Title: General Relativity for Cosmology Lecture - 091223

Speakers: Achim Kempf

Collection: General Relativity for Cosmology

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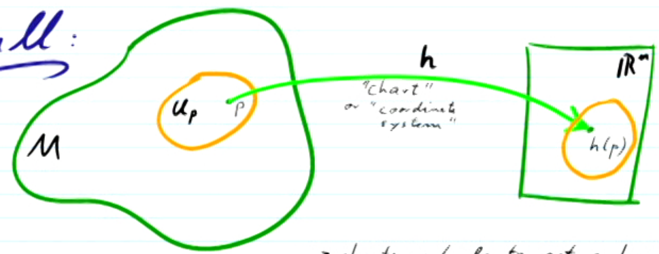
GR for Cosmology, Achim Kempf

Lecture 2

Recall:

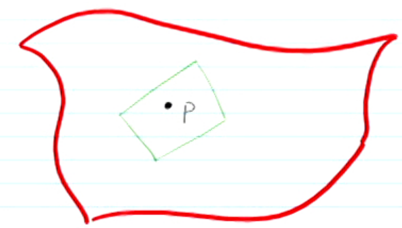


→ charts are tools to get a handle at the otherwise nameless abstract points of the manifold.

Problem:

How to define the abstract "Tangent space, $T_p(M)$", to a diffable mfld at a point p?

Intuition:



⇝ Proper definition should imply:

An n-dim mfld possesses for every point p an n-dim vector space of tangent vectors.

3 equivalent definitions of $T_p(M)$:

Most powerful b/c no need for coordinates →

1. "Algebraic" definition of $T_p(M)$:

Idea: ▫ A tangent vector = directional derivative,

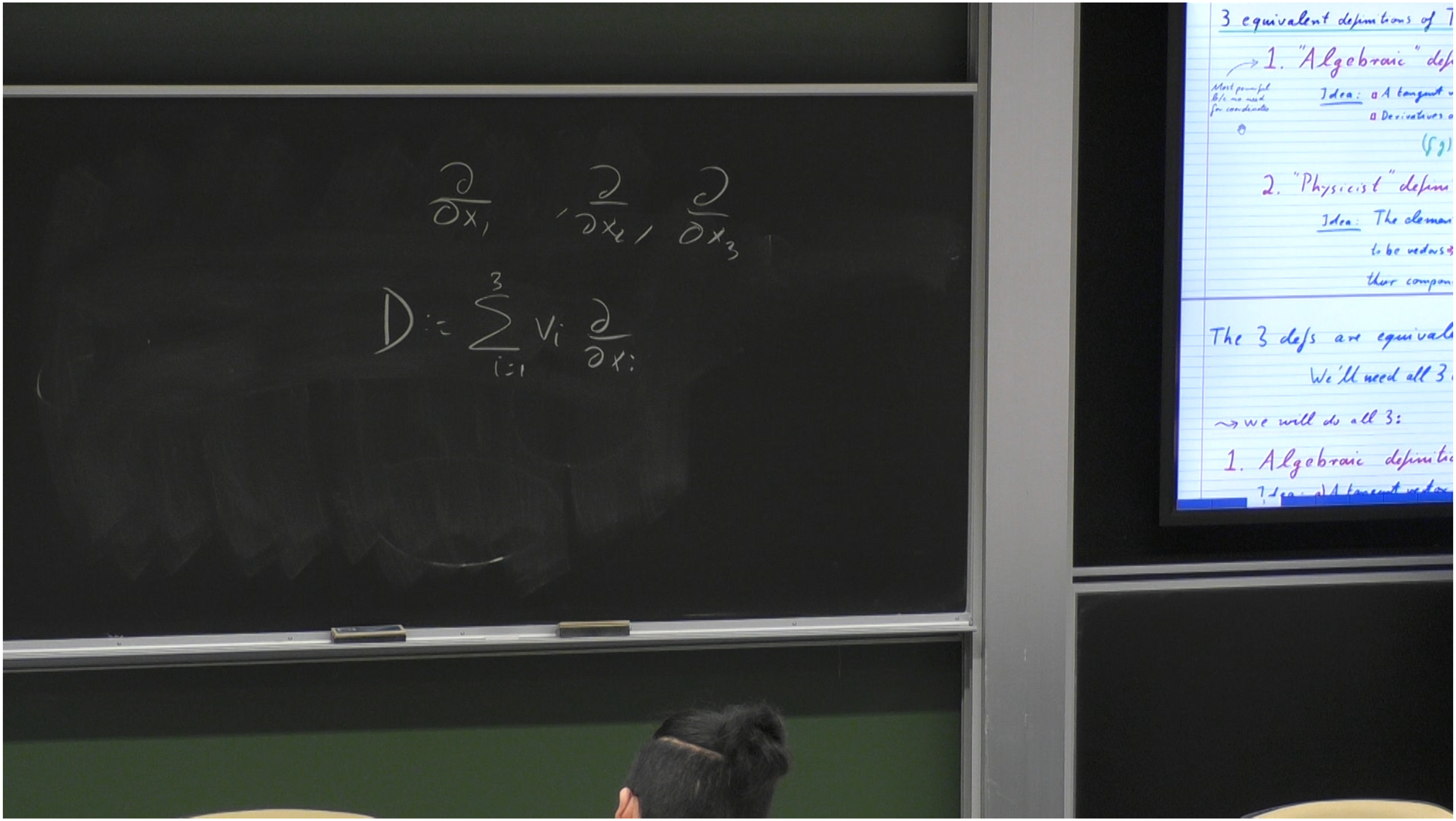
▫ Derivatives definable through Leibniz rule:

