso if V_i are f.g. proj.

Maps out of $M \longrightarrow N$ $\qquad M \otimes_R M^* \cong \mathrm{hom}_R(M, M)$

linear map ρ, proj

$\mathbb{Z}/n\mathbb{Z}$ not projective

R is a commutative ring $\qquad \sum e_i \otimes e_i^*$

M R-module

M is dualizable $\qquad \exists M^*$ R-module

$f \otimes m \longmapsto f(m)$ $\qquad 1 \qquad \cong \mathrm{Hom}_R(M, R) \qquad \mathrm{id}_M$

$M^* \otimes_R M \longrightarrow R$ $\qquad R \xrightarrow[\text{coevaluation}]{} M \otimes M^* \longrightarrow \mathrm{Hom}_R(M, M)$

$M \cong M^{**}$

underlying ring or field $\underset{\mathbb{R}}{\otimes}$

$\mathfrak{X}(M) \underset{C^\infty M}{\otimes} \mathfrak{X}(M)$ $\qquad f\cdot v \otimes v$

$\uparrow$ $\qquad \neq v \otimes f\cdot v$

$\mathfrak{X}(M) \underset{\mathbb{R}}{\otimes} \mathfrak{X}(M)$ $\qquad C^\infty M \underset{C^\infty M}{\otimes} C^\infty M \cong C^\infty M$

$C^\infty M \underset{\mathbb{R}}{\otimes} C^\infty M \subset C^\infty(M\times M)$

$\uparrow$ dense

$A, B \in CAlg_{\mathbb{R}}$ $\qquad A \otimes B$

$(a_1 \otimes b_1)\cdot(a_2\otimes b_2) = a_1 a_2 \otimes b_1 b_2$

$$\begin{tikzcd}
A \arrow[r] \arrow[rrd] & A\otimes B \arrow[rr, dotted, "\exists!"] & & C \\
 & & B \arrow[ul] \arrow[ur, "f"] \arrow[ur, "g"'] &
\end{tikzcd}$$

$a \mapsto a\otimes 1$ $\qquad b \mapsto b \otimes 1$

$h(a\otimes b) = f(a)\cdot g(a)$

completed tensor $\qquad C^\infty$- tensor product

Kolar - Michor - Slovak $\qquad$ Lulu.com

natural operations in diff geo $\qquad$ Nestruev

Michor $\qquad$ Ramanan

topics in differential geometry $\qquad$ global calculus.

Moerdijk - Reyes

models for smooth infinitesimal analysis.

• Def. $W_i = \mathbb{R}$ $\quad V_1^* \otimes V_2^* \longrightarrow (V_1 \otimes V_2)^*$

$$V^{*\otimes n} \longrightarrow (V^{\otimes n})^*$$

V dualizable $\Rightarrow$ iso

$$f_1 \otimes \ldots \otimes f_n \longmapsto (v_1 \otimes \ldots \otimes v_n \longmapsto f_1(v_1) \cdots f_n(v_n)).$$

• Def. $\mathrm{Sym}^n V^* \longrightarrow (\mathrm{Sym}^n V)^* = \hom(\mathrm{Sym}^n V, \mathbb{R})$

$$f_1 \vee \ldots \vee f_n \longmapsto \left(v_1 \vee \ldots \vee v_n \longmapsto \sum_\sigma f_1(v_{\sigma_1}) \cdots f_n(v_{\sigma_n})\right)$$

$$f_1, \ldots, f_n \longmapsto \left(v_1, \ldots, v_n \longmapsto \frac{1}{n!} \sum_\sigma \prod_i f_i(v_{\sigma(i)})\right)$$

$$V^* = \hom(V, \mathbb{R}), \quad V = \hom(V^*, \mathbb{R})$$

$$\hom_{sym}(V, \ldots, V; \mathbb{R}) \cong (V^{\otimes n})^*_{sym} \cong (V^*)^{\otimes n}_{sym}$$

• Prop. $\dim V < \infty \Leftrightarrow V \xrightarrow{\cong} V^{**}$

$$v \longmapsto (f \mapsto f(v))$$

$\boxed{\text{Def}}$

$$V^* \otimes V \xrightarrow{ev} \mathbb{R}$$

$$f, v \longmapsto f(v)$$

$$f^i v_i = \sum_i f^i v_i$$

$\boxed{\text{Def.}}$

$$V \otimes V^* \xrightarrow{\cong \text{ if } < \infty} \mathrm{Hom}(V, V)$$

$$v, f \longmapsto (w \longmapsto f(w) \cdot v)$$

coev

$$1 \longmapsto id_V \quad e^i e_i$$

• Recall Lambda abstraction

$$\{U \longrightarrow \mathrm{Hom}(V,W)\} \cong \{U \otimes V \longrightarrow W\}$$

currying

$$\mathrm{Hom}(U, \mathrm{Hom}(V,W)) \cong \mathrm{Hom}(U \otimes V, W).$$

$$f^{c}(u \longmapsto (v \longmapsto f(u \otimes v)))$$

$$(\mathrm{Sym}^n V^*) \otimes \mathrm{Sym}^n V \longrightarrow \mathbb{R}$$

contravariant in V $\quad V_1 \xrightarrow{g} V_2$

$$\begin{array}{ccc} (u \longmapsto f(u) \circ g) & & \mathrm{Hom}(U, \mathrm{hom}(V_1, W)) \\ \uparrow & & \uparrow \\ f^{u} & & \mathrm{Hom}(U, \mathrm{hom}(V_2, W)) \end{array}$$

Recall

$\dim V < \infty$

iff

$$V^* \otimes W \xrightarrow{\cong} \mathrm{Hom}(V,W)$$

$$\underbrace{V^*, \ldots, V^*}_{\mathrm{Sym}} ; \underbrace{V, \ldots, V}_{\mathrm{Sym}} \longrightarrow \mathbb{R}$$

$$f_1, \ldots, f_n ; v_1, \ldots, v_n \longmapsto \frac{1}{n!} \sum_{\sigma} \prod_i f_i(v_{\sigma(i)})$$

$$\frac{(p+q)!}{(p)!\,(q)!}$$

$$v_1, \ldots, v_n \longmapsto \frac{1}{n!} \sum_{\sigma} \prod_i v_{\sigma(i)}$$

$$\mathrm{Sym}^n V \rightleftarrows V^{\otimes n}_{\mathrm{sym}}$$

$$v_1 \vee \cdots \vee v_n \qquad v_1 \otimes \cdots \otimes v_n$$

$\Lambda^k V^* \otimes V^{\otimes k}_{\text{antisym}} \longrightarrow \mathbb{R}$

$\Lambda^k V^* \otimes \Lambda^k V$

$f_1, f_2 \in V^* \qquad f_1 \wedge f_2 \in \left(V^{\otimes 2}\right)^*_{\text{antisym}}$

$f_1 \wedge f_2 \in \Lambda^2 V^*$

$$\Lambda^2 V \longrightarrow \mathbb{R}$$
$$v_1, v_2 \longmapsto \frac{1}{2}\left(f_1(v_1) f_2(v_2) - f_1(v_2)\cdot f_2(v_1)\right)$$

$\left(V^{\otimes 2}\right)^*_{\text{antisym}}$

convex hull of points.

$\boxed{\text{Symplex ?}} \to$ symplecics

Cartan - diff forms are cochains

Prop. $\dim\left(V^{\otimes n}\right) = (\dim V)^n$

$$\dim\left(\mathrm{Sym}^n V\right) = \binom{\dim V + n - 1}{n}$$

$$\dim\left(\Lambda^n V\right) = \binom{\dim V}{n}$$

Corollary $\dim \Lambda^{\dim V} V = 1$

proof $v_1 \wedge \dots \wedge v_n \qquad v_i = \sum v_i^j e_j$

$$= \left(\sum_{j_1} v_i^{j_1} e_{j_1}\right) \wedge \dots \left(\sum_{j_n} v_i^{j_n} e_{j_n}\right)$$

$$= \sum_{j_1<j_2<j_3<\dots}^{n} a_j (e_{j_1} \wedge e_{j_2} \wedge \dots \wedge e_{j_n})$$

Stars and Bars argument

$$e^*_{j_n} \wedge \dots \wedge e^*_{j_n}$$

$$\Lambda^k V = F(V \times V \times \dots \times V)$$

$$\Lambda^k V = \otimes V / \ker \pi_A \qquad \pi_A = \frac{1}{k!} \sum \operatorname{sgn}(\sigma) \sigma$$

$$\langle v^1 \otimes \dots \otimes v^k, v_1 \otimes \dots \otimes v_k \rangle = v^1(v_1) v^2(v_2) \dots v^k(v_k)$$

$$\pi : \otimes^k V \longrightarrow \otimes^k V / \ker \pi_A$$

$$\langle \pi(v^1 \otimes \dots \otimes v^k), \pi(v_1 \otimes \dots \otimes v_k) \rangle = \frac{1}{k!} \det(v^i(v_j))$$

but $\langle v^1 \wedge \dots \wedge v^k, v_1 \wedge \dots \wedge v_k \rangle = \det(v^i(v_j))$ or $\frac{1}{k!} \det(v^i(v_j))$

$\cancel{A}_k(V) \cong (\Lambda^k V)^* \cong \Lambda^k V^*$

using (1) $\varphi \wedge \psi(v_1, \dots v_{k+l}) = \frac{1}{k!\,l!} \sum \operatorname{sgn}\sigma$
$\varphi(v_{\sigma_1} \cdots v_{\sigma_k})\, \psi(v_{\sigma(k+1)} \dots v_{\sigma(k+l)})$

