GR for Cosmology, Achim Kempf — Lecture 10

Note Title

Recall:

- The curvature map, R, is defined through:

$$R: \ \xi_1, \xi_2, \xi_3 \rightarrow R(\xi_1,\xi_2)\xi_3 = \underbrace{\left(\nabla_{\xi_1}\nabla_{\xi_2} - \nabla_{\xi_2}\nabla_{\xi_1} - \nabla_{[\xi_1,\xi_2]}\right)}_{\overset{''}{R}(\xi_1,\xi_2)}\xi_3$$

So, "R" can stand for the tensor, the map and this R!

- 1st Bianchi Identity:

$$\sum_{cyclic} R(\xi,\eta)\nu = \sum_{cyclic}\Big(T(T(\xi,\eta),\nu) + (\nabla_\xi T)(\eta,\nu)\Big)$$

- 2nd Bianchi Identity:

$$\sum_{cyclic}\Big((\nabla_\xi R)(\eta,\nu) + R(T(\xi,\eta),\nu)\Big) = 0$$

In a chart?

(Assuming no torsion, and using $\frac{\partial}{\partial x^i}$, dx^i bases)

1st Bianchi: $\displaystyle\sum_{(jkl)} R^i{}_{jkl} = 0$

↑ cyclic sum

2nd Bianchi: $\displaystyle\sum_{(klm)} R^i{}_{jkl;m} = 0$

↑ cyclic sum

Other useful properties:

(Note: This antisymmetry will be useful because it allows one to view R as a 2 form, which is (1,1) tensor-valued.)

- $R^i{}_{jkl} = -R^i{}_{jlk}$ ⟵
- $R_{ijkl} = -R_{jikl}$
- $R_{ijkl} = R_{klij}$

$$\begin{pmatrix} \langle R(\xi,\eta)\nu,\varsigma\rangle = \langle R(\xi,\eta)\varsigma,\nu\rangle \\ \langle R(\xi,\eta)\nu,\varsigma\rangle = -\langle R(\nu,\varsigma)\xi,\eta\rangle \end{pmatrix}$$

Contractions of R:

The Ricci Tensor: $R_{jl} := R^{i}{}_{jil}$

⇒ clearly: $R_{jl}\, dx^j \otimes dx^l \in T_p(M)_2$

The Curvature Scalar: $R := g^{jl} R_{jl}$

Then, 2nd Bianchi identity implies:

$$\left(R_i{}^k - \frac{1}{2}\delta_i{}^k R\right)_{jk} = 0$$

⇒ The so-called "Einstein tensor" $G_i{}^k := R_i{}^k - \frac{1}{2}\delta_i{}^k R$ obeys:

$$G_i{}^k{}_{jk} = 0$$

(this property was crucial guidance for Einstein, as we will see)

Recall strategy:

- Specified g ⇒ specified distances in M
  ⇒ implicitly specified "shape" of M

Then, alternatively:

- Specified ∇ ⇒ specified parallel transport in M
  ⇒ specified "shape" of M, namely:
  ∇ specifies Torsion T and Curvature R.

Now assume a manifold is specified by giving a metric g.

There ought to exist a ∇ which describes the same manifold.

How does g determine Γ?

Idea: The parallel transport of vectors η, ν must be such that their inner product (i.e. their lengths and relative angles) stays constant:

Consider any path γ and any two vector fields η, ν that are $\underbrace{\text{parallel transported}}_{\text{(i.e., autoparallel to } \gamma)}$ along γ, i.e., for which:

$$\nabla_{\dot\gamma}\, \eta(\gamma(t)) = 0, \quad \nabla_{\dot\gamma}\, \nu(\gamma(t)) = 0 \quad \text{for all } t.$$

Then, require: $$\frac{d}{dt}\Big(g(\gamma(t))_{bc}\ \eta^b(\gamma(t))\ \nu^c(\gamma(t))\Big) = 0$$

i.e.: $$0 = \overbrace{\dot\gamma^a \left(g_{bc}\,\eta^b \nu^c\right)_{;a}}^{\frac{d}{dt}(\ldots) \,=\, \nabla_{\dot\gamma}\langle g, \eta\otimes\nu\rangle} \overset{\text{by } \nabla \text{ obeying Leibniz rule}}{=} \dot\gamma^a\Big(g_{bc;a}\,\eta^b \nu^c + g_{bc}\,\overbrace{\eta^b{}_{;a}}^{0 \text{ because } \nabla_{\dot\gamma}\eta = 0}\,\nu^c + g_{bc}\,\eta^b\,\overbrace{\nu^c{}_{;a}}^{0 \text{ because } \nabla_{\dot\gamma}\nu = 0}\Big)$$

$\Rightarrow$ $0 = g_{bc;a}\,\dot\gamma^a \eta^b \nu^c$ for all arbitrary $\dot\gamma, \eta, \nu$!

