Title: General Relativity for Cosmology - Lecture 6

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Abstract:

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Note Title

GR for Cosmology, Achim Kempf, Fall 17, Lecture 6

Integration

Q: What is special about totally antisymmetric covariant tensors, i.e., about differential forms?

A: Antisymmetry $\Rightarrow$ special transformation property under chart changes:

$\sim$ det(Jacobian)

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Q: What is special about totally antisymmetric covariant tensors, i.e., about differential forms?

A: Antisymmetry $\Rightarrow$ special transformation property under chart changes:

$\sim$ det(Jacobian)

$\Rightarrow$ suitable for integration:

s-forms have natural integrals in s-dimensional manifolds

Except: Depending on charts, sign of Jacobian may be wrong!

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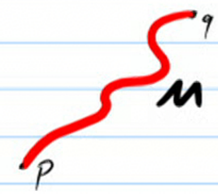
3-dimensional manifolds

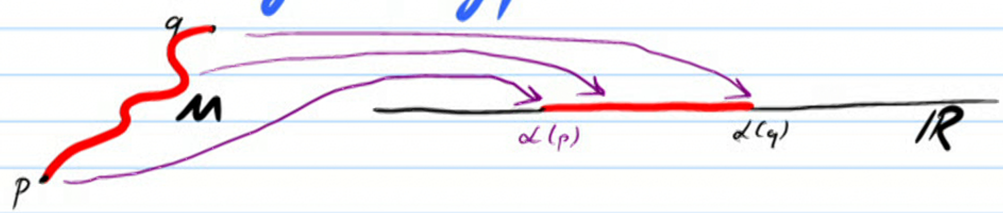
Except: Depending on charts, sign of Jacobian may be wrong!

Thus: Before defining integration on mflds, must study notion of "Orientation" of the mfld.

Namely: Consider e.g. 1-dim mfld:



Could have charts of the type



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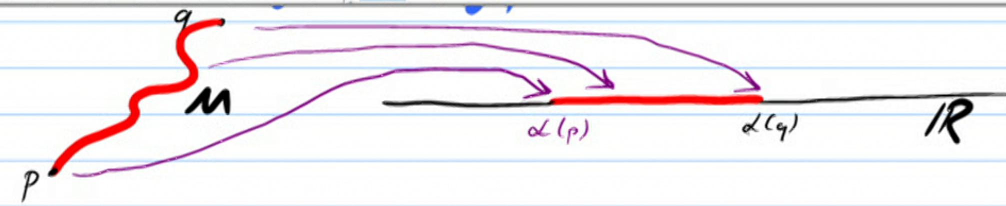
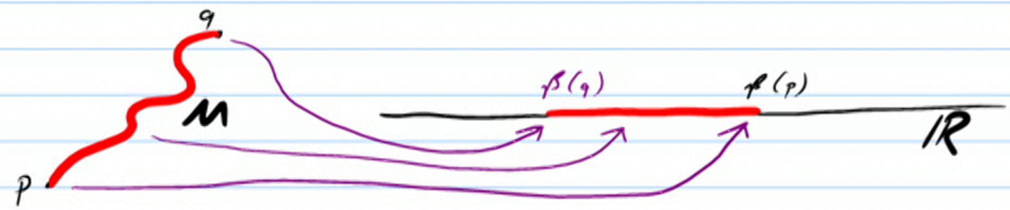


□ or charts of the type



□ But, since $\int_a^b f(t)\,dt = -\int_b^a f(t')\,dt'$ one needs to decide!

because $\frac{dt}{dt'} = -1$ (which is det[Jacobian])

For n-dim mflds, may need several charts.

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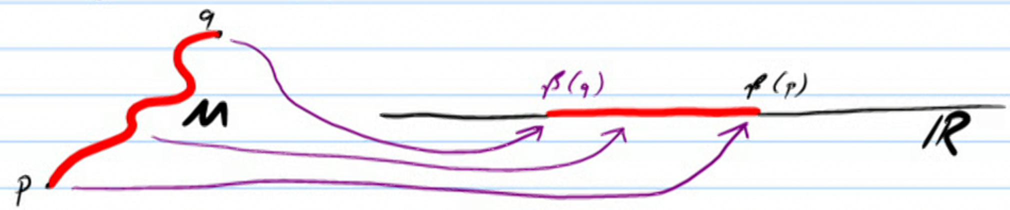

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For n-dim mflds, may need several charts.