$= \frac{(k+l)!}{k!\,l!} \cdot Alt(\varphi \otimes \psi)$

using (2) $(\psi \wedge \varphi)('') := \frac{1}{(k+l)!} \sum ''$

but if $e_1, \dots, e_n$ and $\varepsilon^1, \dots, \varepsilon^n$

$(\varepsilon^{j_1} \wedge \varepsilon^{j_2} \dots \wedge \varepsilon^{j_k})(e_{i_1} \wedge \dots \wedge e_{i_k}) = \frac{1}{k}!$

$(i_v \varphi)(v_1, \dots, v_{k-1}) = \varphi(v_1, v_2, \dots v_{k-1})$

not graded derivation (minor.) Free group algebra

$\Lambda^k V^*$

John Lee:

$(\Lambda^k V)^*$ $\qquad \Lambda^k V^*, A^k V^* \cong$

$\frac{1}{n!}(f_1 \wedge \dots \wedge f_k) \longleftarrow\!\shortmid f_1 \otimes \dots \otimes f_k$

$\Lambda^k V^* \longleftarrow A^k(V, \mathbb{R})$

$\longrightarrow \cong (V^*)^k_{Alt}$

$f_1 \wedge \dots \wedge f_k \mapsto \sum (-1)^\sigma f_{\sigma_1} \otimes \dots \otimes f_{\sigma_k}$

Graded derivation Koszul sign dim

Recall: basis $e_1, \dots, e_n$ $\quad V \quad n$

$e_1^*, \dots, e_n^* \quad V^* \quad n$

$e_{i_1} \otimes \dots \otimes e_{i_k} \quad \otimes^k V \quad n^k$

$j_\alpha = i + \alpha$

$e_{i_0} \vee \dots \vee e_{i_{k-1}} \quad \mathrm{Sym}^k V \quad \binom{n+k-1}{k}$

$e_{i_1 \leq \dots \leq} e_{i_k} \quad \Lambda^k V \quad \binom{n}{k}$

$i_1 < \dots < i_k$

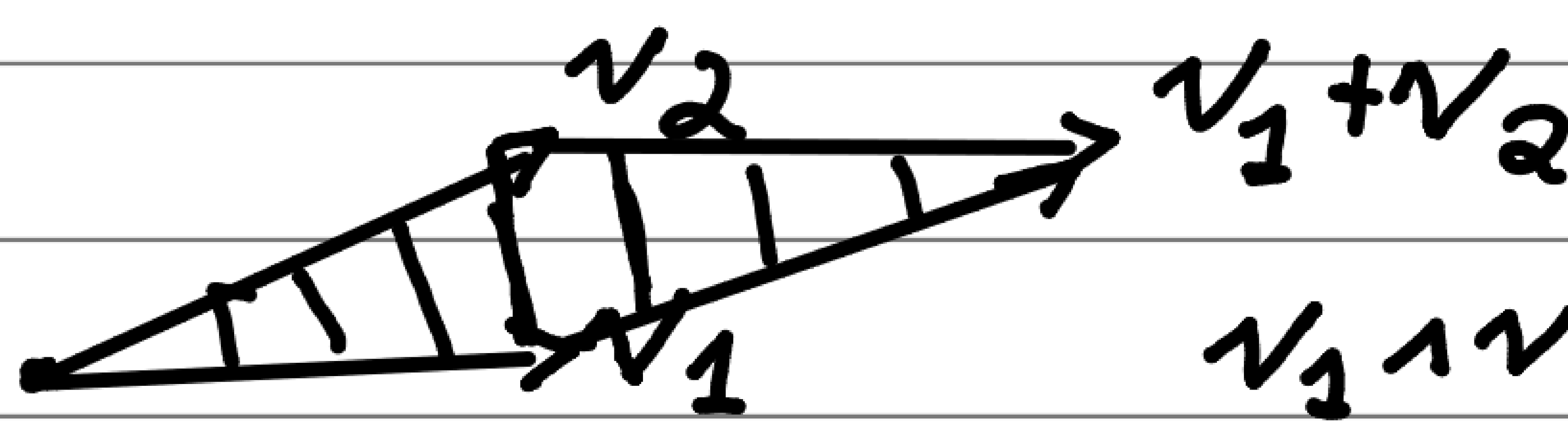
$$\dim \Lambda^{\dim V} V = 1$$

Def

- An oriented volume elements on V is an element of $\Lambda^{\dim V} V$

- An oriented translation-invariant measure on V is an element of

$$\Lambda^{\dim V} V^* \cong \left(\Lambda^{\dim V} V\right)^*$$



signed area

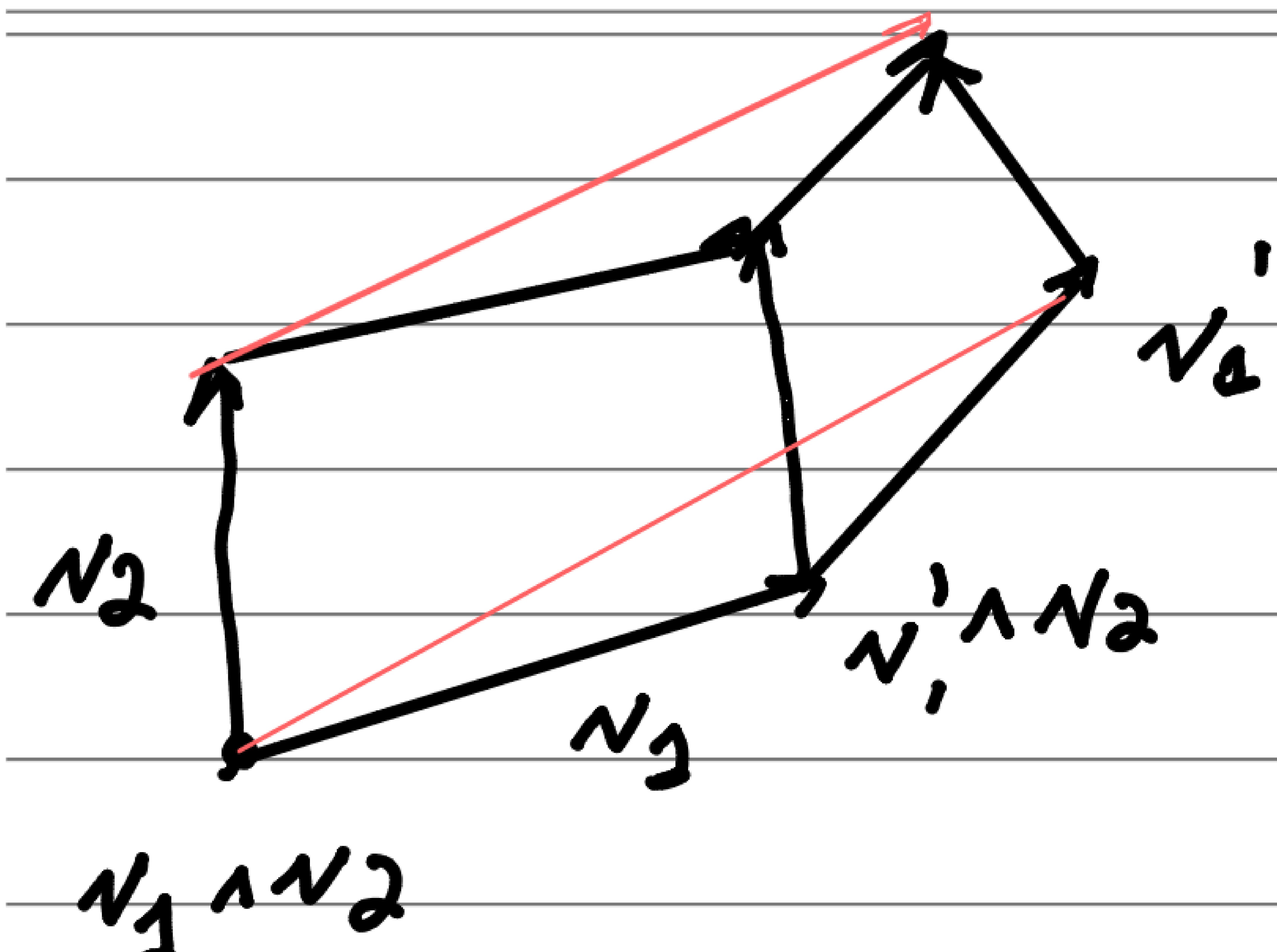
$v_1 \wedge v_2 = -v_2 \wedge v_1$

"volume as a physical idea."

$m \in M \quad t \in T \quad m \cdot t \in M \otimes T$

$$(\lambda v_1) \wedge v_2 = \lambda (v_1 \wedge v_2).$$

Shearing $\to$ $(v_1 + v_1') \wedge v_2 = v_1 \wedge v_2 + v_1' \wedge v_2$



what about indecomposible elements.

$= v_1 \wedge v_2 \wedge v_3 \wedge \dots \wedge v_n =$ λ is the

$\left(\sum_{j_1} v_1^{j_1} e_{j_1}\right) \wedge \dots$ $\quad \lambda(e_1 \wedge \dots \wedge e_n)$ determinant.