$\Rightarrow$ Compatibility of ∇ with g means:

$$\boxed{\nabla_\xi g = 0 \quad \text{for all } \xi}$$

Is there a ∇ for each choice of g? Indeed:

Fund. theorem of (pseudo) Riemannian geometry:

For each (pseudo) Riemannian manifold (M, g) there exists a unique ∇ that is torsionless and compatible with g, i.e., which obeys $\nabla g = 0$, the Levi-Civita connection.

More generally: $\forall (M, g)$ and a tensor field T with $T^k_{ij} = -T^k_{ji}$ there is a metric-preserving ∇ whose torsion is T.

In a chart: How to obtain the Levi-Civita ∇ from g?

$\nabla g = 0$ means $\quad g_{\mu\nu,\alpha} - g_{\mu\beta}\Gamma^{\beta}{}_{\nu\alpha} - g_{\beta\nu}\Gamma^{\beta}{}_{\mu\alpha} = 0 \qquad \underline{\text{I}}$

i.e. $\quad g_{\alpha\mu,\nu} - g_{\alpha\beta}\Gamma^{\beta}{}_{\mu\nu} - g_{\beta\mu}\Gamma^{\beta}{}_{\alpha\nu} = 0 \qquad \underline{\text{II}}$

and $\quad g_{\nu\alpha,\mu} - g_{\nu\beta}\Gamma^{\beta}{}_{\alpha\mu} - g_{\beta\alpha}\Gamma^{\beta}{}_{\nu\mu} = 0 \qquad \underline{\text{III}}$

take: $\frac{1}{2}\left(-\underline{\text{I}} + \underline{\text{II}} + \underline{\text{III}}\right)$

$$\Rightarrow \frac{1}{2}\left(g_{\alpha\mu,\nu} + g_{\nu\alpha,\mu} - g_{\mu\nu,\alpha}\right) = g_{\alpha\beta}\Gamma^{\beta}{}_{\nu\mu}$$

Thus:

$$\Gamma^{\beta}{}_{\nu\mu} = \frac{1}{2} g^{\alpha\beta}\left(g_{\alpha\mu,\nu} + g_{\nu\alpha,\mu} - g_{\mu\nu,\alpha}\right)$$

↑ "Levi-Civita" connection or also called "Riemannian" connection.

Upgrade the math:

- Make use of arbitrary bases e_i, θ^i in (co-) tangent spaces: frames
- Allow forms to be tensor-valued: obtain, e.g., torsion and curvature forms. Also: connection forms.

$\Rightarrow$ We will obtain powerful, simple equations that relate ∇, g, R, T. (Even the Bianchi identities will look simple)

Now: Assume again that ∇ and g are still unrelated and $T \neq 0$.
(possibly)

"Moving frames":

Def: A "moving frame" is a set, $\{e_i\}_{i=1}^{n}$, of contravariant vector fields e_i which, together, at each point $p \in M$ form a basis of $T_p(M)$'.

Def: We denote the dual basis $\{\theta^i\}_{i=1}^{n}$.

It obeys: $\theta^i(e_j) = \delta^i_j$.

Def: For $n=4$ it may be called $\overbrace{\text{vierbein}}^{\text{german: 4 legs.}}$ or tetrad.

(in arb. dimensions: "vielbein" = many legs)

Notice: Each co-vector $\theta^i(x)$ is a 1-form, and $d\theta^i$ is a 2-form!

Def: Collect them in a "Frame": $\theta^i \otimes e_i$, i.e. a (1,0)-tensor valued 1-form

Remark: If we choose e.g. $\theta^i(x) := dx^i$, then $d\theta^i(x) = 0$.

Remark: A general choice for the $\theta^i(x)$ can always be written in the form:

$$\theta^i(x) = \lambda(x)^i{}_j \, dx^j$$

↳ scalar coefficient functions

Def: We denote the expansion coefficients by functions $C^i{}_{jk}$:

$$\boxed{d\theta^i = \overbrace{-\frac{1}{2}}^{\text{convention}} C^i{}_{jk} \, \underbrace{\theta^j \wedge \theta^k}_{\text{basis for space of all 2 forms}} \quad \text{with} \quad \underbrace{C^i{}_{jk} = -C^i{}_{kj}}_{\text{the sym. part would drop out}}}$$

coefficient functions depend on choice of frame

Exercise:

Express the $C^i{}_{jk}$ in terms of the $\lambda^i{}_j$.