Definitions:

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For n-dim mflds, may need several charts.

Definitions:

- A complete collection of charts, i.e., an Atlas, A, is called oriented if among all overlapping charts with coordinates say $x, \tilde{x}$ the Jacobi determinants are positive:

$$\det\left(\frac{\partial \tilde{x}^i}{\partial x^j}\right) > 0$$

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A mfld M is called orientable if it possesses an oriented atlas.

Example: Möbius strips

are not orientable.

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- A mfld, M, together with a choice of oriented atlas, A, is called an oriented manifold.

- Then, an arbitrary chart is called positive (or negative) if its Jacobian determinant with charts of the atlas A is positive (or negative).

Definition :

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Definition:

An n-form $\Omega \in \Lambda_n(M)$ is called a volume form if it nowhere vanishes.

We will later find a preferred volume form for space-time (using the metric).

Proposition:

M possesses a volume form

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Integration:

- Recall change of cds in integration in $\mathbb{R}^n$:

For $(x^1, \ldots, x^n) \to (\tilde{x}^1, \ldots, \tilde{x}^n)$:

$g: \mathbb{R}^n \to \mathbb{R}$

Riemann or Lebesgue integrals

$$\int_{\mathbb{R}^n} g(x^1, \ldots, x^n)\, dx^1 \ldots dx^n = \int_{\mathbb{R}^n} g(x(\tilde{x}))\, \det\left(\frac{\partial x^i}{\partial \tilde{x}^j}\right) d\tilde{x}^1 \ldots d\tilde{x}^n \quad (*)$$

Jacobian determinant is negative if coordinate systems change handedness.

- Now for a general n-dimensional diff'able mfld M,

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for $(x^1, \dots, x^n) \to (\tilde{x}^1, \dots, \tilde{x}^n)$:

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(*)

Riemann or Lebesgue integrals

$$\int_{\mathbb{R}^n} g(x^1, \dots, x^n)\, dx^1 \dots dx^n = \int_{\mathbb{R}^n} g(x(\tilde{x}))\, \det\left(\frac{\partial x^i}{\partial \tilde{x}^j}\right) d\tilde{x}^1 \dots d\tilde{x}^n$$

Jacobian determinant is negative if coordinate systems change handedness.

Now for a general n-dimensional diff'able mfld M, consider an n-form ω in a chart:

$$\omega = f(x)\, dx^1 \wedge dx^2 \wedge \dots \wedge dx^n$$

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ness.

Now for a general n-dimensional diffable mfld M, consider an n-form ω in a chart:

$$\omega = f(x)\, dx^1 \wedge dx^2 \wedge \dots \wedge dx^n$$

Then what is ω in an overlapping, second chart?

$$\omega = f(x(\tilde{x}))\, \frac{\partial x^1}{\partial \tilde{x}^{i_1}} \frac{\partial x^2}{\partial \tilde{x}^{i_2}} \cdots \frac{\partial x^n}{\partial \tilde{x}^{i_n}}\, \underbrace{d\tilde{x}^{i_1} \wedge d\tilde{x}^{i_2} \wedge \dots \wedge d\tilde{x}^{i_n}}_{\text{totally antisymmetric!}}$$

o terms are nonzero only if contain each number 1, ..., n

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Then what is ω in an overlapping, second chart?

$$\omega = f(x(\tilde{x})) \frac{\partial x^1}{\partial \tilde{x}^{i_1}} \frac{\partial x^2}{\partial \tilde{x}^{i_2}} \cdots \frac{\partial x^n}{\partial \tilde{x}^{i_n}} \underbrace{d\tilde{x}^{i_1} \wedge d\tilde{x}^{i_2} \wedge \ldots \wedge d\tilde{x}^{i_n}}_{\text{totally antisymmetric!}}$$

- terms are nonzero only if contain each number $1, \ldots, n$ exactly once, e.g. $d\tilde{x}^1 \wedge d\tilde{x}^3 \wedge d\tilde{x}^2 \wedge d\tilde{x}^4 \wedge d\tilde{x}^5 \wedge \ldots \wedge dx^n$.
- Reorder those terms - they are all

$$d\tilde{x}^1 \wedge d\tilde{x}^2 \wedge \ldots \wedge d\tilde{x}^n$$

up to a possible factor -1 because $dx^i \wedge dx^j = -dx^j \wedge dx^i$

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$$\Rightarrow \quad \omega = f(x(\tilde{x})) \det\left(\frac{\partial x^i}{\partial \tilde{x}^j}\right) d\tilde{x}^1 \wedge d\tilde{x}^2 \wedge \ldots \wedge d\tilde{x}^n$$

Compare with equation (*) above $\Rightarrow$

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The following definition of the integral of n-forms in an n-dim. diffable mfld is chart-independent, i.e., is well-defined:

Definition:

Assume M is an oriented n-dim mfld

and $\omega \in \Lambda_n(M)$ reads in a chart α: $\omega = f(x)\, dx^1 \wedge \ldots \wedge dx^n$.