$v_i = \sum_j v_i^j e_j$

Overlapping terms but antisymmetry kills a ton of terms

$$= \sum_\sigma (v_1^{\sigma_1} \dots v_n^{\sigma_n}) \cdot (e_{\sigma_1} \wedge \dots \wedge e_{\sigma_n})$$

λ " this sum of permuted matrix

Sign of permutation

$$= \left(\sum_\sigma (-1)^\sigma v_1^{\sigma_1} \dots v_n^{\sigma_n}\right) \cdot (e_1 \wedge \dots \wedge e_n)$$

$= \det v \cdot (e_1 \wedge \dots \wedge e_n).$

Remark V, $n = \dim V$

$$\Lambda^n V = F(V \times \dots \times V) / \text{additivity}$$

$$\text{OrVol}(V) \quad (\lambda v_1, \dots, v_n) = \lambda \cdot (v_1, \dots, v_n)$$

$$(v_1, v_2, v_3, \dots, v_n) =$$

$$-(v_2, v_1, v_3, \dots, v_n)$$

$$\text{Vol}(V) = F(V \times \dots \times V) / \text{additivity}$$

$$(\lambda v_1, \dots, v_n) = |\lambda| \cdot (v_1, \dots, v_n)$$

$$(v_1, v_2, v_3, \dots) = (v_2, v_1, \dots)$$

$$(v_1, v_2, \dots, v_n)$$

$$\text{Or}(V) = F(V \times \dots \times V) / \quad (v_1 + \lambda v_i, v_2, \dots, v_n) =$$

$$= \text{sgn}(\lambda)(v_1, \dots, v_n)$$

$$(v_1, v_2, v_3, \dots, v_n) = -(v_2, v_1)$$

$$\dots$$

$$\dim \text{OrVol}(V) = \dim \text{vol}(V) = \dim \text{Or}(V) = 1$$

$[e_1, \dots, e_n]$ is a basis

$v_1, v_2, v_3, \dots, v_n$ Surrogate of multi-linearity.

$\boxed{\text{Prop}}$ $\underset{\Lambda^{\dim V} V}{\overset{}{\underset{||}{\mathrm{OrVol}(V)}}} \cong \mathrm{Vol}(V) \otimes \mathrm{or}(V)$

Def A translation invariant measure on V is an element of $\mathrm{Vol}(V)^* \cong \mathrm{Vol}(V^*)$

Prop $\{$ t-i measures on $V\}$

$\cong \{$ Haar measure

$=$ t-i Radon measure
locally finite and inner regular

finite dimensional
$V \in \mathrm{Vect}_{\mathbb{R}}$

$\mathrm{Vol}(V) \in \mathrm{Line}_{\mathbb{R}}$ determinant line

$\mathrm{OrVol}(V) = \det(V) \in \mathrm{Line}_{\mathbb{R}}$

$\boxed{\text{Def}}$ $\det V = \Lambda^{\dim V} V$ "fiber wise determinant"

$f: V \longrightarrow W$, $n = \dim V = \dim W$

$\det f : \det V \longrightarrow \det W$

$v_1 \wedge \dots \wedge v_n \longmapsto f(v_1) \wedge \dots \wedge f(v_n)$

Special case : $V = W$; $\det f : \det V \longrightarrow \det W$

$\det f \in \mathrm{Hom}(\det V, \det V) \cong \mathbb{R}$

determinant of an endomorphism is a number.

Properties $\quad$ Rem: $\dim V = 1$; $V^* \otimes V \cong \hom(V,V)$

$\dim V < \infty$ $\qquad\qquad\qquad\qquad \cong \mathbb{R}$

$\det V \cong \mathrm{Vol}\,V \otimes \mathrm{Or}(V)$ $\qquad \mathbb{R} \otimes W \cong W$

$\mathrm{vol}(V) \cong \det V \otimes \mathrm{Or}(V)^*$ $\quad$ 1-d vector spaces

$\mathrm{or}(V) \cong \det V \otimes (\mathrm{vol}\,V)^*$ $\quad$ form a group under tensor product

$(\det V)^* \cong \det(V^*)$

$(\mathrm{vol}\,V)^*$

"decomposable multi-linear form" "two-group"

$$f_1 \otimes \dots \otimes f_n \longmapsto \frac{1}{n!}(f_1 \wedge \dots \wedge f_n)$$

$$\sum_\sigma f_{\sigma_1} \otimes \dots \otimes f_{\sigma_n} \longleftarrow (f_1 \wedge \dots \wedge f_n)$$

$$(\mathrm{Or}\,V)^* \cong \mathrm{or}(V^*) \cong \mathrm{Or}\,V$$

$\boxed{\text{Def}}$ $\dim W = 1$ $\qquad \mathrm{vol}\,W$, $\dim = 1$

generated by

a.) $\mathrm{Vol}\,W = F(W) \big/ \lambda \in \mathbb{R}: [\lambda \cdot w] = |\lambda| \cdot [w]$

$[w] = [-w]$

confusion $\qquad \mathrm{Or}(\det V) \cong \mathrm{Or}\,V$

$\mathrm{vol}(\det V) \cong \mathrm{vol}\,V$

exercise

$[0] = 0$

$$W \xrightarrow{1-1} \mathrm{vol}\,W \qquad \underbrace{|\lambda \cdot w|}_{\mathrm{vol}W} = \underbrace{|\lambda|}_{\mathbb{R}} \cdot \underbrace{|w|}_{\mathrm{vol}W}$$

$$w \longmapsto [w]$$

<u>not linear</u>

pseudo-forms? Top-degree pseudo form is a density.

b.) $\mathrm{Or}\,W = F(W) \,/\, [\lambda w] = \mathrm{sign}(\lambda) \cdot [w]$, $\lambda \in \mathbb{R}$

$$W \xrightarrow{\mathrm{sign}} \mathrm{or}\,W$$

$$\mathrm{Sign}(\lambda \cdot w) = \mathrm{sign}(\lambda) \cdot \mathrm{sign}(w)$$

$$F\left(W \setminus \{0\} / \mathbb{R}_{>0}\right) / -[w] = [-w]$$

c.) $\mathrm{or}(\mathrm{vol}\,W) \cong \mathbb{R}$

$\boxed{\text{Recall}}$ (the algebraic construction of ΛV).

$$\Lambda^k V \overset{k \geq 0}{=} (V \otimes \ldots \otimes V) \Big/ {\overset{+\text{ permutations}}{(v_1 \otimes v_2 \otimes \cdots \otimes - v_2 \otimes v_1)}}$$

$$= F(V \times \ldots \times V) / [v_1 + v_1', v_2, \ldots.]$$

$$= [v_1, v_2, \ldots] + [v_1', v_2, \ldots]$$

$$[\lambda \cdot v_1, v_2, \ldots] = \lambda \cdot [v_1, v_2, \ldots]$$

+ Permutations

exterior (wedge) product

$$\Lambda^k V \otimes \Lambda^l V \longrightarrow \Lambda^{k+l} V$$

$$(v_1 \wedge \ldots \wedge v_k) \otimes (v_k \wedge \ldots \wedge v_{k+l}) \longmapsto v_1 \wedge \ldots \wedge v_{k+l}$$

koszul sign rule: $\omega_1 \wedge \omega_2 = (\omega_2 \wedge \omega_1) \cdot (-1)^{k \cdot l}$

Sign iff k and l are odd.

$$[v_1, \ldots, v_k] \otimes [v_{k+1}, \ldots, v_{k+l}] \overset{\wedge}{\longmapsto} [\cdot \ldots \cdot]$$

$$= [v_1] \wedge \ldots \wedge [v_k] \qquad F(v) = [\lambda \cdot v] = \lambda \cdot [v]$$

$$[v] \longleftarrow v \qquad [v + v'] = [v] + [v']$$

$$\Lambda^1 V \cong V$$

This is called a graded commutative algebra.

$\boxed{\text{Def}}$ A $\mathbb{Z}$-graded commutative algebra A is $A_k \in \mathrm{Vect}_{\mathbb{R}}$ $k \in \mathbb{Z}$.

$$A_k \otimes A_l \xrightarrow{\cdot} A_{k+l} \quad , k, l \in \mathbb{Z}$$

$$\begin{tikzcd} A_k \otimes A_l \arrow[d] \arrow[dr, "\cdot"] & \\ A_l \otimes A_k \arrow[r, "\cdot"'] & A_{k+l} \end{tikzcd}$$

$v \otimes w \mapsto (w \otimes v) \, -1^{(k \cdot l)}$

$v \cdot w = (-1)^{k \cdot l} \, w \cdot v$

Example: ΛV

$\Lambda^k V$

Example $\deg 2k : \mathrm{sym}^k V$

$\deg 2k+1 : 0$

$\boxed{\text{Rem}}$ $\mathrm{GCA}_{\mathbb{R}} \underset{\Pi}{\overset{\oplus}{\rightrightarrows}} \mathrm{Alg}_{\mathbb{R}}$

$$\oplus A := \bigoplus_k A_k$$

if $A_k = 0$ for $k < 0$

$$\Pi A := \prod_k A_k$$

$$(a_0, a_1, \dots) \cdot (b_0, b_1, \dots)$$
$$= (a_0 b_0, a_0 b_1 + a_1 b_0, a_0 b_2 + a_1 b_1 + a_2 b_0, \dots)$$

The universal property of ΛV

$A \in GCA_{\mathbb{R}}$

$$\{\Lambda V \longrightarrow A\} \cong \{\overset{\Lambda^1 V}{\overset{\wr\wr}{V}} \xrightarrow{g} A_1\}$$

$f \mapsto f_1$

morphisms of $GCA_{\mathbb{R}}$ — linear maps

$\sum_i v_1 \wedge \ldots \wedge v_{i-1} \wedge f(v_i)$

$g \longmapsto f$

$f_k : \Lambda^k V \longrightarrow A_k$

$v_1 \wedge \ldots \wedge v_k \longmapsto f(v_1) \wedge \ldots \wedge f(v_k)$

• Prop $V \in Vect_{\mathbb{R}}$, $A \in GCA_{\mathbb{R}}$

$$\{V \xrightarrow{f} A_1\} \cong \{\Lambda V \xrightarrow{g} A\}$$

$f \longmapsto (v_1 \wedge \ldots \wedge v_k \longmapsto f(v_1) \wedge \ldots \wedge f(v_k))$

$g_1 \longleftarrow g_1$

ΛV is the free graded commutative algebra generated by V in degree 1.