$$(fg)' = f'g + fg'$$

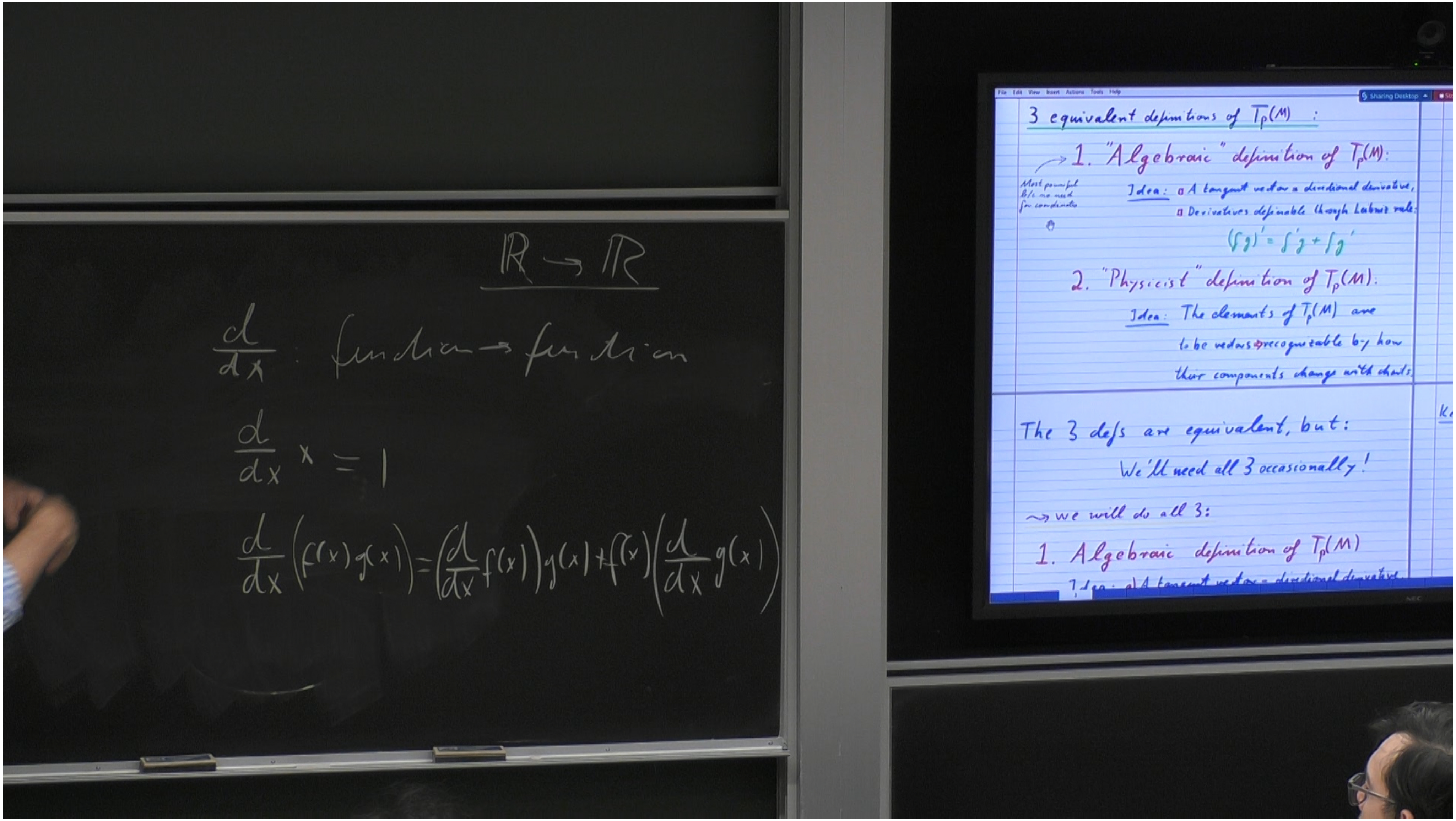
2. "Ph... " definition of $T_p(M)$

3. "Geometric" definition of $T_p(M)$:

Idea: The elements of $T_p(M)$ are to be actual tangent vectors of one-dim. paths in the manifold that pass through p



$\frac{\partial}{\partial x_1}, \frac{\partial}{\partial x_2}, \frac{\partial}{\partial x_3}$
$D := \sum_{i=1}^{3} v_i \frac{\partial}{\partial x_i}$
3 equivalent definitions of
1. "Algebraic"
Idea:
2. "Physicist"
Idea:
to be vectors
The 3 defs are
We'll need all 3
we will do all 3:
1. Algebraic



$\mathbb{R} \to \mathbb{R}$
$\frac{d}{dx}$: function → function
$\frac{d}{dx} x = 1$
$\frac{d}{dx}\left(f(x)g(x)\right) = \left(\frac{d}{dx}f(x)\right)g(x) + f(x)\left(\frac{d}{dx}g(x)\right)$
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3 equivalent definitions of $T_p(M)$:
1. "Algebraic" definition of $T_p(M)$:
Most powerful b/c no need for coordinates
Idea: A tangent vector = directional derivative,
Derivatives definable through Leibniz rule:
$(fg)' = f'g + fg'$
2. "Physicist" definition of $T_p(M)$:
Idea: The elements of $T_p(M)$ are to be vectors → recognizable by how their components change with charts
The 3 defs are equivalent, but:
We'll need all 3 occasionally!
→ we will do all 3:
1. Algebraic definition of $T_p(M)$

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The 3 defs are equivalent, but:

We'll need all 3 occasionally!

$\rightsquigarrow$ we will do all 3:

1. Algebraic definition of $T_p(M)$

Idea: a) A tangent vector = directional derivative,

b) Derivatives definable through Leibniz rule:

$$(fg)' = f'g + fg'$$

Key example: $M = \mathbb{R}$

a) The tangent vectors ξ at a point p are identified with the directional 1st derivatives:

$$\xi = \sum_{i=1}^{n} \xi_i \frac{\partial}{\partial x^i}\Big|_{x=p}$$

b) Thus, tangent vectors at p should be those maps

$$\xi : f \rightarrow \xi(f)$$

which obey the "Leibniz rule" at p:

$$\text{“}\ \xi(fg) = \xi(f)g + f\xi(g)\Big|_{\text{at } p}\ \text{”}$$

Q: How to express the local nature of $\xi \in T_p(M)$ properly?

A: ξ acts on function germs, not on functions.

Def: ▫ Assume M, N are diffable mflds and $p \in M$.

▫ We say that two differentiable functions ϕ, ψ are germ-equivalent about p if in a neighborhood (i.e. an open set) $\mathcal{U} \subset M$ of p:

$$\phi(q) = \psi(q) \quad \forall q \in \mathcal{U}$$

▫ Each such equivalence class of functions is called a germ at p.

▫ Then, the "germ" of ϕ at p, denoted Φ_p, is the equivalence class of all functions ψ which are identical to ϕ in ...

Notice: Assume $\phi : M \rightarrow N$ is diffable at $p \in M$.

Then all $\psi \in \Phi_p$ possess the same first derivative at p.