Then, if one chart suffices:

$$\int_M \omega := \overbrace{\int f(x)\, dx^1 dx^2 \ldots dx^n}^{\text{usual Riemann or Lebesgue integral}}$$

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image of M in $\mathbb{R}^n$

Else: Piece right hand side together from several charts

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$\alpha(M)$: image of M in $\mathbb{R}^n$

Else: Piece right hand side together from several charts

Note: how to piece together does not matter as long as charts are from the atlas that M is equiped with. That's why orientation is important.

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Definition: The boundary operator, ∂

- Assume $G \subset M$ is a region (i.e. an n-dim., open and connected subset) of the n-dim mfld M.

We denote the $(n-1)$ dim. boundary manifold of G by ∂G:

the boundary operator

$$\partial G := \text{boundary}(G)$$

- We say that ∂G is smooth if locally

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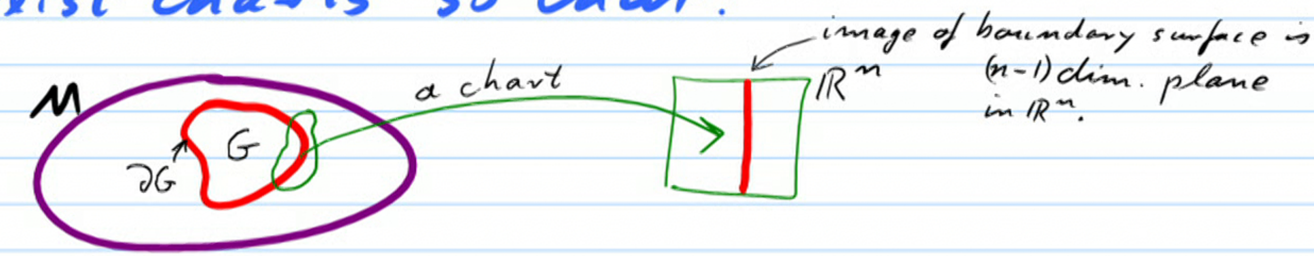
We denote the (n-1) dim. boundary manifold of G by ∂G:

the boundary operator

$$\partial G := \text{boundary}(G)$$

We say that ∂G is smooth if locally there exist charts so that:



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Proposition: If M is orientable, then so is G. Also, the orientation of G induces an orientation of ∂G.

We finally have all ingredients for one of Math's most important theorems:

Stokes' theorem: If closure $\bar{G}$ of G is a compact n-dim region, then:

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Stokes' theorem: If closure $\bar{G}$ of G is a compact n-dim region, then

$$\boxed{\int_G d\omega = \int_{\partial G} \omega \quad \text{for all } \omega \in \Lambda_{n-1}(M)}$$

Definition: d is also called "co-boundary operator".

Remark:

Let us try iterating Stokes!

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Remark:

- Let us try iterating Stokes!
- Assume $G = \partial H$.
- Then, by Stokes we obtain $0 = 0$:

$$\int_H \underbrace{dd\omega}_{\substack{=0 \text{ always} \\ \text{for algebraic} \\ \text{reasons.}}} \overset{\text{Stokes}}{=} \int_{\partial H} d\omega \overset{\text{Stokes}}{=} \int_{\underbrace{\partial\partial H}_{=0}} \omega$$

$=0$ for geometric reasons because, indeed, boundaries don't possess boundaries:

E.g. G = half sph…

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$$\int_H \underbrace{dd\omega}_{} \overset{\text{Stokes}}{=} \int_{\partial H} d\omega \overset{\text{Stokes}}{=} \int_{\underbrace{\partial\partial H}_{=0}} \omega$$

$= 0$ always for algebraic reasons.

$= 0$ for geometric reasons because, indeed, boundaries don't possess boundaries:

E.g.