ΛV has generators and relations

gen: (W, ω) $W \subset V$ subspace $\omega \in \det W = \Lambda^{\dim W} W$

degree $= \dim W$

rel: $(W_1, \omega_1) \wedge (W_2, \omega_2) = \begin{cases} 0 & , W_1 \cap W_2 \neq \{0\} \\ (W_1 + W_2), & \omega \wedge \omega_2 \end{cases}$

if $W_1 \cap W_2 = \{0\}$

$\dim(W_1 + W_2) = \dim W_1 + \dim W_2$

In degree 1 : (w, ω) $\omega \in W$ $\quad \dim W = 1$

$$(w_1, \omega_1) + (w_2, \omega_2) = \begin{cases} 0, & w_1 + w_2 = 0 \\ (\mathrm{span}(w_1 + w_2), \omega_1 + \omega_2) \end{cases}$$

$\boxed{\text{Def}}$ $\Lambda_a V \longrightarrow \Lambda_g V$

is induced by the universal property

$$\begin{tikzcd} V \arrow[r] \arrow[rr, bend right, "\mathrm{id}_V"'] & \Lambda^1_g V \cong & V \end{tikzcd}$$

Essentially,

$$v_1 \wedge \ldots \wedge v_k \longmapsto \begin{cases} 0 & \text{if } (v_i)_i \text{, lindep} \\ (W, \omega) \end{cases}$$

$W = \mathrm{span}(v_1, \ldots, v_k)$

$\omega = v_1 \wedge \ldots \wedge v_k$

Next $\Lambda_g V \longrightarrow \Lambda_a V$

what happens to the generator?

$\omega \in \Lambda^{\dim W} W$

$W \xrightarrow{inc} V$

$\Lambda^{\dim W} W \rightarrowtail \Lambda^{\dim W} V$

equiv classes $\longmapsto$ equiv class

$$(W, \omega) \longmapsto \omega \in \Lambda_a^{\dim W} V$$

1 $\quad (W_1, \omega_1) \wedge (W_2, \omega_2) \mapsto \begin{cases} 0, & W_1 \cap W_2 \neq \{0\} \\ (W_1 + W_2, \omega_1 \wedge \omega_2) \end{cases}$

$\downarrow$

$\omega_1 \wedge \omega_2$

Grassmann calculus

$$\begin{cases} 0, & W_1 \cap W_2 \neq \{0\} \end{cases}$$

Claim if $W_1 \cap W_2 \neq \{0\}$, then $\omega_1 \wedge \omega_2 = 0$.

$\omega_1 \wedge \omega_2 = u_1 \wedge \ldots \wedge u_{k_1} \wedge v_1 \wedge \ldots \wedge v_k$
$= 0$ linear dependence.

$\boxed{\text{Prop}}$ $\Lambda_g V^*$ gen & rel $G \subset A_{\mathbb{R}}$

gen(W, ω) $W \subset$ codim k

Substitute V^* in Λ_g
generators (W, ω)
indegree k $\dim V = n$
$\omega \subset V^*$

$$\underset{k}{W} \xrightarrow{\text{inclusion}} \underset{n}{V^*}$$

$$\underset{n-k}{U} \underset{\text{inclusion}}{\xrightarrow{\ker}} \quad V \cong \underset{n}{V^{**}} \xrightarrow{\iota^*} \underset{k}{W^*}$$

$$w = \{ f : V \to \mathbb{R} \mid f|_U = 0 \}$$

$$U = \{ v \in V \mid \forall w \in W : w(v) = 0 \}$$

$\omega \in \Lambda^k W$ "the map is the important thing..."

$\boxed{\text{Recall}}$

$$\overset{k}{V_1} \xrightarrow[f_1]{} \overset{l}{V_2} \xrightarrow[f_2]{} \overset{m}{V_3}$$

$\operatorname{im} f_1 = \ker f_2$ $V_2 = V_1 \oplus V_3$:

$\det V_2 \cong \det V_1 \otimes \det V_3$ $\det(V_1 \oplus V_3)$

$(a_1 \wedge .. \wedge a_k) \otimes (c_1 \wedge \dots \wedge c_n)$. $\det(V_1) \otimes \det V_3$

$$\left(f_1(a_1) \wedge \dots \wedge f_1(a_k)\right) \wedge \tilde{c}_1 \wedge \dots \wedge \tilde{c}_m)$$

$f_2(\tilde{c}_i) = c_i$ choice

$\det V \cong \det U \otimes \det W^*$ from earlier.

$\det W \cong \det U \otimes \det V^*$

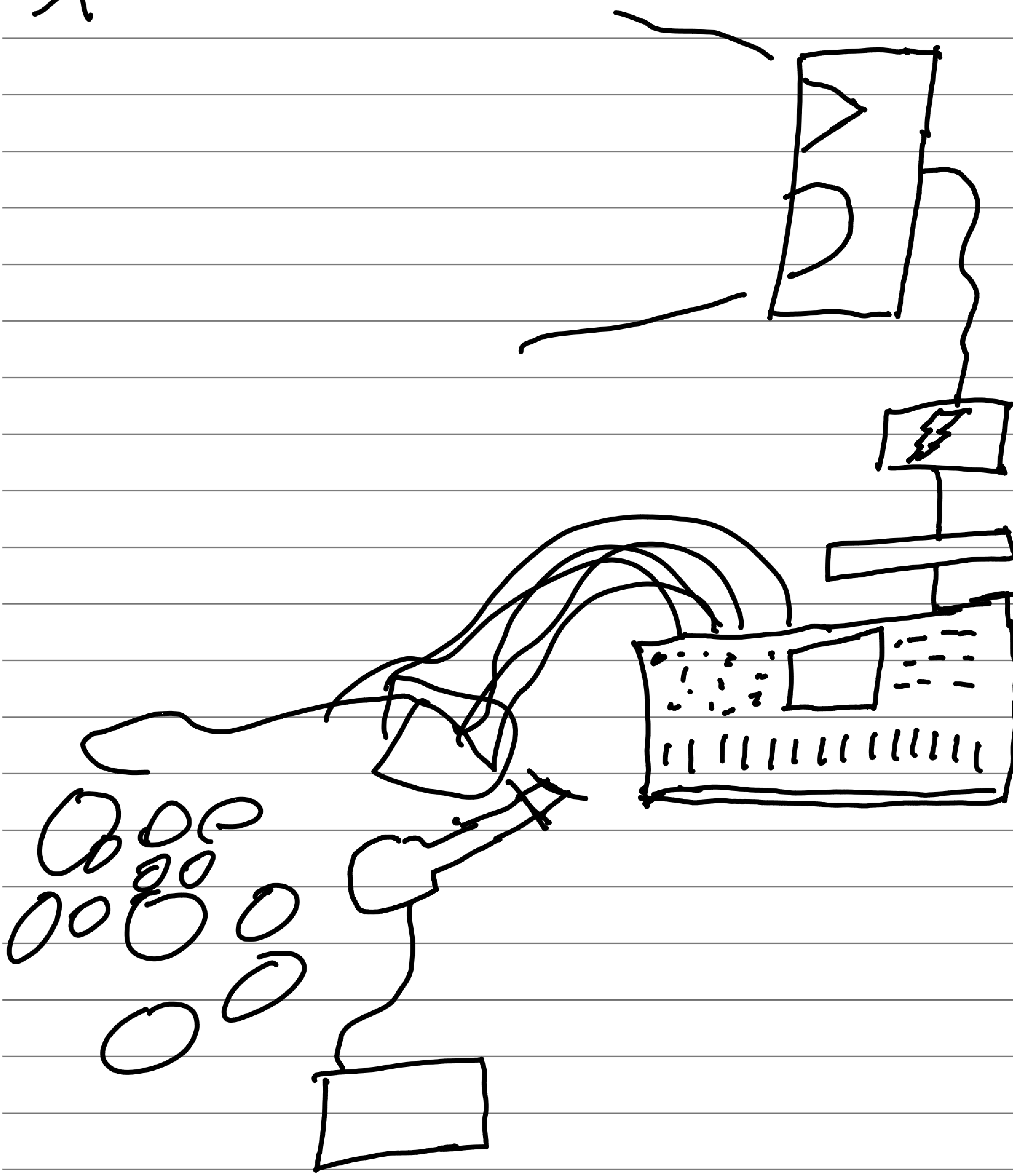
$\psi \in \det U \otimes \det V^*$

$\cong (\det(V/U))^*$ Orthogonal complement ψ is an oriented measure on the quotient V/U

$$(U_1, \psi_1) \wedge (U_2, \psi_2) = \begin{cases} 0 & \operatorname{codim}(U_1 \cap U_2) \neq \operatorname{codim} U_1 + \operatorname{codim} U_2 \\ (U_1 \cap U_2, \psi_1 \wedge \psi_2), & \text{otherwise} \end{cases}$$

"transversality..."