Coefficients:

- Torsion: $T^i{}_{kl} := \langle \theta^i, T(e_k, e_l) \rangle$
- Curvature: $R^i{}_{jkl} := \langle \theta^i, R(e_k, e_l) e_j \rangle$
- Metric: $g_{ik} := g(e_i, e_k) = \langle e_i, e_k \rangle$
- Christoffel: $\Gamma^i{}_{kj} e_i := \nabla_{e_k} e_j$

Consider arbitrary change of frame:

(has nothing to do with a change of chart!)

- assume $\bar{\theta}^i(x) = A^i{}_j(x)\, \theta^j(x)$
- then: $\bar{e}_i(x) = (A^{-1})_i{}^j(x)\, e_j(x)$

(because we chose bases that are dual: $\bar{\theta}^i(\bar{e}_j) = \delta^i{}_j$)

Another step towards more abstract formulation:

Tensor-valued p-forms:

Def: A (r,s)-tensor-valued p-form ϕ is an anti-symmetric p-multilinear mapping at each $q \in M$:

$$\phi : \underbrace{T_q(M)^1 \times \ldots \times T_q{}^1(M)}_{p \text{ factors}} \longrightarrow T_q(M)^r{}_s$$

Def: The p-forms $\phi^{i_1 \ldots i_r}_{j_1 \ldots j_s} := \phi(\theta^{i_1}, \ldots \theta^{i_r}; e_{i_1}, \ldots, e_{i_s})$ are called the component p-forms relative to the basis $\{e_i\}_{i=1}^n$.

Special cases:

- (r,s) tensors are (r,s) tensor-valued 0-forms.
- p-forms are $(0,0)$ tensor-valued forms.

Torsion 2-form:

- We recall that $T(\xi,\eta) = -T(\eta,\xi) \Rightarrow$ can define the torsion's (1,0) tensor-valued 2-form through its action on 2 vector fields ξ, η:

"torsion 2-form"

$$\underbrace{\Theta^i(\xi,\eta)e_i}_{\substack{\text{the 2 form } \Theta^i \\ \text{fed 2 vectors to} \\ \text{yield a vector}}} := T(\xi,\eta)$$

- Given a frame:

using their antisymmetry

$$\Theta^i = \frac{1}{2} T^i{}_{k\ell}\, \theta^k \wedge \theta^\ell$$

Curvature 2-form:

recall that in canonical basis:

$$R^i{}_{jk\ell} = -R^i{}_{j\ell k}$$

- We recall that also $R(\xi,\eta) = -R(\eta,\xi)$

$\Rightarrow$ can define curvature's (1,1) tensor-valued 2-form:

"curvature 2-form"

$$\underbrace{\overbrace{\Omega^i{}_j(\xi,\eta)}^{\text{numbers}}e_i}_{\text{tangent vector}} := \underbrace{R(\xi,\eta)e_j}_{\text{tangent vector}}$$

Recall: $R: \xi\,\eta\, e_j \rightarrow \nabla_\xi \nabla_\eta e_j - \nabla_\eta \nabla_\xi e_j - \nabla_{[\eta,\xi]} e_j$

- Given a frame $\{\theta^i\}_{i=1}^n$:

$$\Omega^i{}_j = \frac{1}{2} R^i{}_{jk\ell}\, \theta^k \wedge \theta^\ell$$

The connection as a form?

- Nontrivial because:

  1. Christoffels $\Gamma^i{}_{kj} e_i := \nabla_{e_k} e_j$ are not tensors to start with!

  2. $\Gamma^i{}_{kj}$ is not anti-sym. in any indices, so can't be a 2-form (but can be 1-form):

- Define the connection 1-forms $\omega^i{}_j$: $\boxed{\omega^i{}_j := \Gamma^i{}_{kj}\,\theta^k}$

Thus:

$$\boxed{\underbrace{\nabla_\xi e_j}_{\text{vector}} = \underbrace{\overbrace{\omega^i{}_j(\xi)}^{\text{scalars}}\, e_i}_{\text{vector}}}$$

(because $\nabla_{\xi^k e_k} e_j = \xi^k \nabla_{e_k} e_j$)

- Proposition: cov. deriv. for covectors reads

$$\nabla_\xi \theta^i = -\omega^i{}_j(\xi)\,\theta^j$$

Proof:

Leibniz rule and using that ∇ and contractions commute

$$0 = \nabla_\xi \underbrace{\langle \theta^i, e_j \rangle}_{=\delta^i_j} = \langle \nabla_\xi \theta^i, e_j \rangle + \langle \theta^i, \nabla_\xi e_j \rangle$$

$$= \langle \nabla_\xi \theta^i, e_j \rangle + \underbrace{\langle \theta^i, \omega^k{}_j(\xi) e_k \rangle}_{= \omega^i{}_j(\xi) \text{ because } \langle \theta^i, e_k \rangle = \delta^i_k} \qquad (*)$$

$\Rightarrow$ indeed:

$$\boxed{\nabla_\xi \theta^i = -\omega^i{}_\ell(\xi)\,\theta^\ell}$$

(contract with $\langle\ , e_j \rangle$ to verify that this is Eq. $(*)$)

✓

Connection 1-forms are non-tensorial:

Proposition: Under change of frame $\bar\theta^i(x) = A^i{}_j(x)\,\theta^j(x)$ the transformation is:

$$\underbrace{\bar\omega^a{}_b}_{\text{1-form}} = \underbrace{\overset{\text{functions}}{A^a{}_i}\,\overset{\text{1-form}}{\omega^i{}_j}\,\overset{\text{functions}}{A^{-1\,j}{}_b}}_{\text{1-form}} - \underbrace{\underbrace{(d\overset{\text{function}}{A})^a{}_i}_{\text{1-form}}\underbrace{(A^{\overset{\text{matrix inverse.}}{-1}})^i{}_b}_{\text{functions}}}_{\text{1-form}}$$

Proof:

$$-\bar\omega(\xi)^a{}_b\,\bar\theta^b = \nabla_\xi\bar\theta^a = \nabla_\xi(A^a_b\theta^b) \overset{\text{Leibniz rule}}{=} \big(\overbrace{dA^a_b(\xi)}^{=\xi(A^a{}_b)}\big)\,\theta^b + A^a_b\nabla_\xi\theta^b$$

$$= dA^a{}_b(\xi)\,\theta^b - A^a{}_b\,\omega(\xi)^b{}_c\,\theta^c$$

$$= dA^b{}_b(\xi)\,A^{-1\,b}{}_c\,\bar\theta^c - A^a{}_b\,\omega(\xi)^b{}_c\,A^{-1\,c}{}_d\,\bar\theta^d \quad ✓$$

true for all $\bar\theta$ ⇒ proposition above.

The "absolute exterior differential" D:

(It generalizes both ∇ and d)

▯ **Proposition:** (proof, see e.g. Straumann: check tensorial behavior under frame change)

For every (r,s) tensor-valued p-form ϕ there exists a unique (r,s) tensor-valued $(p+1)$ form $D\phi$ whose components relative to $\{\theta^i\}$ are:

$$(D\phi)^{i_1\ldots i_r}_{j_1\ldots j_s} = \underbrace{d\,\underbrace{\phi^{i_1\ldots i_r}_{j_1\ldots j_s}}_{p\text{-form}}}_{p+1\text{ form}} + \overbrace{\overset{\text{1 form}}{\omega^{i_1}{}_l}\wedge\overset{p\text{-form}}{\phi^{l i_2\ldots i_r}_{j_1\ldots j_s}}}^{(p+1)\text{-form}} + \ldots$$

$$- \omega^l{}_{j_1}\wedge\phi^{i_1,\ldots,i_r}_{l,\ldots,j_s} - \ldots \qquad (*)$$

Proposition: D is an anti-derivation:

degree of ϕ

$$D(\phi\wedge\psi) = D\phi\wedge\psi + (-1)^p\,\phi\wedge D\psi$$

Special cases:

- An ordinary p-form is (0,0) tensor-valued. In this case, clearly:

$$D = d$$

- An ordinary tensor field is a tensor-valued 0-form. In this case:

$$D = \nabla$$

Exercise: Verify

Hint: Choose frame $\theta^i = dx^i$, use $\omega^i{}_j = \Gamma^i{}_{kj}\theta^k$, then show (*) implies indeed:

$$\phi^{i_1\ldots i_r}{}_{j_1\ldots j_s;k} = \phi^{i_1\ldots i_r}{}_{j_1\ldots j_s,k} + \Gamma^{i_1}{}_{kl}\,\phi^{l i_2\ldots i_r}{}_{j_1\ldots j_s} + \ldots - \Gamma^{l}{}_{kj_1}\,\phi^{i_1\ldots i_r}{}_{l j_2\ldots j_s} - \ldots$$

How are $\omega, g, \Theta, \Omega$ related now?