G = half sphere
∂G = equator
$\partial\partial G = \emptyset$

i.e.: Stokes implies $d^2 = 0 \Leftrightarrow \partial^2 = 0$

Stokes links homology (geometric) to cohomology (algebraic).

Special case I:

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Special case I:

Assume: $M = \mathbb{R}$, $G = (a, b)$

Therefore: $\partial G = \{a, b\}$

Then, Stokes' theorem is $\int_G df = \int_{\partial G} f$, namely:

$$\int_a^b df = f\Big|_a^b$$ (fund. thm of calculus)

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(fund. thm of calculus)

$$= \frac{df}{dx}\, dx$$

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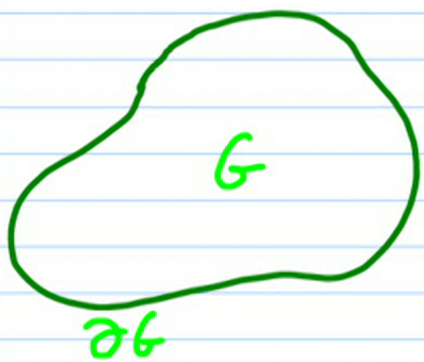
Special case II: "Green's theorem".



- $M = \mathbb{R}^2$, $G \subset \mathbb{R}^2$ a region with (closed) boundary curve ∂G.

recall: this is automatic because $\partial \circ \partial = 0$

- Consider an arbitrary 1-form $\omega \in \Lambda_1(M)$:

$$\omega = \omega_1(x)\, dx^1 + \omega_2(x)\, dx^2$$

Then: $d\omega = d\omega_1(x) \wedge dx^1 + d\omega_2(x) \wedge dx^2$

$$= \left(\frac{\partial \omega_1}{\partial x^1} dx^1 + \frac{\partial \omega_1}{\partial x^2} dx^2\right) \wedge dx^1$$

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∂G

Consider an arbitrary 1-form $\omega \in \Lambda_1(M)$.

$$\omega = \omega_1(x)\, dx^1 + \omega_2(x)\, dx^2$$

Then: $d\omega = d\omega_1(x) \wedge dx^1 + d\omega_2(x) \wedge dx^2$

$$= \left(\frac{\partial\omega_1}{\partial x^1} dx^1 + \frac{\partial\omega_1}{\partial x^2} dx^2\right) \wedge dx^1$$

$$+ \left(\frac{\partial\omega_2}{\partial x^1} dx^1 + \frac{\partial\omega_2}{\partial x^2} dx^2\right) \wedge dx^2$$

$$= \frac{\partial\omega_1}{\partial x^2} dx^2 \wedge dx^1 + \frac{\partial\omega_1}{\partial x^1} dx^1 \wedge dx^2$$

$$\longrightarrow d\omega = \left(\frac{\partial\omega_2}{\partial x^1} - \frac{\partial\omega_1}{\partial x^2}\right) dx^1 \wedge dx^2$$

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$$+\left(\frac{\partial \omega_2}{\partial x^1}dx^1+\frac{\partial \omega_2}{\partial x^2}dx^2\right)\wedge dx^2$$

$$=\frac{\partial \omega_1}{\partial x^2}dx^2\wedge dx^1+\frac{\partial \omega_1}{\partial x^1}dx^1\wedge dx^2$$

$$\Longrightarrow d\omega=\left(\frac{\partial \omega_2}{\partial x^1}-\frac{\partial \omega_1}{\partial x^2}\right)dx^1\wedge dx^2$$

Now, Stokes' theorem $\int_G d\omega=\int_{\partial G}\omega$ becomes:

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$G \qquad \partial G$

$$\int_G \left(\frac{\partial \omega_2}{\partial x^1} - \frac{\partial \omega_1}{\partial x^2}\right) dx^1 dx^2 = \int_{\partial G} \left(\omega_1 dx^1 + \omega_2 dx^2\right)$$

Recall: How to evaluate, e.g., the RHS, in practice?