I am retarded



triang

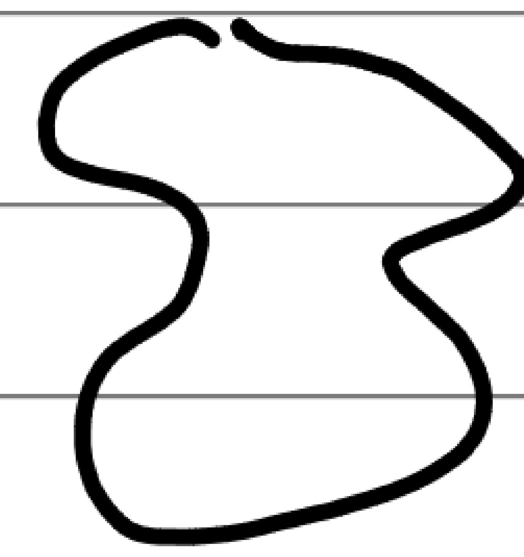
- Cairns
- Prasolov

ball nLab

Demailly

Guillemin - Haine

$U \subset \mathbb{R}^n$ starshaped



$$U \to \mathbb{R}^n$$
$$p \mapsto f(p) \cdot p$$
$$f : U \to \mathbb{R}_{>0}$$

Sheaves

good cover ?

Redundant!

Last time: $W \subset V$

$$\underbrace{\Lambda_g V}_{\text{Graded commutative Algebra}} = \quad (W, \omega) \quad \dim W = \text{degree}$$
$$\omega \in \det W$$

① $(W_1, \omega_1) \wedge (W_2, \omega_2) = \begin{cases} 0, & W_1 \cap W_2 \neq \{0\} \\ (W_1 + W_2, \omega_1 \wedge \omega_2) \end{cases}$

degree one: $\dim W = 1 \quad \det W = W$

$\omega \in W$, $\omega \neq 0$

$\Rightarrow W = \operatorname{span}\{\omega\}$

$\omega = 0 \Rightarrow (W, \omega) = 0$

$$\omega \in \det W = \Lambda^{\dim W} W \subset \Lambda^{\dim W} V$$

$$W = \{\omega \in V \mid \forall u \in U : u(\omega) = 0\}$$

$$U = \{u \in V^* \mid u \lrcorner \omega = 0\}$$

contraction

② $V \cong \Lambda^1_g V$

(U, ψ) degree $=$ codim U

$$(U_1, \psi_1) \wedge (U_2, \psi_2) = \begin{cases} 0, \\ (U_1 \cap U_2, \psi_1 \wedge \psi_2) \end{cases}$$

in degree 1: $\psi \in (V/U)^*$

$\psi : V \longrightarrow \mathbb{R}$, $\psi|_U = 0 \Rightarrow U = \ker \psi$

Pairing $\Lambda V \otimes \underset{\Lambda(V^*)}{\underset{\cong}{\Lambda V^*}} = \mathbb{R}$

$$\Lambda^m V \otimes \Lambda^m V^*$$

Bourbaki: Algebra chapter III

$$\underset{m}{(W}, \underset{\det W}{\underset{\cap}{\omega}}) \otimes (\underset{n-m}{U}, \psi) \longmapsto \quad \psi \in (\det(V/U))^*$$

$$\overset{m}{W} \overset{\iota}{\rightarrowtail} \overset{n}{V} \overset{q}{\twoheadrightarrow} \overset{m}{V/U}$$

$$\det(q \cdot \iota) : \det W \longrightarrow \det(V/U)$$

$$\psi\big(\det(q\iota)(\omega)\big)$$

Contractions

$$V \otimes \underset{\substack{\text{"S} \\ (\Lambda^k V)^*}}{\Lambda^k V^*} \longrightarrow \Lambda^{k-1} V^* \qquad v \lrcorner \omega$$

$$\qquad\qquad\qquad\qquad\qquad\qquad /\!/ \ \iota_v \omega$$

$$v \otimes \underset{\substack{\cap \\ (\Lambda^k V)^*}}{\omega} \longmapsto (v_2, \dots, v_k) \qquad \omega \llcorner v$$

$$\longmapsto \omega(v, v_2, \dots, v_k)$$

$$V^* \otimes \Lambda^k V \longrightarrow \Lambda^{k-1} V$$

$$f \otimes (v_1 \wedge \dots \wedge v_k) \longmapsto \sum_i f(v_i) (-1)^i v_1 \wedge v \dots \wedge \hat{v}_i \wedge \dots \wedge v_k$$

Proposition $A \in GCA_{\mathbb{R}}$, $d \in \mathbb{Z}$

$\mathcal{D} : A_k \xrightarrow{\mathbb{R}\text{-linear}} A_{k+d}$ is a <u>grated derivation</u> of degree d if $\mathcal{D}(a \cdot b) = (\mathcal{D}a) \cdot b + (-1)^{d \cdot |a|} \cdot a \cdot \mathcal{D} b$

$a \in A_{|a|}$ $\quad b \in A_{|b|}$

Proposition $\forall\ v \in V : \iota_v$ g.d. -1 of ΛV^*

$\forall f \in V^* : \iota_f$ g.d. -1 of ΛV

$f : V^*$

$f \lrcorner (v_1 \wedge \dots \wedge v_k \wedge v_{k+1} \wedge \dots \wedge v_{k+l})$

$(f \lrcorner (v_1 \wedge \dots \wedge v_k)) \wedge (v_{k+1} \wedge \dots \wedge v_{k+l}) + (-1)^k (v_1 \wedge \dots \wedge v_k)$
$\wedge (f \lrcorner (v_{k+1} \wedge \dots \wedge v_{k+l}))$

$= \sum_i^k f(v_i) (-1)^i (v_1 \wedge \dots \wedge \widehat{v_i} \wedge \dots \wedge v_k \wedge v_{k+1} \wedge \dots \wedge v_l)$

$+ (-1)^k \sum_{j=1}^{l} f(v_{k+j}) \cdot (-1)^j (v_1 \wedge \dots \wedge v_k \wedge v_{k+1} \wedge \dots \wedge \widehat{v_{k+j}} \wedge \dots \wedge v_{k+l})$

$= \sum_{i=1}^{k+l} f(v_i) (-1)^i (v_1 \wedge \dots \wedge \widehat{v_i} \wedge \dots \wedge v_{k+l}).$

$V^* \not\cong \bigoplus_{k \geq 0} \mathbb{R}$

$\det W = \Lambda^{\dim W} W$

$\psi \in \det U \otimes (\det V)^*$

$\det U = \Lambda^{\dim U} U$

$\subset \Lambda^{\dim U} V$

$\Lambda^l V \otimes \Lambda^k V^* \xrightarrow{\lrcorner} \Lambda^{k-l} V^*$

$(W, \omega) \otimes (U, \psi) \longmapsto (W + U,$

$l \quad \overset{\in}{\det W} \quad n-k \qquad\qquad n-k+l$

transversally?

if $\dim(W+U) = n-k+l$

$\boxed{\text{contractions}}$

$\dim V = n$

$$\Lambda^k V \otimes \Lambda^\ell V^* \xrightarrow{\lrcorner} \Lambda^{\ell-k} V^*$$

$$(v_1 \wedge \dots \wedge v_n) \quad \omega \longmapsto (v_{k+1} \wedge \dots \wedge v_{k+\ell})$$

$$\frac{1}{(\ell-k)!} \sum_\sigma \omega(v_1, \dots, v_k)$$

$$\overset{k}{(W}, \overset{\det W}{\underset{\psi}{\omega}}) \lrcorner \overset{n-\ell}{(U}, \overset{\psi}{\psi}) \qquad (\det(V/U))^* = \det U \otimes (\det V)^*$$

$$= \begin{cases} 0, & (\dim W + U) \neq n-\ell+k \\ (W+U, \omega \otimes \psi) \end{cases}$$

$$\Lambda^k V^* \otimes \Lambda^\ell V \xrightarrow{\lrcorner} \Lambda^{\ell-k} V$$

$$\underset{k-\ell}{(U, \psi)} \otimes \underset{\ell}{(W, \omega)} \longmapsto \begin{cases} 0 & \text{if} \dim(U \cap W) \neq \ell-k \\ U \cap W, & \psi \otimes \omega \end{cases}$$

$$U \cap W \longrightarrow W \longrightarrow W/(U \cap W)$$

$$\cong V/U$$

$$\det(U \cap W) \cong \underset{\omega}{\det W} \otimes \underset{\psi}{\det (V/U)^*}$$

$$(W_1, \omega_1) \wedge (W_1, \omega_2) = \begin{cases} 0, & \dim(W_1 + W_2) \neq k+\ell \\ (W_1 + W_2, & \omega_1 \otimes \omega_2 \end{cases}$$

$$\overset{n-k}{(U_1}, \psi_1) \wedge \overset{n-\ell}{(U_2}, \psi_2) = \begin{cases} 0 & , \dim(U_1, U_2) \neq n+k-\ell \\ (U_1 \cap U_2), & \psi_1 \otimes \psi_2 \end{cases}$$

Important Special case
Hodge Star

$\ell = n = \dim V$

Fix $\omega \in \Lambda^m V^*$ (an oriented volume form)

$\Lambda^m V^* \otimes \Lambda^n V \longrightarrow \mathbb{R}$
$\omega \otimes \psi \longmapsto 1$ $\qquad V \otimes V \longrightarrow \mathbb{R}$

$*: \Lambda^k V \longrightarrow \Lambda^{\ell-k}(V^*)$ $\qquad V \xrightarrow{\cong} \mathrm{Hom}(V, \mathbb{R}) \cong V^*$
$\varphi \longmapsto \varphi \lrcorner \omega$

$*: \Lambda^k V^* \longrightarrow \Lambda^{\ell-k} V$
$x \longmapsto x \lrcorner \psi$

$(w^\perp, \varphi \otimes \omega)$
$(\omega, \varphi) \longmapsto (W, \varphi \otimes \omega)$
$\in \Lambda^k V$ $\qquad \Lambda^{\ell-k} V^*$

$(U, x) \longmapsto (U, x \otimes \psi)$
$(U^\perp, x)$

If V is equipped w/ a nondegenerate metric $V/U \cong U^\perp$
$\Lambda^m V^* \cong \Lambda^m V$

Differential Forms

$\omega \in \Omega^n M$

A differential n-form on a smooth manifold M is an anti-symmetric $C^\infty M$-multilinear form

$$\underbrace{\mathfrak{X}M}_{\text{vectorfields}}, \dots, \mathfrak{X}M \longrightarrow C^\infty M.$$

Equivalently,

ω maps $m \in M$

to an element of $\Lambda^n T_m^* M \cong (\Lambda^n T_m M)^*$

has to be a smooth map.