For example:

Consider germs of scalar functions f

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Assume D obeys I, II

$$D x^n = D(x\, x^{n-1}) = x\, D x^{n-1} + \overset{1}{(Dx)}\, x^{n-1}$$

$$= x\, D x^{n-1} + x^{n-1}$$

$$= x\left(D\, x\, x^{n-2}\right) + x^{n-1}$$

$$= x\left(x\, D x^{n-2} + \overset{1}{(Dx)}\, x^{n-2}\right) + x^{n-1}$$

$$= x^2 D x^{n-2} + x^{n-1} + x^{n-1}$$

$$= \dots = n\, x^{n-1}$$

$$D = \sum \xi_i \frac{\partial}{\partial x_i}$$

A: ξ acts on function germs, not on functions.

Def:
- Assume M, N are diffable mflds and $p \in M$.
- We say that two differentiable functions ϕ, ψ are germ-equivalent about p if in a neighborhood (i.e. an open set) $\mathcal{U} \subset M$ of p:
$$\phi(q) = \psi(q) \quad \forall q \in \mathcal{U}$$
- Each such equivalence class of functions is called a germ at p.
- Then, the "germ" of ϕ at p, denoted Φ_p, is the equivalence class of all functions ψ which are identical to ϕ in some neighborhood of p:

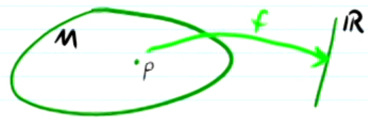
$$\psi \in \Phi_p \text{ if } \underbrace{\exists}_{\text{"there exists"}} \overbrace{\mathcal{U}_p}^{\text{some open neighborhood of } p \text{ in } M} \forall q \in \mathcal{U}_p : \ \phi(q) = \psi(q)$$

Notice: Assume $\phi : M \to N$ is diffable at $p \in M$.

Then all $\psi \in \Phi_p$ possess the same first derivative at p.

For example:

Consider germs of scalar functions f:



, i.e.: $f : M \to \mathbb{R}$

Note:
- To specify a germ, it suffices to specify any arbitrary one of its functions.
- The set of all germs at p is denoted $\mathcal{F}(p)$.

Note:
- One has for all $c \in \mathbb{R}$ and $f, g \in \mathcal{F}(p)$:
$$\overline{c \cdot f} = c\,\overline{f} \qquad (a)$$

Finally: Algebraic definition of $T_p(M)$

Recall idea: The elements of $T_p(M)$ are to be 1st derivatives $\Rightarrow$ definable by Leibniz rule.

Definition: The tangent space $T_p(M)$ is the set of "derivations" of $\mathcal{F}(p)$, i.e. the

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Note:

- One has for all $c \in \mathbb{R}$ and $f, g \in \mathcal{F}(p)$:

$$\overline{c \cdot f} = c\,\bar{f} \qquad (a)$$

$$\overline{f \cdot g} = \bar{f}\,\bar{g} \qquad (b)$$

$$\overline{f + g} = \bar{f} + \bar{g} \qquad (c)$$

$\Rightarrow$ $\mathcal{F}(p)$ obeys the axioms of an associative algebra.

Remark:

- this definition is abstract enough not only for arbitrary diff'able mf'lds!
- this definition (as derivations of the algebra of functions) is also suitable for "Noncommutative Geometry":

Finally: Algebraic definition of $T_p(M)$

Recall idea: The elements of $T_p(M)$ are to be 1st derivatives $\Rightarrow$ definable by Leibniz rule.

Definition: The tangent space $T_p(M)$ is the set of "derivations" of $\mathcal{F}(p)$, i.e. the set of linear maps $\xi: \mathcal{F}(p) \to \mathbb{R}$ which obey:

$$\xi\left(\bar{f}_p\,\bar{g}_p\right) = \xi\left(\bar{f}_p\right)\,\underbrace{\bar{g}_p(p)}_{=g(p)} + \underbrace{\bar{f}_p(p)}_{=f(p)}\,\xi\left(\bar{g}_p\right)$$

remember this $(*)$

First example: a constant function, c, and its germ $\bar{c}$.

$c(x) := c$ and c is a constant: $c \in \mathbb{R}$

Then: $\xi(\bar{c}) = 0$ for all $\xi \in T_p(M)$

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Remark:

- this definition is abstract enough not only for arbitrary diff'able mf'lds!
- this definition (as derivations of the algebra of functions) is also suitable for "Noncommutative Geometry": There, (Quantum Gravity) the algebra of functions $F(p)$ is noncommutative.
- Note: Can't do Newton's derivatives then but algebraic def'n of derivation still works.

First example: a constant function, c, and its germ $\bar{c}$.