- Choose a chart for ∂G, i.e., a diff'able map, invertible map $\partial G \to \mathbb{R}$.
- Its inverse is a path: $\gamma : I \subset \mathbb{R} \to \partial G$, with $\gamma(t) = (x^1(t), x^2(t))$
- Now use $dx^1 = \frac{dx^1}{dt} dt$ to obtain an integral over $I \subset \mathbb{R}$

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Special case of Green's theorem:

Assume $\omega \in \Lambda_1$ is closed, i.e., $d\omega = 0$, i.e., $\frac{\partial \omega_1}{\partial x^2} - \frac{\partial \omega_2}{\partial x^1} = 0$

Then: $$\int_{\partial G} \omega = 0$$

Compare: (From the residue theorem)

If a function $w: G \subset \mathbb{C} \to \mathbb{C}$ is holomorphic, i.e., it obeys the Cauchy Riemann equations, then:

$$\int_{\partial G} w(z)\, dz = 0$$

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∂G

Compare: (From the residue theorem)

If a function $w: G \subset \mathbb{C} \to \mathbb{C}$ is holomorphic, i.e., it obeys the Cauchy Riemann equations, then:

$$\int_{\partial G} w(z)\, dz = 0$$

Indeed:

The Cauchy-Riemann equations mean that a diff. form is closed and co-closed. We'll define "co-closedness" later.

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Special case III: (exercise)

Similarly, one can show that what is often called the Stokes theorem for $M = \mathbb{R}^3$, namely

"cross product": $\vec{a} \times \vec{b} = (a_2 b_3 - a_3 b_2, a_3 b_1 - a_1 b_3, a_1 b_2 - a_2 b_1)$

$$\int_G \vec{\nabla} \times \vec{w} \, dG = \int_{\partial G} \vec{w} \cdot d\vec{s}$$

$\vec{\nabla}$ "=" $\left(\frac{\partial}{\partial x^1}, \frac{\partial}{\partial x^2}, \frac{\partial}{\partial x^3}\right)$

$\vec{w}$: vector field

G: a 2dim submanifold of M

∂G: 1 dim boundary of A.

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"cross product": $\vec{a} \times \vec{b} = (a_2 b_3 - a_3 b_1, a_3 b_1 - a_1 b_3, a_1 b_2 - a_2 b_1)$

$$\left(\frac{\partial}{\partial x^1}, \frac{\partial}{\partial x^2}, \frac{\partial}{\partial x^3}\right)'' \qquad \int_G \vec{\nabla} \times \vec{w} \, dG = \int_{\partial G} \vec{w} \cdot \vec{ds}$$

vector field

a 2 dim submanifold of M

1 dim boundary of A.

is indeed this special case:

$$w \in \Lambda_1(G) \text{ with } \vec{\nabla} \times \vec{w} = dw \in \Lambda_2(G)$$

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Before we can discuss the next example:

How to define the volume of a region $G \subset \mathcal{M}$ of a diff'able manifold $\mathcal{M}$?

- In $\mathbb{R}^n$, we had:

$$V = \int_G dx^1 \dots dx^n$$

- In general, we need to choose a Volume form

$$\Omega \in \Lambda_n$$

obeying $\Omega(p) \neq 0 \ \forall p \in G$. Then the ($\Omega$-dependent) volume is defined as:

$$V := \int \Omega$$

(We will later use the metric tensor to define

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obeying $\Omega(p) \neq 0 \ \forall p \in G$. Then the ($\Omega$-dependent) volume is defined as:

$$V := \int_G \Omega$$

(We will later use the metric tensor to define a volume form for spacetime.)

Proposition: G orientable $\Leftrightarrow$ $\exists$ volume forms Ω

(In fact ∞ many)

Special case IV: Gauss' theorem

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Special case IV: Gauss' theorem

To obtain Gauß' theorem we need to define yet a new derivative the divergence of a vector field.

Recall: On $\mathbb{R}^n$, the divergence of a vector field, ξ, was defined as

$$\operatorname{div} \xi = \sum_{i=1}^{n} \frac{\partial}{\partial x^i} \xi^i = \xi^i_{,i}$$

$\rightsquigarrow$ How to generalize to arbitrary manifolds?

Where in this course did we see $\xi^i(x)_{,i}$ before?

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$$\operatorname{div}\xi = \sum_{i=1}^{n} \frac{\partial}{\partial x^i}\xi^i = \xi^i_{\ ,i}$$

How to generalize to arbitrary manifolds?

Where in this course did we see $\xi^i(x)_{,i}$ before?