Example: $n=0$: 0-form $\equiv$ smooth function.

Examples

$$\Omega^0 M \cong C^\infty M$$

$M = V \in Vect_{\mathbb{R}}$ more generally

$T_m M \cong V$ $\quad M \underset{\text{open}}{\subset} V$

$T_m^* M \cong V^*$

An n-form ω is a smooth map

$$M \longrightarrow \Lambda^n V^* \cong (\Lambda^n V)^*$$

Fix a basis $e_1, \dots, e_m$ of V and a dual basis $x_1, \dots, x_m$ of $V^* \cong \Lambda^1 V^* \cong (\Lambda^1 V)^*$

$dx_i : M \longrightarrow \Lambda^1 V^*$ $\quad$ if $v \in \mathfrak{X}M$,

$m \longmapsto x_i$. $\quad dx_i(v) = v_i$ $\quad$ projection map ?

Example

we have the wedge product

$$\Omega^m M \otimes \Omega^n M \longrightarrow \Omega^{m+n} M$$
$$\omega_1 \otimes \omega_2 \longmapsto \omega_1 \wedge \omega_2$$

Example $M \underset{\text{open}}{\subset} V$

$$dx_i \wedge dx_j \in \Omega^2 M$$

$$(dx_i \wedge dx_j)(v_1, v_2) = dx_i(v_1) \cdot dx_j(v_2) - dx_i(v_2) \cdot dx_j(v_1)$$
$$= v_{1,i}\, v_{2,j} - v_{2,i}\, v_{1,j}$$

$$= \det \begin{pmatrix} v_{1,i} & v_{1,j} \\ v_{2,i} & v_{2,j} \end{pmatrix}$$

a basis for $\Omega^k M$

$$(dx_{i_1} \wedge \dots \wedge dx_{i_k})(v_1, \dots, v_k)$$

$$= \det \begin{pmatrix} v_{1,i_1} & v_{1,i_2} & \dots & v_{1,i_k} \\ & & & \end{pmatrix}$$

Example $f : M \to \mathbb{R}$

$$Tf : TM \longrightarrow T\mathbb{R} = \mathbb{R} \times \mathbb{R}$$
$$\downarrow \pi_2$$
$$\mathbb{R}$$

directional derivative

$df \in \Omega^1 M$

$(df)(v) = \partial_v f$

The DGCA of differential forms

Ω

$\boxed{\text{Def}}$ A differential graded algebra A is $A_n \in \mathrm{Vect}_{\mathbb{R}}$ $n \in \mathbb{Z}$ — cochain complex

- A is a graded algebra (commutative)
- $d : A_n \longrightarrow A_{n+1}$ $\mathbb{R}$-linear map (cohomological grading convention)
- $d(a \cdot b) = d(a) \cdot b + a \cdot d(b) \cdot (-1)^{|a| \cdot 1}$
- graded commutative if $a \cdot b = (-1)^{|a||b|} b \cdot a$

$M = \mathbb{R}^n$ $\quad df \quad f = \sum_i x_i \cdot g_i$

__Algebraic Def__ $\quad df = \sum dx_i \cdot g_i + x_i \cdot dg_i$

"kahler differentials" $\Omega^1 M = C^\infty$-kahler differenital

Ω is the free C^∞-DGA (A_0 is a C^∞-ring, $d : A_0 \longrightarrow A_1$, C^∞ derivation (

$$d(f(a_1, \dots, a_n)) = \sum_i \frac{\partial f}{\partial x_i}(a_1, \dots, a_n) \cdot da_i \,))$$

on $C^\infty M$ in degree 0. In practice a

$\omega \in \Omega^n M$

C^∞DGCA

$$\{\Omega M \xrightarrow{p} B\} \cong \{C^\infty M \xrightarrow{q} B_0\}$$

C^∞Ring

$p \longmapsto p_0$

$p \longleftarrow q$

$p(\sum f \wedge dg_1 \wedge \dots \wedge dg_k)$

$\sum p(f) \wedge dp(g_1) \wedge \dots \wedge d(p(g_k)))$

In practice $\omega \in \Omega^k M$: $\omega = \sum_{\text{finite}} f \wedge dg_1 \wedge \dots \wedge dg_k$

$f, g \in C^\infty M$

what is a concrete example of

$\mathcal{B} = C^\infty(\mathbb{R}^n) \otimes \mathrm{GrSym}(V^*)$ $\quad V \in \mathrm{GrVect}_{\mathbb{R}}$

$$\mathrm{GrSym}\, V^* = \bigotimes_{k\geq 1} \mathrm{GrSym}(V_k^*[k])$$

\bigotimes

$$= \bigotimes_{\substack{k\geq 1\\ k \text{ odd}}} \Lambda V_k^* \otimes \bigotimes_{\substack{k\geq 1\\ k \text{ even}}} \mathrm{Sym}\, V_k^*$$

\otimes

Geometric Definition

$\Omega_g M \in \mathrm{DGCA}_{\mathbb{R}}$

ΩM = smooth infinitesimal singular cochain complex.

$$\Omega^k M = \Gamma(\Lambda^k T^* M) \cong \Lambda^k_{C^\infty M} \Gamma(T^*M) \cong \Lambda^k_{C^\infty M}(\mathfrak{X}M)^*_{C^\infty M}$$

$(\underset{M}{\overset{}{m}} \longmapsto \omega_m \in \Lambda^k T^*_m M)$, $m \in M$

$\omega_m(v_1, \dots, v_k) \in \mathbb{R}$

$v_i \in TM$

vector-bundles....

$\omega(X_1, \dots, X_k) \in C^\infty M$

$\omega(f \cdot X_1, \dots) = f \cdot \omega(X_1, \dots,)$

$\Omega_a M \longrightarrow \Omega_g M \iff C^\infty M \xrightarrow[id]{\varphi} (\Omega_g^0 M) = C^\infty M$

Def $\Omega^0 M \longrightarrow \Omega^1 M$
$C^\infty M \xrightarrow{d} (\mathfrak{X} M)^*_{C^\infty M}$

$(df)(X) = \mathcal{L}_X f = X(f)$

Thm. Isomorphic!

de Rham time

Proposition $\omega \in \Omega^k M$

$$(d\omega)(X_0, \dots, X_k)$$

$$= \sum_{0 \le i \le k} (-1)^i \mathcal{L}_{X_i} \omega(X_0, \dots, \widehat{X_i}, \dots, X_k)$$

$$+ \sum_{0 \le i \le j \le k} (-1)^{i+j} \omega([X_i, X_j], X_0, \dots, \widehat{X_i}, \dots, \widehat{X_j}, \dots, X_k)$$

Suppose $M \subset_{open} \mathbb{R}^n = V$

$TM \cong M \times V \qquad T^*M \cong M \times V^*$
$\Lambda^k T^* M = M \times \Lambda^k V^*$
$\Omega^k M = C^\infty(M, \Lambda^k V^*)$

take $\omega \in \Omega^k M = C^\infty(M, \Lambda^k V^*)$

$D\omega$ derivative

c^{III} $\quad D\omega : M \times V \longrightarrow \Lambda^k V^*$

$(D\omega)_m (v_0, \underbrace{v_1, \dots, v_k}) \in \mathbb{R}^n$

antisymetrize the whole thing

$d\omega = \mathrm{Alt}_k(D\omega)$

$(\mathrm{Alt}(D\omega)(x_0, \dots, x_k)$
$= \sum (-1)^i (D\omega)(x_i, x_0, \dots, \hat{x}_i, \dots, x_k)$

$\underbrace{\qquad\qquad\qquad\qquad}$

multi-linear in ω and x_i

$D(\omega(x_0, x_1, \dots, \hat{x}_i, \dots, x_n))$

in ω and x_i

$(D_{x_i}\omega)(x_0, \dots, \hat{x}_i, \dots, x_k) + \sum_j \omega(x_0, \dots, \hat{x}_i, \dots, D_{x_i} x_j, x_n)$

$k=0$: $d\omega(X_0) = \mathcal{L}_{X_0}\omega$

$k=1$: $(d\omega)(x_0, x_1) = \mathcal{L}_{x_0}\omega(x_1) - \mathcal{L}_{x_1}\omega(x_0)$
$- \omega([x_0, x_1])$.