$c(x) := c$ and c is a constant: $c \in \mathbb{R}$

Then: $\xi(\bar{c}) = 0$ for all $\xi \in T_p(M)$

Proof: $\xi(\bar{c}) = c\,\xi(1) = c\,\xi(1\cdot 1) \overset{\text{Leibniz rule}}{=} c\left(\xi(1)\,1 + 1\,\xi(1)\right)$

$= 2c\,\xi(1) \Longrightarrow \xi(\bar{c}) = 0$ ✓

Example: The case $M = \mathbb{R}^n$

If our definition for $T_p(M)$ is good, we expect that every $\xi \in T_p(M)$ is of the form:

$$\xi = \sum_{i=1}^{n} \xi^i \frac{\partial}{\partial x^i}\Big|_{x=p}$$

- Notation: $h_{,i}(a^1,\dots,a^n) := \frac{\partial}{\partial a^i} h(a^1,\dots,a^n)$

Then:

(Note: these are not 3 numbers! These are 3 function germs, i.e., 3 equivalence classes of functions.)

germ of a constant function

$$\xi\left(\overline{f(x)}\right) = \xi\left(\overline{f(0)} + \overline{f(x)} - \overline{\underbrace{f(0)}_{\text{a constant function}}}\right)$$

$$\overset{(c)}{=} \xi\left(\overline{f(0)} + \int_0^1 \frac{d}{dt}\bar{f}(tx^1,\dots,tx^n)\,dt\right)$$

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Example: The case $M = \mathbb{R}^n$

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$$\xi = \sum_{i=1}^{n} \xi^i \frac{\partial}{\partial x^i}\Big|_{x=p}$$

Proof:

- We choose p to have coordinates $x = (0, 0, \dots)$.
- Assume $\xi \in T_p(M)$ and $\bar{f} \in \mathcal{F}(p)$.

- Notation: $h_{,i}(a^1, \dots, a^n) := \frac{\partial}{\partial a^i} h(a^1, \dots, a^n)$

Then:

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$$\overset{(c)}{=} \xi\Big(\overline{f(0)} + \int_0^1 \frac{d}{dt} \bar{f}(tx^1, \dots, tx^n)\, dt\Big)$$

$$\overset{(b)}{=} \underbrace{\xi(\bar{f}(0))}_{=0} + \xi\Big(\int_0^1 \sum_{i=1}^{n} \frac{\partial \bar{f}(tx^1, \dots, tx^n)}{\partial(tx^i)} \frac{d(\overline{tx^i})}{dt}\, dt\Big)$$

$$= \xi\Big(\int_0^1 \sum_{i=1}^{n} \bar{f}_{,i}(tx^1, \dots, tx^n)\, \bar{x}^i\, dt\Big)$$

Linearity of ξ ⇒

$$= \sum_{i=1}^{n} \xi\Big(\int_0^1 \bar{f}_{,i}(tx^1, \dots, tx^n) dt \cdot \bar{x}^i\Big)$$

Leibniz rule ⇒

$$= \sum_{i=1}^{n} \xi\Big(\int_0^1 \bar{f}_{,i}(tx^1, \dots, tx^n) dt\Big) \cdot \underbrace{\bar{x}^i\Big|_{x=p=0}}_{=0}$$

(Remember from (b) above)

$$+ \sum_{i=1}^{n} \Big(\int_0^1 \bar{f}_{,i}(tx^1, \dots, tx^n) dt\Big)\Big|_{x=p=0} \cdot \xi(\bar{x}^i)$$

⇒ Indeed, every $\xi \in T_p(M)$ is of the form

$$\xi = \sum_{i=1}^{n} \xi^i \frac{\partial}{\partial x^i}\Big|_{x=p} \qquad (\mathrm{I})$$

namely with

$$\xi^i = \xi(\bar{x}^i) \qquad (\mathrm{II})$$

□

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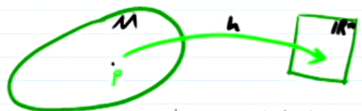
But:

- This was the simple example: $M = \mathbb{R}^n$
- How does our definition of $T_p(M)$ work for $M \neq \mathbb{R}^n$, concretely?
- Recall:



h gives abstract points a name, i.e. makes them concrete.

- Problem: How to make abstract $\xi \in T_p(M)$ concrete?
- Solution: Make use of charts in clever way!