Recall: $$(L_\xi \tau)^{i_1 \dots i_r}_{j_1 \dots j_s}(x) = \tau^{i_1 \dots i_r}_{j_1 \dots j_s, k}(x)\,\xi^k(x) - \tau^{\bar{i} \dots i_r}_{j_1 \dots j_s}(x)\,\xi^{i_1}_{\ ,\bar{i}}(x) - \dots$$

$$+ \tau^{i_1 \dots i_r}_{\bar{j} \dots j_s}(x)\,\xi^{\bar{j}}_{\ ,j_1}(x) + \dots \tau^{i_1 \dots i_r}_{j_1 \dots \bar{j}}(x)\,\xi^{\bar{j}}_{\ ,j_s}(x)$$

$\tau \in T(M)^r_s$

Strategy: If we choose τ to be the volume form,

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Strategy: If we choose τ to be the volume form, which on flat $\mathbb{R}^n$ we may choose to be $\Omega = 1\, dx^1 \wedge \ldots dx^n$, then the first term will drop out on $\mathbb{R}^n$ b/c $1_{,i} = 0$, and so we may be generalizing $\xi^i{}_{,i}$ on $\mathbb{R}^n$!

Def: The Divergence of a vector field ξ with respect to a volume form, Ω, is defined to be:

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Def: The Divergence of a vector field ξ with respect to a volume form, Ω, is defined to be:

$$\boxed{\mathrm{div}_\Omega\, \xi := L_\xi(\Omega) \qquad \text{Lie derivative}}$$

□ Assume $\Omega = a(x)\, dx^1 \wedge \ldots \wedge dx^n$ (volume form)

$a(x) \in \Lambda_0(M)$

and $\xi = \xi^i(x)\, \partial_i$ (vector field)

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- Assume $\Omega = a(x)\, dx^1 \wedge \ldots \wedge dx^n$ (volume form)

$a(x) \in \Lambda_0(M)$

and $\xi = \xi^i(x) \frac{\partial}{\partial x^i}$ (vector field)

- Then:

$$\operatorname{div}_\Omega \xi = L_\xi \Omega \overset{\text{by Leibnitz rule}}{=} \underbrace{\xi(a)}_{= \xi^i \frac{\partial}{\partial x^i} a(x)} dx^1 \wedge \ldots \wedge dx^n + \ldots$$

$$+ a \sum_{i=1}^{n} dx^1 \wedge \ldots \wedge L_\xi(dx^i) \wedge \ldots \wedge dx^n$$

$$\left(\text{recall: } L_\xi(dx^i) = d(\xi(x^i)) = d\left(\xi^j \frac{\partial}{\partial x^j} x^i\right) = d(\xi^j \delta^i_j) = d(\xi^i) = \frac{\partial \xi^i}{\partial x^r} dx^r \right)$$

only dx^i term survives in wedge product

$$\Rightarrow \quad \operatorname{div}_\Omega \xi = \left(\xi^i a_{,i} + a\, \xi^i_{,i}\right) dx^1 \wedge \ldots \wedge dx^n$$

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and $\xi = \xi^i(x)\frac{\partial}{\partial x^i}$ (vector field)

Then:

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only dx^i term survives in wedge product

$$\Rightarrow \operatorname{div}_\Omega \xi = \left(\xi^i a_{,i} + a\, \xi^i_{\ ,i}\right) dx^1 \wedge \ldots \wedge dx^n$$

$$\Rightarrow \boxed{\operatorname{div}_\Omega \xi = \frac{1}{a}\left(a\, \xi^i\right)_{,i} \Omega}$$

Notice: If $a \equiv 1$ then $\operatorname{div}_\Omega \xi = \frac{\partial \xi^i}{\partial x^i}$ as expected for the divergence in the simplest case.

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$$\Longrightarrow \boxed{\mathrm{div}_\Omega \xi = d \circ i_\xi(\Omega)}$$

Recall: $d\Omega = 0$ because anti-symmetry doesn't allow $(n+1)$ forms.

We can now apply Stokes' theorem $\int_G dv = \int_{\partial G} v$:

$$\int_G d\, i_\xi(\Omega) = \int_{\partial G} i_\xi(\Omega)$$

i.e.:

$$\boxed{\int_G \overbrace{\mathrm{div}_\Omega \xi}^{n\text{-form}} = \int_{\partial G} \overbrace{i_\xi(\Omega)}^{(n-1)\text{ form}} \qquad \text{"Gauß' theorem"}}$$

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→ So far, we have:

- differentiations, ξ, d, i_ξ, L_ξ, $\mathrm{div}_\xi \Omega$
- integration $\int_G \nu$

But, still lacking:

- A notion of distance between points!

The problem:

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