Riemann curvature tensor

$\int$ area graph

$f: V \to \mathbb{R}$

$G \subset \mathbb{R} \times V$

can integrate $f: V \longrightarrow \mathrm{Dens}_1(V)$

$= \mathrm{Vol}(V^*) = \underset{\dim 1}{\det(V^*)} \otimes \underset{\dim 1}{\mathrm{or}(V^*)}$

Analogous figure

$f: V \to D$

$V \times \mathrm{Dens}, V$ has a canonical measure!?

Recall: a TIM on $W \in \mathrm{Vect}_{\mathbb{R}}$ is an element of $\mathrm{Vol}(W^*) = \det(W^*) \otimes \mathrm{or}(W^*)$

$\mathrm{Vol}(W^*) = \mathrm{Vol}\left(V^* \times (\mathrm{Dens}, V)^*\right)$

$\cong \mathrm{Vol}(V^*) * \mathrm{Vol}\left((\mathrm{Dens}, V)^*\right)$

$= \mathrm{Dens}_1 V \otimes (\mathrm{Dens}_1 V)^* \cong \mathbb{R} \ni 1$

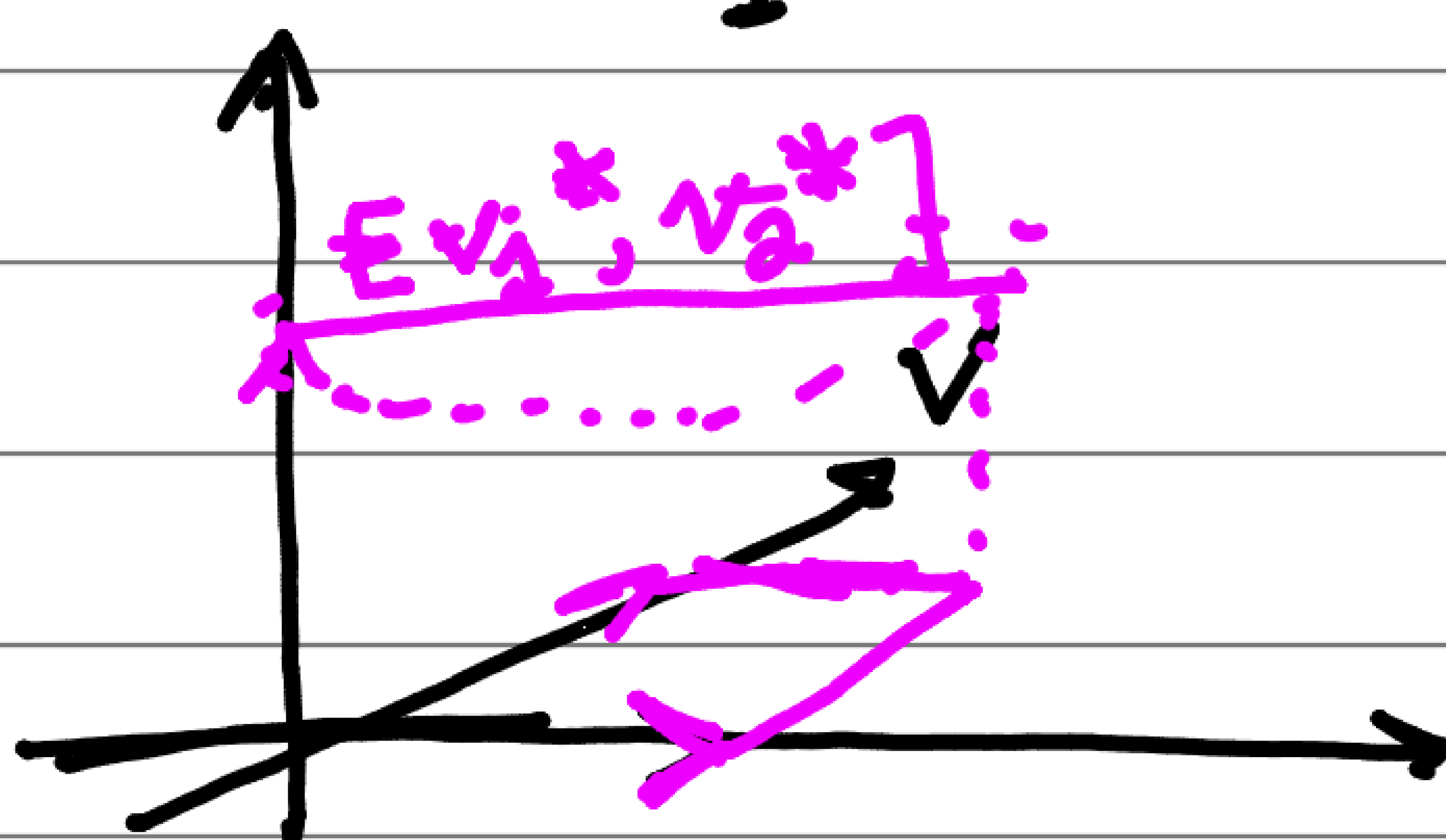
Suppose
basis
$v_1, \dots, v_n \in V$

$v_1^*, \dots, v_n^* \in V^*$

$[v_1^*, v_2^*, \dots, v_n^*, [v_1, \dots, v_n]]$

$\mathrm{vol}\,\hat{V} \simeq (\mathrm{Dens}, V)^*$

$\mathrm{Dens}_1(V)$



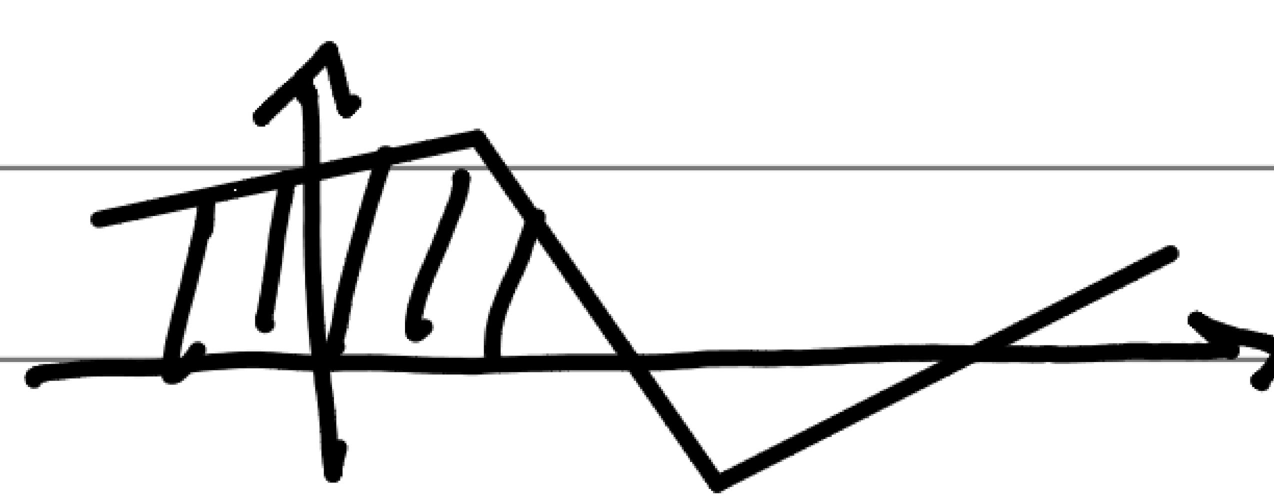
$\dim V = 2$

$[v_1, \dots, v_n, [v_1^*, \dots, v_n^*]]$
$\in \mathrm{Vol}(W)$
$\simeq (\mathrm{Dens}, W)^*$

a 1-density

Suppose $f : V \to \mathrm{dens}_1 V$
$= (\mathrm{vol}\, V)^* = \det V^* \otimes \mathrm{or}\, V^*$

$\mu \in \mathrm{Vol}(W^*)$
a measure



$$\int f := \mu\left(\{ (v, \omega) \in V \times \mathrm{Dens}_1 V \mid 0 \le \omega \le f(v) \right)$$

$$- \mu\left(\{ (v, \omega) \mid f(v) \le \omega \le 0 \} \right.$$

Any oriented 1 dim V space has a canonical ordering.

$$\operatorname{or}(\mathrm{Dens}_1 V)$$
$$= \operatorname{or}\left(\det V^* \otimes \operatorname{or} V^*\right)$$
$$= \operatorname{or}(\det V^*) \otimes \operatorname{or}(\operatorname{or}(V^*))$$
$$= \operatorname{or} V^* \otimes \operatorname{or} V^* \qquad \text{what is } \mathbb{R}$$
$$= \operatorname{or} V \otimes \operatorname{or} V^* \cong \mathbb{R}$$

If V is oriented,
$$\mathrm{Dens}_1 V \cong \det V^*$$

$$f : V \longrightarrow \det V^* \quad f \in \Omega^{\dim V} V$$

Recall
$$\det V^* \xrightarrow{1-1} \mathrm{Dens}_1 V$$
$$[v_1, \dots, v_n] \longmapsto [v_1, \dots, v_n]$$
non-linear

$$[v_2, v_1, v_3 \dots] \longmapsto [v_2, v_1, \dots]$$
$$-[v_2, \dots, v_n] \qquad \overset{\shortparallel}{[v_1, \dots, v_n]}$$

If $\omega \in \Omega^{\dim V} V$

$|\omega| \in \mathrm{dens}_1 V$ or $\in C^\infty(V, \mathrm{dens}_1 V)$

Set $\int \omega = \int |\omega|$

$V = \mathbb{R}^n$

$\Omega^0 M \xrightarrow{d} \Omega^1 M \to \dots \to \Omega^{\dim M} M$

$\Lambda^0 T^*_m M \qquad \Lambda^1 T^*_\cdot M$

$\Lambda^0 T^* M \otimes \mathrm{or} M \qquad \Lambda^1 T^* M \otimes \mathrm{or} M \qquad \Lambda^{\dim M} T^* M \otimes \mathrm{or} M$

fiber by fiber $\to$ Line bundle

$\mathrm{or} M = \mathrm{or}(T^* M)$

$$\begin{array}{c} \mathbb{R} \\ \uparrow \int \end{array}$$

$\tilde{\Omega}^0 M \to \tilde{\Omega}^1 M \to \dots \to \tilde{\Omega}^{\dim M} M$

$\Gamma(\mathrm{Dens}_1(TM))$

Lower degree are not twisted forms.