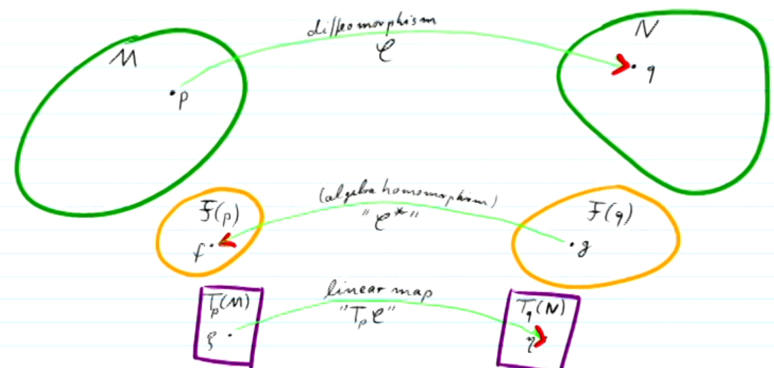
Preparation: $T_p(M)$ and Diffeomorphisms.

Consider two diff'able manifolds, M and N:

Note: If $N = \mathbb{R}^n$, then φ is a chart.

(that's the case we'll need but it's easy to keep a general N too)

Here: $\mathcal{F}(q)$ and $\mathcal{F}(p)$ are algebras of function (germs).

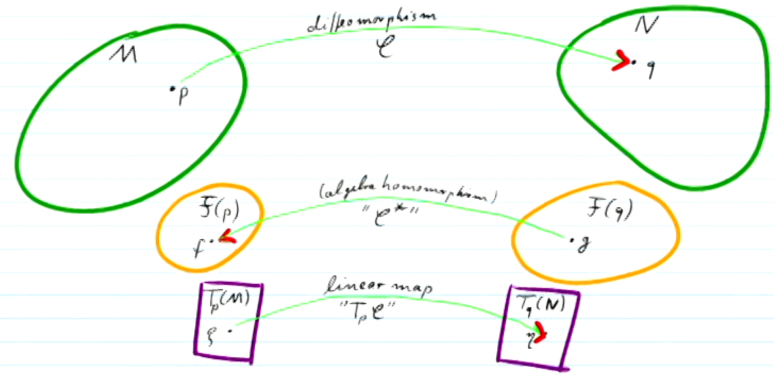


Here: □ $\mathcal{F}(q)$ and $\mathcal{F}(p)$ are algebras of function (germs).

□ Given φ we obtain a map $\varphi^*: \mathcal{F}(q) \to \mathcal{F}(p)$

$$\varphi^*: g \to f = \varphi^*(g) \quad \text{with } f(x) = g(\varphi(x)) \ \forall x \in M$$

$$\text{i.e.: } f = \varphi^*(g) = g \circ \varphi \qquad (+)$$



Here: □ Given $\varphi^*: \mathcal{F}(q) \to \mathcal{F}(p)$ we obtain the "tangent map":

$$T_p\varphi: T_p(M) \to T_q(N)$$

$$T_p\varphi: \xi \to \eta$$

(when choosing $M = \mathbb{R}^n$, we obtain the desired concrete representation of $T_p(M)$ this way)

□ Namely: $\eta = \xi \circ \varphi^*$

i.e.: $\eta(g) = \xi(\varphi^*(g))$

□ From (+) ⇒

$$\eta(g) = \xi(g \circ \varphi)$$

The crucial special case:

⇒ We do obtain a concrete handle on the abstract tangent vectors $\xi \in T_p(M)$, given a chart h:

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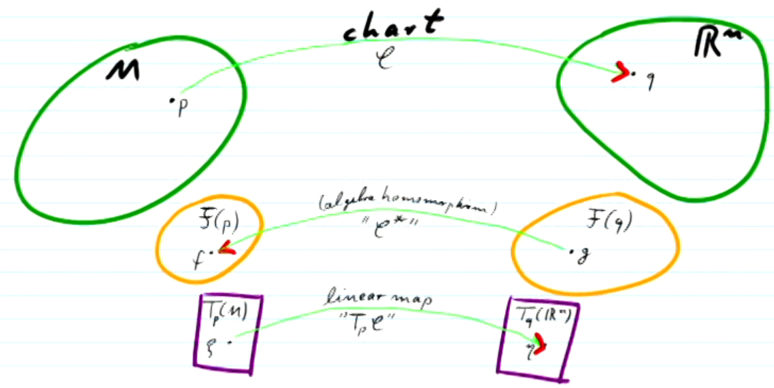
□ From (+) $\Rightarrow$
$\eta(g) = \xi(g \circ \varphi)$