Proposition: (Exercise: check)

An affine connection ∇ is metric, if and only if $Dg = 0$, i.e., iff:

$$\boxed{\underbrace{dg_{ik}}_{(0,2)\text{ tensor-valued 1-form}} - \omega_{ik} - \omega_{ki} = 0}$$

Theorem: "The Cartan structure equations"

They express torsion and curvature in terms of the connection

In special case of frame $\theta^i = dx^i$:

$T^i{}_{kj} = \Gamma^i{}_{kj} - \Gamma^i{}_{jk}$

1.) $\Theta^i = d\theta^i + \omega^i{}_j\wedge\theta^j$ i.e. $\Theta^i = D\theta^i$

$= 0$ for metric connection

Torsion $\Theta = \Theta^i e_i$ is (1,0) tensor-valued 2-form

(The frame, $\theta = \theta^i e_i$ is a $\underbrace{(1,0)\text{ tensor-valued}}_{\text{notice the upper index}}$ $\underbrace{1\text{-form}}_{\text{clear}}$.)

$R^i{}_{jkl} = \Gamma^i{}_{lj,k} - \Gamma^i{}_{kj,l} + \Gamma^s{}_{lj}\Gamma^i{}_{ks} - \Gamma^s{}_{kj}\Gamma^i{}_{ls}$

2.) $\Omega^i{}_j = d\omega^i{}_j + \omega^i{}_k\wedge\omega^k{}_j$

Proof of 2.:

$$\Omega^i{}_j(\xi,\eta)e_i = \nabla_\xi \nabla_\eta e_j - \nabla_\eta \nabla_\xi e_j - \nabla_{[\xi,\eta]} e_j$$

$$= \underbrace{\nabla_\xi\left(\omega^i{}_j(\eta)e_i\right)} - \nabla_\eta\left(\omega^i{}_j(\xi)e_i\right) - \omega^i{}_j([\xi,\eta])e_i$$

Leibniz

$$= \Big(\overbrace{\xi\big(\omega^i{}_j(\eta)\big)} - \eta\big(\omega^i{}_j(\xi)\big) - \omega^i{}_j([\xi,\eta])\Big)e_i$$

Exercise: Fill in all steps.

$$+\Big(\overbrace{\omega^i{}_j(\eta)}\,\omega^k{}_i(\xi) - \omega^i{}_j(\xi)\,\omega^k{}_i(\eta)\Big)e_k$$

$$= d\omega^i{}_j(\xi,\eta)e_i + \left(\omega^i{}_k \wedge \omega^k{}_j\right)(\xi,\eta)e_i$$

true for all $\xi, \eta, e_i \Rightarrow$ ✓

Use of the Cartan Structure equations?

☐ Allow proof of simple formulation of the Bianchi identities:

1st Bianchi: $D\Theta^i = \Omega^i{}_j \wedge \theta^j$

2nd Bianchi: $D\Omega^i{}_j = 0$

i.e. "Riemannian", i.e. "Levi Civita", without torsion.

☐ Thus, for metric connection, i.e. when $dg_{ik} = \omega_{ik} + \omega_{ki}$ and $\Theta^i = 0$ (same as $\nabla g = 0$, and $\Gamma_{ij} = \Gamma_{ji}$)

then:

$$\boxed{\begin{aligned} \Omega^i{}_j \wedge \theta^j &= 0 \\ D\Omega^i{}_j &= 0 \end{aligned}}$$

Proposition:

- In the case of metric connection, the Cartan equations yield for <u>arbitrary</u> bases:

$$\Gamma^l_{ki} = \frac{1}{2}\Big(\overbrace{C^l_{ki} - g_{is}g^{lj}C^s_{kj} - g_{ks}g^{lj}C^s_{ij}}^{C^l_{ki} = 0 \text{ in canonical frame } \{dx^i\}}\Big)$$

$$+\frac{1}{2}\, g^{lj}\left(g_{ij,k} + g_{jk,i} - g_{ki,j}\right)$$

Recall:

$$d\theta^i = \overbrace{-}^{\text{convention}}\frac{1}{2}\underbrace{C^i_{jk}}_{\substack{\text{coefficient functions}\\ \text{depend on choice of frame}}}\underbrace{\theta^j \wedge \theta^k}_{\substack{\text{basis for space}\\ \text{of all 2 forms}}}$$

- In this case, also:

$$R^i_{jab} = \Gamma^i_{bj,a} - \Gamma^i_{aj,b} + \Gamma^i_{al}\Gamma^l_{bj} - \Gamma^i_{bl}\Gamma^l_{aj} - \Gamma^i_{lj}\overset{\substack{\text{absent in}\\ \text{canonical frame}}}{\downarrow}{C^l_{ab}}$$