$V = \mathbb{R}^n$

$V = \mathbb{R}^n$

$$M \xrightarrow{f} N \xrightarrow{g} \mathbb{R} \qquad \dim M = k$$

$$\Omega^k M \xleftarrow{f^*} \Omega^k N$$

pullback! remember this

$$C^\infty N \longrightarrow C^\infty M$$
$$g \longmapsto g \circ f$$
$$\Omega M \longleftarrow \Omega N$$
$$\sum (h \circ f) \, d g_1 \circ f \wedge \dots \wedge d(g_k \circ f) \longleftarrow\!\!\shortmid \sum h \, dg_1 \wedge \dots \wedge dg_k$$

$V = \mathbb{R}^n$

$x_i : \mathbb{R}^n \longrightarrow \mathbb{R}$

$dx_i \in \Omega^1 \mathbb{R}^n$

$dx_1 \wedge \dots \wedge dx_n \in \Omega^n \mathbb{R}^n$

$|dx_1 \wedge \dots \wedge dx_n| \in |\Omega^n \mathbb{R}^n|$

$f : \mathbb{R}^n \longrightarrow \mathbb{R}$

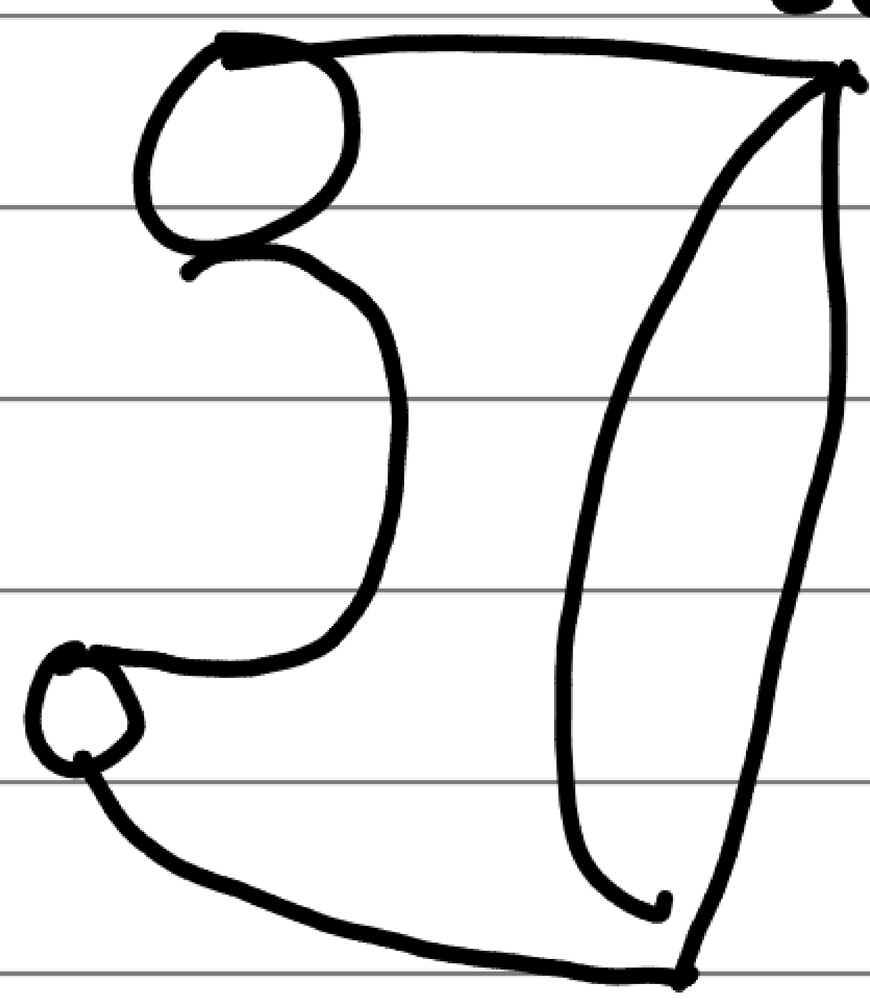
$$\int f \cdot |dx_1 \wedge \dots \wedge dx_n| \in \mathbb{R}$$

nLab generalized differential form

The Stokes Theorem

$$\int_M d\omega = \int_{\partial M} \iota^* \omega$$

Local $\mathbb{R}^n$ or $\{x \in \mathbb{R}^n \mid x_1 \geq 0\}$



$$\iota : \partial M \longrightarrow M$$

$$\omega \in \Omega^{\dim M - 1} M \otimes \mathrm{or}\, M$$

$$d\omega \in \Omega^{\dim M} M \otimes \mathrm{or}\, M$$

Example $M = [a, b]$

$\partial M = \underset{-}{\overset{a}{\leftarrow}} \quad \underset{+}{\overset{b}{\rightarrow}}$

$\omega \in \Omega^0 M \otimes \mathrm{or}\, M$

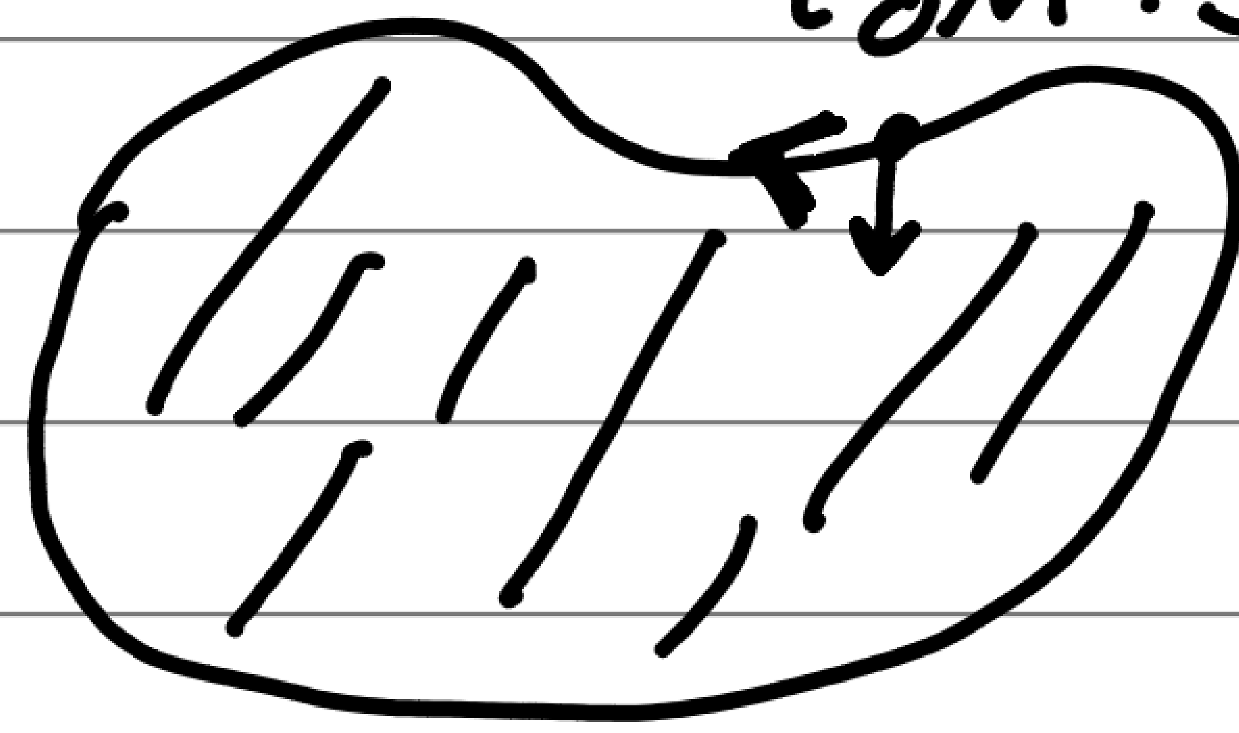
$\omega : M \longrightarrow \mathbb{R}$

$d\omega = \omega' dx$

$$\int_{[a,b]} \omega' |dx| = \int_{\leftarrow a}^{\rightarrow b} \iota^* \omega = \omega(b) - \omega(a)$$

$\mathbb{R}^2$

$\partial M : S^1 \to M$



$\omega \in \Omega^1 M$

$\omega = f_x dx + f_y dy$

$$d\omega = \frac{\partial f_x}{\partial y}(dy \wedge dx) + \frac{\partial f_y}{\partial x}(dx \wedge dy)$$

$$= \left(\frac{\partial f_y}{\partial x} - \frac{\partial f_x}{\partial y}\right)(dx \wedge dy)$$

$$\int \left|\frac{\partial f_y}{\partial x} - \frac{\partial f_x}{\partial y}\right| |(dx \wedge dy)| =$$

$$\int_{S^1} f_x dx + f_y dy$$

Green's Formula

bonus HW: [13]

dim 3
Stokes formula