The crucial special case:

- $N = \mathbb{R}^n$ (with $n = \dim(N)$)
- φ is invertible
- ($\Rightarrow$ φ^* is algebra isomorphism)
- $\Rightarrow T_p\varphi$ is vector space isomorphism

$\Rightarrow$ We do obtain a concrete handle on the abstract tangent vectors $\xi \in T_p(M)$, given a chart h:



Namely:

□ Given a chart φ, every abstract point $p \in M$ has a concrete image $\varphi(p) \in \mathbb{R}^m$, and:

□ Every abstract vector $\xi \in T_p(M)$ has a concrete image $\eta \in T_{\varphi(p)}(\mathbb{R}^m)$ namely:

$\eta = T_p\varphi(\xi)$ $\quad \underbrace{\varphi(p)} = q$

form (we showed this):

$$\eta = \sum_{i=1}^{m} \eta^i \frac{\partial}{\partial x^i}\Big|_{x=q}$$

concrete numbers.

Conversely: (and very conveniently)

□ Assuming a fixed φ, any choice

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- Every abstract vector $\xi \in T_p(M)$ has a concrete image $\eta \in T_{\underbrace{\varphi(p)}_{=q}}(\mathbb{R}^n)$ namely:

$$\eta = T_p\varphi(\xi)$$

- The image η is concrete because η is tangent vector to a point $q \in \mathbb{R}^n$, and it therefore must take the form (we showed this):

$$\eta = \sum_{i=1}^{n} \eta^i \frac{\partial}{\partial x^i}\bigg|_{x=q}$$

η^i: concrete numbers.

- E.g. $\eta = \frac{\partial}{\partial x^i}\Big|_{x=q}$ is the image of some abstract $\xi \in T_p(M)$, for fixed φ.

Notation: $\xi = {}''\frac{\partial}{\partial x^i}\Big|_{x=p}{}''$

symbolic notation

Conversely: (and very conveniently)

- Assuming a fixed φ, any choice of a $q = (x^1, \ldots, x^n)$ denotes a $p \in M$ and any choice of a $(\eta^1, \ldots, \eta^n)$ denotes a $\xi \in T_p(M)$.

$(\eta^1, \ldots, \eta^n)$: some numbers

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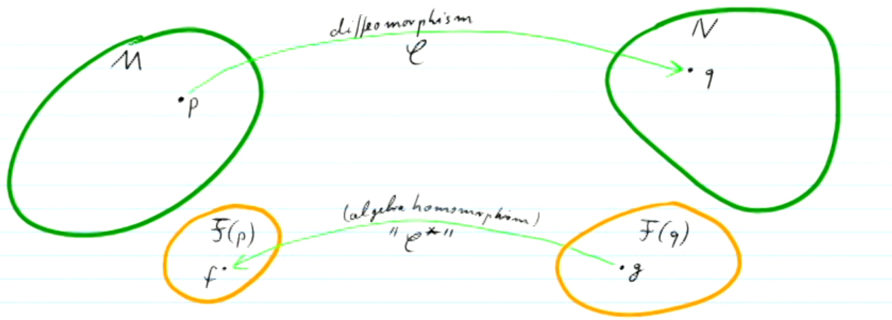

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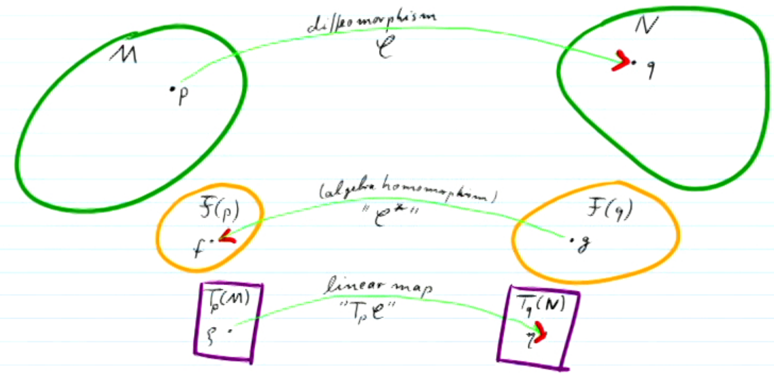

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